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STAFF REPORT

SB 423 Emerging Renewable and Firm Zero-Carbon Resources Report

Assessment of Firm Zero-Carbon Resources to Support a Clean, Reliable, and Resilient California Grid

December 2024 | CEC-200-2024-012

California Energy Commission

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ABSTRACT

This report addresses a requirement in Senate Bill 423, (Stern, Chapter 243, Statutes of 2021). 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 firm zero-carbon resources that support a clean, reliable, and resilient electrical grid in California.

Keywords: Reliability, demand side resources, supply side resources, extreme events, climate change, reliability assessments

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Background

California's electricity system is undergoing significant transition with the overarching goal of achieving 100 percent clean electricity by 2045, as mandated through 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 renewables complemented by natural gas power plants, offering operational flexibility and reliability during the transition. This transitional phase underscores the incremental integration of cleaner technologies, marking a significant departure from conventional fossil sources. The ultimate objective is a paradigm shift towards a 100 percent clean electricity system, by gradually displacing carbon-intensive technologies with innovative, zero-emission solutions. This report addresses the need to assess emerging firm zero-carbon resources through Senate Bill 423 (Stern, Chapter 243, Statutes of 2021). These resources will be considered for deployment to address (1) local reliability, (2) system reliability, and (3) emissions reductions within California.

This report defines and 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. Each technology is thoroughly reviewed, encompassing technological overviews, manufacturing and supply chain considerations, anticipated improvements, and performance and cost characteristics. The reliability assessment utilizes the California Public Utilities Commission's (CPUC) Preferred System Plan and the California Energy Commission (CEC) Reliability Model, analyzing multi-day events across different seasons and assessing the potential need for firm resources. Furthermore, current research and development initiatives and projects are discussed for long-duration energy storage, renewable natural gas, and hydrogen. The report concludes by summarizing key barriers and providing recommendations to address challenges in the adoption and implementation of firm zero-carbon resources.

Resource Eligibility

Within the context of this analysis, firm zero-carbon resources are defined as those that reliably produce zero-carbon or renewable electricity on demand, as defined by the Renewables Portfolio Standard in SB 100, ensuring a consistent and stable power supply for extended periods. There were eight resources that met these criteria and were considered within the assessment. These resources, along with a high-level synopsis, are described below:

- **Long duration energy storage** covers durations of eight hours or more via (1) electrochemical, (2) thermal, (3) mechanical, and (4) gaseous storage technologies and can be zero-carbon when charged with clean generating resources. Only lithium-ion batteries and vanadium redox flow batteries have reached full maturity, while all other technologies are still emergent. Typical technological challenges exist for long duration energy storage such as high capital costs and insufficient efficiency and durability. Uniquely, though, energy markets are not designed to support these technologies, necessitating new market participation rules.

- **Hydropower** resources are fully mature, but most viable sites for traditional hydropower within California have already been exhausted. The existing fleet is aging and funds must be used to refurbish these plants. There is also expected to be growth within pumped storage hydropower, which is currently the least expensive, large-scale energy storage technology in terms of cost per megawatt hour.
- **Geothermal** technologies have historically relied upon natural geological conditions, but a majority of future deployments are expected to be enhanced geothermal systems which can unlock reservoirs previously deemed unsuitable due to limited permeability or fluid saturation. California must allow for significant development lead time to prepare for project complexity and required environmental review at the federal and state levels.
- **Renewable natural gas** can be utilized within existing natural gas power generators so production technologies are the primary challenge; these vary in maturity with anaerobic digesters, landfill gas collectors, and certain gasification configurations already deployed throughout California. Renewable natural gas viability may be enhanced with greater system adaptability to feedstock variations and fuel cost competitiveness with fossil natural gas.
- **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 like fuel cells, which are better suited for distributed applications. Despite their potential for clean electricity production, all hydrogen generation technologies are nascent and face certain challenges to deployment, including - relatively low volumetric energy density, high costs associated with production and storage, and criteria pollutant emissions from combustion processes.
- **Small Modular Reactors**, largely at the demonstration phase, vary significantly in physical design, coolant type, and nuclear process. They generally offer lower initial capital investments, increased siting flexibility, and greater scalability than traditional fission reactors. Challenges exist with public perception of safety, and new deployment is barred in California due to California's moratorium on new fission reactors.
- **Fusion** technologies offer transformative potential without the production of nuclear waste, but systems are not close to commercial readiness and research has remained within a laboratory environment so far. As development progresses, cost reduction, reactor safety with high operating temperatures, and system decommissioning impacts must be high priorities.
- **Carbon capture** allows for existing fossil-fuel power generation assets, which are firm resources, to remain active while abating most associated carbon emissions. Carbon capture resources for natural gas power generation are somewhat nascent and systems must improve cost-effectiveness and capture efficiency with flue gas containing low CO_2 concentrations.

In addition to the resources discussed above, California needs to continue advance demand flexibility technologies and programs, which can allow more effectively **utilizing** customer resources, such as residential energy storage and **vehicle-to-grid**, to support the grid during high net-peak hours. As discussed in the SB 846 Load Shift Goal report, load flexibility must play a critical part in grid decarbonization by aligning customer demand with the supply of clean energy to integrate new renewables onto the grid, reduce the strain new electric load places on the grid, and help maintain electric reliability during extreme events, such as record-setting heat, droughts, and wildfires.

Reliability Analysis

This analysis looked at outage probability during multi-day events in all seasons and the potential need for firm zero-carbon resources in meeting reliability goals. These events were studied using the CEC's statewide probabilistic reliability model.

The multi-day events studied were all three days long and had either high net peaks, high net loads, or low penetration of variable renewable energy resources. Each event was studied under four import conditions. Only summer events showed significant probability of outages. With the 2023 resource build and forecasted demand, only the high peak events stressed the system, while under the projected 2033 resource build and demand, both high net peak and high net load events experienced challenges when imports were restricted overnight. The high net load event experienced long overnight outages and issues with charging batteries fully that suggest firm and/or longer duration storage resources would provide more reliability benefit than 4-hour storage.

The potential need for firm resources was studied by analyzing how much firm/non-firm resources can be added to or removed from the model to meet reliability standards. Staff observed that 1,600 MW of firm resources was approximately equal to a combination of 2,000 MW of use-limited resources and 3,000 MW of intermittent resources. This equivalence scales linearly and is used to quantify the need for firm resources on a capacity-basis.

Barriers and Recommendations

This comprehensive evaluation explores the fundamental barriers and recommendations for firm zero-carbon resources, encompassing key areas such as research and development, improvements, interconnection and permitting, as well as policy and finance. In the area of research and development, the focus is directed towards addressing evolving technological development needs. The assessment identifies opportunities for improvements in interconnection and permitting processes crucial for developing firm zero-carbon resources, while simultaneously considering outreach and educational elements essential for public collaboration and engagement. Lastly, policy and finance considerations are imperative to signal markets effectively and construct financial models that facilitate continued resource development, contribute to well-informed policies aligned with California's long-term climate goals and promote innovation and improved project development.

As technologies mature and reach commercialization, overcoming key barriers becomes essential for optimal performance and adoption. A comprehensive analysis explored various barrier categories, including research & development, siting requirements, manufacturing, interconnection, permitting & regulations, financing, competitiveness, operations & maintenance, safety, environmental impact, and public perception. Six common barriers were identified across all firm zero-carbon resources, emphasizing challenges such as:

1. Elevated costs
2. Supply chain limitations

3. Public perception concerns
4. Infrastructure dependencies
5. Specific siting requirements
6. Performance challenges

The shared challenges emphasize the need for strategic recommendations to facilitate greater adoption of firm zero-carbon resources. These recommendations include:

1. Supporting cost reduction and efficiency initiatives,
2. Developing sustainable systems,
3. Exploring market structure redesigns,
4. Investigating the impacts of drought,
5. Implementing efficient environmental review processes,
6. Encouraging investments,
7. Emphasizing community engagement, and
8. Optimizing feedstock and fuel infrastructure.

Stakeholder Feedback and Continuous Improvement

The CEC released the Draft SB 423 report[1] on August 2, 2024, for public comment and received robust and thoughtful feedback. While not all suggested changes are incorporated into this Final Report, the feedback will guide future reporting as part of a commitment to continuous improvement. The CEC remains dedicated to refining its analysis and reporting, with planned updates in future Integrated Energy Policy Reports. Future reporting will include updates to costs, improvements to technology characterization, changes to better evaluate biomass/bioenergy technologies, and improvements to models and valuation of various technologies in this report.

In conclusion, ongoing support for these evolving resources is crucial for their effective development, systematic barrier resolution, and seamless integration, while contributing to California's climate goals and securing the broader benefits of firm zero-carbon resources to the electric system.

1 CEC. 2024. *Draft SB 423 Emerging Renewable and Firm Zero-Carbon Resources Report*. Docket number 21-ESR-01. https://efiling.energy.ca.gov/GetDocument.aspx?tn=258290&DocumentContentId=94286.

CHAPTER 1: Introduction

Background

California has a longstanding history of pioneering ambitious renewable energy and climate policies that have set the bar for the nation and the world. With a vision of fostering a cleaner, more equitable economy, the state is on a mission to achieve 100 percent clean electricity by 2045 and subsequently achieve net negative emissions. Central to this endeavor is the imperative task of decarbonizing the electric grid, an essential step towards realizing economy-wide carbon neutrality.

At the forefront of this effort stands the Renewables Portfolio Standard (RPS), which has played a pivotal role in driving the growth of clean electricity generation. Mandating that the state's electric utilities progressively incorporate renewable energy sources such as solar and wind into their power generation mixes, California has not only exceeded expectations in reaching its 33 percent renewable energy target by 2020 but is also on a trajectory to achieve 60 percent renewable energy by 2030.

California SB 100 sets forth ambitious requirements for the state's transition to renewable and zero-carbon resources, underscoring the commitment to a sustainable energy future. The bill, passed in 2018, commits California to achieve 100 percent clean electricity by 2045. The bill states, "[i]t is the policy of the state that eligible renewable energy resources and zero-carbon resources supply 100 percent of all retail sales of electricity in California by December 31, 2045." This landmark legislation not only emphasizes the imperative of renewable energy but also recognizes the importance of zero-carbon resources, such as nuclear and hydropower, in the comprehensive effort to combat climate change and ensure a clean energy landscape for the state of California. Meeting the requirements of SB 100 requires a multifaceted approach, harnessing the potential of various zero-carbon technologies to drive California towards a sustainable, decarbonized energy future.

As California faces a new climate reality and advances towards a predominantly renewable energy grid, it bis evident that planning processes must evolve to cater to the diverse needs of all Californians who rely on safe, affordable, and dependable electricity daily. The successful integration of 100 percent renewable and zero-carbon electricity, along with the goal of achieving carbon neutrality by 2045, necessitates meticulous analysis of implementation factors and a coordinated approach across state agencies.

In addition to implementation efforts, there are several challenges. One of these challenges is maintaining reliability through the peak and net peak, which is when electricity usage is highest and after sunset when electricity usage is still high but solar and wind are no longer available. With the retirement of aging conventional resources and rising demand due to electrification, economic growth, and increased usage of air conditioning during climate-driven heat events, renewable, zero-carbon and storage technologies are becoming increasingly crucial to ensure we can meet future demand. California is projecting 10.5 GW Net Qualifying Capacity (NQC) to be added in the next 3 years. However, supply chain issues can disrupt the deployment of renewable energy technologies and infrastructure, potentially causing delays and cost overruns.

Legislative Requirements

Senate Bill (Stern, Chapter 243, Statutes of 2021) requires that the CEC, in consultation with CPUC, California Independent System Operator (California ISO), and California Air Resources Board, submit to the Legislature an assessment of emerging firm zero-carbon resources that support a clean, reliable, and resilient electrical grid in California. In developing the report, the assessment shall identify available, commercially feasible and near-commercially feasible emerging renewable energy and firm zero-carbon resources and distinguish which resources can address system reliability needs, local reliability needs, and de-energization events. The assessment shall evaluate the potential needs for and role of these resources using a reasonable range of resource cost and performance assumptions. The assessment shall also identify barriers to the procurement of these resources and possible pathways for additional procurement. The report was due to the Legislature by December 31, 2023.

Firm Zero-Carbon Resources

This report aims to identify and assess available, commercially feasible, and near-commercially feasible firm zero-carbon resources to support a clean, reliable, and resilient electrical grid. The focus is on resources capable of addressing both system-wide and local reliability needs while concurrently reducing emissions of greenhouse gases, toxic air contaminants, and criteria air pollutants. For the purposes of this assessment, firm zero-carbon resources are defined as those that reliably produce zero-carbon or renewable, as defined by the Renewables Portfolio Standard, electricity on demand, ensuring a consistent and stable power supply for extended periods.

To meet the criteria outlined, identified resources must exhibit steady electricity output, disqualifying stand-alone wind or solar resources due to their variable power output. Additionally, the resources may employ zero-carbon fuel storage technologies, such as hydrogen storage and reservoirs, and must be capable of multi-day operations during extreme events. These resources should be dispatchable while operating on a schedule that ensures reliability but do not necessarily have continuous 24/7 operation. Furthermore, the assessment explores the potential of natural gas paired with carbon capture, allowing for flexibility in fuel usage, with considerations for a 100 percent capture rate or partial counting for less than 100 percent

Role of Firm Zero-Carbon Resources

Firm zero-carbon resources, as identified in SB 423, have three major roles: local reliability, system reliability, and produce minimal emissions within California's energy system. This assessment provides an overview of firm zero-carbon resources and their ability to fit within each role. Local reliability, within the California ISO system, entails ensuring specific areas consistently meet their electricity needs, especially in regions with limited transmission access. Simultaneously, the assessment extends to the broader context of system reliability, encompassing the overall ability of the electricity grid to provide a stable and adequate supply while upholding established standards. Furthermore, in alignment with the state's commitment to environmental sustainability, the assessment incorporates emission metrics to underscore the role of firm zero-carbon resources in mitigating the environmental impact of the energy sector.

In addressing local reliability within the California ISO system, the primary focus lies in ensuring that areas with transmission constraints can consistently meet their electricity needs and adhere to established reliability standards. In these areas, the availability of robust local power generation becomes necessary for maintaining a dependable electricity supply. To determine potential deployment regions for firm zero-carbon resources, staff examined the annual California ISO local capacity requirements study and evaluated the suitability of potential regions for the deployment of specific resource technologies, based on technology profile such as size, footprint, and geographical constraints. The local reliability assessment method used in this report was qualitative and may benefit from more detailed analysis.

The concept of energy resiliency was a focal point during the CPUC March 2023 Resiliency workshop,[2] with diverse perspectives being brought forward. Against the complex backdrop of a changing climate, and with a grid that includes aging infrastructure, a resilient grid, generally speaking, means a system that is able to respond to, adapt to, and promptly recover from such disruptions and outages. The approaches taken to pursuing resiliency will be varied and will include new approaches to responding to outages and working to provide a reliable and sustainable energy supply. The workshop facilitated a nuanced understanding of the complex nature of resiliency, considering the diverse challenges and potential solutions that can contribute to a more robust and adaptable energy infrastructure.

In assigning the role of each resource on local reliability and 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 resource be deployed in a distributed fashion to address system disruptions and localized outages?

If the answer to any of those questions 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 low and/or no emissions, staff asked the following questions:

1. **No emissions**: Does the resource not produce emissions during power generation?
2. **Low emissions**: If the answer to the "no emissions" question is no, then does it produce less emissions relative to fossil-fueled generation[3]?

If the answer to any of those questions was yes, then staff assigned one or both roles to the respective resource. Notably, some resources with both designations can be interpreted as having the potential to be within the spectrum of low to zero emissions, based on factors such as configuration, technology advancements, and technology type.

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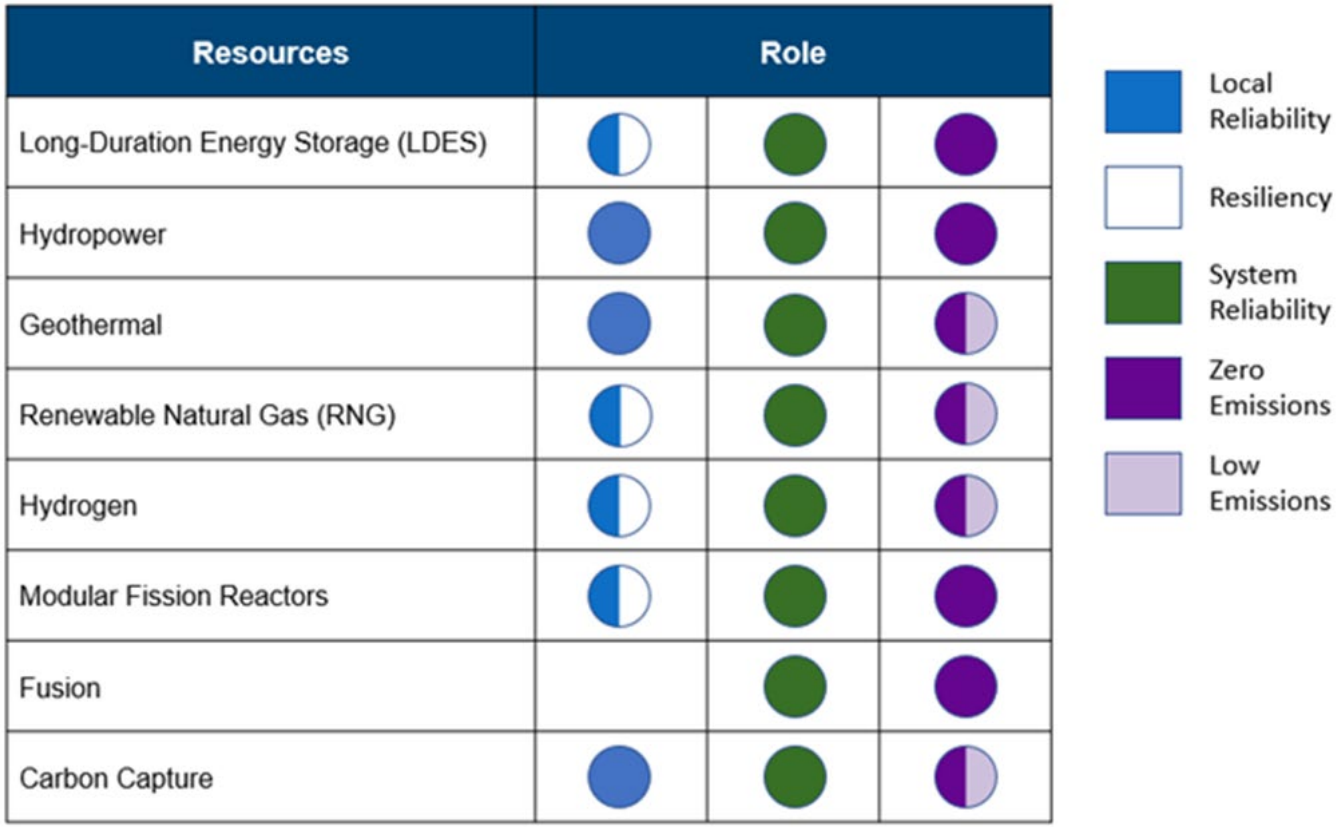
2 CPUC. March 2023. "Value of Resiliency: Resiliency Standards - Definitions Workshop." https://www.cpuc.ca.gov/events-and-meetings/r1909009-workshop-2023-03-21.

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

Figure 1: Overview – Role of Firm Zero-Carbon Resources



Chapter 2: Identification and Assessment of Firm Zero-Carbon Resources

Overview of Technologies

This chapter describes, examines and defines various energy resources that contribute to the overarching objective of achieving firm zero-carbon power generation. Long-duration energy storage (LDES) provides flexibility and firm zero-carbon power when charged by a zero-carbon source. Hydropower produces zero-carbon electricity by harnessing the kinetic energy of flowing or falling water, offering adaptability for both baseload power and short-term supply-demand variations. Geothermal resources contribute to this objective, generating low to zero-carbon electricity suitable for prolonged operational needs. Other additional low to zero-carbon resources include renewable natural gas (RNG), hydrogen (H_2), modular fission reactors (SMRs), fusion, and carbon capture.

Table 1: Resource List

	Resources	Description
1	Long-Duration Energy Storage (LDES)	While not a power generation resource, LDES represents energy storage systems that are able to be dispatched to discharge electricity for durations of 8 hours or more and can be made zero-carbon when charged with clean energy.
2	Hydropower	Renewable energy source that generates zero-carbon electricity by harnessing the energy of flowing or falling water to generate electricity. Hydropower can be utilized for baseload power to serve longer operational needs or as a flexible resource to satisfy short-term supply-demand imbalances.
3	Geothermal	Geothermal resources are reservoirs of hot water below Earth's surface used to produce steam, spin a turbine and activate a generator to produce zero-carbon electricity. This resource is best suited for longer operational needs, such as baseload, due to its ability to run all hours of the day, regardless of weather conditions.
4	Renewable Natural Gas (RNG)	Pipeline-quality gas that is interchangeable with natural gas due to its high methane content and can leverage the same infrastructure for power generation. RNG can operate to address power needs that are currently met by natural gas. RNG is primarily obtained from biomass or organic waste resources, making it a carbon-neutral gaseous fuel.

	Resources	Description
5	Hydrogen	Gaseous fuel that can be utilized for power generation via combustion, fuel cells, or other generator designs. H_2 can operate to address power needs that are currently met by natural gas. H_2 can be zero-carbon when produced with renewable energy or carbon-neutral when produced from biomass and organic waste resources.
6	Modular Fission Reactors (SMRs)	A class of nuclear reactors in development with a power capacity up to 300 MW and the ability to be factory-assembled. Compared to traditional reactors, SMRs offer increased siting flexibility, greater scalability, and lower initial capital investments to provide baseload zero-carbon energy.
7	Fusion	Power generation from nuclear fusion is a potential baseload zero-carbon energy source that harnesses the energy released from the nuclear fusion of two light atomic nuclei, typically hydrogen, in a high temperature environment.
8	Carbon Capture	While not a power generating technology, carbon capture can trap or capture carbon dioxide (CO_2) from different processes, such as fossil fuel combustion for power generation, to avoid or reduce emissions making these low-emissions or zero-carbon. Carbon capture systems are designed to operate based on the emissions of the resource it is paired with.

Source: Guidehouse analysis for this report

Long-Duration Energy Storage (LDES)

As California continues to strive for grid decarbonization, energy storage will play an increasingly critical role in the system to ensure reliability and resilience. While energy storage is already being deployed at scale into the grid, these have primarily been shorter duration (less than four hour) batteries, which are not sufficient to support extended outages, shutoffs, or other longer duration needs. Therefore, LDES[4] systems are promising resources that can support future grid needs, considering longer emergencies and higher renewable energy penetration. While LDES resources are currently not charged by a zero-carbon resource, staff anticipate that LDES will become a firm zero-carbon resource as the technology matures and more renewables come online. In the context of this analysis, LDES is assumed to be charged with zero-carbon energy generation, such as solar and wind, to qualify as a zero-carbon firm resource. More details related to LDES technologies, current deployments, maturity, manufacturing, performance characteristics, costs, and barriers can be found in Appendix C.

Technology Overview

Energy storage technologies are identified primarily by the process by which they store energy. There are four main categories that make up LDES technologies: (1) electrochemical, (2) thermal, (3) mechanical, and (4) gaseous fuels. Gaseous fuel was not covered in detail in

4 LDES is typically defined as energy storage systems that are able to discharge for a duration of 8 hours or more.

this section as this more closely aligns with and depends on the RNG and Hydrogen sections of this analysis. Thermal energy storage technologies were considered in the analysis. However, more data will be needed to capture the performance of these systems within the framework of this report. Notably, various thermal electric energy storage manufacturers, such as Antora Energy, Siemens Gamesa, and Malta, could fit as a LDES firm zero-carbon solution.

For the purpose of this evaluation, the list of potential LDES technologies was limited to those that show the most promise based on their current technology readiness level (TRL),[5] minimum emissions, current deployments, investments, and general ability to be successfully paired with renewable energy sources. There are nine TRLs - 1 is the lowest, which means technology is conceptual, and 9 is the highest, which means the technology has been proven under actual real-world conditions. See glossary for a description of each level.

Table 2 provides a list of the LDES technologies that were evaluated.[6] Lithium-ion (li-ion) systems were excluded from this analysis as they are better suited for shorter duration applications, such as supporting solar and wind plants. Appendix C provides more details about technology characteristics and maturity.

Table 2: Overview of LDES Technologies Evaluated

Categories	LDES Technology	Characteristics	Technology Chemistry	TRL
Electrochemical	Flow Batteries	• Transforms the electron flow from activated liquid electrolyte into electric current • Distinguished by the type of electrolyte used (e.g., vanadium or, zinc) and the state of their energy storing chemical component • Common use cases: large-scale utility or C&I applications	Vanadium Redox	9
Electrochemical	Flow Batteries	• Transforms the electron flow from activated liquid electrolyte into electric current. • Distinguished by the type of electrolyte used (e.g., vanadium or, zinc) and the state of their energy storing chemical component • Common use cases: large-scale utility or C&I applications	Zinc Bromine	8

5 TechLink Center. *Technology Readiness Level (TRL) - Department of Defense*. https://techlinkcenter.org/news/technology-readiness-level-dod/.

6 Most promising LDES technologies were determined from a Guidehouse engagement with CEC focused on LDES where technology developers, manufacturers, and subject-matter experts were interviewed directly.

Categories	LDES Technology	Characteristics	Technology Chemistry	TRL
Electrochemical	Iron Air Batteries	• Uses iron-based anode, air-based cathode, and aqueous electrolyte solution, leveraging rusting as system's oxidation process to produce current. • The use of simple and abundant raw materials, provides potential for low costs as manufacturing capacity scales up	Iron Air	6
Electrochemical	Zinc Batteries	• Systems that utilize metallic zinc as an energy carrier in aqueous electrolytes to produce electrical current • Provides high energy density, abundant uses, cost-effective materials, and decreases risk of fire & thermal runaway	Zinc	5-6
Mechanical	Compressed Air Energy Storage (CAES)	• CAES is a method of storing grid electricity via electromechanical energy conversion, where air is pressurized, cooled and injected into a container. When needed the air is reheated and passed through a turbine to produce power. • Adiabatic CAES (aCAES) stores compression heat to be later used in the expansion process to produce electricity.	Adiabatic CAES	8-9

Source: Developed by Guidehouse from data and information obtained via developer and manufacturer interviews.

Manufacturing and Supply Chain

The only LDES technologies currently at TRL of 9 are vanadium redox flow batteries and CAES. The other LDES technologies in this analysis are still under development and have limited commercial deployments to date. Of the other technologies, some are expected to be commercially available at a faster rate than others. For example, zinc batteries are expected to advance from TRL 5 to TRL 8 in the next three years, as there are multiple companies developing this technology and many projects already in the pipeline. Appendix C contains more detail regarding current manufacturing players and notable supply chain limitations for each LDES technology in this analysis.

A large concern regarding LDES supply chain is the availability and cost of the elements and chemicals that make them up. For example, there are concerns that there may be global shortages of lithium and cobalt by 2025[7] due to drastic increase in demand for li-ion batteries and limited mining growth. Therefore, technologies that do not depend on these materials or

7 McDonald, Joe. 2023. *Threatened by shortages, electric car makers race for supplies of lithium for batteries*. AP News. https://apnews.com/article/china-ev-lithium-united-states-battery-87eb9382a0181bb7ee64e835efe7b170.

depend on more readily available ones, such as iron air batteries, will likely have fewer supply chain limitations and concerns.

Performance Characteristics

The performance of LDES systems can be evaluated based on energy metrics, degradation, cycles, and response time.

Table 3 provides detailed performance characteristics for LDES technologies in this analysis. The data in this table comes from a mixture of subject-matter expert (SME) and developer interviews, and literature review. The ranges in data are a result of a variety of system designs and sizes that can result in different performance characteristics.

Table 3: LDES Performance Characteristics Overview

Criteria	Unit	Vanadium Redox	Zinc Bromine	Iron Air	Zinc Battery	aCAES
Power Output Range	MW	0.25 – 25	0.025 – 25	3.5 – 100	1 – 10	10 – 1,000
Duration at Rated Capacity	Hours	4 – 12	4 – 10	100	10 – 48	4 – 350
Round Trip Efficiency	%	70 – 75	70%	40%	70%	60 – 75
System Efficiency	%	68%	65%	40%	68%	70%
Usable Energy	%	100%	100%	100%	80%	80%
Cycle Life	# of Cycles	20,000	7,300	400-800	6,000	5,000 – 40,000
Discharge Cycles	Cycles / Year	Unlimited	365	20 full cycles	365	250 – 1,000
Response Time	Min / Sec	< sec	< sec	< 10 min (offline to full power)	< sec	< 10 min
Degradation Per Cycle	% Per Cycle	0%	0%	0.001%	0.33%	< 0.001%
Lifetime	Years	20	20	20 - 40	17	20 – 40

Source: Developed by Guidehouse from data and information obtained via developer and manufacturer interviews.

It is also important to understand the duration class of each LDES technology, as this can result in different applications. Current energy storage systems are typically utilized for shorter duration applications, four hours or less, with some venturing into longer durations. Iron air systems are designed for longer durations, closer to 24- and 100-hour applications, but they are not currently in use. Additionally, CAES systems can perform for the longest durations, close to several weeks, and thus can have different benefits and applications than other systems. Appendix C provides more details related to duration categorization for the LDES technologies in this analysis.

Hydropower

Hydropower plants are located on or near a water source so that water flows through the system to turn blades in a turbine that powers a generator and produces electricity. Today, California has the second most cumulative hydropower capacity in the U.S. at 10.1 GW (~12.6 percent of total U.S. hydropower capacity), trailing only Washington.[8] While hydropower is a crucial firm zero-carbon resource for California's generation capacity, most suitable sites for hydropower generation in California have already been utilized since development of these systems is locationally constrained to areas with specific geological characteristics. The pipeline of upcoming energy projects further suggests that the growth of both large and small hydropower plants will be minimal going forward. However, growth is expected to be significant in pumped storage hydropower (PSH).[9] More details related to hydropower technologies, current deployments, maturity, manufacturing, performance characteristics, costs, and barriers can be found in Appendix D.

Technology Overview

Hydropower resources can be classified by size and function. Typical hydroelectric generators are used to provide baseload power production and are considered either large hydropower (greater than 30 MW) or small hydropower (less than 30 MW). Small and large hydropower plants typically leverage a dam to store water in a reservoir, which can be consistently dispatched. To generate electricity, gates release the stored water to drive the turbines, and afterwards the water is released into a basin or river.[10]

Hydropower can also be leveraged as a bulk storage resource when two reservoirs are positioned next to one another at different elevations. The system consumes electricity to pump water from a lower reservoir to a higher reservoir, typically when electricity supply is plentiful and relatively cheap. The water can later be strategically released back down to the lower reservoir to generate electricity when electricity supply is more constrained and prices are higher. Table 4 provides an overview of the distinctions between these technology types.

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8 U.S. Department of Energy. 2023. "U.S. Hydropower Market Report 2023 Edition." https://www.energy.gov/sites/default/files/2023-09/U.S.%20Hydropower%20Market%20Report%202023%20Edition.pdf.

9 Oak Ridge National Laboratory staff. 2023. Datasets. https://www.ornl.gov/project/hydrosource.

10 Blume-Werry, Eike, Martin Everts. 2022. *Hydropower*. The Palgrave Handbook of International Energy Economics. https://link.springer.com/chapter/10.1007/978-3-030-86884-0_8.

Table 4: Hydropower Technology Types

Hydropower Resources	Characteristics
Pumped Storage Hydropower (PSH)[11]	• PSH is the most dominant utility-scale electricity storage technology in California and worldwide • PSH as a firm resource is dispatchable by operators who control the timing and quantity of electricity production • PSH is the least expensive large-scale energy storage technology today on a $/MWh basis
Large Hydropower (> 30 MW)[12]	• Large hydropower is a form of renewable energy generation, where power is derived from flowing water used to drive large water turbines • Large hydropower as a firm resource is dispatchable by operators who control the timing and quantity of electricity production • Large hydropower facilities are typically operated by the California Department of Water Resources and the U.S. Bureau of Reclamation
Small Hydropower (< 30 MW)[13]	• Small hydropower projects can produce electricity from low-head stream flows or using existing dam or irrigation infrastructure • Small hydropower as a firm resource is dispatchable by operators who control the timing and quantity of electricity production • Small hydropower facilities are typically operated by local utilities

Technological Maturity and Anticipated Improvements

All hydropower technologies are fully mature (TRL of 9) and widespread throughout California. While hydropower is a mature technology, there is still advancement and innovation within the industry. U.S. Department of Energy (DOE) supports the Hydropower Program within the Water Power Technologies Office, which has focused R&D efforts across five key objectives: (1) innovations for low-impact hydropower growth, (2) grid reliability, resilience, and integration, (3) fleet modernization, maintenance, and cybersecurity, (4) environmental and hydrologic systems science, and (5) data access and analytics.[14] These areas are described in more detail in Appendix D along with some of their desired impact.

PSH operation and day-to-day management has changed over the past decade and may continue to do so. With expanding solar generation in the state, PSH operators have found it increasingly optimal to pump water to the higher reservoir during the middle of the day when solar power production is at its height. Traditionally, the resource has operated in pumping mode late into the night when demand is low. It is expected that operating profiles will

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11 Doughty, Collin, Linda Kelly, John Mathias. 2016. *Bulk Energy Storage in California*. CEC. Publication number CEC-200-2016-006. https://www.energy.ca.gov/sites/default/files/2021-06/CEC-200-2016-006.pdf.

12 CEC. "Hydroelectric Power." https://www.energy.ca.gov/data-reports/california-power-generation-and-power-sources/hydroelectric-power.

13 Ibid.

14 U.S. Department of Energy. "Hydropower Program." https://www.energy.gov/eere/water/hydropower-program.

continue to modify as renewable penetration increases, as is allowed by permits and contracts.[15]

Performance Characteristics

Technology specifications for the different hydropower system types are described in Table 5.

Table 5: Hydropower Technological Profile

Criteria	Unit	PSH	Large Hydro – Lake	Small Hydro – Run of River
Power Output Range	MW	N/A	> 30 MW	< 30 MW
Net Capacity Factor[16]	%	N/A	41	66
Annual Energy Production	kWh/ kW	N/A	3,680	5,430
Round Trip Efficiency	%	80	N/A	N/A
Lifetime	years	100	100	100

Source: 2023 NREL ATB

Performance characteristics are largely similar for the different hydropower technologies and configurations. Notably, energy generation characteristics are not applicable to pumped storage hydropower because it is a storage technology.

Geothermal

Geothermal is a form of renewable energy defined as heat energy from the earth. Geothermal resources are reservoirs of hot water that are naturally occurring or are manufactured to operate at varying temperatures and depths below Earth's surface. Wells, ranging from a few feet to several miles deep, can be drilled into underground reservoirs to tap steam and hot water that can be brought to the surface for use in a variety of energy applications.[17] For a geothermal resource used for electricity generation, steam is used to spin a turbine and activate a generator to produce electricity. The United States is the world's largest producer of geothermal electricity and California has the highest geothermal capacity of all states. Still, geothermal energy has room for growth, especially given its ability to provide clean, baseload power without relying on large land areas or fuel imports. More details related to geothermal resource classes, current deployments, maturity, manufacturing, performance characteristics, costs, and barriers can be found in Appendix E.

15 Doughty, Collin, Linda Kelly, John Mathias. 2016. *Bulk Energy Storage in California*, CEC. Publication number CEC-200-2016-006. https://www.energy.ca.gov/sites/default/files/2021-06/CEC-200-2016-006.pdf.

16 Net capacity factor is the ratio of the net electricity generated, for the time considered, to the energy that could have been generated at continuous full-power operation during the same period.

17 U.S. Department of Energy. "Geothermal Basics." https://www.energy.gov/eere/geothermal/geothermal-basics.

Technology Overview

Natural geothermal systems are found in in areas where hot rocks, fluid, and underground permeability are found. These conditions allow for a conventional hydrothermal system to be built over reservoirs without manipulating the ecological conditions. For hydrothermal resources that do not contain all three of these elements, other modifications are required, yielding other geothermal resource classes. For example, enhanced geothermal systems (EGS) use manufactured reservoirs to create the proper conditions by injecting fluid into hot rocks to reopen fractures and enhance the size and connectivity of fluid pathways.

Notably, conventional hydrothermal resources and co-produced geothermal resources make up all geothermal deployments in the U.S. to date. However, domestic EGS demonstrations are underway and EGS resources are expected to dominate future geothermal deployments. EGS systems can be located near conventional hydrothermal fields (referred to as NF EGS) or further from these sites by drilling deeply enough to access high-temperature reservoirs (referred to as deep EGS). In 2022, the DOE launched the Enhanced Geothermal Shot, "a department-wide effort to dramatically reduce the cost of EGS – by 90 percent, to $45 per MWh by 2035." This initiative recognizes that only a small portion of the existing geothermal energy potential in the U.S. is accessible with conventional technology and asserts that R&D to advance EGS can unlock new reservoirs domestically. Enhanced Geothermal Shot analysis estimates the technical potential of EGS under American soil is enough to meet the electricity demand of the entire world.[18]

In addition to resource classes, geothermal resources are powered by three technologies: dry steam, flash steam, and binary. Table 6 describes the characteristics of each geothermal technology.

Table 6: Geothermal Technology Characteristics

Geothermal Technologies	Characteristics
Dry Steam	• Saturated or geothermal steam at high pressure is obtained directly from the geothermal well and is delivered to a steam turbine coupled with a generator to produce electricity. • Dry steam geothermal is only applicable to locations where dry steam is produced directly from the geothermal reservoir. • The first geothermal plants that were developed used the dry steam method, although almost all dry steam-capable locations have already been utilized (e.g., The Geysers).

18 U.S. Department of Energy. 2023. "Enhanced Geothermal Shot: Unlocking the Power of Geothermal Energy." https://www.energy.gov/sites/default/files/2023-08/EERE-ES-Enhancing-Geothermal-082223-508.pdf.

Geothermal Technologies	Characteristics
Flash Steam	• Flash steam utilizes two-phase geothermal fluids under high pressure and high temperature by vaporizing the geothermal fluid at a lower pressure, a process known as "flashing." • The steam component is expanded through a turbine coupled to a generator to produce electricity. The separated liquid component of the geothermal fluid may be flashed further to generate additional steam for electricity generation. • Globally, flash steam is the most common technology used in existing geothermal plants, due to large developments in the late 1980s.
Binary Steam	• Binary plants operate by transferring heat from geothermal fluid to a secondary working fluid with a lower boiling point than water, contained in a closed loop. The secondary working fluid vaporizes and generates enough pressure to drive a turbine. • The optimal size of a binary plant is inherently smaller than other technologies that leverage higher temperature resources. • Binary plants can operate as zero-emission resources in a completely closed cycle, in which 100 percent of the geothermal fluid extracted is returned to the reservoir. • Almost all geothermal capacity additions since 2000 have been binary plants due to their flexibility which enables the utilization of lower-temperature resources. Binary plants are expected to remain a key technology for future geothermal power development.

Source: NREL, IRENA

Technological Maturity and Anticipated Improvements

All three geothermal technologies have reached market maturity (TRL of 9), but EGS configurations of flash and binary geothermal are mostly still in the early phase of demonstration, with one pilot project having recently transitioned to commercial operation.[19] The primary area of anticipated improvement for geothermal resources is through the development and use of EGS with flash or binary geothermal plants. While development of EGS has been encouraging, unexpected premature thermal decline in production wells and insufficient circulation rates have prevented EGS from reaching widespread commercialization.[20] Furthermore, when injecting large volumes of fluids below earth's surface, as is required for the EGS process, there is some risk of inducing seismic events that

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19 Gallucci, Maria. 2023. "America's first 'enhanced' geothermal plant just got up and running." Canary Media. https://www.canarymedia.com/articles/geothermal/americas-first-enhanced-geothermal-plant-just-got-up-and-running.

20 Augustine, Chad, Kate Baker, Doug Blankenship, Charles Carrigan, Branko Damjanac, Tom Dewers, Thomas Doe et al. 2021. *Performance Evaluation of Engineered Geothermal Systems Using Discrete Fracture Network Simulations*. U.S. Department of Energy Office of Scientific and Technical Information. https://www.osti.gov/biblio/1775421.

may be felt at the surface.[21] Several pathways are being explored to address these challenges. For example, one possible solution to address thermal decline is stimulating multiple fracture sets via fluid injection to increase the surface area for heat transfer and reduce the flow rate from each fracture. Both effects help enhance thermal longevity. In addition, simulations show the value in positioning wells to optimize circulation for improving heat exchange surface area.[22] Potential solutions to minimize seismic risk associated with EGS include stopping reservoir stimulation when risk reaches an unacceptable level or reducing production flow rates when seismicity occurs during operation.[23]

Performance Characteristics

The performance metrics and operating characteristics for geothermal power generation are relatively similar between configurations and there are just a few key areas of difference. Flash geothermal plants (both EGS and non-EGS), when compared with binary geothermal plants, are slightly larger in capacity (except deep flash EGS which is similarly sized to binary systems) and typically operate at higher net capacity factors. Higher capacity factors also lead to flash geothermal plants producing ~13 percent more electricity on average annually than binary geothermal plants. Well depth is expected to be larger for flash geothermal when compared to binary, but the most notable difference is with deep EGS for both flash and binary geothermal, which is typically 40 percent and 50 percent greater than their NF EGS counterparts. Lastly, of note, any EGS configuration has significantly lower flow rates than conventional flash or binary geothermal plants. Further detail can be found in Table 7.[24]

Table 7: Geothermal Technology Profiles

Criteria	Unit	Geothermal (Flash)	Geothermal (Binary)	NF EGS (Flash)	NF EGS (Binary)	Deep EGS (Flash)	Deep EGS (Binary)
Example System Size	MW	40	30	40	30	30	25
Net Capacity Factor	%	90	80	90	80	90	80

21 Huenges, E. 2016. "Enhanced geothermal systems: Review and status of research and development." *Geothermal Power Generation*. https://www.sciencedirect.com/science/article/abs/pii/B9780081003374000255.

22 Augustine, Chad, Kate Baker, Doug Blankenship, Charles Carrigan, Branko Damjanac, Tom Dewers, Thomas Doe et al. 2021. *Performance Evaluation of Engineered Geothermal Systems Using Discrete Fracture Network Simulations.* U.S. Department of Energy Office of Scientific and Technical Information. https://www.osti.gov/biblio/1775421.

23 Mignan, A., D. Karvounis, M. Broccardo, S. Wiemer, D. Giardini. 2019. "Including seismic risk mitigation measures into the Levelized Cost of Electricity in enhanced geothermal systems for optimal siting." https://www.sciencedirect.com/science/article/pii/S0306261919301230#:~:text=The%20seismic%20risk%20associated%20with,occurs%20during%20the%20operational%20phase.

24 National Renewable Energy Laboratory staff. 2023. *2023 Electricity ATB Technologies*. NREL Annual Technology Baseline. https://atb.nrel.gov/electricity/2023/technologies.

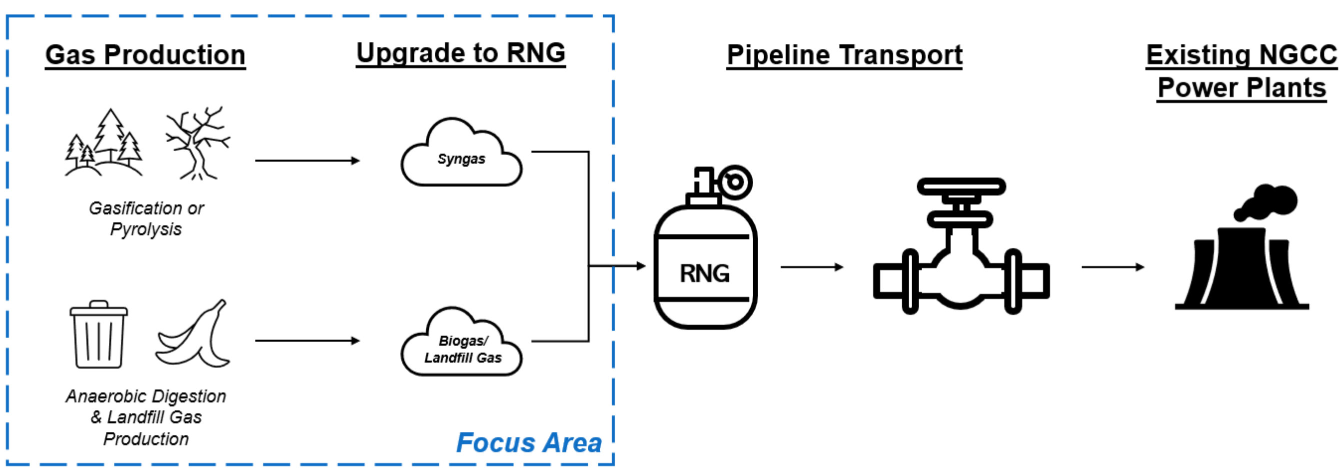
Criteria	Unit	Geothermal (Flash)	Geothermal (Binary)	NF EGS (Flash)	NF EGS (Binary)	Deep EGS (Flash)	Deep EGS (Binary)
Annual Energy Production	kWh/ kW	7,900	7,000	7,900	7,000	7,900	7,000
Well Depth	km	2.5	1.5	2.5	1.5	3.5	3
Flow Rate	kg/s	80	110	40	40	40	40
Lifetime	years	30	30	30	30	30	30

Source: NREL

Renewable Natural Gas (RNG)

Biofuels can be produced from biomass and waste feedstocks that have a variety of characteristics and uses. This analysis focuses on gaseous biofuels that are able to provide similar power generation to natural gas but are carbon neutral or potentially carbon negative when implementing with carbon sequestration strategies. When looking at gaseous biofuels the most common include biogas from anaerobic digestion or landfills and syngas from thermochemical processes. While these gases can be utilized directly for power production, they contain contaminants which reduce their performance and require additional upgrading and cleaning to increase their methane (CH_4) content, forming RNG or biomethane, in order to directly replace natural gas. Once refined into RNG, it can be used within existing natural gas infrastructure for pipeline transportation and power generation, such as combustion turbines and reciprocating engines. Therefore, the primary challenge and focus for this analysis is RNG production, as illustrated in Figure 2. More details related to RNG production and upgrading, current deployments, maturity, manufacturing, and costs can be found in Appendix F.

Figure 2: RNG and Biogas Firm Zero-Carbon Resource Lifecycle for Power Generation



Source: Guidehouse-produced figure

Technology Overview

RNG production consists of the production of intermediary gases from waste and biomass feedstocks, biogas and syngas, followed by the upgrade and/or purification of those gases to produce pipeline quality RNG, with higher contents of methane.

Table 8 provides an overview of the intermediary gas production pathways.

Table 8: Gas Production Overview

Gas Production Pathway	Feedstock	Characteristics
Thermochemical conversion (gasification & pyrolysis) produces syngas[25]	Fibrous feedstocks (e.g., woody biomass, forest waste, crop residue) and waste (e.g., municipal solid waste, livestock manure)	Uses high temperatures and controlled amount of oxygen (gasification) or no oxygen (pyrolysis) to convert liquid or solid feedstocks to gaseous products (syngas) without combustion
Anaerobic digestion produces biogas[26]	Organic waste feedstocks (e.g., landfill, wastewater treatment, food waste, livestock manure)	Process where bacteria breaks down/digests organic matter in the absence of oxygen to produce biogas
Landfills produce landfill gas (LFG)[27]	Takes place in landfill and municipal solid waste	Natural degradation of waste by anaerobic microorganisms in landfills, resulting in landfill gas.

Source: Guidehouse analysis for this report

Once the intermediary gas (syngas, biogas, or LFG) is produced from the waste and biomass feedstocks it needs to be cleaned and upgraded to properly serve as a replacement equivalent to natural gas. This cleaning and upgrade involves removing impurities from the gas and increasing the methane content to align with the natural gas infrastructure gas quality requirements of >98% methane. Since biogas and LFG have very similar impurities and gaseous components, these intermediary gases can be upgraded using similar processes. Table 9 provides an overview of the technologies required to clean and upgrade the intermediary gases to RNG.

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25 Capaldi, Romain, Al Abbas Lamrini. 2023. *Thermal Gasification: A key technology to decarbonize Europe and improve energy security*. Guidehouse Insights. https://guidehouse.com/insights/energy/2023/thermal-gasification.

26 Environmental Protection Agency AgSTAR staff. "How Does Anaerobic Digestion Work?" United States Environmental Protection Agency AgSTAR. https://www.epa.gov/agstar/how-does-anaerobic-digestion-work.

27 Environmental Protection Agency staff. "Basic Information about Landfill Gas." Unites States Environmental Protection Agency. https://www.epa.gov/lmop/basic-information-about-landfill-gas.

Table 9: Gas Upgrade to RNG Overview

Gas Upgrade Pathway	Characteristics
Syngas upgrade to RNG[28]	• The syngas produced from gasification includes hydrogen, carbon monoxide, carbon dioxide, water, methane, tar and other impurities that need to be removed to produce biomethane or RNG. Removal of tars and impurities is achieved through simple gas cleaning. • Methanation is the conversion of carbon monoxide and carbon dioxide into methane through hydrogenation and specialized catalysts. By using the hydrogen and carbon monoxide and carbon dioxide in the syngas, methanation increases the yield of methane from the syngas.
Biogas and LFG upgrade to RNG[29]	• Biogas resulting from digestion and landfill gas can be refined by removing carbon dioxide, water, hydrogen sulfide, and other gases to produce RNG • Treatment of biogas to RNG involves (1) moisture and particulate removal, (2) contaminant removal and compression, and (3) carbon dioxide, oxygen, nitrogen, and volatile organic compound removal. Methods to remove carbon dioxide include membrane separation, pressure swing adsorption, solvent scrubbing, and water scrubbing.

Source: Guidehouse analysis for this report

Generally, syngas has higher content of solid impurities, such as tar, that can be easily removed through simple cleaning. However, the remaining clean syngas tends to have a lower methane content than biogas or LFG and thus the hydrogen, carbon monoxide and carbon dioxide are leveraged to increase the content of methane. On the other hand, biogas and LFG already contain higher contents of methane and, if desired, could be used directly in local, smaller scale power generation, but not for pipeline integration.

Technological Maturity and Anticipated Improvements

Both anaerobic digestion and landfill gas collection are mature technologies that have been in the market for years, therefore both technologies have a TRL of 9. While the technologies are mature, there are still opportunities for these technologies to improve in terms of efficiency of methane recovery, increased methane production from digestion, and improving the treatment and upgrading of the resulting biogas and LFG.

On the other hand, thermochemical technologies have a variety of readiness maturities as there are a variety of technical approaches to achieve gasification. There are several gasification technologies that are mature, commercially available, and with existing plants with TRLs at 9, these are mostly commercialized for operation with coal and petroleum coke or smaller biomass and waste powered plants. The most common gasifier technologies currently

28 Seiser, Dr. Reinhar, Dr. Robert Cattolica, Michael Long. 2020. *Renewable Natural Gas Production from Woody Biomass via Gasification and Fluidized-Bed Methanation*. California Energy Commission. Publication Number: CEC-500-2020-055. https://www.energy.ca.gov/sites/default/files/2021-05/CEC-500-2020-055.pdf.

29 Environmental Protection Agency staff. 2021. *An Overview of Renewable Natural Gas from Biogas. United States Environmental Protection Agency*. https://www.epa.gov/sites/default/files/2021-02/documents/lmop_rng_document.pdf.

include fixed bed gasifiers, fluidized bed gasifiers, and entrained flow gasifiers. There are a variety of new technologies in development that aim to resolve some of the challenges and technical limitations that commercialized systems still face, such as feedstock flexibility, gasification efficiency, temperature stability, and costs. New technologies being explored range in terms of TRL levels but are as early as TRL 5 and include advancements such as microwave, ionic, plasma, and hydrothermal gasification processes.[30]

Performance Characteristics

RNG production technology profiles and characteristics are tracked in Table 10. The values in this table are provided as ranges based on current deployments and existing projects. Given that these technologies produce gas that is then utilized to produce electricity, the gas output rate is also included in these technology characteristics, with the exception of gasification where direct power output data was unavailable.

Table 10: RNG Production Technology Profiles

Criteria	Unit	Thermochemical[31]	Anaerobic Digestion[32]	Landfill Gas
Gas Output	MM ft^3/day	N/A	0.015 – 9.1[33,34]	0.1 - 27[35]
Power Output	MW	0.1 – 100[36,37]	0.7 – 20	0.15 – 23
Capacity Factor	%	65 – 85	90	15 – 100
Lifetime	years	>20	15 – 20[38]	25

30 For more detail about a subset of promising emerging gasification technologies, see IEA's 2020 "Emerging Gasification Technologies for Waste & Biomass" report. https://www.ieabioenergy.com/wp-content/uploads/2021/02/Emerging-Gasification-Technologies_final.pdf.

31 Scarlat, Nicolae and Fernando Fahl. 2019. Heat and Power from Biomass: Technology Development Report. Publications Office of the European Union. ISBN 978-92-76-12433-7, doi:10.2760/19308. https://publications.jrc.ec.europa.eu/repository/handle/JRC118318.

32 Environmental Protection Agency AgSTAR staff. Project Development Handbook: A Handbook for Developing Anaerobic Digestion/Biogas Systems on Farms in the United States. https://www.epa.gov/sites/default/files/2014-12/documents/agstar-handbook.pdf.

33 US EPA. LMOP Landfill and Project Database. United States Environmental Protection Agency. https://www.epa.gov/lmop/lmop-landfill-and-project-database.

34 Large systems from wastewater treatment and food waste. Argonne National Laboratory staff. 2022. Renewable Natural Gas Database. Argonne National Laboratory. https://www.anl.gov/esia/reference/renewable-natural-gas-database.

35 Ibid.

36 Scarlat, Nicolae and Fernando Fahl. 2019. Heat and Power from Biomass: Technology Development Report. Publications Office of the European Union. ISBN 978-92-76-12433-7, doi:10.2760/19308. https://publications.jrc.ec.europa.eu/repository/handle/JRC118318.

37 Mann, Margaret and Panela Spath. Life Cycle Assessment of a Biomass Gasification Combined-Cycle Power System. National Renewable energy Laboratory. https://www.nrel.gov/docs/legosti/fy98/23076.pdf.

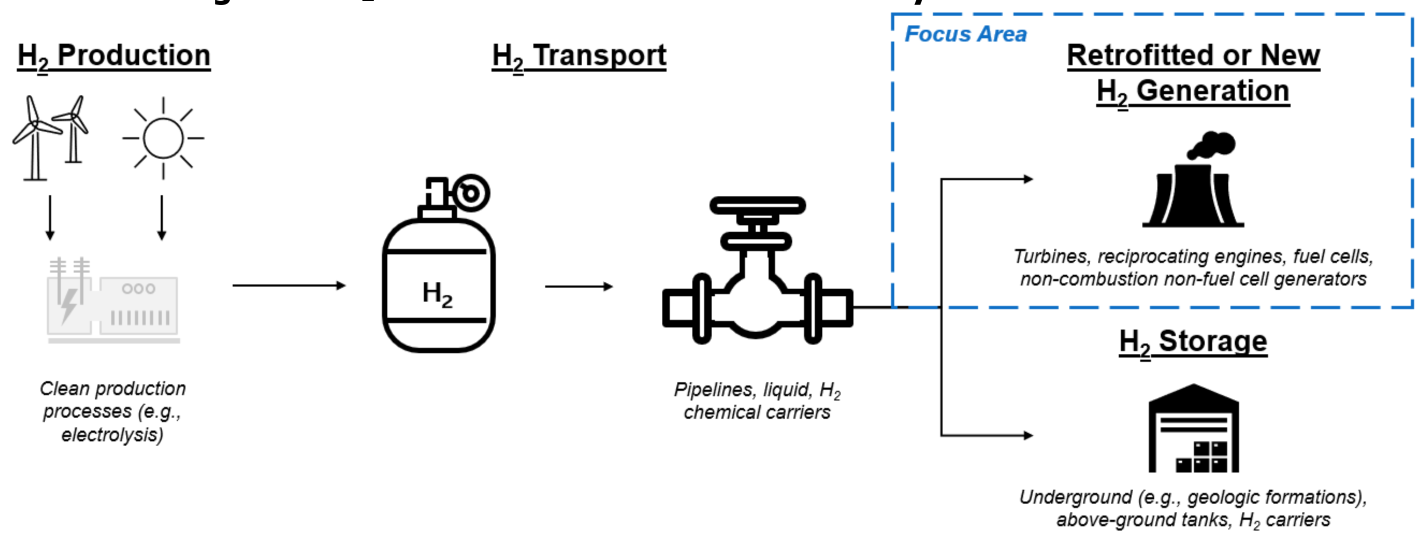
38 International Energy Agency staff. 2020. Outlook for biogas and biomethane. International Energy Agency. https://iea.blob.core.windows.net/assets/03aeb10c-c38c-4d10-bcec-de92e9ab815f/Outlook_for_biogas_and_biomethane.pdf

Notably, the technology profiles show how RNG production systems can range in size, but thermochemical technologies have the largest power output capabilities. All technologies have a similar lifetime associated with system degradation and accumulation of contaminants and build up from feedstocks and operating conditions.

Hydrogen

While hydrogen power generation technologies are included in this analysis, H_2 is a less mature fuel than RNG and it requires R&D across the lifecycle, including production and storage of H_2, to enable full-scale, cost-effective deployment. Like RNG, H_2 can be produced via biomass-derived processes (e.g., gasification, liquid reforming, microbial conversion), but it can also be produced using renewable energy generated from solar and wind through a process called electrolysis, solar-based processes, or fossil fuel reforming. Fossil fuel reforming is only carbon neutral when paired with carbon capture. H_2 can be stored for future use in geologic formations, above ground tanks, or liquid organic hydrogen carriers (LOHCs). Figure 3 illustrates a simplified lifecycle of H_2 as it is used for power generation.

Figure 3: H_2 Firm Zero-Carbon Resource Lifecycle for Power



Source: Guidehouse-produced figure

Additional detail on hydrogen-related technologies, current deployments, technological maturity, manufacturers, costs, barriers, and recommendations can be found in Appendix GAPPENDIX G: Additional Information on Hydrogen and APPENDIX C: Additional Information on Long-Duration Energy Storage (LDES).

Technology Overview

H_2 generation technologies are either retrofitted from existing natural gas technologies and can operate on a blend of hydrogen and natural gas or are newly developed generators capable of utilizing up to 100% H_2.

Table 11 provides an overview of the key technologies in this area.

Table 11: H_2 Generation Technology Overview

H_2 Generation Technology	Characteristics
Fuel cells	• Stationary hydrogen fuel cells (FCs) convert energy stored as gas into electricity without combustion • FCs separate H_2 into protons and electrons, which are run through an external circuit to create electricity; when hydrogen is used the only products are electricity, water, and heat • Many types of FCs exist including proton exchange membrane (PEM), solid oxide, molten carbonate, and phosphoric acid[39] • The low-temperature nature of most H_2 FC systems minimizes NO_x emissions[40]
Combustion turbines	• Systems that leverage H_2 (blends or pure H_2) to produce high-temperature and high-pressure gas that spins turbine blades to produce electricity • Existing natural gas combustion turbines can be retrofitted to use blended H_2 and CH_4 at up to 30% H_2 (vol.) with modification (e.g., de-rating by reducing flame temperature)[41] • NO_x emission production is a concern from H_2 combustion, but mitigation efforts are in early stage deployment (e.g., dry low-emission combustion turbines)[42,43]

39 Energy research Centre of the Netherlands (ECN) Policy Studies. "Fuel cells for stationary applications." https://www.ctc-n.org/technologies/fuel-cells-stationary-applications#:~:text=Phosphoric%20Acid%20Fuel%20Cells%20(PAFC,fuel%20cells%20for%20stationary%20applications.

40 Fouad, Fouad H., Robert W. Peters, Virginia P. Sisiopiku, Andrew J. Sullivan, Rajesh K. Ahluwalia. 2007. Global Assessment of Hydrogen Technologies. U.S. Department of Energy Office of Scientific and Technical Information. https://www.osti.gov/servlets/purl/923761.

41 ETN Global staff. 2020. Hydrogen Gas Turbines. https://etn.global/wp-content/uploads/2020/02/ETN-Hydrogen-Gas-Turbines-report.pdf.

42 Ibid.

43 Faqih, Mochammad, Madiah Binti Omar, Rosdiazli Ibrahim, Bahaswan A. A. Omar. 2022. Dry-Low Emission Gas Turbine Technology: Recent Trends and Challenges. Applied Sciences Journal. https://www.mdpi.com/2076-3417/12/21/10922.

H_2 Generation Technology	Characteristics
Reciprocating engines	• Power generating systems that ignite pure H_2 or H_2 gas blends to spur linear motion from a piston that is transformed into rotary motion by a crankshaft • Efficiency losses are smaller with reduced load than combustion turbines and start-up times are also more favorable comparatively, enhancing operational flexibility[44,45] • Most current reciprocating engines can handle up to 25% (vol.) H_2, and manufacturers are aiming to deliver products capable of handling 100% (vol.) in the future[46]
Non-combustion and non-fuel cell (NCNFC) gas fueled generators	• Linear generators convert motion along an axis into electricity, achieved through the compression of a fuel and air mixture until the mixture reacts without any combustion necessary • The low-temperature nature of this technology minimizes NO_x emissions[47] • Generator adjusts compression and expansion based on fuel type and quality so it can operate with a variety of fuels, including 100% hydrogen[48]

Source: Guidehouse analysis for this report

Technological Maturity and Anticipated Improvements

As a more nascent pathway than other firm zero-carbon resources, pilots and demonstrations are beginning to emerge but the extent of H_2 generation technologies deployed at full-scale, especially within the U.S. and California, is relatively minimal. The technological readiness of the key H_2 generation technologies is described in Table 12.

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44 Darrow, Ken, Rick Tidball, James Wang, Anne Hampson. 2015. Catalog of CHP Technologies. U.S. Environmental Protection Agency. https://www.epa.gov/sites/default/files/2015-07/documents/catalog_of_chp_technologies_section_2._technology_characterization_-_reciprocating_internal_combustion_engines.pdf.

45 Clark, Kevin. 2016. "Turbines vs. Reciprocating Engines." Power Engineering Magazine. https://www.power-eng.com/coal/turbines-vs-reciprocating-engines/#gref.

46 Clark, Kevin. 2023. "A 'seminal study': Examining the results of hydrogen blending in a reciprocating engine." Power Engineering Magazine. https://www.power-eng.com/hydrogen/a-seminal-study-examining-the-results-of-hydrogen-blending-in-a-reciprocating-engine/#gref.

47 "Technology Overview." Mainspring. https://www.mainspringenergy.com/technology/#:~:text=Mainspring's%20linear%20generator%20uses%20a,temperatures%20and%20high%20NOx%20emissions.

48 Ibid.

Table 12: H_2 Generation Technology Readiness Level

Technology Type	TRL (1-9)
Fuel cells[49,50]	7-8
Combustion turbines[51,52,53,54]	6-8
Reciprocating engines[55,56,57]	5-7
NCNFC generators[58,59]	7

Source: Guidehouse analysis for this report

Explanations and anticipated areas for improvement for each technology type are described in Appendix GAPPENDIX G: Additional Information on Hydrogen.

Performance Characteristics

Technological characteristics of H_2 generation technologies are tracked in Table 13. Most values reported below are specifically referencing the technology as it is operated with (blended) H_2, but in a few select instances, when reasonable, values for these technologies with other gaseous fuels are used as proxies. Capacity factor values assume a steady stream of H_2 is available.

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49 IEA staff. 2022. Global Hydrogen Review 2022. IEA. https://www.iea.org/reports/global-hydrogen-review-2022.

50 Wang, Junye, Hualin Wang, Yi Fan. 2018. Techno-Economic Challenges of Fuel Cell Commercialization. Engineering Journal. https://www.researchgate.net/publication/325290160_Techno-Economic_Challenges_of_Fuel_Cell_Commercialization#pf7.

51 ETN Global staff. 2020. Hydrogen Gas Turbines. https://etn.global/wp-content/uploads/2020/02/ETN-Hydrogen-Gas-Turbines-report.pdf.

52 2020. "World's First Successful Technology Verification of 100% Hydrogen-fueled Gas Turbine Operation with Dry Low NOx Combustion Technology." New Energy and Industrial Technology Development Organization. https://www.nedo.go.jp/english/news/AA5en_100427.html.

53 "Hydrogen Fueled Gas Turbines." General Electric. https://www.ge.com/gas-power/future-of-energy/hydrogen-fueled-gas-turbines.

54 IEA staff. 2023. Global Hydrogen Review 2023. https://iea.blob.core.windows.net/assets/cb9d5903-0df2-4c6c-afa1-4012f9ed45d2/GlobalHydrogenReview2023.pdf.

55 2021. "Wärtsilä launches major test programme towards carbon-free solutions with hydrogen and ammonia." Wärtsilä. https://www.wartsila.com/media/news/14-07-2021-wartsila-launches-major-test-programme-towards-carbon-free-solutions-with-hydrogen-and-ammonia-2953362.

56 Patel, Sonal. 2022. "Much-Watched Reciprocating Engine Hydrogen Pilot Kicks Off at Michigan Power Plant" Power Magazine. https://www.powermag.com/much-watched-reciprocating-engine-hydrogen-pilot-kicks-off-at-michigan-power-plant/.

57 Giacomazzi, Eugenio, Guido Troiani, Antonio Di Nardo, Giorgio Calchetti, Donato Cecere, Giuseppe Messina, Simone Carpenella. 2023. Hydrogen Combustion: Features and Barriers to Its Exploitation in the Energy Transition. https://www.mdpi.com/1996-1073/16/20/7174.

58 Simpson, Adam, Keith Davidson. 2021. Linear Generation for Combined Heat and Power. California Energy Commission. Publication Number: CEC-500-2021-017. https://www.energy.ca.gov/sites/default/files/2021-05/CEC-500-2021-017.pdf.

59 Aston, Adam. 2021. "PG&E is first utility client for Mainspring's novel 'linear generator'" GreenBiz. https://www.greenbiz.com/article/pge-first-utility-client-mainsprings-novel-linear-generator.

Table 13: H2 Generation Technology Profiles

Criteria	Unit	Fuel Cells	Combustion Turbines	Reciprocating Engines	NCNFC Generators
Power Output Range	MW	0.0004[60] – 80[61]	30 – 1,300[62]	0.03 – 30[63,*]	0.25 – 25[64]
Net Capacity Factor	%	70[65,*]	85	N/A	80[66,**]
Efficiency	%	60[67]	40[68] – 65[69]	30 – 80[70,*,‡]	45 – 80[71,‡]
Lifetime	Years	15[72]	25 – 30[73]	N/A	20[74]

Source: Guidehouse analysis for this report

60 Bellini, Emiliano. 2021. "Portable hydrogen fuel cell generator with power output of 400 W." PV Magazine. https://www.pv-magazine.com/2021/07/14/portable-hydrogen-fuel-cell-generator-with-power-output-of-400-w/.

61 2021. World's largest hydrogen fuel cell power plant. Fuel Cells Bulletin. https://www.sciencedirect.com/science/article/abs/pii/S1464285921006027.

62 U.S. Environmental Protection Agency staff. Hydrogen in Combustion Turbine Electric Generating Units. U.S. Environmental Protection Agency. https://www.epa.gov/system/files/documents/2023-05/TSD%20-%20Hydrogen%20in%20Combustion%20Turbine%20EGUs.pdf.

63 Darrow, Ken, Rick Tidball, James Wang, Anne Hampson. 2015. Catalog of CHP Technologies. U.S. Environmental Protection Agency. https://www.epa.gov/sites/default/files/2015-07/documents/catalog_of_chp_technologies_section_2._technology_characterization_-_reciprocating_internal_combustion_engines.pdf.

64 "Solutions." Mainspring. https://www.mainspringenergy.com/solutions/#specs.

⁎ Value based on technology used with different or unspecified gaseous fuel

65 2018. "Fuel cell power plants are used in diverse ways across the United States." EIA. https://www.eia.gov/todayinenergy/detail.php?id=35872.

66 Simpson, Adam, Keith Davidson. 2021. Linear Generation for Combined Heat and Power. California Energy Commission. Publication Number: CEC-500-2021-017. https://www.energy.ca.gov/sites/default/files/2021-05/CEC-500-2021-017.pdf.

** Based on industry interviews, this value varies significantly with observed values ranging from 20% to 95%.

67 2017. "Fuel Cells for Stationary Power Applications." U.S. Department of Energy. https://www.energy.gov/eere/fuelcells/articles/fuel-cells-stationary-power-applications#:~:text=A%20conventional%20combustion%2D%20based%20power,and%20even%20higher%20with%20cogeneration.

68 "Hydrogen gas turbine offers promise of clean electricity." Nature Portfolio. https://www.nature.com/articles/d42473-022-00211-0#:~:text=The%20project%20was%20funded%20by,fueled%20operation)%20of%2040.3%25.

69 "Meet JAC." Mitsubishi Power. https://www.changeinpower.com/our-solutions/decarbonizing-power/advanced-class-gas-turbines/.

† Round trip efficiency assuming electrolytically produced hydrogen would be close to 30%. Collins, Leah, Agnete Klevstrand. 2023. "Los Angeles moves forward with $800m plan to convert 830MW gas-fired power plant to run on green hydrogen." Hydrogen Insight. https://www.hydrogeninsight.com/power/los-angeles-moves-forward-with-800m-plan-to-convert-830mw-gas-fired-power-plant-to-run-on-green-hydrogen/2-1-1401866.

‡ Lower bound is for electric efficiency and the upper bound is for CHP

Notable within Table 13 is the fact that the typical H_2 combustion power output is significantly higher than any of the other technology types.

Modular Fission Reactors

Modular fission nuclear reactors, also known as small modular reactors (SMRs), are a class of advanced fission nuclear reactors in development. SMRs are characterized by a power capacity up to 300 MW electric and the ability of the unit to be factory-assembled and installed on-site. Compared to currently deployed nuclear reactors (~1000 MW), SMRs offer lower initial capital investments, increased siting flexibility, and greater scalability. 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 to the disposal of radioactive waste.[75] The use of SMRs in California is contingent on policy change at the state level or a long-term solution implemented at the federal level.

Technology Overview

Beyond size and modularity, SMR technologies vary widely in the physical design, coolant type, and nuclear process applied. This study focuses on light water cooled thermal-spectrum fission SMRs, as they are one of the more technologically mature types of SMRs under development and are the most widely deployed conventional reactors.[76] The two classes of light water reactors are pressurized water reactors (PWRs) and boiling water reactors (BWRs) which use light (ordinary) water as the fluid to transfer heat from the reactor core to the turbine for power generation. Both designs use low enriched (3-5 percent) uranium fuel and have expected lifetimes of 60 to 80 years. The classes differ in the number of loops used in the designs and, in turn, the operating pressure and temperature. Non-water cooled SMR technologies are discussed further in Appendix H.

Technological Maturity and Anticipated Improvements

Both PWRs and BWRs, as small modular reactor technologies, have a TRL of 6, representing that validation of the technology through prototypes and models have been demonstrated in relevant environments. United States-based developers of light water SMRs are in the NRC

70 2016. "Combined Heat and Power Technology Fact Sheet Series." U.S. Department of Energy. https://www.energy.gov/eere/amo/articles/reciprocating-engines-doe-chp-technology-fact-sheet-series-fact-sheet-2016.

71 Simpson, Adam, Keith Davidson. 2021. Linear Generation for Combined Heat and Power. California Energy Commission. Publication Number: CEC-500-2021-017. https://www.energy.ca.gov/sites/default/files/2021-05/CEC-500-2021-017.pdf.

72 "Stationary Power Generation." Ballard. https://www.ballard.com/stationary-power-generation/.

73 De Vos, Rolf. "Ten fundamentals to hydrogen readiness." Siemens Energy. https://www.siemens-energy.com/global/en/home/stories/hydrogen-ready.html.

74 Ming, Zach, Sumin Wang, Chen Zhang. 2021. The Role of Firming Generation in Microgrids. Energy and Environmental Economics. https://www.ethree.com/wp-content/uploads/2021/03/The-Role-of-Firming-Generation-in-Microgrids-E3-and-Mainspring-Energy.pdf.

75 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.

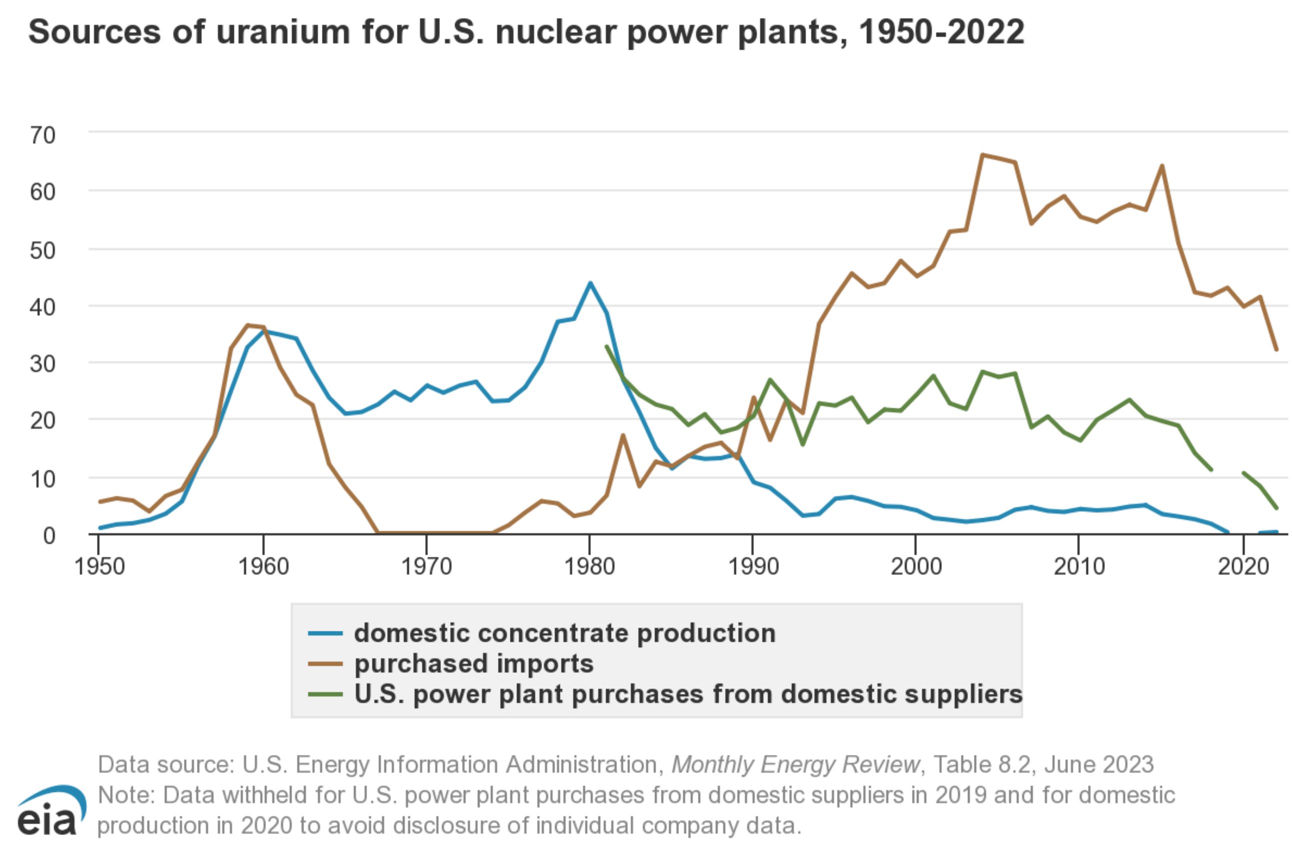
76 McGarry, James, John Stevens, Mengyao Yuan, Bill Wheatle, Aaron Burdick, Nick Schlag, Roderick Go, Oluwafemi Sawyerr. 2022. CPUC IRP Zero-Carbon Technology Assessment Final Report. Energy and Environmental Economics, Inc. https://www.ethree.com/wp-content/uploads/2023/03/CPUC-IRP-Zero-Carbon-Technology-Assessment.pdf.

pre-licensing and design certification process, which requires validation of the technology.[77] Anticipated improvements for both technologies include improved economies of scale and supply chain optimization as more SMRs are deployed.

Manufacturing and Supply Chain

Compared to conventional nuclear reactors, SMRs have the advantage that they can be fabricated off-site, thus reducing costs compared to conventional reactors. Growing interest and eventual deployment of SMRs in the United States will likely drive a need for a more robust uranium supply chain. Light water SMRs, like conventional light water reactors, rely on fuel in the form of uranium oxide enriched to 3 to 5 percent U-235. The uranium must be mined, enriched, and fabricated to uranium oxide. Historically, the majority of uranium oxide for use in U.S. nuclear power plants is imported as shown in Figure 4.

Figure 4: Sources of Uranium for U.S. Nuclear Power Plants, 1950-2022



Source: U.S. Energy Information Administration.

Performance Characteristics

Table 14 compares the performance characteristics and requirements for light water SMR types. The technology types are expected to have similar capacity factors and lifetimes, with variations expected due to site location and other factors external to the design.

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77 Carson, Allan, Tom Bergman, Alexander Bolgarov, Karel Deknopper, Shin Whan Kim, John Lillington, Carlos Lorencez, et. al. 2021. Design Maturity and Regulatory Expectations for Small Modular Reactors. World Nuclear Association. https://world-nuclear.org/images/articles/smr-design-maturity-report-FINAL.pdf.

Table 14: SMR Performance Characteristics

Criteria	Unit	PWR	BWR
Capacity Factor (Annual)	%	92%	92%
Thermal Efficiency	%	33%	33%
Operating Pressure	bar	150-160	70
Maximum Operating Temperature	°C	325	285
Lifetime	Years	60-80	60-80

Source: World Nuclear Association.

Fusion

Nuclear fusion offers a potential long-term energy source. Compared to nuclear fission, fusion could generate four times more energy per kilogram of fuel and future fission reactors will not produce long-lived nuclear waste.[78] However, significant engineering and logistical barriers must be overcome before nuclear fusion reactor technology can reach the market. Appendix I provides more information about nuclear fusion.

Technology Overview

To achieve controlled fusion, confinement is necessary to capture the energy produced from the reaction. Table 15 displays the characteristics of the most mature fusion technology types. For the past several decades, scientists worldwide have researched nuclear fusion with the goal of achieving net energy. In 2022, the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory was the first fusion device to demonstrate net energy with their single-shot facility. Further development is needed to overcome technical challenges associated with creating a sustained energy source.[79]

Table 15: 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. Other configurations include field-reversed configuration (FRC). Tokamaks commonly use deuterium-tritium fuel while in-development FRC technologies use hydrogen-boron fuel in an aneutronic reaction.

Source: International Atomic Energy Agency.

78 Barbarino, Matteo. 2023. *What is Nuclear Fusion?* International Atomic Energy Agency. https://www.iaea.org/newscenter/news/what-is-nuclear-fusion.
79 2009. How NIF Works. Lawrence Livermore National Laboratory. https://lasers.llnl.gov/about/how-nif-works.

Technological Maturity and Anticipated Improvements

Given its potential as a zero-carbon energy source, there has been significant investment in the field of nuclear fusion. Both ICF and MCF have a TRL of 4, indicating that basic validation has been conducted in a laboratory environment. These tests have demonstrated the capabilities and current limitations of the technology. Despite having the same TRL rating, it is expected that MCF-based technologies will go to market before ICF-based designs since the physics of MCF are regarded as better suited for sustained fusion applications.

Manufacturing and Supply Chain

Most nuclear fusion reactions rely on fuel made up of deuterium and tritium, isotopes of hydrogen. Deuterium is naturally occurring and can be separated from seawater while tritium must be produced by nuclear reactors or high energy accelerators.[80,81] As a result, tritium is a scarce resource that will require increased global production and supply chains to meet the fuel needs of fusion reactors. MCF designs require large quantities of superconductors for the magnet system and will likely necessitate a more robust global supply chain in the future. Aneutronic reactions, which produce no neutrons as a byproduct, use hydrogen-boron fuel and advanced beam-driven field-reversed configuration (FRC); aneutronic fusion based technologies require no tritium or superconductors.

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.[82] In order to be economically and technologically viable, projects are expected to have a Q value of 10 or greater.[83]

When commercially viable, fusion technology may be more attractive than fission given the reduced risks of radiation from long-lived isotopes. Furthermore, California has a statewide moratorium on the siting and licensing of new fission reactors until a solution for long-lived isotopes is reached but there are no policy regulations against fusion. 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 Integrated Energy Policy Report.[84]

Carbon Capture

Carbon capture is not a firm zero-carbon resource on its own, but it enables the continued use of existing fossil-fuel based power generation which is a firm resource. While carbon capture technologies cannot currently achieve zero-carbon at scale, carbon capture decreases most or at least a significant amount of CO_2 emissions associated with power generation from fossil

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

81 2005. Fact Sheet: Tritium Production. U.S. Nuclear Regulatory Commission. https://www.nrc.gov/docs/ML0325/ML032521359.pdf.

82 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.

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

84 2023. AB-1172 Integrated energy policy report: fusion energy. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202320240AB1172.

fuels or even RNG, although there is less data and traction on the latter. As such, it is an option to support achieving California's decarbonization goals while continuing to leverage legacy power generation resources such as natural gas combined cycle (NGCC) combustion turbines. It is also important to note that once CO_2 emissions are captured, they must either be utilized as an input for other processes or be safely sequestered within the natural environment. Appendix J provides more information about technology characteristics, current deployments, manufacturing and supply chain, costs, and barriers and recommendations for carbon capture.

Technology Overview

Carbon capture technologies can be classified as (1) post-combustion capture, (2) oxy-fuel combustion, and (3) pre-combustion capture. Post-combustion capture is the focus of this report and refers to the separation and capture of CO_2 from flue gas produced from fossil fuel combustion at power generation or industrial plants (e.g., smelters, cement kilns, steelworks). Deployment of industrial post-combustion capture plants is more widespread with greater technological maturity than for power generation, but it is not a focus of this report.

There are four key technology types for post-combustion capture, which all rely on unique differences in the properties of gasses present in the flue gas to separate CO_2 and capture it from the mixture. These are (1) absorption, (2) swing adsorption, (3) membrane separation, and (4) cryogenic capture. Specifically, the technologies separate and capture CO_2 using differences in its solubility in a solvent, affinity to a sorbent surface, rate of permeation through a membrane system, and desublimation temperature, respectively.[85,86]

Technological Maturity and Anticipated Improvements

The technological and commercialization maturity of these four technology types is described in Table 16.

Table 16: Carbon Capture Technology Readiness Level

Technology Type	TRL (1-9)
Absorption[87]	8-9
Swing Adsorption[88,89]	5-9

85 Kearns, David, Harry Liu, Chris Consoli. 2021. Technology Readiness and Costs of CCS. Global CCS Institute. https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Technology-Readiness-and-Costs-for-CCS-2021-1.pdf.

86 Hoeger, Christopher, Stephanie Burt, Larry Baxter. 2021. Cryogenic Carbon Capture™ Technoeconomic Analysis. Elsevier. https://www.osti.gov/servlets/purl/1781605.

87 2023. "Carbon Capture, Utilisation, and Storage." IEA. https://www.iea.org/reports/about-ccus.

88 Ibid.

89 Kearns, David, Harry Liu, Chris Consoli. 2021. Technology Readiness and Costs of CCS. Global CCS Institute. https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Technology-Readiness-and-Costs-for-CCS-2021-1.pdf.

Technology Type	TRL (1-9)
Membrane Separation[90,91]	5-9
Cryogenic Capture[92]	4-6

Source: Guidehouse analysis for this report

Absorption most commonly leverages amine-based solvents in the carbon capture process. Solvents, in addition to natural gas sweetening and hydrogen production,[93] have been widely used for decades in small- and large-scale power generation. While most deployments within power generation involve coal-fired power plants, full scale deployment with NGCC plants are under development though not yet widespread.

Swing adsorption technologies are mature when used with natural gas processing or hydrogen production, leading to an upper bound TRL of 9. There are some experimental lab demonstrations for coal[94] and natural gas[95] plants, but the technology is generally less mature within this application.

Membranes for CO_2 removal from syngas and biogas are a mature technology, but membrane separation is only at the demonstration and development stage for natural gas processing and flue gas treatment from power generation, respectively. Cryogenic carbon capture technology is still in the development stage with initial pilots being explored but is furthest from widespread deployment from a technical and commercialization perspective.

Performance Characteristics

CO_2 capture efficiency, energy input required, cost per ton of captured CO_2, specific emissions, and lifetime were all analyzed for the four key carbon capture technologies. Where possible, values were identified for the technologies when applied to carbon capture for NGCC plants or generally for post-combustion applications, but when noted, values from direct air capture (DAC) and coal power plant systems were used as reasonable proxies.

Table 17 describes the performance characteristics across the four key technologies discussed.

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90 2023. "Carbon Capture, Utilisation, and Storage." IEA. https://www.iea.org/reports/about-ccus.

91 He, Xuezhong, Danlin Chen, Zhicong Liang, Feng Yang. 2022. Insight and Comparison of Energy-efficient Membrane Processes for CO2 Capture from Flue Gases in Power Plant and Energy-intensive Industry. Carbon Capture Science & Technology. https://www.sciencedirect.com/science/article/pii/S2772656821000208.

92 Kearns, David, Harry Liu, Chris Consoli. 2021. Technology Readiness and Costs of CCS. Global CCS Institute. https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Technology-Readiness-and-Costs-for-CCS-2021-1.pdf.

93 Soares, Claire. 2015. Gaseous Emissions and the Environment. Gas Turbines (Second Edition). https://www.sciencedirect.com/science/article/abs/pii/B9780124104617000110.

94 Dhoke, Chaitana, Abdelghafour Zaabout, Schalk Cloete, Hwimin Seo, Yong-ki Park, Leyne Demoulin, Shahriar Amini. 2020. Demonstration of the Novel Swing Adsorption Reactor Cluster Concept in a Multistage Fluidized Bed with Heat-Transfer Surfaces for Postcombustion CO2 Capture. I&EC Research. https://pubs.acs.org/doi/abs/10.1021/acs.iecr.0c05951.

95 Mondino, Giorgia, Carlos A. Grande, Richard Blom, Lars O. Nord. 2019. Moving bed temperature swing adsorption for CO2 capture from a natural gas combined cycle power plant. International Journal of Greenhouse Gas Control. https://www.sciencedirect.com/science/article/pii/S1750583618306868?ref=pdf_download&fr=RR-2&rr=81bf82939ad529bd.

Table 17: Post Combustion Technology Performance Profiles

Criteria	Unit	Amine Solvents	Swing Adsorption	Membranes	Cryogenic
CO_2 Capture Efficiency	%	90[96] – 97[97]	96 – 98.2[98]	42 – 90[99]	99.9[100]
Energy Input Required	GJ/tonne CO_2	2.9[101] – 3.95[102]	1.4 – 2.2[103]	0.7[‡,104]	0.35 – 0.55[105]
Cost per Quantity Captured	$/tonne CO_2	40[106] – 75[‡,107]	80 – 180[108]	80 – 105[109]	27[‡,110]
Specific Emissions[111]	Kg/MWh	9.5 – 32.5	6 – 13.2	32.5 – 183	0.3
Lifetime	years	50[112]	20[†,113]	5 – 7[114]	20[115]

Source: Guidehouse analysis for this report

Currently, amine solvent technologies are more cost-effective than most alternatives in large part due to a greater level of maturity, and with increased deployment for power generation

96 Ibid.

97 2023. "Electricity Annual Technology Baseline (ATB) Data Download." NREL. https://atb.nrel.gov/electricity/2023/data.

98 Mondino, Giorgia, Carlos A. Grande, Richard Blom, Lars O. Nord. 2019. Moving bed temperature swing adsorption for CO2 capture from a natural gas combined cycle power plant. International Journal of Greenhouse Gas Control. https://www.sciencedirect.com/science/article/pii/S1750583618306868?ref=pdf_download&fr=RR-2&rr=81c54a944da213ff.

99 He, Xuezhong. 2018. A review of material development in the field of carbon capture and the application of membrane-based processes in power plants and energy-intensive industries. Energy, Sustainability and Society. https://energsustainsoc.biomedcentral.com/articles/10.1186/s13705-018-0177-9.

100 Kim, Yurim, Jaewon Lee, Hyungtae Cho, Junghwan Kim. 2022. Novel cryogenic carbon dioxide capture and storage process using LNG cold energy in a natural gas combined cycle power plant. Chemical Engineering Journal. https://www.sciencedirect.com/science/article/pii/S1385894722064610.

101 Strojny, Magdalena, Paweł Gładysz, Dawid P. Hanak, Wojciech Nowak. 2023. Comparative analysis of CO2 capture technologies using amine absorption and calcium looping integrated with natural gas combined cycle power plant. Elsevier. https://www.sciencedirect.com/science/article/abs/pii/S036054422301993X.

102 Mondino, Giorgia, Carlos A. Grande, Richard Blom, Lars O. Nord. 2019. Moving bed temperature swing adsorption for CO2 capture from a natural gas combined cycle power plant. International Journal of Greenhouse Gas Control. https://www.sciencedirect.com/science/article/pii/S1750583618306868?ref=pdf_download&fr=RR-2&rr=81c54a944da213ff.

103 Ibid.

104 He, Xuezhong, Danlin Chen, Zhicong Liang, Feng Yang. 2022. Insight and Comparison of Energy-efficient Membrane Processes for CO2 Capture from Flue Gases in Power Plant and Energy-intensive Industry. Carbon Capture Science & Technology. https://www.sciencedirect.com/science/article/pii/S2772656821000208.

105 Kim, Yurim, Jaewon Lee, Hyungtae Cho, Junghwan Kim. 2022. Novel cryogenic carbon dioxide capture and storage process using LNG cold energy in a natural gas combined cycle power plant. Chemical Engineering Journal. https://www.sciencedirect.com/science/article/pii/S1385894722064610. ‡ Coal Power Plant CC metric as a proxy.

applications, costs should further decrease. However, the technology is energy-intensive in nature, meaning there is an opportunity for alternatives to supplant it in favorability for carbon capture plants at NGCC with R&D developments.

Swing adsorption and membrane carbon capture technologies offer lower energy input requirements but face other challenges. Swing adsorption is a fully mature technology for pre-combustion carbon capture with gasification but struggles with long cycle times in power generation applications. Membrane technologies suffer from permeance limitations that have historically limited CO_2 capture efficiency, also yielding higher specific emissions. Both swing adsorption and membrane technologies offer significantly lower system lifetimes than amine solvents, especially membranes which typically have a lifetime of just five to seven years. Both technologies also do not benefit from economies of scale in the same way as absorbents, so they may prove to be more favorable with smaller plant sizes where that is less of a factor.

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106 "CO2BOL Solvents for Cheaper Carbon Capture and Sequestration, Pre- and Post-Combustion." PNNL. https://www.pnnl.gov/available-technologies/co2bol-solvents-cheaper-carbon-capture-and-sequestration-pre-and-post.

107 Panja, Palash, Brian McPherson, Milind D. Deo. 2022. Techno-Economic Analysis of Amine-based CO2 Capture Technology: Hunter Plant Case Study. Carbon Capture Science & Technology. https://www.researchgate.net/publication/358961181_Techno-Economic_Analysis_of_Amine-based_CO2_Capture_Technology_Hunter_Plant_Case_Study.

108 Zanco, Stefano E., José-Francisco Pérez-Calvo, Antonio Gasós, Beatrice Cordiano, Viola Becattini, Marco Mazzotti. 2021. Postcombustion CO2 Capture: A Comparative Techno-Economic Assessment of Three Technologies Using a Solvent, an Adsorbent, and a Membrane. American Chemical Society. https://pubs.acs.org/doi/10.1021/acsengineeringau.1c00002#.

109 Ibid.

110 Hoeger, Christopher, Stephanie Burt, Larry Baxter. 2021. Cryogenic Carbon Capture™ Technoeconomic Analysis. Elsevier. https://www.osti.gov/servlets/purl/1781605.

111 Mondino, Giorgia, Carlos A. Grande, Richard Blom, Lars O. Nord. 2019. Moving bed temperature swing adsorption for CO2 capture from a natural gas combined cycle power plant. International Journal of Greenhouse Gas Control. https://www.sciencedirect.com/science/article/pii/S1750583618306868?ref=pdf_download&fr=RR-2&rr=81c54a944da213ff.

112 Rosental, Marian, Thomas Fröhlich, Axel Liebich. 2020. Life Cycle Assessment of Carbon Capture and Utilization for the Production of Large Volume Organic Chemicals. Institute for Energy and Environmental Research. https://www.frontiersin.org/articles/10.3389/fclim.2020.586199/full#:~:text=Typical%20amine%20solutions%20consist%20of,a%20lifetime%20of%2050%20years.

† DAC CC metric as a proxy.

‡ Coal Power Plant CC metric as a proxy.

113 Terlouw, Tom, Karin Treyer, Christian Bauer, Marco Mazzotti. 2021. Life Cycle Assessment of Direct Air Carbon Capture and Storage with Low-Carbon Energy Sources. American Chemical Society. https://pubs.acs.org/doi/10.1021/acs.est.1c03263.

114 "Membrane-based post combustion capture." GCC Association. https://gccassociation.org/cement-and-concrete-innovation/carbon-capture-and-utilisation/membrane-based-post-combustion-capture/.

115 He, Ting, Zhongxuan Liu, Heechang Son, Truls Gundersen, Wensheng Lin. 2023. Comparative analysis of cryogenic distillation and chemical absorption for carbon capture in integrated natural gas liquefaction processes. Journal of Cleaner Production. https://www.sciencedirect.com/science/article/abs/pii/S0959652622048387.

Cryogenic carbon capture is favorable from a theoretical perspective with the lowest required energy input per ton of captured CO_2, and thus the lowest efficiency penalty.[116] Economic modeling also indicates that costs compared to an amine solvent baseline are significantly lower (by ~40 percent), even if this was in reference to carbon capture for a coal plant.[117] The technology will need to be proven at a pilot and demonstration scale prior to gaining any real traction, but the promise is there.

116 Kim, Yurim, Jaewon Lee, Hyungtae Cho, Junghwan Kim. 2022. Novel cryogenic carbon dioxide capture and storage process using LNG cold energy in a natural gas combined cycle power plant. Chemical Engineering Journal. https://www.sciencedirect.com/science/article/pii/S1385894722064610.

117 Hoeger, Christopher, Stephanie Burt, Larry Baxter. 2021. Cryogenic Carbon Capture™ Technoeconomic Analysis. Elsevier. https://www.osti.gov/servlets/purl/1781605.

Chapter 3: Reliability Assessment

CEC Reliability Model

SB 423 requires the CEC to assess the reliability of LSE portfolios during multi-day weather events and the potential need for firm resources to meet reliability needs. The CEC used a probabilistic model to evaluate these objectives at the system level. For multi-day events, the reliability of the entire 2021 Preferred System Plan (PSP), which is an aggregation of LSE portfolios, was assessed rather than individual LSE portfolios. For the potential need for firm resources, the CEC looked at how increasing or decreasing firm resources changes the need for non-firm resources in the expansion portfolio to meet reliability goals.

The model used demand and renewable shapes for 15 weather years representing 2007 to 2021. The demand shapes are the same used in CPUC modeling for the PSP and, this involves scaling weather years to the demand forecast 1 in 2 peak and then adding load modifiers (e.g., energy efficiency, transportation electrification) on top. Load modifiers are not varied by weather year.

The model is California-centric, meaning power plants for the state are modeled in detail, but areas outside the state are represented as generic imports. Imports for the state are constrained to 12,400 MW in all hours of the day and imports for the California ISO are constrained to 5,500 MW of generic imports and 1,942 MW of pseudo-tied resources during peak (hours 15 to 21). The state import constraint was determined by an analysis of interchange data reported to EIA 930, and the 12,400 MW number represents the 95th percentile of historic imports reported. Below is a table describing the data sources for the major inputs to the model.

Table 18: Model Input Data Sources

Model Input	Data Source	Comments
Demand Shapes	CPUC Weather-Sensitive Load	Based on 2022 CED vintage
Forced Outage Rates	NERC GADS	
Plant Capacities	QFER	
Plant Heat Rates	QFER	
Expansion Resources	CPUC Preferred System Plan	Core Scenario released in June 2021
Solar Shapes	NREL PV WATTS	
Wind Shapes, 2007-2014	NREL WTK	Calibrated using actual monthly generation totals reported to EIA 923
Wind Shapes 2015-2021	Actual Generation Data from California ISO Subpoena	Aggregated by Wind Resource Area
Transmission Line Ratings	WECC Path Limits	
Hydro Monthly Energy Budget	EIA 923	

Source: CEC Staff

Multi-Day Reliability Events

Analytical Design

Legislation required the analysis examine multi-day events in all seasons that occur at least as frequently as once every 10 years and include periods of low renewable generation. However, the demand and renewable shapes together cover only about 15 years, which makes assessing the true frequency of various weather events challenging. The study mainly looked at data from 2009 to 2018 because during these years, the staff had the most reliable information about electricity demand and renewable energy patterns. Staff initially checked for unusual events lasting from two to six days, but surprisingly, more than 80 percent of these events lasted for three days. Because of this, staff focused on finding the most extreme three-day events for each season.

Three kinds of events were evaluated: High Daily Net Load, High Daily Net Peak, and Low Variable Renewable Energy (VRE).

- High Daily Net Load events looked at the total net load experienced over three days.
- High Daily Net Peak events looked at the highest consecutive peaks experienced over three days.
- The Low Variable Renewable Energy (VRE) events looked at days where VRE provided the lowest share of energy as a percentage of gross load.

The following tables show the weather year from which each event derived and their modeled peaks and loads for summer and winter. The summer load event also has high net peaks, and the summer peak event also has high net loads, but the low VRE event is far behind those two in peak and load. The analysis was performed for modeled years 2023 and 2033, using the modeled loads for economic year 2023 and 2033 and the resource portfolios in the PSP for 2023 and 2033. References to 2023 in the following tables are for modeled year 2023 and not actual year 2023. The resource portfolio has no new resources for 2023 and about 20 GW of solar, 13 GW of stand-alone storage, 7 GW of wind, and 3 GW of other resources in 2033.

Table 19: Summer Statewide Net Peaks and Energy by Event for Modeled Year 2023

Summer 2023	Weather Year Date	Daily Net Peak (MW)	Daily Net Energy (MWh)
Daily Net Load	8/1/2017	53,388	890,417
Daily Net Load	8/2/2017	55,047	1,003,179
Daily Net Load	8/3/2017	53,255	986,909
Daily Net Peak	8/31/2017	58,039	950,482
Daily Net Peak	9/1/2017	58,815	877,420
Daily Net Peak	9/2/2017	58,310	880,638
Available VRE Generation	9/18/2016	48,032	703,266
Available VRE Generation	9/19/2016	50,901	823,848
Available VRE Generation	9/20/2016	51,196	875,981
2022 Heat Event	9/6/2022	53,388	890,417

Source: California Energy Commission

Each event was modeled with 250 outage samples, for four import cases restricting imports at various hours. The purpose of the import cases was to put additional stress on the system to see if multi-day events could experience greater challenges with energy and overnight capacity restricted. Peak is defined as 4 to 9 p.m. PDT, hour beginning, and midday was defined as 7 a.m. to 3 p.m. PDT, hour beginning. The table below summarizes the import restrictions used in each scenario.

Table 20: Import Definitions

Import Case	Definition
Default Imports	5,500 MW at peak, 12,400 MW other hours
Daytime Imports	5,500 MW at peak and overnight, 12,400 MW midday
Contracted Imports	5,500 MW all hours
No Imports	0 imports all hours

Source: California Energy Commission

Multi-Day Analysis Summer Results

Results for the multi-day analysis were reported as the probability of experiencing unserved energy anywhere in a sample. Since only one weather year is being modeled, the peaks and net peaks in each scenario are identical, and the samples differ from each other only in the forced outage draws. Forced outage draws have smaller variation between them than weather years do, so cases tend to see unserved energy in either almost all or almost none of their draws. The table below includes the probabilities of outages described.

Table 21: Probability of Experiencing Unserved Energy Anywhere in a Sample

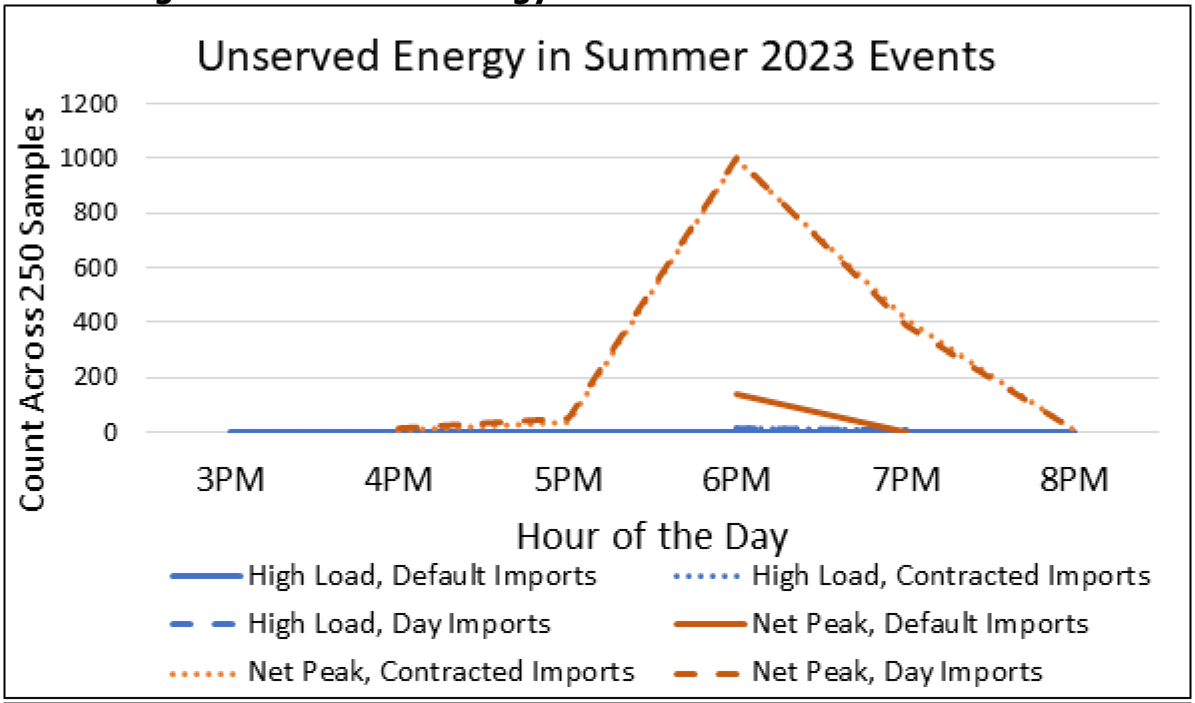
Imports Case	Load 2023	Peak 2023	VRE 2023	Load 2033	Peak 2033	VRE 2033
Default	0%	36%	0%	1%	4%	0%
Daytime	6%	100%	0%	61%	100%	1%
Contracted	5%	100%	0%	72%	100%	2%
No Imports	100%	100%	99.60%	100%	100%	100%

Source: California Energy Commission

For the 2023 portfolio, only the summer net peak event experienced significant unserved energy, while for the 2033 portfolio, the summer high load event also showed high probabilities of unserved energy. The low VRE event, with its more moderate peak loads, experiences no unserved energy outside of the case where imports are restricted completely. The default import case also tends to perform better than any of the cases with restricted imports, showing the reliability benefits of economic imports even outside of traditional peak hours. However, it is critical to acknowledge that other modeling efforts on the PSP show that the portfolios satisfy a traditional 1-in-10 loss of load expectation (LOLE) metric.

The graphs below illustrate the hours of the day that experience unserved energy. The y axis counts the number of hours experiencing unserved energy across all 250 samples. This shows not only when unserved occurs, but just how much more often the import-restricted cases experience issues compared to the default case.

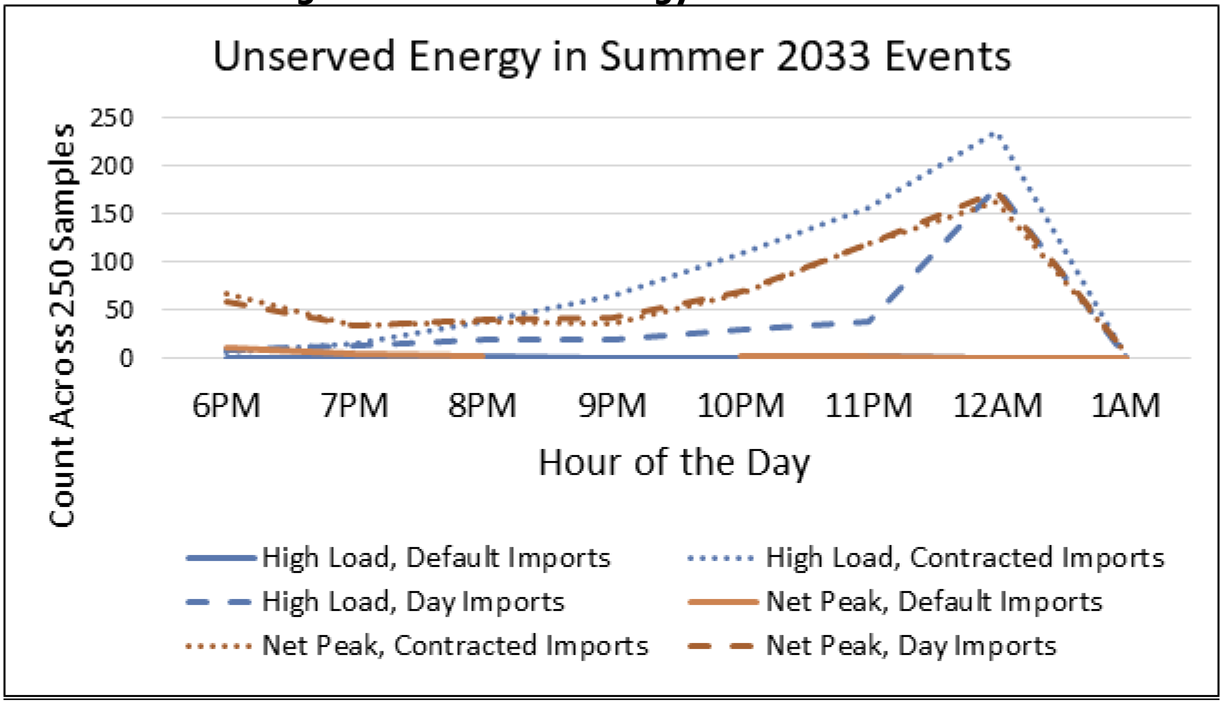
Figure 5: Unserved Energy in Summer for Modeled Year 2023 Events



Source: California Energy Commission

For the 2023 portfolio, unserved energy only occurs at net peak, and is much more likely in the net peak event than the net load event. There is no difference between the case where contracted imports are allowed during the day and the case where contracted imports are restricted for all hours, suggesting the issues lie not in getting batteries charged but in lack of peak/overnight capacity. For this case, the 4-hour batteries are charged to the maximum level and discharged fully during net peak. Firm and longer-duration storage resources would not be expected to provide more value than four-hour storage during capacity shortfalls like these. The graphs below illustrate the hours of the day that experience unserved energy. The y axis counts the number of hours experiencing unserved energy across all 250 samples.

Figure 6: Unserved Energy in Summer 2033 Events



Source: California Energy Commission

The 2033 portfolio's addition of 16,000 MW of 4-hour energy storage results in less unserved energy overall and less unserved energy at net peak compared to the 2023 portfolio, but more unserved energy after net peak across cases when batteries are depleted but loads are still higher than firm resources can support alone. There is also significantly more unserved energy experienced by the high load event when imports are restricted during the day. During the high load event for both import-restricted cases, both gas and imports run close to maximum levels for the entirety of the multi-day event and still cannot get batteries charged fully. Firm or longer duration storage resources are likely to provide more reliability benefit in these events than 4-hour storage.

Multi-Day Events in Other Seasons

This analysis was repeated for winter, spring, and fall. The statewide net peaks for these seasons are much lower than summer, even in 2033. This may change with future versions of the demand forecast, which will include more building electrification than the 2022 demand forecast used in this analysis. The table below shows the net peaks for all seasons, demonstrating how much slower the non-summer seasons are.

Table 22: All Seasons Statewide Net Peaks

Season	Event Type	2023 Net Peak (MW)	2033 Net Peak (MW)
Fall	Load (Energy/Peak Coincide)	50,016	58,833
Fall	VRE Share	35,857	41,576
Spring	Load (Energy/Peak Coincide)	40,608	57,518
Spring	VRE Share	33,232	38,996
Summer	Available VRE Generation	51,196	58,304
Summer	Daily Net Load	55,047	61,792
Summer	Daily Net Peak	58,815	67,745

Season	Event Type	2023 Net Peak (MW)	2033 Net Peak (MW)
Winter	Daily Net Load	36,508	42,841
Winter	Daily Net Peak	40,115	47,116
Winter	VRE Share	36,420	36,371

Source: California Energy Commission

Winter and spring saw almost no unserved energy under either portfolio. The fall event did experience some unserved energy. The peak and load fall event occurs in late October, when solar, wind, and available hydro generation tend to be low. This is also a time of year when some generators become unavailable due to scheduled maintenance following the peak summer season. This particular event also combines the challenges of high net peaks and high net loads into the same three days. The table below describes the outage results for non-summer seasons, using the same metrics as the summer ones described in Table 21.

Table 23: Unserved Energy Probability by Event

Season	Import Case	Load 2023	Peak 2023	VRE 2023	Load 2033	Peak 2033	VRE 2033
Winter	Default Imports	0%	0%	0%	0%	0%	0%
Winter	Daytime Imports	0%	0%	0%	0%	0%	0%
Winter	Contracted Imports	0%	0%	0%	0%	0%	0%
Winter	No Imports	0%	0%	0%	0%	22%	0%
Season	**Import Case**	**Load 2023**	**Peak 2023**	**VRE 2023**	**Load 2033**	**Peak 2033**	**VRE 2033**
Spring	Default Imports	0%	0%	0%	0%	0%	0%
Spring	Daytime Imports	0%	0%	0%	0%	0%	0%
Spring	Contracted Imports	0%	0%	0%	0%	0%	0%
Spring	No Imports	0%	0%	0%	8%	0%	0%
Season	**Import Case**	**Load & Peak 2023**		**VRE 2023**	**Load & Peak 2033**		**VRE 2033**
Fall	Default Imports	0%		0%	0.40%		0%
Fall	Daytime Imports	0%		0%	19%		0%
Fall	Contracted Imports	0%		0%	14%		0%
Fall	No Imports	100%		0%	100%		0%

Source: California Energy Commission

Potential Need for Firm Resources

Analytical Design

The legislation required that the CEC assess the potential need for firm resources and long-duration storage. This was done by evaluating the quantity of non-firm resources required to replace the firm resources in the PSP for 2028. This year was chosen because it is when the 2,000 MW of firm resources required by the 2021 Mid Term Reliability order are scheduled to come online in the 2021 vintage of the PSP.

Because the PSP exceeds reliability standards in 2028, the build was first scaled back 13% to reach the target baseline of one day of outage in 10 years (0.1 LOLE). Then, firm resources were doubled, lowering the LOLE. Non-firm resources were removed until the LOLE returned to the baseline 0.1. This same process was repeated for 3x firm resources, 4x firm resources, etc., and also done in reverse (removing firm resources and adding in non-firm). The non-firm resources were scaled up in the same proportions as they exist in the PSP.

The table below summarizes which resources are considered firm and their quantities in the baseline, scaled-back portfolio.

Table 24: Resource Baseline Portfolio Scaled to .1 LOLD

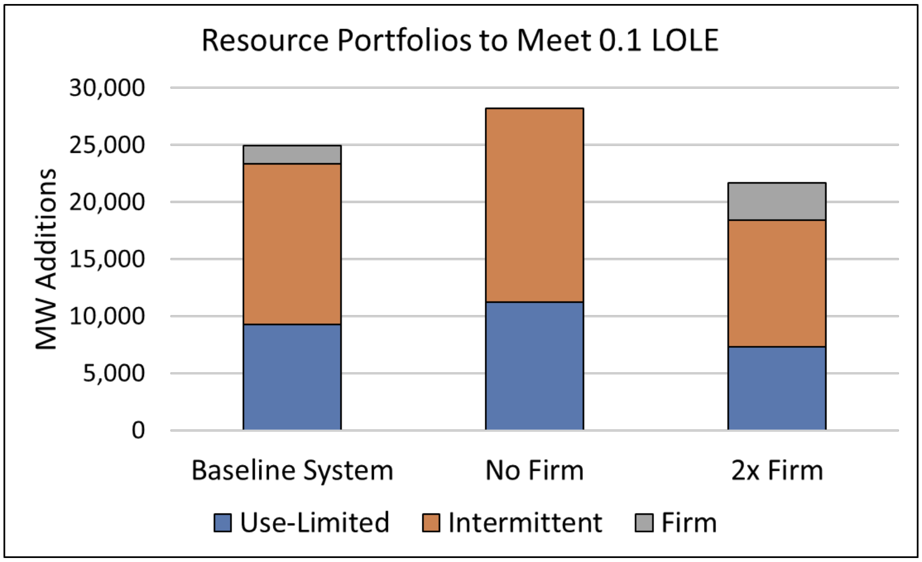
Resource Type	Resource	Baseline Portfolio (MW)
Firm	Biomass	194
Firm	Geothermal	544
Firm	Pumped Hydro Storage (PSH)	870
Use-Limited	Demand Response	2,115
Use-Limited	4-Hour Storage	7,145
Intermittent	In-State Wind	2,196
Intermittent	Offshore Wind	170
Intermittent	Out of State Wind	272
Intermittent	Solar	11,412

Source: California Energy Commission

Portfolio Results

Generally, the 1,600 MW of firm resources in the baseline portfolio can be substituted by about 2,000 MW of use-limited dispatchable resources and 3,000 MW of intermittent resources. The relationship is remarkably linear from 0x firm resources to 5x firm resources. Based on this linear relationship, we estimate it would take about 6.7x more firm resources, in the PSP, to completely replace the non-firm portfolio. This relationship may not hold were we to remove firm resources from the base portfolio but does seem to hold for resources across the expansion portfolio. The figure below compares the resource makeup for the Baseline, No Firm, and 2x Firm portfolios.

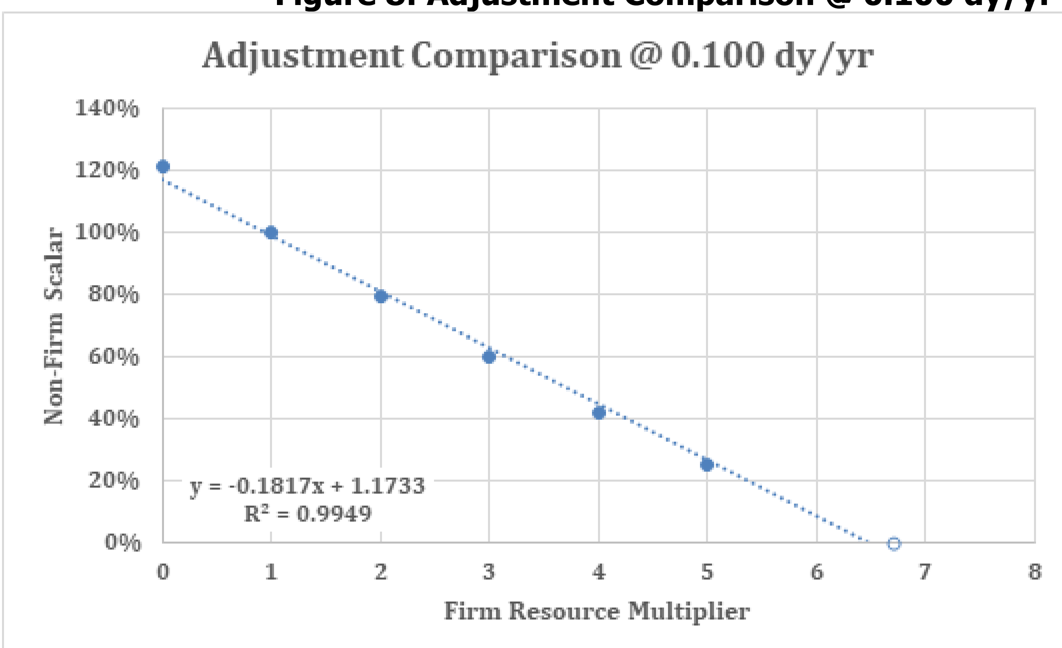
Figure 7: Resource Portfolios to Meet 0.1 LOLE



Source: California Energy Commission

While ensuring that the reliability standard of 0.1 LOLE is met, Figure 8 shows the linear relationship between firm and non-firm resources – the first 1,600 MW of firm resources are replaced by 5,000 MW of non-firm and so are the last 1,600 MW of firm resources.

Figure 8: Adjustment Comparison @ 0.100 dy/yr



Source: California Energy Commission

The focus of the model was on reliability equivalence, and the portfolios were not optimized for cost or renewable energy production. The non-firm produces more renewable energy overall than the firm portfolio. The table below analyzes system-wide generation from different sources for three different portfolios compared to baseline. For example, the 97 percent fossil generation for the 0x Firm, 121 percent Non-Firm case means that case generated 97 percent as much energy from fossil sources as the baseline case with 1x Firm and 1x Non-Firm. This shows that even though firm resources produce renewable energy steadily around the clock, the non-firm portfolio is still able to produce more renewable energy overall.

Table 25: System-wide Generation Analysis

	0x Firm, 121% Non-Firm	2x Firm, 79% Non-Firm	3x Firm, 60% Non-Firm
Firm Renewable	82%	119%	137%
Fossil	97%	103%	106%
Imports	99%	101%	101%
Intermittent Renewable	102%	97%	95%

Source: California Energy Commission

Chapter 4: Research and Development Approaches

This chapter outlines active and planned CEC research funding related to firm, zero-carbon resources. The CEC administers relevant clean energy research and development programs. The Electric Program Investment Charge (EPIC) program invests more than $130 million through the CEC annually to support decarbonization of electricity generation and consumption.[118] This program is funded by California utility customers under the auspices of the California Public Utilities Commission. The 2021-2025 Investment Plan (EPIC 4) outlines initiatives to fund research leading to technological advancements and scientific breakthroughs supporting California's clean energy goals, with a focus on providing ratepayer benefits, including reliability, lower costs, and safety. The Gas R&D Program funds public interest research and development projects to advance efficient, safe, and health-protective roles for gas and related fuels.

Long-Duration Energy Storage

The EPIC program has invested in long duration energy storage research and development since 2014. This portfolio includes a wide range of technologies including electrochemical, thermal, and mechanical energy storage at various stages of technology readiness. With this funding, a number of these companies have progressed to the demonstration phase, including Eos Energy, Antora Energy, and Form Energy. EPIC 4 funding continues to address these topics and includes initiatives that will further research and development efforts as well as demonstrations targeting short- and long-duration energy storage to improve grid reliability. This funding aims to lower the cost of emerging technologies, improve battery performance and cycle life, increase system safety, and reduce the use of critical materials to diversify the battery supply chain.

Building off the initiatives addressed by EPIC, the LDES Program invests in the deployment of non-lithium-ion energy storage technologies to aid in the commercialization of LDES technology. The Budget Act of 2023, as per Assembly Bill 102 (Ting, Chapter 38, Statutes of 2023), allocated additional funding to further incentivize and promote LDES initiatives. As of 2023, the program has committed up to $330 million in investments for LDES projects throughout California, with the aim of leveraging funds through federal cost-sharing initiatives and releasing additional competitive solicitations. The LDES program prioritizes the allocation of resources to projects that will benefit under-resourced communities, including recently funded projects with the Viejas Band of Kumeyaay Indians and Paskenta Band of Nomlaki Indians.

Demonstrations of LDES will improve grid reliability by offering multiple services, including customer load shifting and management, ancillary grid services, and deferral of infrastructure upgrades at the distribution and transmission levels. In addition, these demonstrations will illustrate the value of these systems and the compensation mechanisms needed to

118 CEC. Electric Program Investment Charge Program (EPIC). https://www.energy.ca.gov/programs-and-topics/programs/electric-program-investment-charge-epic-program.

commercialize them, which will inform grid operators, planners, and policy makers of the market potential of these technologies for future resource procurement objectives.

Renewable Natural Gas

The Gas R&D Program has funded projects to lower the cost and improve the performance of low-carbon gas products, like renewable natural gas (RNG), infrastructure, and services. Project focuses included using RNG for heat and power generation, for distributed generation and grid support, and storage, as well as flexible power generation. The CEC has one active Gas R&D project focused on converting forest fuels to renewable gas, with goals of reducing the cost of RNG and increasing reliability.

The EPIC Program is funding projects to support the growth of bioenergy technologies for power generation and fuels production in California by addressing critical research needs, encouraging lower costs for energy, and investing in technology maturation. These projects aim to produce renewable, community-scale, grid-connected electricity using forest biomass.

Hydrogen

EPIC 4 includes an initiative to advance clean, dispatchable generation, which aims to reduce dependence on fossil-based peaker power plants, complement intermittent renewable systems, and support Senate Bill 100 implementation using zero-carbon renewable fuels like hydrogen. The potential solicitation from the initiative can include a range of clean, dispatchable technologies, such as fuel cells or hydrogen combustion systems.

The CEC has active gas R&D projects focused on hydrogen production and use. In March 2022, the CEC announced awards to address the technical and economic challenges of producing hydrogen from carbon-neutral production pathways.[119] Advancing emerging hydrogen production technologies that achieve cost-competitiveness with traditional fossil-based production pathways will increase adoption of low-carbon hydrogen and displace the use of fossil gas. In July 2023, the CEC announced awards to advance technologies for reducing NOx emissions from combusting hydrogen and hydrogen blends in turbines and engines to provide zero-carbon, firm dispatchable generation.[120] Enabling hydrogen gas-fired generation systems in California can improve reliability and reduce reliance on fossil gas.

In 2022, California enacted Assembly Bill 209 (Committee on Budget, Energy, and Climate Change, Chapter 251, Statutes of 2022) to create the Clean Hydrogen Program[121] with $100 million of state general funds. The program is administered by the CEC and provides financial incentives for strategic, in-state projects to demonstrate or scale-up clean and renewable hydrogen production, processing, delivery, storage, and end use. Eligible projects under AB 209 are specific to hydrogen derived from water using eligible renewable energy resources, as defined in Section 399.12 of the Public Utilities Code, or produced from these eligible

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119 GFO-21-502 – Advancing Cost and Efficiency Improvements for Low Carbon Hydrogen Production. April 2023. https://www.grants.ca.gov/grants/gfo-21-502-advancing-cost-and-efficiency-improvements-for-low-carbon-hydrogen-production/

120 GFO-22-504 – Hydrogen Blending and Lower Oxides of Nitrogen Emissions in Gas-Fired Generation (HyBLOX). August 2023. https://www.energy.ca.gov/solicitations/2023-01/gfo-22-504-hydrogen-blending-and-lower-oxides-nitrogen-emissions-gas-fired.

121 CEC. Clean Hydrogen Program. https://www.energy.ca.gov/programs-and-topics/programs/clean-hydrogen-program.

renewable energy resources, including biomass. The program prioritizes projects that maximize air quality improvements, equity, health, and workforce benefits.

In October 2023, the federal government awarded California $1.2 billion to fund a hydrogen hub in the state.[122] The California's Alliance for Renewable Clean Hydrogen Energy Systems,[123] a statewide public-private partnership, successfully competed for the funding and is focused on developing hydrogen for uses that are challenging to electrify, such as heavy-duty transportation, grid-supporting power plants, and cargo-handling equipment at ports.

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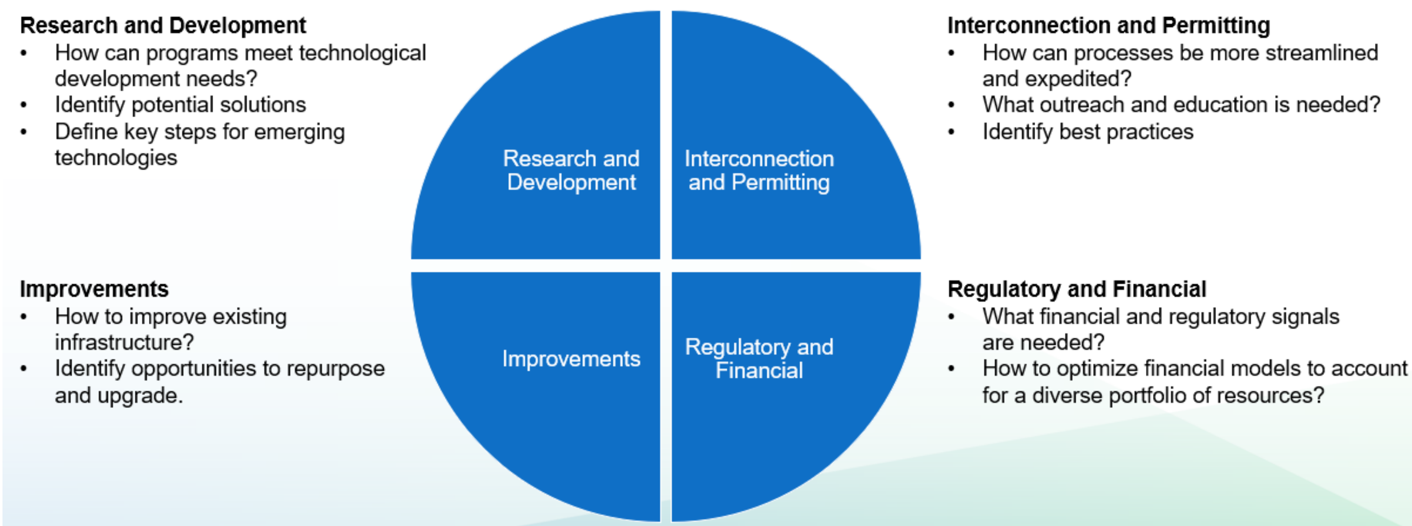
122 U.S. DOE, news release. Biden-Harris Administration Announces $7 Billion For America's First Clean Hydrogend Hubs, Driving Clean Manufacturing and Delivering New Economic Opportunities Nationwide. https://www.energy.gov/articles/biden-harris-administration-announces-7-billion-americas-first-clean-hydrogen-hubs-driving.

123 ARCHES H2. Alliance for Renewable Clean Hydrogen Energy Systems. https://archesh2.org/.

Chapter 5: Conclusion (Barriers and Recommendations)

This comprehensive assessment explores the key barriers and recommendations for firm zero-carbon resources in the broad areas of research and development, improvements, interconnection and permitting, as well as policy and finance. In research and development, the focus is addressing the technological development needs of evolving technologies. For interconnection and permitting, the assessment identifies opportunities for improvements to streamline and expedite processes critical for developing firm zero-carbon resources. Concurrently, it considers the outreach and educational elements necessary for public collaboration and engagement. Lastly, policy and finance considerations are needed to send essential market signals and develop financial models to build pathways for continued development of these resources. This section aims to contribute to the formulation of well-informed policies while promoting innovation, improved project development, and alignment with California's long-term climate goals.

Figure 9: Barriers and Recommendations Framework



Source: CEC staff

As these technologies continue to develop and are further implemented within the system, barriers must be overcome to ensure optimal performance and adoption. As part of this analysis barriers were explored to understand the challenges each technology faces. General categories of barriers evaluated include research & development, siting requirements, manufacturing, interconnection, permitting & regulations, financing, competitiveness, operations & maintenance, safety, environmental impact, and public perception. These categories were utilized to broadly evaluate barriers, ranging from the technology performance itself to external elements that restrict growth to overall impacts of the system.

Six common barriers were identified across all firm zero-carbon resources, identified in this report. It is important to note that the barriers in this chapter are not exhaustive, but rather a common group of key barriers was identified. A more comprehensive set of barriers and recommendations can be found in the appropriate appendix for each technology.

Barriers

From the perspective of potential obstacles, key factors include the challenge of elevated costs relative to existing alternatives, thereby limiting competitiveness and investment appeal. Additionally, concerns related to supply chain limitations and feedstock and fuel availability contribute to heightened project risks and extended timelines. Public perception challenges, infrastructure dependencies, and specific siting requirements further compound the intricacies of technology integration.

Land-Use Considerations

To evaluate the land-use impacts of the resources, staff used the Land-Use Intensity of Energy (LUIE)[124] metric. This metric is calculated by dividing the amount of land occupied by a resource (in hectares) by the amount of energy produced by the resource in a year. The LUIE is calculated by the below equation:

$$LUIE\left(\frac{ha * year}{Twh}\right) = \frac{Area}{Annual\ Energy\ Production}$$

As shown in Table 26, each firm zero-carbon resource received a LUIE value that describes the land-use impacts. Resources with a smaller LUIE were relatively more energy dense, meaning the resource produced more energy compared to its footprint. However, some resources with a higher LUIE were generally tied to some geographical needs or unique feedstock requirements. Because some resources are emerging technologies, staff made some assumptions based on deployment conditions and modeling assumptions. The LUIE evaluation draws upon literature, deployments both nationally and outside of the U.S, and manufacturer data. In the case of fusion resources, staff assumed that footprint and energy production would be similar or identical to fission.

Table 26: LUIE Metric

Technology	Type	ha/TWh/Year
Large Hydro	Hydropower	30,654
General Hydropower	Hydropower	14,038
Landfill Gas	RNG	12,289
aCAES	LDES[125]	9,274
Zinc Bromine	LDES	7,000
Vanadium Redox	LDES	5,838
General LDES	LDES	5,521
Zinc (non-flow)	LDES	4,877
General RNG	RNG	4,141

124 Lovering J, Swain M, Blomqvist L, Hernandez RR. 2022. Land-use intensity of electricity production and tomorrow's energy landscape. PLOS ONE 17(7): e0270155. https://doi.org/10.1371/journal.pone.0270155.

125 Due to limited deployments. LDES technologies used rated energy discharge specs instead of annual energy production.

Technology	Type	ha/TWh/Year
Iron Air	LDES	2,698
EGS[126]	Geothermal	146
Traditional Binary	Geothermal	146
General Geothermal	Geothermal	141
Traditional Flash	Geothermal	130
Anaerobic Digestion	RNG	110
Carbon Capture with Coal Plant	Carbon Capture	54
Combustion Turbines	Hydrogen	36
Traditional Dry Steam	Geothermal	36
Carbon Capture with Natural Gas Plant	Carbon Capture	33
Thermochemical	RNG	24
PWR SMR	Fission	14
General Fission SMR	Fission	14
BWR SMR	Fission	14
Fuel Cells	Hydrogen	9
Magnetic Confinement Fusion	Fusion	7
Inertial Confinement Fusion	Fusion	7
General Fusion	Fusion	7
General Fission (Traditional-1000 MW+)	Fission	7
NCNFC Generators	Hydrogen	2

Source: CEC staff with Guidehouse data

While land-use considerations were studied using the LUIE metric, this metric uses footprint and capacity factor to evaluate resources across all technologies considered in this report. The deployment of firm zero-carbon resources may potentially lead to reduced land requirements, but that aspect of these resources has not been extensively studied in this report. More details on land use will be available in the SB 100 Joint Agency Report.

Overview of Barriers

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126 Based on feedback from developer. Mainspring Energy Comments on Draft SB 423 Emerging Renewable and Firm Zero-Carbon Resources Report. 2024. https://efiling.energy.ca.gov/GetDocument.aspx?tn=258545&DocumentContentId=94575.

The following bullet points define these shared barriers, providing an overview of the challenges that warrant consideration in the ongoing efforts to adopt and widely-deploy firm zero-carbon resources.

- **High Costs:** The prevalent challenge involves elevated costs in comparison to existing alternatives, constraining competitiveness, and discouraging investment.
- **Supply Chain and Feedstock Limitations:** Concerns related to supply chain limitations, long lead times for equipment, and feedstock availability contribute to increased project risk and extended timelines.
- **Public Perception:** The negative or uncertain public perception poses a shared obstacle, escalating project risk and diminishing investor confidence.
- **Infrastructure Dependencies:** The reliance on new or modified infrastructure introduces complexities to the system, adding to implementation challenges. This includes interconnection delays.
- **Siting Requirements:** Specific siting requirements limit potential deployment locations, restricting the flexibility of technology placement.
- **Performance Challenges:** Struggles in performance characteristics, either in comparison to alternatives or in terms of economic viability, pose common hurdles.

Recommendations

Based on the identified barriers and challenges, the below recommendations were identified to help with greater adoption of firm zero-carbon resources. The recommendations recognize the need to balance supporting initiatives that achieve cost reductions with electric rate affordability and constraints on the availability of state funding.

1. **Efficiency:** Support initiatives that enhance resource and production efficiency in both LDES and H_2 technologies to achieve economies of scale leading to technology cost reductions, which is needed for greater adoption of these technologies.
2. **Material Sustainability:** Develop systems and technologies that minimize reliance on limited materials, favoring easier manufacturing processes. Leverage recycled materials to avoid supply constraints.
3. **Market Structure Redesign:** Explore redesign of existing market structures and participation rules to better incorporate LDES. Introduce incentives and compensation mechanisms for these systems.
4. **Drought Impact Assessment:** Investigate drought severity and forecasted impacts on hydropower and other technologies relying on water (e.g., hydrogen production) to accurately understand resource capacity.
5. **Environmental Review Efficiency:** Broadly, across all technology types, continue to re-evaluate current approaches to existing environmental review processes to find opportunities for improvements.
6. **Investment:** Encourage investment in firm zero-carbon projects through federal and private partnerships, existing government incentives, and cost reductions from research and development (R&D).

7. **Community Engagement:** Emphasize strong community engagement, including tribal communities, and address concerns to ensure public support for energy projects.
8. **Optimized Feedstock and Fuel Infrastructure:** Identify pathways to develop reliable feedstock collection and processing systems, leveraging co-location to optimize feedstock and fuel infrastructure (RNG and H_2).

Stakeholder Feedback and Continuous Improvement

The CEC released the Draft SB 423 report on August 2, 2024, for public comment and received robust and thoughtful feedback. While not all suggested changes could be incorporated into this Final Report, the feedback will guide future reporting as part of a commitment to continuous improvement. The CEC remains dedicated to refining its analysis and reporting, with planned updates in future Integrated Energy Policy Reports. Future reporting will include updates to costs, improvements to technology characterization, changes to better evaluate biomass/bioenergy technologies, and improvements to models and valuation of various technologies in this report.

In summary, ongoing support for these evolving resources is essential for their effective development and implementation. It is crucial to systematically address existing barriers and enhance the benefits associated with these resources to enable seamless adoption and integration. Acknowledging the shared challenges outlined provides an opportunity to create an environment favorable to the efficient advancement of firm zero-carbon resources and their broad benefits to the electric system and California’s climate goals.

APPENDIX A: Acronyms and Abbreviations

ACES	Advanced Clean Energy Storage
BTM	Behind-the-meter
CA	California
CAES	Compressed air energy storage
California ISO	California Independent System Operator
CAPEX	Capital expenditure
CBP	Capacity Bidding Program
CEC	California Energy Commission
CPUC	California Public Utilities Commission
DCPP	Diablo Canyon Power Plant
DER	Distributed energy resource
DOE	Department of Energy
DR	Demand response
DRAM	Demand Response Auction Mechanism
EIA	Energy Information Administration
ELRP	Emergency Load Reduction Program
EUCG	Electric Utility Cost Group
GHG	Greenhouse gas
GRC	General Rate Case
GW	Gigawatt
GWh	Gigawatt hour
HVAC	Heating, ventilation, and air conditioning
IRP	Integrated Resource Plan
LBNL	Lawrence Berkeley National Laboratory
LDES	Long duration energy storage
LSE	Load serving entity
MW	Megawatt
MWC	Major Work Category
NOC	Nuclear operating costs
NRC	Nuclear Regulatory Commission

PG&E	Pacific Gas & Electric
POU	Publicly owned utility
PSH	Pumped storage hydro
RIMS	Resource Interconnection Management System
RPS	Renewables Portfolio Standard
SB	Senate Bill
SME	Subject-matter Expert
TURN	The Utility Reform Network
VPP	Virtual Power Plant

APPENDIX B: Glossary

Blended gas

Blending of alternative gaseous fuels, such as hydrogen and renewable gas, with fossil gas to operate a system with lower carbon footprint than just operating on fossil gas. Most technologies require modifications or upgrades to properly function with high blends of alternative fuels, where lower blends could potentially be integrated into the system without major modifications.

Combustion turbine

A combustion or gas turbine is a combustion engine installed in a power plant that can convert gaseous fuels to mechanical energy, which in turn drives a generator that produces electrical energy. This conversion is achieved through the localized combustion of the fuel in a combustion system resulting in high temperature, high pressure gas stream that spins the blades that make up the turbine that then spin the generator to produce electricity.

Compressed air energy storage (CAES)

Compressed air energy storage is a type of storage that involves compressing air using an electricity-powered compressor into an underground cavern or other storage area. This compressed air is then expanded through a turbine to generate electricity. Usually, fuel is burned before the expansion process to increase the quantity of electricity produced and improve the overall efficiency. Similarly, heat losses from compression are sometimes re-captured and supplied to the air before expansion.[127]

CAPEX

CAPEX is the contraction of the term capital expenditure, and refers to the expenditures made to acquire, upgrade, and maintain physical assets such as property, plants, buildings, technology, or equipment.[128]

Distributed energy resources (DER)

Small-scale power generation technologies (typically in the range of 3 to 10,000 kilowatts) located close to where electricity is used (for example, a home or business) to provide an alternative to or an enhancement of the traditional electric power system.

Demand response (DR)

Demand response refers to providing wholesale and retail electricity customers with the ability to choose to respond to time-based prices and other incentives by reducing or shifting electricity use ("shift DR"), particularly during peak demand periods, so that changes in customer demand become a viable option for addressing pricing, system operations and reliability, infrastructure planning, operation and deferral, and other issues. It has been used

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127 Electric Power Research Institute. 2022. "Compressed Air Energy Storage." EPRI Storage Wiki. https://storagewiki.epri.com/index.php/DER_VET_User_Guide/Technologies/Compressed_Air_Energy_Storage.

128 Fernando, Jason. 2023. "Capital Expenditure (CapEx) Definition, Formula, and Examples." Investopedia. https://www.investopedia.com/terms/c/capitalexpenditure.asp.

traditionally to shed load in extreme events ("shed DR"). It also has the potential to be used as a low-greenhouse gas, low-cost, price-responsive option to help integrate renewable energy and provide grid-stabilizing services, especially when multiple distributed energy resources are used in combination and opportunities to earn income make the investment worthwhile. For more information, see the CPUC Demand Response Web page.

Electric vehicle control infrastructure

Electric vehicle (EV) control infrastructure are components and technologies in EV charging networks. In the context of this analysis and advanced EV charging these primarily refer to smart chargers and bidirectional chargers. Smart chargers are EV chargers that respond automatically to price signals and can optimize EV charging loads. Bidirectional chargers are chargers that allow energy to flow two ways into the vehicle and out of the vehicle. Common uses for these types of chargers are commonly referred to as vehicle-to-everything (V2X) and include applications such as vehicle-to-grid (V2G) and vehicle-to-building (V2B). In the context of this analysis and demand response (DR), bidirectional chargers are typically connected to the electrical grid (V2G) to provide support with load reduction and shifting.

Firm energy

Power supplies that are guaranteed to be delivered under terms defined by contract.

Fuel cells

A device or an electrochemical engine with no moving parts that converts the chemical energy of a fuel, such as hydrogen, and an oxidant, such as oxygen, directly into electricity. The principal components of a fuel cell are catalytically activated electrodes for the fuel (anode) and the oxidant (cathode) and an electrolyte to conduct ions between the two electrodes, thus producing electricity.

Heating, ventilation, and air conditioning (HVAC)

HVAC refers to equipment and systems that regulate and move heated and cooled air throughout residential and commercial buildings. While there are a wide variety of HVAC systems, in principle, they all take air and use a mechanical ventilation system to heat or cool it to a desired temperature.

Integrated Resource Planning (IRP)

The CPUC's Integrated Resource Planning (IRP) process is an "umbrella" planning proceeding to consider all of its electric procurement policies and programs and ensure California has a safe, reliable, and cost-effective electricity supply. The proceeding is also the Commission's primary venue for implementation of the Senate Bill 350 (De León, Chapter 547, Statutes of 2015) requirements related to IRP (Public Utilities Code Sections 454.51 and 454.52). The process ensures that load serving entities meet targets that allow the electricity sector to contribute to California's economy-wide greenhouse gas emissions reductions goals. For more information see the CPUC Integrated Resource Plan and Long-Term Procurement Plan (IRP-LTPP) Web page.

Long-duration energy storage (LDES)

There is no single definition for LDES in the energy community. For this analysis, long-duration energy storage (LDES) is an energy storage system that is able to provide at least eight hours of stored energy. There are systems that look to go well beyond 8 hours to provide 100 hours or even seasonal storage capabilities. There are multiple types of LDES technologies that are currently being explored, including:

- **Electrochemical:** These are the most known storage technologies in the market. These are systems that are capable of using electrical energy to facilitate chemical reactions, thus storing electricity as chemical energy, and inversely can convert the stored chemical energy into electric energy, discharging. Common electrochemical technologies include lithium-ion, flow, iron air, zinc, and sodium.
- **Mechanical:** Technologies that are capable of storing energy by applying force to an appropriate medium, such as water and air, to deliver acceleration, compression, or displacement against gravity. This is the storage of kinetic energy or potential energy. This process can be reversed to recover the stored energy. Common systems include pumped storage hydro storage, compressed air energy storage, and flywheels.
- **Thermal:** Technologies that are capable of storing energy by heating a medium. A medium gains energy when its temperature is increased and loses it when it is decreased. Common mediums and materials used for these energy storage systems include solid (e.g., sand) and liquid (e.g., molten salts).

Load serving entity (LSE)

A load serving entity is defined by the California Independent System Operator as an entity that has been "granted authority by state or local law, regulation or franchise to serve [their] own load directly through wholesale energy purchases." For more information see the California Independent System Operator's Web page.

Publicly owned utility (POU)

Non-profit utility providers owned by a community and operated by municipalities, counties, states, public power districts, or other public organizations. Within POUs, residents have a say in decisions and policies about rates, services, generating fuels and the environment.

Pumped storage hydropower (PSH)

Pumped storage hydropower (PSH) is a type of hydroelectric energy storage. It is a configuration of two water reservoirs at different elevations that can generate power as water moves down from one to the other (discharge), passing through a turbine. The system also requires power as it pumps water back into the upper reservoir (recharge). PSH acts similarly to a giant battery because it can store power and then release it when needed.[129]

Reciprocating engine

A reciprocating engine is an engine that uses reciprocating pistons to convert high temperature and high pressure into a rotating motion. Reciprocating engines are typically

129 Department of Energy, Office of Energy Efficiency & Renewable Energy. "Pumped Storage Hydropower." https://www.energy.gov/eere/water/pumped-storage-hydropower.

internal combustion engines and can be used for power generation, transportation, and other uses.[130]

Renewable gas

Renewable gas is essentially biogas or biomethane, which has been cleaned and conditioned and can be a direct replacement of natural gas. It can be used to generate electricity, heat, and combined electricity and heating for power plants. Biogas can be produced through a biochemical process such as anaerobic digestion, thermochemical means such as gasification, or from landfills.[131]

Technology readiness level (TRL)

Technology Readiness Levels (TRL) are a type of measurement system used to assess the maturity level of a particular technology. Each technology project is evaluated against the parameters for each technology level and is then assigned a TRL rating based on the projects progress. There are nine technology readiness levels. TRL 1 is the lowest and TRL 9 is the highest.[132]

- **TRL 1:** Basic principles observed and reported
- **TRL 2:** Technology concept and/or application formulated
- **TRL 3:** Analytical and experimental critical function and/or characteristic proof-of-concept
- **TRL 4:** Technology validation in laboratory environment
- **TRL 5:** Technology validation in relevant environment
- **TRL 6:** System/subsystem model or prototype demonstration in a relevant environment
- **TRL 7:** System prototype demonstration in an operational environment
- **TRL 8:** Actual system completed through test and demonstration
- **TRL 9:** Actual system proven in an operational environment

Virtual power plant (VPP)

In the context of this analysis, VPPs are actively controlled aggregations of zero-carbon Distributed Energy Resources (DERs) and dispatchable Demand Response (DR) measures optimized to provide clean energy, reliability, and grid services. The following provide two more general definitions of VPPs:

- **Department of Energy:** Virtual power plants, generally considered a connected aggregation of distributed energy resource (DER) technologies, offer deeper integration

130 Department of Energy, Office of Energy Efficiency & Renewable Energy. 2016. "Reciprocating Engines." https://www.energy.gov/eere/amo/articles/reciprocating-engines-doe-chp-technology-fact-sheet-series-fact-sheet-2016.

131 Department of Energy, Alternative Fuels Data Center. "Renewable Natural Gas Production." https://afdc.energy.gov/fuels/natural_gas_renewable.html.

132 Manning, Catherine. 2023. "Technology Readiness Levels." The National Aeronautics and Space Administration. www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/.

of renewables and demand flexibility, which in turn offers more Americans cleaner and more affordable power.[133]

- **Brattle Group:** A VPP is a portfolio of actively controlled distributed energy resources (DERs). Operation of the DERs is optimized to provide benefits to the power system, consumers, and the environment.[134]
- **Firm Power/Firm Energy**: Power and/or energy, intended to be available at all times during the period covered by a guaranteed ability to deliver, even under adverse conditions.

133 Department of Energy, Loan Programs Office. "Virtual Power Plants." https://www.energy.gov/lpo/virtual-power-plants.

134 Hledik, Ryan, Kate Peters. 2023. "Real Reliability: The Value of Virtual Power." The Brattle Group. https://www.brattle.com/wp-content/uploads/2023/04/Real-Reliability-The-Value-of-Virtual-Power_5.3.2023.pdf.

APPENDIX C: Additional Information on Long-Duration Energy Storage (LDES)

Additional information on long-duration energy storage (LDES) is provided within this section of the appendix. This section is intended to be read in conjunction with the main report and includes further detail on the technological characteristics, current deployments, technology maturity, manufacturing and supply chain, performance characteristics, costs, and barriers and recommendations for LDES technologies.

Technology Overview

Electrochemical energy storage technologies or batteries are those that can convert chemical energy into electrical energy via chemical reactions. There are a wide range of different battery chemistries that result in unique performance characteristics, but the most common commercialized battery chemistry is lithium-ion, typically for shorter durations. Thermal energy storage technologies leverage temperature gradients in materials or mediums to store and deliver energy for extended periods of time, with variations in this technology coming from different materials and mediums and their ability to handle thermal energy. Mechanical energy storage systems take advantage of kinetic or gravitational forces to store and deliver energy. Finally, gaseous fuel energy storage systems refer to the use of electricity to produce gaseous fuels, such as electrolytic hydrogen, that can be stored and later utilized as a fuel to generate electricity, such as hydrogen in fuel cells. Gaseous fuel energy is covered under the hydrogen section later on.

Table 27: LDES Technologies Evaluated

Categories	LDES Technology	Characteristics	Technology Chemistry
Electrochemical	Flow Batteries	• Flow batteries are distinguished by the type of electrolyte used (vanadium, zinc, iron, etc.) as well as by the state of their energy storing chemical component • "Redox" has completely dissolved active chemicals, while "hybrid" flow batteries have at least one chemical plated as a solid during the charging cycle • Common use cases: large scale utility or C&I applications	Vanadium Redox

Categories	LDES Technology	Characteristics	Technology Chemistry
Electrochemical	Flow Batteries	• Flow batteries are distinguished by the type of electrolyte used (vanadium, zinc, iron, etc.) as well as by the state of their energy storing chemical component • “Redox” has completely dissolved active chemicals, while “hybrid” flow batteries have at least one chemical plated as a solid during the charging cycle • Common use cases: large scale utility or C&I applications	Zinc Bromine
Electrochemical	Iron Air Batteries	• Utilizes simple and abundant raw materials, providing potential for lower costs than Li-Ion as manufacturing capacity scales up • Relatively low energy density, resulting in large footprints	Iron Air
Electrochemical	Zinc Batteries	• Emerging as a viable LDES resource due to high energy density, the use of abundant, cost-effective materials, and the decreased risk of fire/thermal runaway	Zinc
Mechanical	Compressed Air Energy Storage (CAES)	• CAES is a method of storing grid electricity via electromechanical energy conversion • CAES can integrate renewable energy as it is suitable for overnight storage in regions where curtailment is high • CAES requires limited use of natural resources (no water use and no rare earth materials)	Adiabatic CAES

Source: Developed by Guidehouse from data and information obtained via developer and manufacturer interviews.

Current Deployments

LDES systems are still relatively new technologies in development and thus it is difficult to determine the current deployed capacity for each of these technologies. However, Table 28 outlines current and announced LDES projects for each technology that provide some insight into the development and deployment of each technology.

Table 28: Current and Announced LDES Projects

Site Name	Plant Capacity	LDES Tech. & Purpose	Developer(s)	Status & Location
Rongke Power – Vanadium Redox[135]	200MW/ 800 MWh	Vanadium Redox for peak shaving and grid services	Rongke Power and Dalian Institute of Chemical Physics	Commissioned in 2022, China
Sumitomo Electric – Vanadium Redox[136]	17MW/ 51 MWh	Vanadium Redox for grid storage	Sumitomo Electric and Hokkaido Electric Power	Operational since 2019, Japan
NEDO Project[137]	2MW/ 8MWh	Vanadium Redox for peak shaving and grid services	Sumitomo Electric and SDG&E	Operational since 2022, USA
Cambridge Energy Storage Project[138]	1.5MW/ 150 MWh	Iron Air for renewable energy supplement	Form Energy and Great River Energy	Expected between 2023 and 2024, USA
Form – Xcel Energy Partners[139]	Two - 10MW/ 1,000MWh systems	Iron Air for multi-day grid storage	Form Energy	Expected to be online 2025, Becker, MN & Pueblo, CO
Zinc8 – Fresh Meadows Demonstration[140]	100kW/ 1.5MWh	Zinc battery for behind the meter applications	Zinc8 and Fresh Meadows Apartments	Announced 2020, USA

135 Colthorpe, Andy. 2022. First phase of 800MWh world biggest flow battery commissioned in China. Energy Storage News. https://www.energy-storage.news/first-phase-of-800mwh-world-biggest-flow-battery-commissioned-in-china/.

136 Installations Worldwide. Sumitomo Electric. https://sumitomoelectric.com/products/redox/cases.

137 Ibid.

138 Great River Energy staff. 2021. Battery project includes Minnesota flair. Great River Energy. https://greatriverenergy.com/company-news/battery-project-includes-minnesota-flair/.

139 Bray, Sarah, Kevin Cross. 2023. Form Energy Partners with Xcel Energy on Two Multi-day Energy Storage Projects. Form Energy. https://formenergy.com/form-energy-partners-with-xcel-energy-on-two-multi-day-energy-storage-projects/.

140 Schneck, Kristina, Eric Negraeff. 2022. Zinc8 Energy Solutions Inc. Announces Signing of Host Site Agreement with Partner Digital Energy & Fresh Meadows Community Apartments in Queens, New York. Zinc8 Energy Solutions Inc. https://www.zinc8energy.com/zinc8-energy-solutions-inc-announces-signing-of-host-site-agreement-with-partner-digital-energy-fresh-meadows-community-apartments-in-queens-new-york/.

Site Name	Plant Capacity	LDES Tech. & Purpose	Developer(s)	Status & Location
Eos – Zinc Hybrid Cathode[141]	300MWh	Zinc battery for grid storage	Eos and Blue Ridge Power	Installation initiated in 2022, USA
Goderich Energy Storage[142]	2.2MW/ 10MWh	a CAES system for commercial reference facility and peaking capacity	Hydrostor and Ontario IESO	Operational since 2019, Ontario, Canada

Source: Guidehouse analysis for this report

As seen by the table above the most established technology for larger commercial deployments are lithium-ion systems while the rest of the technologies are seeking demonstrations or developing first commercial deployments. Iron air, through Form Energy, and zinc batteries, through Eos, have a large pipeline of projects and show promise in terms of deployments but are yet to be demonstrated at scale commercially.

Technological Maturity and Anticipated Improvements

The technological maturity evaluation for LDES resources draws from two distinct perspectives, technological and commercialization. The first, looking at technology readiness, evaluates the current and expected development of the LDES technology itself. This analysis leverages the Technology Readiness Level (TRL) framework commonly utilized to evaluate technical maturity of a technology during its development phase.[143]

29 provides a summary of the current TRL for each LDES technology and battery chemistry evaluated under this analysis.

Table 29: LDES Technology Readiness Level

LDES Technology	Chemistries/Design	TRL (1-9)
Flow Batteries	Vanadium Redox	9
Flow Batteries	Zinc Bromine	8
Iron Air Batteries	Iron Air	6

141 Eos staff. 2022. Eos Energy Enterprises, Inc. Secures Over 1 GWh in New Orders, More Than Doubles Backlog to Over $460 Million. Eos Energy Enterprises, Inc. https://www.eose.com/eos-energy-enterprises-inc-secures-over-1-gwh-in-new-orders-more-than-doubles-backlog-to-over-460-million/.

142 Hydrostor staff. Goderich Energy Storage Facility. Hydrostor. https://www.hydrostor.ca/goderich-a-caes-facility/. Archived at https://web.archive.org/web/20240119133241/https://www.hydrostor.ca/goderich-a-caes-facility/.

143 The framework is based on a scale from 1 to 9 where 1 represents technologies where only the basic principles have been explored and 9 represents technologies that are in their final form and have been successfully operated in operational conditions, ready for commercial deployment. More generally, TRLs ranging from 1 – 3 denote a technology in the research phase, from 4 – 6 a technology in development (controlled demonstrations and pilots), and from 7 – 9 a technology in deployment (systems in operational environments).

LDES Technology	Chemistries/Design	TRL (1-9)
Zinc Batteries	Zinc	5-6
Compressed Air Energy Storage (CAES)	Adiabatic CAES	8-9

Source: Developed by Guidehouse from data and information obtained via developer and manufacturer interviews.

Manufacturing and Supply Chain

Table 30 provides an overview of the current manufacturing players and the notable supply chain limitations for each LDES technology in this analysis.

Table 30: LDES Manufacturing and Supply Chain Overview

LDES Chemistries/ Design	Manufacturing	Supply Chain
Vanadium Redox	Notable Manufacturers: CellCube (Austria), Sumitomo (Japan), Invinity (UK), Largo (Canada), Rongke (China)	Vanadium supplies[144] may be a concern as China and Russia are the two top producers with South Africa and Brazil rounding out the top four.
Zinc Bromine	Redflow (Australia) and Prlmus Power (US)	Zinc[145] can be sourced from a diversified mix of countries
Iron Air	Single manufacturer – Form Energy (US) Large scale manufacturing location being developed in Weirton, WV[146]	Diversified sourcing of materials at competitive prices is expected
Zinc	Leading manufacturers include Eos (US) and Zinc8 (Canada)	Zinc[147] can be sourced from a diversified mix of countries

144 US Geological Survey, Mineral Commodity Summaries - Vanadium. January 2023. https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-vanadium.pdf.

145 US Geological Survey, Mineral Commodity Summaries – Zinc. January 2023. https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-zinc.pdf.

146 Form Energy. "West Virginia Governor Jim Justice announces Form Energy will site first American battery manufacturing plant in Weirton, creating hundreds of jobs." December 2022. https://formenergy.com/west-virginia-governor-jim-justice-announces-form-energy-will-site-first-american-battery-manufacturing-plant-in-weirton-creating-hundreds-of-jobs/.

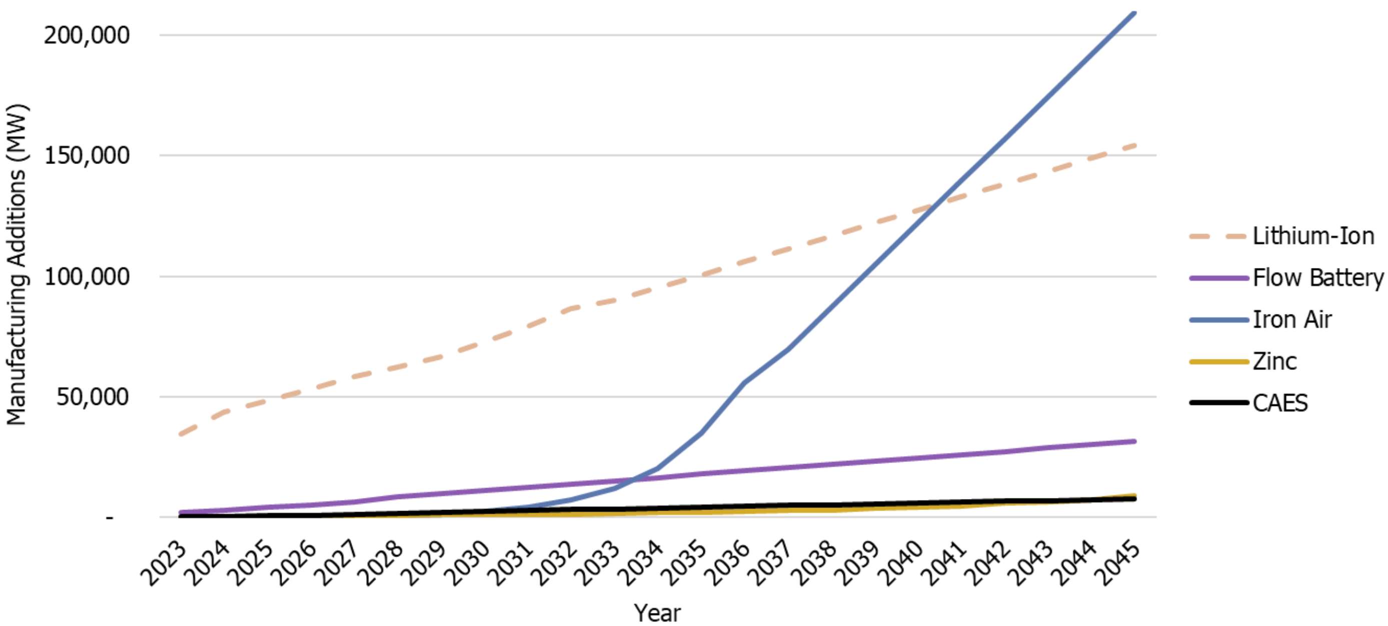
147 US Geological Survey, Mineral Commodity Summaries – Zinc. January 2023. https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-zinc.pdf.

LDES Chemistries/ Design	Manufacturing	Supply Chain
Adiabatic CAES	Most notable manufacturer: Hydrostor (Canada) CAES has environmental impacts related to construction of the project and operation of the system	aCAES' dependence on the presence of a suitable cavern makes it fragile and exposes it to competition with other geologic gas storage options. Hydrostor's built-up cavities avoid this issue but would require excavation.

Source: Developed by Guidehouse from data and information obtained via developer and manufacturer interviews.

With these manufacturing and supply chain considerations in mind Figure 10 shows each technology's potential global annual additions, or the capacity that could be manufactured each year. The data for this figure comes primarily from Guidehouse Insight's Energy Storage Forecasting Database (ESFD) with the exception of iron air and zinc batteries. Iron air and zinc batteries were forecasted differently as these are not yet included in the ESFD. For both these technologies, their current announced and purchased capacities were used as a baseline and then applied the growth rate lithium-ion exhibited in the early 2010s as a proxy. However, since zinc batteries have a similar technology profile to lithium-ion batteries (duration and performance), they will have a harder time penetrating the market and thus growing at a limited rate. On the other hand, iron air batteries cover a different duration class than lithium-ion and thus do not directly compete and are expected to more closely follow the exponential growth lithium-ion batteries experienced.

Figure 10: Global Annual Additions By Technology, 2023-2045



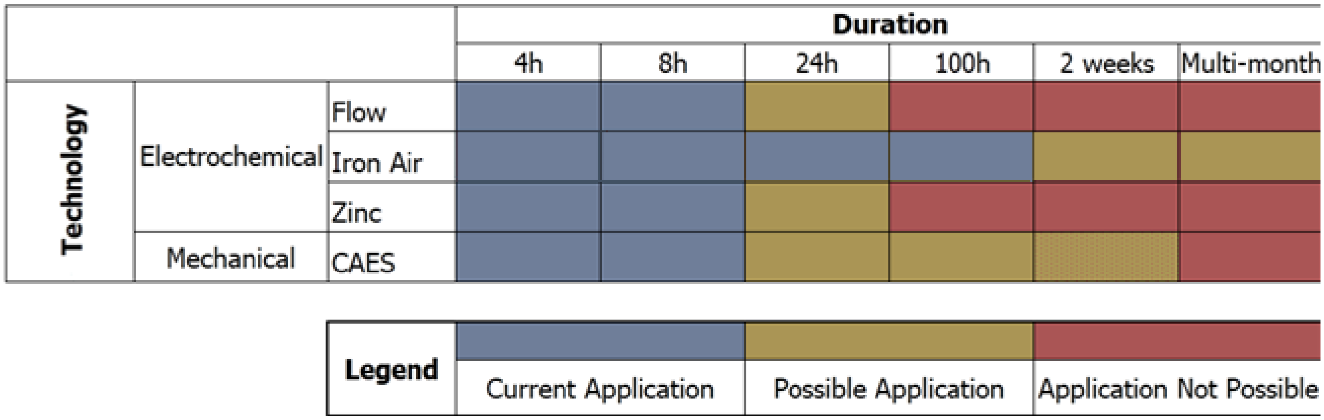
Source: Developed by Guidehouse from data and information obtained via developer and manufacturer interviews, Guidehouse Insights internal model, DOE Global Energy Storage Database, EIA Energy Storage Market Trends

This figure includes lithium-ion as a point of comparison as it is currently the most manufactured energy storage systems globally. However, iron air shows great potential starting around 2034 and rapidly increasing to potentially match and exceed lithium-ion by 2041, as lithium-ion is expected to face continued supply chain limitations while iron air is not expected to face these issues. With flow batteries showing significant capacity growth as well.

Performance Characteristics

Figure 11 provides an overview of the different duration classes for each of the technologies evaluated in this analysis. Current applications refer to current deployments and the durations it can address. The possible applications refer to proposed durations and project sizing by developers. If a technology is not within a shorter duration class, it does not mean that they are not able to address shorter durations but rather that the design is not directly/solely focused on those durations.

Figure 11: Duration Classes for LDES Technologies



Source: Developed by Guidehouse from data obtained via manufacturer interviews and Guidehouse Insights subject matter experts. Refined by way of public comment on the Draft SB 423 Report.

Current and Expected Costs

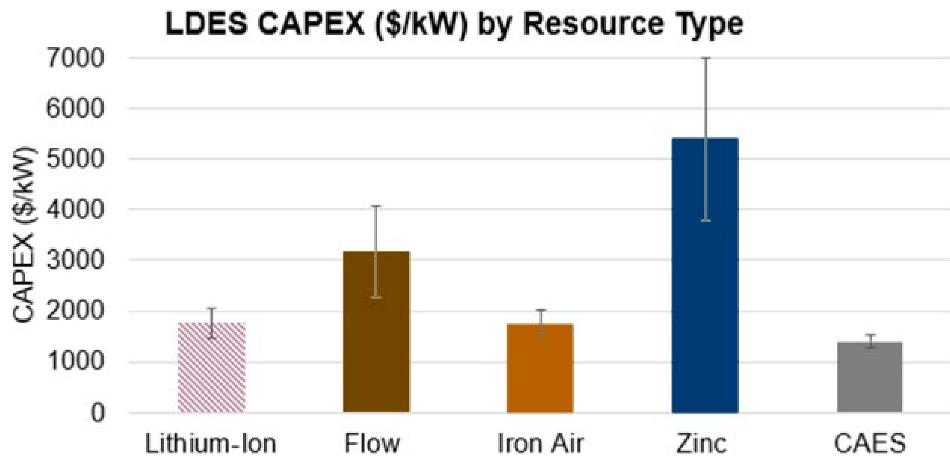
In order to properly evaluate the costs of an LDES system it is important to understand the system size, defined in this context as the power output and duration. Therefore, this analysis focuses the cost evaluation on specific system sizes that are expected for each technology. The data for these costs comes primarily from literature review and developer and SME interviews. **Error! Reference source not found.** provides an overview of the system size assumptions and capital expenses (CAPEX) and fixed operation and maintenance (O&M) associated with these. Variable O&M costs were excluded as they were not readily available or not confident for emerging technologies and thus an effective comparison was difficult to achieve.

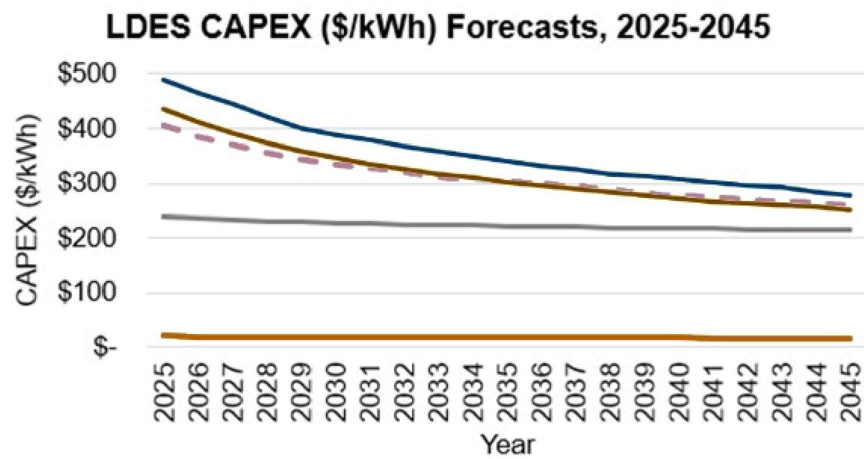
Table 31: Overview of LDES Cost Assumptions and Costs

System Evaluation	Unit	Vanadium Redox	Zinc Bromine	Iron Air	Zinc Battery	aCAES
System Size	MW, hr	100 MW 8 hr	100 MW 6 hr	100 MW 100 hr	10 MW 24 hr	100 MW 10 hr
Power-based CAPEX	$/kW	2,550 – 4,080	2,270 – 2,670	1,500 – 2,000	3,790 – 7,000	1,280 – 1,530
Fixed O&M	$/kW-yr	10.6	10.1	15.2	12.2	18.2

Figure 12 provides graphical representations of the CAPEX of these LDES systems and forecasted CAPEX to provide more insight into the cost comparisons across technologies. The forecast out to 2045 was achieved leveraging learning rates and manufacturing trends described previously.

Figure 12: LDES CAPEX Comparison and Forecast by Resource Type





**Before further analysis it is important to note that iron air has the lowest announced price starting around $20/kWh provided by Form Energy. Since there are no other major figures to influence this number at this time this figure was utilized, but this number needs to be investigated further.*

Source: Developed by Guidehouse from data and information obtained via developer and manufacturer interviews, DOE Global Energy Storage Database, PNNL Grid Energy Storage Technology Cost and Performance Assessment, PNNL Energy Storage Cost and Performance Database, Argonne National Laboratory Development of Energy Storage: Cost Models

Lithium-ion is again used as a baseline for cost comparison for this figure as the most common storage technology in the market currently. Based on the figure one can see that at about $300/kWh in the year 2035, flow batteries are expected to become price competitive with lithium-ion batteries. CAES and iron air are cheaper overall than li-ion. By 2045, none of the other leading technologies will become cheaper than li-ion but the price for zinc begins to fall within range and could be competitive soon after 2045.

Barriers and Recommendations

The largest barriers LDES technologies face revolve around the (1) research & development, (2) siting, (3) manufacturing, (4) interconnection & energy markets, and (5) safety. These barriers and recommendations to address them are outlined in more detail in Table 32. These insights were gained primarily via literature review and claims made by SMEs and developers via interviews.[148,149,150]

Table 32: LDES Barriers and Recommendations

Category	Barriers	Recommendations
Research & Development	• LDES technologies face limited investment/ challenges securing capital due to high capital costs, uncompetitive performance (efficiencies and duration), and supply chain issues. • As more reliability is needed on the grid, longer duration systems (days, weeks and months) will be needed to ensure grid reliability	• According to DOE the goal is to achieve a 45-55% cost reduction and 7-15% improvement in efficiency by 2030 to attract sustained investment. • Longer duration systems are being developed, such as iron air and mechanical systems, that can address 100+ hour discharge.
Siting	• Mechanical and thermal systems are limited by the geographic location and land acquisition required to successfully deploy the technology. In certain cases, electrochemical technologies can be so large that land acquisition is also a challenge. • Local jurisdictions considering bans on battery projects over fire risks.	• Proper locations need to be identified for the development of systems that require land or certain geographic features, while also optimizing ease of interconnection and development. • Technologies need to be developed to become more modular, compact and flexible so siting becomes less of a constraint. • Energy storage can be sited with existing solar and wind plants to minimize land impacts and simplify siting process

148 Department of Energy staff. The Pathway to: Long Duration Energy Storage Commercial Liftoff. United States Department of Energy: Pathways to Commercial Liftoff. https://liftoff.energy.gov/long-duration-energy-storage/.

149 Scott, Kate, Stephen Hendrickson, Nicole Ryan, Andrew Dawson, Kenneth Kort, Jill Capotosto, Benjamin Shrager, et al. 2023. Pathways to Commercial Liftoff: Long Duration Energy Storage. United States Department of Energy. https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-LDES-vPUB-0329-update.pdf.

150 Goodhand, Jason. Overcoming barriers to expanding energy storage. DNV. https://www.dnv.com/article/overcoming-barriers-to-expanding-energy-storage--247350.

Category	Barriers	Recommendations
Manufacturing	• LDES systems, especially electrochemical, require special minerals, semiconductors, and materials that face supply chain vulnerabilities and limitations which limit the scaling of manufacturing, delay system development and increase prices.	• There have been developments of systems and technologies that rely less on constrained/limited minerals and materials making them easier to manufacture. • Mineral and battery recycling has also become a relevant pathway for reducing strain on supply chain and reducing system environmental impacts.
Interconnection and Energy Markets	• Current interconnection rules are causing significant LDES project backlog and may take several years to get approved. • Current energy markets are not designed for LDES technologies and thus are not currently being properly valued in these markets	• Grid operators and state & federal regulatory agencies can work to accelerate the interconnection of LDES systems. • New market participation rules need to be redesigned to properly incorporate LDES, including proper incentives and compensation for these systems. • Energy storage can be co-located with new and existing solar and wind facilities to simplify interconnection process
Safety	• Certain systems are vulnerable to overheating, leakage, and potential thermal runaway that may lead to explosion. This is possible for electrochemical systems that are not properly utilized. • Potentially hazardous minerals, chemicals and materials if disposed of incorrectly at the systems end of life	• Safety concerns can be readily mitigated with proper regulations on the technologies and operational procedures. • Proper disposal regulations of minerals, chemicals, and materials is necessary. Increased interest in proper disposal and recycling reduces environmental impact of systems and improves economics.

Source: Developed by Guidehouse from data and information obtained via developer and manufacturer interviews.

APPENDIX D: Additional Information on Hydropower

Hydropower has been a highly important firm zero-carbon resource for California since the first hydroelectric plant opened in the U.S. in San Bernadino in 1887.[151] Within a California-specific context, hydropower provides 16.5 percent of the total installed in-state generation capacity.[152] This section of the appendix provides additional information about current deployments, technology maturity, manufacturing and supply chain, costs, and barriers and recommendations for hydropower. This section is intended to be read in conjunction with the main report.

Current Deployments

California has an abundance of pumped storage hydro (PSH), large hydro, and small hydro currently deployed. PSH capacity is currently provided by seven facilities at Lake Hodges, Castaic Lake, Helms, San Luis Reservoir, O'Neill Forebay, Big Creek, and Oroville. Large and small hydro is provided across more sites.

By contrast, there has been very little recent traction for new large and small hydropower resources. Just PSH has a significant amount of capacity in the development pipeline. Table 33 illustrates the current and future pipeline of projects across the hydropower technology classifications.

Table 33: Deployments by Hydropower Technology

Hydropower Resource	Current Deployments	Deployment Pipeline
PSH	3.8 GW	15 GW
Large Hydropower	12.3 GW	54 MW
Small Hydropower	1.8 GW	6.5 MW

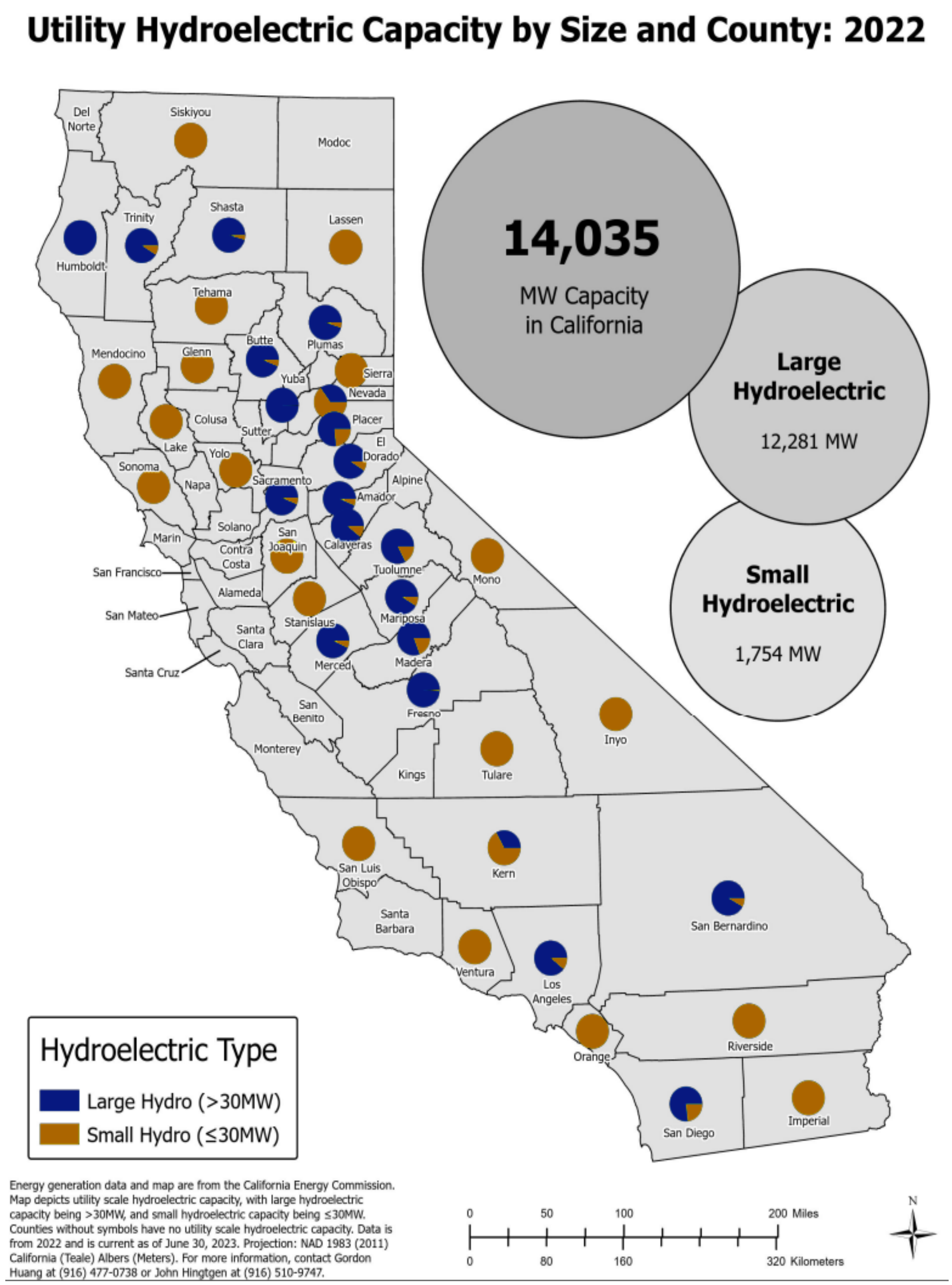
Sources: Oak Ridge National Laboratory, California Energy Commission

Table 33 provides greater insights into the geographical spread of utility hydropower by the counties in California. It specifically shows the balance of large and small hydropower, as well as the capacity of each by county.

151 National Hydropower Association. "History." https://www.hydro.org/about/history/#:~:text=Hydropower%20Milestones&text=1887%3A%20The%20first%20hydroelectric%20plant,percent%20of%20U.S.%20electrical%20generation.

152 California Energy Commission. 2023. "Electric Generation Capacity and Energy." https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/electric-generation-capacity-and-energy.

Figure 13: Hydropower Capacity and Type by County



Source: California Energy Commission

Technological Maturity and Anticipated Improvements

TRL values for all hydropower production types are 9 as illustrated in Table 34.

Table 34: Hydropower Production Technology Readiness Level

Technology Type	TRL (1-9)
PSH	9
Large Hydropower	9
Small Hydropower	9

Source: Guidehouse analysis

Table 35: Hydropower Development Areas by DOE Hydropower Program Objectives[153]

Objective	Development Areas & Desired Impact
Innovations for Low-Impact Hydropower Growth	• Advancements in manufacturing and materials, such as new composite material, that can significantly lower component and system design lifetime costs. • Exploration of conduit hydropower that uses pipelines and irrigation canals as the driver of turbines, reducing environmental impacts, simplifying permitting processes, and expanding hydropower's reach.
Grid Reliability, Resilience, & Integration	• Assessment of additional opportunities for hydropower to support system reliability, resilience, and integration. • Technological concepts and innovations in PSH including submersible pump-turbines and motor generators, geomechanical PSH, open-pit mine PSH, and hybrid PSH systems to explore performance improvement.[154]
Fleet Modernization, Maintenance & Cybersecurity	• Development of digital systems and advanced sensor suites to enable data-driven decision making on O&M and asset management. • Techniques to minimize cavitation erosion of metals within hydropower systems, enhancing performance and service life of new and repaired hydropower components. • Cybersecurity tools and analysis to identify cybersecurity targets, risks, and recovery landscape.

153 US Department of Energy staff. Hydropower Program. United States Department of Energy. https://www.energy.gov/eere/water/hydropower-program

154 Koritarov, Vladimir, Jonghwan Kwon, Quentin Ploussard, Patrick Balducci. 2022. A Review of Technology Innovations for Pumped Storage Hydropower. https://publications.anl.gov/anlpubs/2022/05/175341.pdf

Objective	Development Areas & Desired Impact
Environmental & Hydrologic Systems Science	• Evolution of turbine system design with thicker turbine blades, rounded leading edges, and a forward blade slant to enable the safe passage for fish of varying sizes while maintaining high performance. • Creation of metrics to better evaluate environmental sustainability impact for hydropower. • Analysis of drought impacts on hydropower generation capacity and flexible power supply.
Data Access & Analytics	• Improved accessibility of centralized data on the composition, performance, costs, market participation, and regulatory best practices of hydropower and PSH throughout the U.S. • Development of educational resources to support an evolving hydropower workforce and increase awareness of hydropower opportunities.

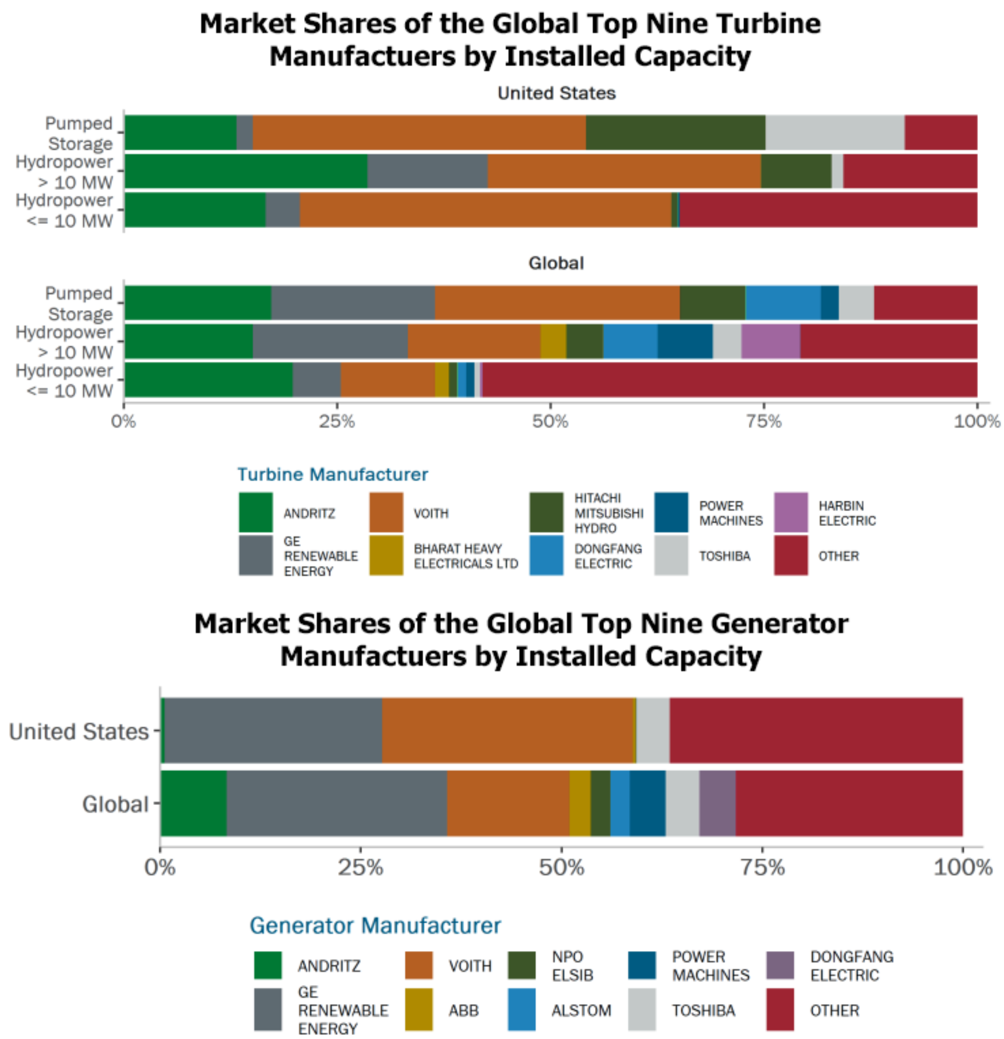
Source: Department of Energy Water Power Technologies Office

Manufacturing and Supply Chain

The manufacturing landscape for hydropower is relatively consolidated with the three largest global turbine manufacturers (Andritz, GE Renewable Energy, and Voith) accounting for almost 50 percent of global nameplate capacity. Their combined market share within the U.S. is even higher than that (almost 75 percent). Only Hitachi Mitsubishi Hydro and Toshiba also have a sizable presence in the U.S. There is significant overlap between turbine and generator manufacturers, but within the U.S. Andritz and Hitachi Mitsubishi Hydro primarily specialize in turbines and GE Renewable Energy focuses on generators.[155] This is described in further detail in Figure 14.

155 U.S. Department of Energy staff. 2022. Hydropower Supply Chain Deep Dive Assessment. https://www.energy.gov/sites/default/files/2022-02/Hydropower%20Supply%20Chain%20Report%20-%20Final.pdf.

Figure 14: Hydropower Manufacturer Landscape



Source: U.S. Department of Energy

While these are the dominant players in the hydropower market in the U.S. there are plenty of smaller companies that play a role, too, especially in California. There are 247 unique companies within the hydropower supply chain located in California, which is second among all states behind only Pennsylvania.

While the supply chain is adequate for the current large hydropower fleet, anticipated expansion, refurbishment, upgrades, and relicensing may necessitate the scale up of domestic activities. Some of the largest current constraints are securing large system components with long lead times, handling global volatility, and maintaining a qualified workforce.[156]

With industry consolidation over the years, there are fewer domestic manufacturers that have the necessary tooling and expertise for larger components, especially large steel castings (>10 tons) and stator windings for large units (>100 MW). Large foundries that used to operate in

156 U.S. Department of Energy staff. 2022. Hydropower Supply Chain Deep Dive Assessment. https://www.energy.gov/sites/default/files/2022-02/Hydropower%20Supply%20Chain%20Report%20-%20Final.pdf.

the U.S. were offshored due to lower labor costs and less stringent safety and environmental regulations outside of the states. Today, steel castings are primarily imported from Brazil, China, Eastern Europe, and South Korea. Special insulation requirements for stator windings limit the companies worldwide capable of manufacturing them. Most stator winding imports come from Canada, Brazil, Mexico, and Europe.

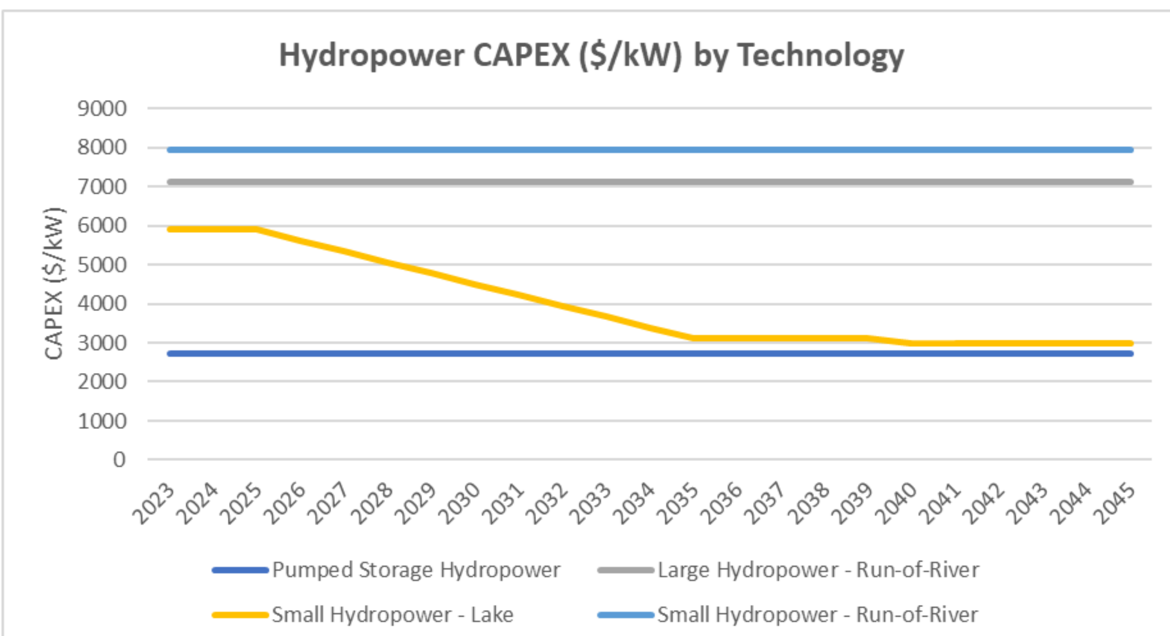
Secondly, the supply chain is opaque and subject to regular delay with ocean shipping volatility. Hydropower operators and original equipment manufacturer (OEMs) alike have expressed an increased desire to trace where materials and electronic components are manufactured. As such, many have stated a willingness to pay a premium for domestically produced components. Additionally, multiple components within the hydropower supply chain are impacted by the current microchip shortage. Expanded domestic penetration into the microchip industry may be an important piece to mitigating reliance upon the global supply chain for hydropower component manufacturing.

Lastly, high retirement rates are anticipated for all positions in the hydropower workforce within the next 5-10 years, and there is a need for labor across the board including for engineers, machinists, welders, and construction workers. It has proven particularly challenging to attract and return construction workers at often remote locations. Emphasis needs to be placed onto training and expanding the workforce if domestic hydropower manufacturing is to expand.[157]

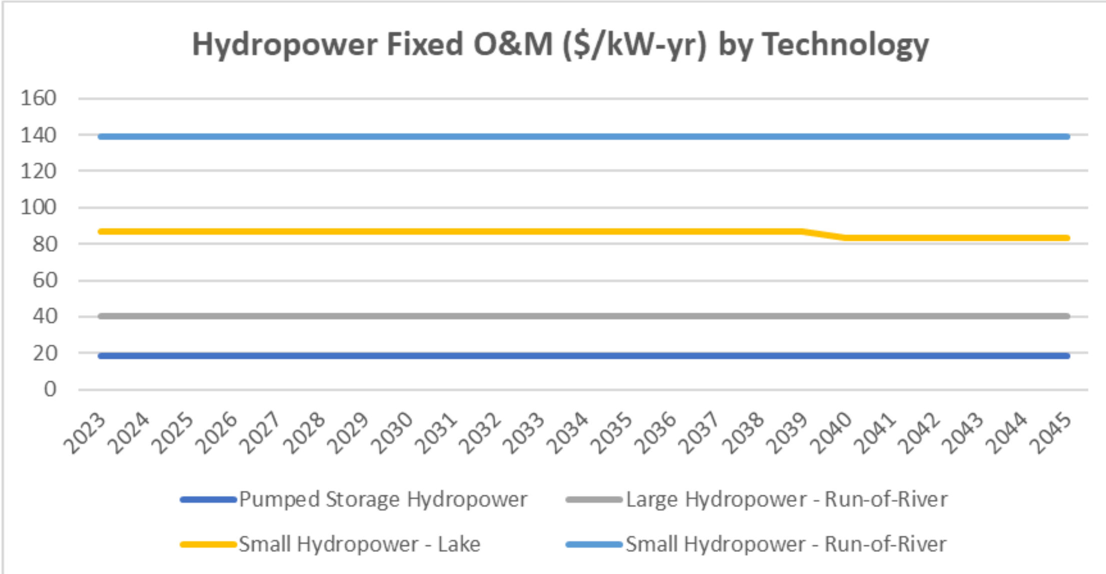
Current and Expected Costs

Hydropower capital and operating costs vary relatively significantly depending on the technology and size. Figure 15 illustrates the cost profiles for these different configurations.

Figure 15: Hydropower Cost Profiles



157 U.S. Department of Energy staff. 2022. Hydropower Supply Chain Deep Dive Assessment. https://www.energy.gov/sites/default/files/2022-02/Hydropower%20Supply%20Chain%20Report%20-%20Final.pdf.



Source: NREL

Upfront costs are generally high across all hydropower resources, although they are most significant (~$8,000/kW) for run-of-river small hydro. PSH, on the other hand, is the most economical hydropower option by a large margin, currently under $3,000/kW, where it will remain through 2045. Lake-based small hydropower capital expenditures are notably higher than PSH but they are far closer to cost competitiveness with PSH than large hydropower. Capital costs are expected to remain relatively flat from 2023 through 2045. The most notable change is lake-based small hydro is expected to decline to ~$3,000/kW by 2045.

While capital costs are still important for hydropower, fixed O&M costs are especially crucial for hydropower resources with the very long lifespan of these technologies (~100 years). These costs are expected to remain more or less stagnant through 2045 for all technologies. Fixed O&M costs are expected to be much more significant for small run-of-river hydropower resources (~$140/kW). Just as it is with capital costs, PSH is the most economical technology from an O&M perspective (~$20/kW). Large run-of-river hydropower fixed O&M costs are double the O&M cost of PSH but are still significantly lower than small hydro resources at ~$40/kW.[158]

Barriers and Recommendations

Globally, the development of new hydropower plants faces hurdles such as environmental regulation and stakeholder opposition. These barriers and associated recommendations are detailed in Table 36.

158 NREL staff. 2023. "2023 Electricity ATB Technologies." https://atb.nrel.gov/electricity/2023/technologies.

Table 36: Hydropower Barriers and Recommendations

Category	Barriers	Recommendations
Siting	• Hydropower developments have historically struggled to correctly identify and manage **environmental and social impacts.** • Hydropower is **highly site specific**, resulting in the need to have multiple components individually designed for a specific project. • Site specificity requires manufacturers to precisely predict geotechnical conditions pre-construction, leaving projects subject to **delays and unexpected costs.**	• New hydropower projects must place huge **emphasis on the planning process** to avoid costly project errors. • **Comprehensive environmental and social evaluations** must be performed for new hydropower projects.
Financial	• Hydropower financing requires **long-term financing**, making projects **less attractive** than shorter-term projects. • Plus, hydropower poses **construction risk**, affecting the attractiveness of projects for investors.	• As higher-risk, long-term projects with large upfront costs, hydro plants may **rely on public financing**, although they can be developed and financed as public-private partnerships.
Manufacturing	• The U.S. hydropower manufacturing industry has an **aging workforce** and struggles to recruit and retain new hires for a wide array of positions. • The U.S. **struggles to produce steel castings** heavier than 10 lbs and **stator windings** for large turbine-generator units.	• Expand **apprenticeship programs** and hydropower **educational curricula.** • **Procurement rules** (Buy American Act), **domestic content requirements** in the Bipartisan Infrastructure Law hydropower incentives (Build America, Buy America Act), and **domestic content adders** in the IRA tax credits are already in place.

Category	Barriers	Recommendations
Maintenance	• There is currently an **aging hydropower fleet.** • The **average age** of a hydropower plants in operation is close to **40 years**, while the average lifetime of already **retired hydropower plants** was around **60 years.**	• Funds will need to be allocated towards **refurbishment** of aging California hydropower plants.
Environment	• Large **year to year variations in rain and snowfall** can affect river flows and reservoir levels and have huge effects on hydroelectric energy generation. • California's conventional **hydroelectric power generation fell by 55%** between 2019 and 2022 due to a **prolonged drought** that dried up state reservoirs.	• A reduction of hydroelectricity due to drought conditions would force California to import more electricity from other markets, rely more heavily on other renewables, or use more in-state natural gas-fired generation. • **Further investigate drought severity and forecasted impact before taking drastic action**: a PNNL study on hydro drought impacts in the Western U.S. found that "**even during the most severe droughts** experienced since the turn of the century, the western **hydropower fleet sustained four-fifths or more of its typical annual generation.**"

Sources: NREL, U.S. Department of Energy, PNNL, IRENA, IEA

APPENDIX E: Additional Information on Geothermal

Additional information on geothermal resources is provided within this section of the appendix. This section is intended to be read in conjunction with the main report and includes further detail on the geothermal resource classes, current deployments, technology maturity, manufacturing and supply chain, performance characteristics, costs, and barriers and recommendations for geothermal resources.

Technology Overview

The varying types of geothermal resource classes are shown in Table 37.

Table 37: Geothermal Resource Classes

Geothermal Resources	Characteristics
Conventional Hydrothermal (Unproduced Resource)	Geothermal resource where levels of geothermal reservoir temperature and reservoir flow capacity are naturally sufficient to produce electricity, and where development of the geothermal reservoir has not previously occurred to the extent that it supported the operation of geothermal plant(s).
Conventional Hydrothermal (Produced Resource)	Geothermal resource where levels of geothermal reservoir temperature and reservoir flow capacity are naturally sufficient to produce electricity, and where development of the geothermal reservoir has previously occurred to the extent that it currently supports or has supported the operation of geothermal plant(s).
Conventional Hydrothermal Expansion	The expansion of an existing geothermal plant and its associated drilling area to increase the level of power that the plant produces.
Geothermal Energy and Hydrocarbon Co-Production	The utilization of produced fluids resulting from oil- and/or gas-field development to produce geothermal power.
Enhanced Geothermal Systems (EGS)	The development of a geothermal system where the natural flow capacity of the system is not sufficient to support adequate power production, but where the injection of fluid into the system can allow production at a commercial level.

Source: NREL

Current Deployments

Geothermal resources are currently significant within California. Notably, though, geothermal production within the state is highly concentrated to a few areas. "The Geysers" geothermal steam field, located within Lake, Mendocino, and Sonoma Counties, contains 349 out of California's 563 high-temperature geothermal wells within the state. Imperial County (including the Salton Sea) houses 194 of these wells, and the remaining 20 are located in Lassen, Modoc, and Mono Counties.[159] Specifically for geothermal power production, California has installed a nameplate capacity of 2,627 MW or 72 percent of the total U.S. geothermal plant capacity.[160] Even though there is a large amount of geothermal power currently operational within California, the state has plans for significant development going forwards, especially within the Salton Sea area. Table 38 describes these projects in greater detail.

Table 38: Geothermal Project Pipeline

Project Name	Location	Expected Output	Technology Type	Status	Deployment Considerations
Hell's Kitchen	Salton Sea	1,100 MW	Flash Steam	Permitting	• **PPA signed**, expected to be commissioned in mid-2025. • Staged to deliver 50 MW in 2025 with total project capacity up to 1,100 MW.
Casa Diablo	Mammoth Lakes	30 MW	Binary	Operational	• First geothermal plant built within California ISO in the last 30 years. • Operational in 2022.
Morton Bay Geothermal	Salton Sea	140 MW	Flash Steam	Application Under Review	• Construction is expected to begin no later than Q2 2024 and full-scale commercial operation is expected to begin by June 2026. • The capital cost is estimated to be between $750 million and $1.3 billion.
Elmore North Geothermal	Salton Sea	140 MW	Flash Steam	Application Under Review	• Construction is expected to begin no later than Q2 2024 and full-scale commercial operation is expected to begin by June 2026. • The capital cost is estimated to be between $750 million and $1.3 billion.

159 California Department of Conservation staff. 2020. California Oil and Gas Supervisor Annual Report 2020. https://www.conservation.ca.gov/calgem/Documents/Final%20CalGEM%20Supervisor%20Annual%20Report%202020%20-%202023.05.30.pdf.

160 Robins, Jody C., Amanda Kolker, Francisco Flores-Espino, Will Pettitt, Brian Schmidt, Koenraad Beckers, Hannah Pauling et al. 2021. U.S. Geothermal Power Production and District Heating Market Report. https://www.nrel.gov/docs/fy21osti/78291.pdf.

Project Name	Location	Expected Output	Technology Type	Status	Deployment Considerations
Black Rock Geothermal	Salton Sea	77 MW	Flash Steam	Application Under Review	• Construction will commence Q2 2024 with commercial operation expected June 2026. • The capital cost is estimated to be between $475 million and $800 million.

Sources: EIA, California Department of Ecology, Bureau of Land Management, Power Technology

Technological Maturity and Anticipated Improvements

All three geothermal technologies have reached market maturity, but EGS configurations of flash and binary geothermal are still in the early phase of demonstration, as is shown in Table 39.

Table 39: Geothermal Technology Readiness Level

Technology Type / Resource Class	TRL (1-9)
Dry Steam	9
Flash Steam	9
Binary Steam	9
EGS	7-8

Source: Guidehouse analysis for this report

One other area for potential improvement not mentioned in the report body for most geothermal technologies includes enhancing efficiency and durability of geothermal turbines. Steam from geothermal production contains chloride, methane, sulfate, hydrogen sulfide, and other corrosive chemicals that can erode the surfaces of turbine components such as the blades and rotor.[161] One solution that uses surface-active inhibitors to prevent erosion in geothermal power generation equipment has appeared promising, and other solutions should continue to be explored.[162]

Manufacturing and Supply Chain

The geothermal manufacturer landscape has undergone significant transition over the past decade. Since 2016 there has been a reduction in the number of U.S. geothermal operators due to consolidation of manufacturers, companies leaving the industry, or companies going

161 2021. "Redesign Can Increase Geothermal Turbine Efficiency." Power Magazine. https://www.powermag.com/redesign-can-increase-geothermal-turbine-efficiency/.

162 Tomarov, Grigory V., Dmitry V. Kolesnikov, Valery N. Semenov, Viktor M. Podverbny, Andrey A. Shipkov. 2015. Prevention of Corrosion and Scaling in Geothermal Power Plants Equipment. https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2015/27032.pdf.

out of business. This has contributed to a reduction in projects under development and an aging population of existing geothermal plants, with 44 percent of plants over 30 years old.[163]

Currently, the U.S. geothermal power industry is dominated by two operators: Calpine and Ormat. Calpine produces ~1,400 MW from 15 dry steam power plants at the Geysers in Lake and Sonoma Counties in California. Ormat produces ~1,000 MW from 34 power plants, the majority of which are binary plants that leverage lower temperatures. Most Ormat geothermal plants within California are in Imperial and Mono Counties.[164]

Geothermal energy is fortunate to have a healthy supply chain. According to the Intergovernmental Panel on Climate Change (IPCC), there are not anticipated to be any "mid- or long-term constraints to materials supply, labor availability, or manufacturing capacity…from a global perspective."[165] Also of note, it is believed that geothermal energy production can uplift the lithium supply chain through the extraction of geothermal brine, yielding ancillary benefits for other technology supply chains that can help provide firm zero-carbon energy such as LDES. California, in particular, aspires to develop a prominent lithium industry in the Salton Sea through its Lithium Valley project by recovering significant amounts of lithium from geothermal brine.[166]

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163 Robins, Jody C., Amanda Kolker, Francisco Flores-Espino, Will Pettitt, Brian Schmidt, Koenraad Beckers, Hannah Pauling et al. 2021. U.S. Geothermal Power Production and District Heating Market Report. https://www.nrel.gov/docs/fy21osti/78291.pdf.

164 Ibid.

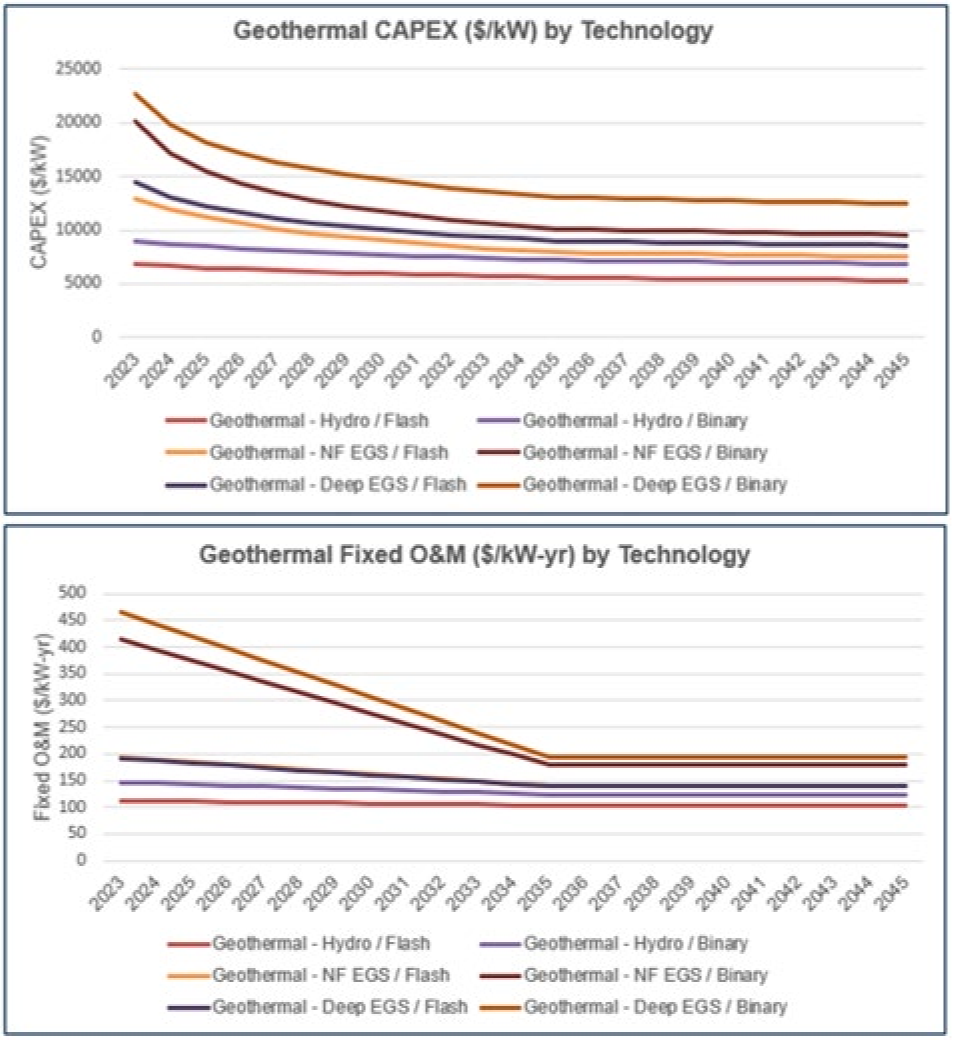
165 Goldstein, Barry, Gerardo Hiriart, Ruggero Bertani, Christopher Bromley, Luis Gutiérrez-Negrín, Ernst Huenges, Hirofumi Muraoka et al. 2018. Geothermal Energy. https://www.ipcc.ch/site/assets/uploads/2018/03/Chapter-4-Geothermal-Energy-1.pdf.

166 California Energy Commission staff. 2022. "Lithium Valley Commission." California Energy Commission. https://www.energy.ca.gov/data-reports/california-power-generation-and-power-sources/geothermal-energy/lithium-valley.

Current and Expected Costs

CAPEX and Fixed O&M cost projections for geothermal technologies are illustrated in Figure 16.

Figure 16: Geothermal Cost Profiles



Source: NREL

Conventional geothermal technologies are projected to be the most cost-effective resources through 2045 from both capital and operating cost perspectives. Additionally, flash geothermal technologies generally are cheaper than binary technologies. Binary EGS technologies are currently the most expensive geothermal options from a capital cost and, especially, a fixed O&M lens. However, they are also expected to undergo the most significant cost declines by 2045 and ultimately reach similar, albeit slightly higher, cost metrics.

Barriers and Recommendations

The key barriers and associated recommendations for geothermal resources are listed in Table 40.

Table 40: Geothermal Barriers and Recommendations

Category	Barriers	Recommendations
Permitting & Regulations	• Geothermal projects in CA are subject to environmental **review processes at the federal** (National Environmental Policy Act) **and state level** (California Environmental Quality Act). • The state California Environmental Quality Act process is **inconsistent and time consuming**, which may lead to **permitting and project development delays.** • **Staff shortages + heavy workloads** increase the review process and permitting timelines. • There are **competing water interests** associated with water reduction, decreased water quality, and loss of species habitat in the Salton Sea region. • Projects in Imperial County may require a **Clean Water Act permit** from the U.S. Army Corps of Engineers + attain a **water quality certification** from the CA Water Board.	• **Tiering to existing environmental review documents** (National Environmental Policy Act) may **create efficiencies** in the environmental review process by aiding agency staff in developing mitigation measures. • **Tiering to recently conducted baseline resource studies** may save federal state agencies time and resources during environmental reviews. • California must develop a **holistic, integrated environmental review process.** • Leverage **federal/state regulatory working groups** and increase inter-agency coordination. • Develop interagency **Memoranda of Understanding (MOUs)** to reduce overall project timelines, costs, and uncertainties by **clearly delineating agency roles and responsibilities** and aligning agency permitting processes to reduce duplication and reduce permitting timelines. • Leverage the CEC's Application for Certification process, which provides an option for **projects over 50 MW** to use a single process that can **cover permitting requirements from multiple agencies** and include **statutorily mandated timelines.** • Issue a **jurisdictional determination** evaluating the **Salton Sea** (not case-by-case).

Category	Barriers	Recommendations
Financial	• Projects have **difficulty mobilizing or accessing capital** for early exploration and project financing due to **project complexity, investment risk**, and **long development timelines.** • Protracted geothermal development timelines caused by **delays** in acquiring necessary permits or environmental reviews often **drive-up project costs and economic uncertainty.** • Delays lead to **lost generated electricity revenue**, **additional financing costs**, and **inflated LCOE's** from compounding intertest that may accrue while construction is on hold.	• **Public-private partnerships** and **government incentives** can encourage investment in geothermal projects. • **Cost reduction** through **technological advancements** and **economies of scale** can enhance the economic feasibility of geothermal. • Explore **innovative financial models** (PPAs, feed-in tariffs).
Public Acceptance	• Projects are often met with **opposition** from **local people** and **indigenous communities.**	• Always maintain **strong community engagement** and **stakeholder consideration.**

Sources: NREL 1, NREL 2, IRENA

APPENDIX F: Additional Information on Renewable Natural Gas (RNG)

Additional information on renewable natural gas (RNG) is provided within this section of the appendix. This section is intended to be read in conjunction with the main report and includes further detail on RNG production and upgrading, current deployments, technology maturity, manufacturing and supply chain, performance characteristics, costs, and barriers and recommendations for RNG.

Technology Overview

The tables below provide additional details related to the gas production and gas upgrading necessary to produce RNG that was not covered in the body of this report.

Table 41: Gas Production Overview

Gas Production Pathway	Feedstock	Characteristics
Thermochemical production pathways **(Gasification & Pyrolysis)** produce intermediary gas: **Syngas**[167]	Can take more fibrous feedstocks (e.g., woody biomass, forest waste, crop residue) while also taking waste (e.g., municipal solid waste, livestock manure)	• Thermochemical conversion process that uses high temperatures and **controlled amount of oxygen (gasification) or no oxygen (pyrolysis)** to convert liquid or solid feedstocks to gaseous products (syngas) without combustion. • Heat in the system comes from burning a small portion of the biomass or small fraction of the syngas. • Fast pyrolysis is mostly used to produce bio-oils as it has a higher market potential.
Anaerobic Digestion production pathway produces intermediary gas: **Biogas**[168]	Takes more organic waste feedstocks (e.g., landfill, wastewater treatment, food waste, livestock manure)	• Process where bacteria breaks down/digests organic matter in the absence of oxygen. • Waste is broken down in a digester, which contains a complex microbial community, and produces biogas (45-75% methane) and digestate (solid and liquid products after digestion). • Multiple organic materials can be combined in a single digester in a process called co-digestion.

167 Capaldi, Romain, Al Abbas Lamrini. 2023. Thermal Gasification: A key technology to decarbonize Europe and improve energy security. Guidehouse Insights. https://guidehouse.com/insights/energy/2023/thermal-gasification.

168 Environmental Protection Agency AgSTAR staff. How Does Anaerobic Digestion Work? United States Environmental Protection Agency AgSTAR. https://www.epa.gov/agstar/how-does-anaerobic-digestion-work.

Gas Production Pathway	Feedstock	Characteristics
Landfills produce intermediary gas: **Landfill Gas (LFG)**[169]	Takes place in landfill and municipal solid waste	• Natural degradation of waste by anaerobic microorganisms in landfills, resulting in landfill gas that is mostly made up of methane, hydrogen sulfide and CO_2.

Source: Guidehouse-developed table for this analysis

Table 42: Gas Upgrade to RNG Overview

Gas Upgrade Pathway	Characteristics
Syngas Upgrade to RNG[170]	• The syngas produced from gasification includes hydrogen, carbon monoxide, carbon dioxide, water, methane, tar and other impurities that need to be removed to produce biomethane or RNG. • Removal of tars and impurities is achieved through simple gas cleaning. • The clean syngas can also be conditioned to increase the hydrogen to CO ratio to ensure high CO conversion during methanation and increase methane yield. This conditioning can be achieved via water gas shift reactions where water and CO result in hydrogen and CO_2. • Methanation is the conversion of CO and CO_2 into methane through hydrogenation and specialized catalysts. Thus, using the hydrogen and CO/CO_2 in the syngas methanation increases the yield of methane from the syngas from gasification.

169 Environmental Protection Agency staff. Basic Information about Landfill Gas. United States Environmental Protection Agency. https://www.epa.gov/lmop/basic-information-about-landfill-gas.

170 Seiser, Dr. Reinhar, Dr. Robert Cattolica, Michael Long. 2020. Renewable Natural Gas Production from Woody Biomass via Gasification and Fluidized-Bed Methanation. California Energy Commission. Publication Number: CEC-500-2020-055. https://www.energy.ca.gov/sites/default/files/2021-05/CEC-500-2020-055.pdf.

Gas Upgrade Pathway	Characteristics
Biogas and LFG Upgrade to RNG[171]	• Biogas resulting from digestion and landfill gas can be refined by removing CO_2, water, hydrogen sulfide, and other gases to produce RNG. • RNG is regulated to have >90% concentrations of methane depending on pipeline specifications or other end -requirements to ensure greater similarity with natural gas. • Treatment of biogas to RNG involves (1) moisture and particulate removal, (2) contaminant removal and compression, and (3) CO_2, O_2, N_2, and volatile organic compound removal. • Methods to remove CO_2 in the third step of treatment include membrane separation, pressure swing adsorption (PSA), solvent scrubbing, and water scrubbing. In the U.S. LFG is typically cleaned using membranes (24%), solvents (24%), PSA (10%), or unknown (42%). Manure-based AD uses membrane (64%), PSA (12%), water scrubbing (6%), or unknown (18%). • Membrane systems are filters with specific design that separate particles larger than the pore size, in this case CO_2. These systems can typically capture 65-99% of the CH_4 from the gas inlet stream. • PSA systems combine a pressurized adsorbent media with incoming biogas where the media captures the CO_2 and N_2 while allowing the methane to pass to the product gas. These systems can typically capture 95-98% of the CH_4 from the gas inlet stream. • Solvent scrubbing uses chemical or solid solvents to strip CO_2 and H_2S from biogas stream allowing CH_4 to pass into the product stream. These systems can typically capture 97-99% of the CH_4 from the gas inlet stream.

Source: Guidehouse-developed table for this analysis

Current Deployments

Of the biomass and waste gas production technologies by far the most common are anaerobic digester and landfill gas collection. Within California alone there are about 100 operational livestock anaerobic digesters with another 40 in construction.[172] There are a variety of anaerobic digestor designs that can be implemented but almost all of the current digesters in California are covered lagoon systems. Similarly, there are about 300 unique landfills in California of which 54 has operational landfill gas energy projects with another 29 landfills being potential candidates for projects.[173] These projects include methane for transportation,

171 Environmental Protection Agency staff. 2021. An Overview of Renewable Natural Gas from Biogas. United States Environmental Protection Agency. https://www.epa.gov/sites/default/files/2021-02/documents/lmop_rng_document.pdf.

172 Environmental Protection Agency AgSTAR staff. Livestock Anaerobic Digester Database. United States Environmental Protection Agency. https://www.epa.gov/agstar/livestock-anaerobic-digester-database.

173 Environmental Protection Agency staff. Project and Landfill Data by State. United States Environmental Protection Agency. https://www.epa.gov/lmop/project-and-landfill-data-state.

local combined heat and power, and power generation. On the other hand, gasification and pyrolysis are much less developed and mature technologies and have more limited deployments. According to IEA Bioenergy in 2020 there were 686 gasifiers, not limited to biomass and waste, operating across the world in 272 unique large-capacity plants. There are significantly less deployments of large biomass and waste gasifiers for power generation. There are only 108 projects worldwide of biomass/waste gasification/pyrolysis for power generation, of which only 2 are in the US and only 20 are larger than 1 MW. Some noteworthy deployments in California include a 2MW forest wood waste gasifier under construction in North Fork, California[174]; Southern California Gas's application for the largest RNG pilot project, San Joaquin Renewables[175]; and VGrid's mobile modular biomass gasification generator with seven deployments in California.[176]

Technological Maturity and Anticipated Improvements

For anerobic digestion and landfills the increase in methane production and capture can be achieved via system design of waste lagoons and operational design. The improvement of gas treatment and upgrading of the biogas and LFG to RNG comes from an improvement in the removal of CO_2 from membranes, PSA, solvent scrubbing, or water scrubbing. These technologies are expected to continue to develop and improve as these are the same technologies as carbon capture, which continues to receive attention and investments globally and are discussed in more detail in the Carbon Capture section of this report. The table below displays the technology readiness level (TRL) of the RNG production technology types.

Table 43: RNG and Biogas Production Technology Readiness Level

Technology Type	TRL (1-9)
Thermochemical	4-5[177]
Anaerobic Digestion	9[178]
Landfill Gas	9[179]

Source: Guidehouse analysis for this report

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174 EQTEC staff. 2022. North Fork, California Project Fact Sheet. EQTEC. https://eqtec.com/wp-content/uploads/EQTEC-North-Fork-Project-Fact-File-Aug-2022.pdf.

175 Smeenk, Sadie. 2023. SoCalGas Files for San Joaquin Renewables Project Permits With CPUC. San Joaquin Renewables: Natural Gas from Biomass. https://sjrgas.com/uncategorized/socalgas-files-for-san-joaquin-renewables-project-permits-with-cpuc/.

176 VGrid staff. The Bioserver: A mobile, modular, and scalable biomass energy solution. VGrid. https://vgridenergy.com/bioserver/.

177 Jafri, Yawer, Lars Waldheim, Joakim Lundgren. 2020. Emerging Gasification Technologies for Waste & Biomass. IEA Bioenergy: Technology Collaboration Programme. https://www.ieabioenergy.com/wp-content/uploads/2021/02/Emerging-Gasification-Technologies_final.pdf.

178 Environmental Protection Agency AgSTAR staff. How Does Anaerobic Digestion Work? United States Environmental Protection Agency AgSTAR. https://www.epa.gov/agstar/how-does-anaerobic-digestion-work.

179 Environmental Protection Agency staff. Basic Information about Landfill Gas. United States Environmental Protection Agency. https://www.epa.gov/lmop/basic-information-about-landfill-gas.

Manufacturing and Supply Chain

Since many of these technologies are already quite mature and commercialized, plenty of vendors and manufacturers exist in the market. For thermochemical technologies, IEA Bioenergy tracks the variety of vendors and developers of waste and biomass gasification technologies. While the list is not entirely exhaustive, in 2018 the IEA tracked about 84 distinct developers of gasification systems, of which the majority are focused on combined heat and power application and only about 12 are exclusively focused on power generation, including JFE in Japan, Kawasaki Heavy Industries in Japan, Mitsubishi Heavy Industries in Japan, Outotec Energy Production in the USA, Taylor Biomass Energy in the USA, and Thermochem Recovery Inc. in the USA.[180,181] Current gasifiers are predominantly used for production of chemical, fuels, synthetic natural gas for transportation, and power generation. Likewise, the majority of the gasifiers currently being manufactured and utilized use feedstocks such as solid and liquid fuels, coal, petroleum coke, and residual hydrocarbons, while only a limited amount use biomass and waste feedstock streams.

From an anerobic digestion perspective, AgSTAR has tracked close to 182 vendors in the USA alone that can support the development of anaerobic digestion systems, including consultants, developers, and manufacturers.[182] For operational livestock anerobic digestion projects common vendors include 4Creeks, California Bioenergy LLC, Maas Energy Works, Martin construction Resource LLC, and Calgren Dairy Fuels LLC. Other developers in CA (across food waste and wastewater treatment plant systems) include Anaergia, BioFuels Energy LLC, and Biogas Energy, Inc. The largest supply chain limitation with these systems is also related to the feedstock and the proximity and access to the desired feedstock. As a result, the majority of the systems found in California are covered lagoons near dairy farms.

For landfill gas production the manufacturing required to utilize the methane captured from landfills in existing gas collection and control systems is much less complex than the other technologies. Existing landfills could be retrofitted to deal with methane emissions and landfill gas by swapping the flare for an engine/turbine genset. California has 300 unique landfills of which 197 has LFG collection systems, 54 of those have LFG-related energy projects for electricity, direct use in boilers, and RNG for vehicles.[183] The remaining question with landfill gas collection is its utilization, as currently the LFG projects that produce electricity utilize the LFG, after removing water and H2S, in gas power generating systems, such as combustion turbines and reciprocating engines with no upgrading. Therefore, there are no significant supply chain concerns with LFG as it utilizes existing capture systems and simple methane upgrading technologies.

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180 Waldheim, Lars. 2018. Gasification of waste for energy carriers. IEA Bioenergy. https://www.ieabioenergy.com/wp-content/uploads/2019/01/IEA-Bioenergy-Task-33-Gasification-of-waste-for-energy-carriers-20181205-1.pdf.

181 Gasification Systems and Suppliers. Bioenergy Lists: Gasifiers. https://gasifiers.bioenergylists.org/content/gasification-systems-and-suppliers.

182 Environmental Protection Agency AgSTAR staff. AgSTAR Vendor Directory for Manure Digester Systems. United States Environmental Protection Agency AgSTAR. https://www.epa.gov/agstar/agstar-vendor-directory-manure-digester-systems.

183 Environmental Protection Agency staff. Landfill Gas Energy Project Data. United States Environmental Protection Agency. https://www.epa.gov/lmop/landfill-gas-energy-project-data.

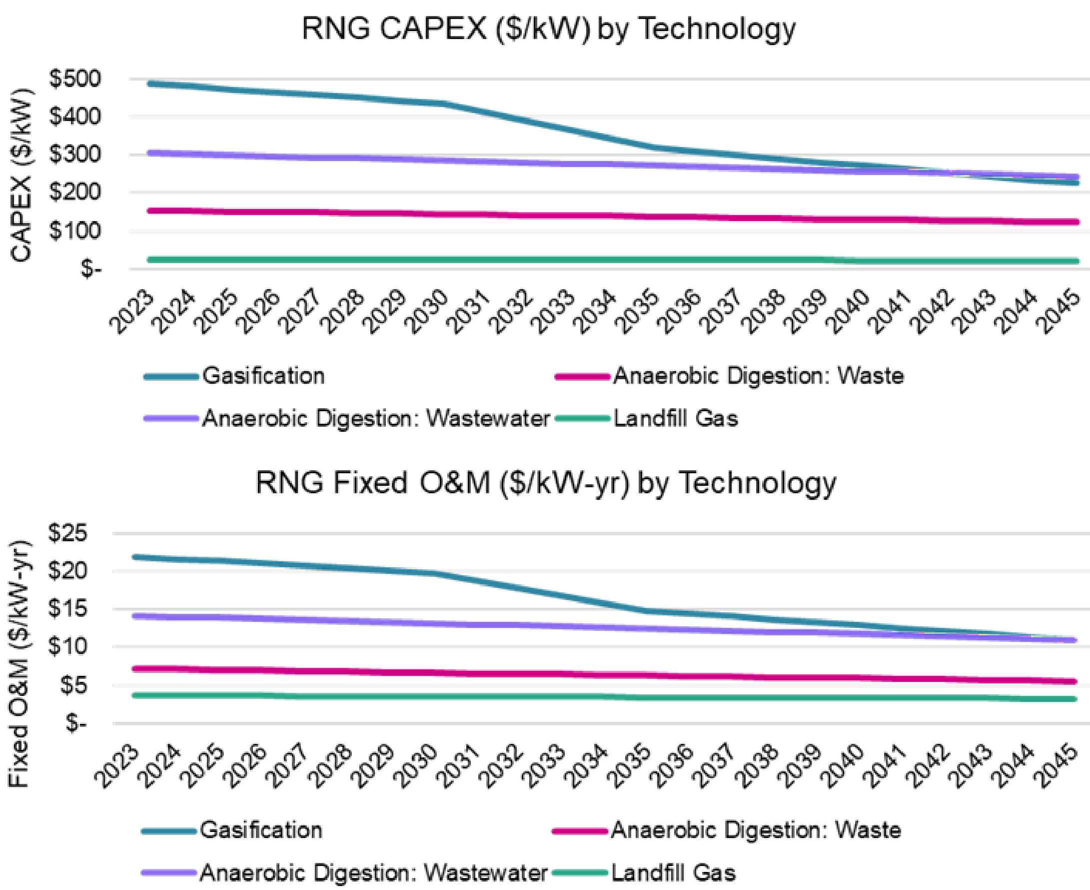
Current and Expected Costs

Current costs, both CAPEX and operating expenses (OPEX), are obtained primarily via literature review and technology forecasting.[184,185,186,187] Given the resources utilized, the costs were focused on gasification, anaerobic digestion of waste and from wastewater, and landfill gas.

Figure 17: RNG Production Cost Profiles

shows the current costs and projections associated with RNG production technologies.

Figure 17: RNG Production Cost Profiles



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184 IEA staff. Outlook for biogas and biomethane: Prospect for organic growth. International Energy Agency. https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth/sustainable-supply-potential-and-costs.

185 Environmental Protection Agency staff. 2024. LFG Energy Project Development Handbook, Chapter 3: Project Technology Options. United States Environmental Protection Agency Landfill Methane Outreach Program. https://www.epa.gov/system/files/documents/2024-01/pdh_chapter3.pdf.

186 Environmental Protection Agency staff. 2024. LFG Energy Project Development Handbook, Chapter 4: Project Economics and Financing. United States Environmental Protection Agency Landfill Methane Outreach Program. https://www.epa.gov/system/files/documents/2021-07/pdh_chapter4.pdf.

187 International Energy Agency staff. 2020. Outlook for biogas and biomethane. International Energy Agency. https://iea.blob.core.windows.net/assets/03aeb10c-c38c-4d10-bcec-de92e9ab815f/Outlook_for_biogas_and_biomethane.pdf.

Source: Guidehouse-developed figures for this analysis. IEA, IRENA, Guidehouse Insights, Oxford Institute for Energy Studies.

RNG production costs decrease about 25 percent on average globally by 2050 due to economies of scale, but feedstock costs remain uncertain due to increased demand and competition for these resources. Landfill gas has the lowest initial cost and the overall lowest cost decline as this is the most established technology and has limited technological improvement in sight that would reduce its costs other than higher gas collection efficiency. Gasification, as the least mature of these technologies, has the largest initial costs but also the largest cost reduction as it approaches optimal maturity, while anaerobic digestion will only see modest improvements in efficiency and subsequent cost reductions.

Barriers and Recommendations

The largest barriers that RNG production technologies face revolve around the (1) availability and pre-processing of feedstocks, (2) research & development, (3) economic viability and competitiveness, and (4) operation of systems. These barriers and recommendations to address them are outlined in more detail in Table 44.

Table 44: RNG Production Barriers and Recommendations

Category	Barriers[188,189,190,191]	Recommendations
Feedstock Availability and Processing	• While organic waste is abundant, the collection and handling of it can be complex and expensive to meet requirements of gasifiers, such as moisture content and size. • Biomass and animal waste collection tends to be more spread out geographically and contains a higher degree of contaminants and moisture that needs to be treated before RNG production, especially via gasification.	• Need to establish efficient and reliable systems for organic waste collection, transport, and treatment. • Co-locating multiple systems, co-digestion for AD and multiple feedstock streams for gasification can optimize the collection of feedstock and processing.

188 Environmental Protection Agency staff. 2021. An Overview of Renewable Natural Gas from Biogas. United States Environmental Protection Agency. https://www.epa.gov/sites/default/files/2021-02/documents/lmop_rng_document.pdf.

189 Orozco, Emmanuel, Bruce Springsteen, Christina Darlington. 2022. Woody Biomass Gasification Technology in California. Placer County Air Pollution Control District and California Law Empowering Renewable Energy. https://www.placerair.org/DocumentCenter/View/61254/Placer-APCD-wood-conversion-tech-2022?bidId=.

190 Scarlat, Nicolae and Fernando Fahl. 2019. Heat and Power from Biomass: Technology Development Report. Publications Office of the European Union. ISBN 978-92-76-12433-7, doi:10.2760/19308. https://publications.jrc.ec.europa.eu/repository/handle/JRC118318.

191 Raju, Arun. 2016. Renewable Natural Gas – Challenges & Opportunities. Center for Renewable Natural Gas, University of California Riverside. https://www.cert.ucr.edu/sites/default/files/2019-01/RNG_white_paper.pdf.

Category	Barriers[188,189,190,191]	Recommendations
Research & Development	• Gasification needs pre-processing of feedstock and specific levels of moisture and impurities. • Gasification is currently not very flexible when it comes to feedstocks and efficiency. • Non-landfill biogas sources typically general lower biogas flows which can be challenging to process and scale. • Landfill gas usually has N_2 which reduces heating value in RNG and is difficult to remove.	• Improve the flexibility of feedstocks and feedstock characteristics that can be processed in AD and gasification via new bacterial strains with a greater tolerance to process changes and feedstock types and new gasifiers. • Improve upon the purification and processing of biogas/syngas technologies to allow to scale at low gas flows and high contaminants. • Improve overall efficiency of biogas/syngas recovery, methane separation and cleaning of RNG.
Economic Viability and Competitiveness	• Current pricing of capturing biogas/producing syngas and processing into RNG is not competitive with fossil natural gas prices. • Pricing and environmental attribute volatility for RNG make it less appealing for state and federal incentives. • Pipeline interconnection can be costly and have a long lead time for RNG projects, especially for projects that incur this cost but produce relatively small quantities of RNG. • Long economic returns compared to conventional generation and long lead times limit investments.	• Unfavorable RNG price disparity with fossil gas can be mitigated by policy or legislation that creates demand for and premium pricing for RNG. • Costs associated with gas cleanup and interconnection can be reduced through scale economies from shared infrastructure, such as digester clusters that share upgrading sites and injection points.

Category	Barriers[188,189,190,191]	Recommendations
Operation	• Processing and disposal of digestate and solid waste (e.g., bio-char) resulting from AD and gasification can be logistically challenging. • Meeting gas quality specifications and standards for pipeline injection may vary by state or pipeline and requires different levels of upgrading and cleaning. • Projects are developed with the idea of a "one-size fits all technology" to a unique problem that requires a unique design and technology.	• Digesters and gasifiers must be adequately designed and matched to the type of waste and operation at the location to optimize gas production. • Maximize the use of digestate and bio-char from AD or gasification as fertilizer, soil additive, animal feed additive, filtration medium, etc. to get more value from these byproducts.

Source: Guidehouse analysis for this report

APPENDIX G: Additional Information on Hydrogen

Additional information on hydrogen resources is provided within this section of the appendix. This section is intended to be read in conjunction with the main report and includes further detail on the use of hydrogen for power generation, hydrogen production and storage, current deployments, technology maturity, manufacturing and supply chain, costs, and barriers and recommendations for hydrogen. The production and storage of hydrogen are critical components of the hydrogen lifecycle that are pre-requisites to the deployment of hydrogen power generation as a firm zero-carbon resource within California.

Technology Overview

H_2 production and storage technologies are covered at a high level in Table 45 and Table 46.

Table 45: H_2 Production Overview

H_2 Production Process	Characteristics	Current Deployments
Electrolysis	• Electrolysis is the process of splitting water into hydrogen and oxygen with electricity (reaction happens in a unit calls electrolyzer). This can be a clean process by utilizing renewable electricity. • Electrolyzers can vary in the way they function due to different electrolyte materials and ionic species conducted. Common electrolyzers include polymer electrolyte membrane (PEM), alkaline, and solid oxide.	CA has won funding for a statewide Hydrogen Hub supported by ARCHES. Advanced Clean Energy Storage (ACES) uses a 220-megawatt bank of electrolyzers and intermittent renewable energy to produce hydrogen. The hydrogen is stored in in salt caverns, and delivered for future dispatchable generation to serve the California electricity market. This project will be deployed as part of the Intermountain Power Plant renewal in Utah.

H_2 Production Process	Characteristics	Current Deployments
Biomass-Derived	• **Biomass gasification** can convert crop and forest residues, municipal solid waste, and animal waste, into syngas, which contains hydrogen, through a high temperature non-combustion process. Absorbers or special membranes can be used to separate the hydrogen from the syngas stream. • **Biomass-derived liquid reforming** takes liquids derived from biomass resources (such as ethanol and bio-oils) and can be reformed similarly to fossil fuel reforming. Liquid fuel is reacted with steam at high temperatures with a catalyst to form reformate gas (H_2, CO, CO_2), before further H_2 and CO_2 are produced from waster-gas shift reaction. Hydrogen is then separated and purified. • **Microbial biomass conversion** utilizes microorganisms to consume and digest biomass and release hydrogen through processes such as fermentation. Can occur via direct fermentation of microbial electrolysis cells (MECs) that harness the energy produced by microbes to produce hydrogen.	SGH2 is developing the world's largest clean H_2 facility in Lancaster, CA. Capable of producing 12,000kg of H_2 per day from 40,000 tons of waste annually.
Solar	• **Thermochemical water splitting** uses high temperatures (500^O - 2000^{O}C) from concentrated solar to drive a series of chemical reactions to produce H_2. • **Photoelectrochemical water splitting (PEC)** produces hydrogen from water, sunlight, and specialized semiconductors to directly dissociate water molecules into hydrogen and oxygen. • **Photobiological hydrogen production** uses microorganisms, such as green microalgae, and sunlight to turn water into hydrogen.	Project scales are still small and limited.
Fossil Fuel Reforming	• Natural gas reforming is the most common pathway for hydrogen production in the US today, accounting for 95% of H_2 in the country. • When paired with carbon capture this process can be made nearly carbon neutral (blue hydrogen).	CA produces about 766,000 tons/yr from steam methane reforming. Currently none with carbon capture.

Source: Guidehouse analysis for this report

Table 46: H_2 Storage Overview

H_2 Storage	Characteristics	Current Deployments
H_2 Storage within Geologic Formations (Gaseous H_2)	• The storage of gaseous H_2 underground in formations capable of withstanding high pressures around 350-700 bar. • Types of geologic formations suitable for H_2 storage include salt caverns, depleted gas fields, aquifers, and lined hard rock caverns. • Salt caverns are the most mature storage option, but there is minimal opportunity for them within California.[192]	9 Global Salt Cavern H_2 Storage Sites Built. First Depleted Gas Reservoir H_2 Storage Demonstration (Australia). ACES will combine 220 megawatts of electrolysis with two salt caverns to store up to 300 GWh of hydrogen
H_2 Storage within Above-Ground Tanks (Gaseous & Liquid H_2)	• The storage of gaseous or liquid H_2 in man-made tanks that must be able to withstand 60-700 bar pressure; liquid H_2 tanks must also withstand cryogenic temperatures. • Tanks are classified as Type I, Type II, Type III, or Type IV which vary based on their material and approximate maximum temperatures. • Material options include steel, aluminum, carbon fiber, composite materials, and fiberglass with typical tank volumes at approximately 150 L to 2,250 L. • Gaseous and liquid tanks have established markets, especially for smaller tanks, but liquid tanks are less common at power generation facilities. • Gaseous tanks currently outperform liquid on cost and performance.[193]	>70 Hydrogen Refueling Stations in CA.

192 2023. "California Natural Gas Underground Storage Salt Caverns Capacity." EIA. https://www.eia.gov/dnav/ng/hist/na1393_sca_2a.htm.

193 U.S. Department of Energy staff. 2022. Bulk Storage of Gaseous Hydrogen. U.S. Department of Energy. https://www.energy.gov/sites/default/files/2022-05/bulk-storage-gaseous-hydrogen-2022_0.pdf.

H_2 Storage	Characteristics	Current Deployments
H_2 Carriers (Liquid & Solid H_2)[194]	• Method of transforming and storing H_2 as energy in chemical compounds and not as free H_2 molecules. • Ammonia, ammonia borane, alane, benzyl toluene, and liquid organic hydrogen carriers (LOHCs) are being explored as potential H_2 carrier options. • Storage in this manner allows for greater flexibility with storage type and transportation. • Ultimately, the chemical compound is broken down to separate the H_2, through a heat exchanger and purifier for ammonia.	Hydrogenious Hector LOHC Storage (Germany). Hydrogenious HySTOC LOHC Storage (EU). 4 Other Hydrogenious H_2 Plants with LOHC Storage.

Source: Developed by Guidehouse from data and information obtained via developer and manufacturer interviews.

Current Deployments

Table 47 describes some of the key current deployments for the hydrogen generation technologies included in this analysis.

Table 47: H_2 Generation Technology Current Deployments

Site Name	Plant Capacity	Tech. Type / Purpose	Developer(s)	Status
Total U.S. FCs for Backup Power[195]	>500 MW	FCs for Backup Power	N/A	Existing Capacity
City of Calistoga H_2 Fuel Cell[196]	8 MW	PEM FC for Backup Power during Public Safety Power Shutoff Events	Plug Power / Energy Vault Holdings	Planned

194 2018. "Hydrogen Carriers for Bulk Storage and Transport of Hydrogen Webinar: Text Version." U.S. Department of Energy. https://www.energy.gov/eere/fuelcells/hydrogen-carriers-bulk-storage-and-transport-hydrogen-webinar-text-version.

195 2021. "U.S. Department of Energy Hydrogen and Fuel Cell Technologies Office and Global Perspectives." U.S. Department of Energy. https://www.energy.gov/eere/fuelcells/articles/us-department-energy-hydrogen-and-fuel-cell-technologies-office-and-global.

196 2023. "Plug Supplies 8 MW of Hydrogen Fuel Cells to Energy Vault to Displace Diesel Generators in California Wine Country." Globe News wire. https://www.globenewswire.com/en/news-release/2023/06/07/2683611/9619/en/Plug-Supplies-8-MW-of-Hydrogen-Fuel-Cells-to-Energy-Vault-to-Displace-Diesel-Generators-in-California-Wine-Country.html.

Site Name	Plant Capacity	Tech. Type / Purpose	Developer(s)	Status
Honda Torrance Campus H_2 FC[197]	500 kW	Reused FCs from Honda Vehicles for Data Center Backup Power	Honda / General Motors	Operational Demonstration
Total General Electric H_2 Turbine Deployment[198]	N/A	Combustion Turbines Running on H_2 (Blends Range from 5 – 100%)	General Electric	>120 H_2 Combustion Turbines Deployed
LADWP Scattergood H_2 Combustion Turbine Retrofit[199]	346 MW	Retrofitted Combustion Turbine Capable of Burning 30% H_2 on Day 1 and 100% Ultimately	N/A	Planned for 2029
A.J. Mihm Power Plant H_2 Reciprocating Engine[200]	18.8 MW	Reciprocating Engine Operating with up to 25% H_2	Wärtsilä, Electric Power Research Institute (EPRI), Burns & McDonnell	Active Pilot
Menlo Park Linear Generator[201]	70 kW	Linear Generator for Combined Heat and Power (CHP)	Mainspring (Formerly EtaGen)	Former Pilot from 2017-2018

Source: Guidehouse analysis for this report

Technological Maturity and Anticipated Improvements

Across all applications and technology types, the TRL of FCs can range across the entire one through nine spectra. However, within power generation and especially backup power generation, both PEM and solid oxide FCs have been deployed and are relatively developed. To

197 2023. "Honda's Zero Emission Stationary Fuel Cell Provides Back Up Power to a Data Center." Honda. https://global.honda/en/newsroom/news/2023/c230306eng.html.

198 "Hydrogen Fueled Gas Turbines." General Electric. https://www.ge.com/gas-power/future-of-energy/hydrogen-fueled-gas-turbines.

199 Clark, Kevin. 2023. "L.A. authorizes conversion of largest gas plant to hydrogen." https://www.power-eng.com/hydrogen/l-a-authorizes-conversion-of-largest-gas-plant-to-green-hydrogen/#gref.

200 Patel, Sonal. 2022. "Much-Watched Reciprocating Engine Hydrogen Pilot Kicks Off at Michigan Power Plant." Power Magazine. https://www.powermag.com/much-watched-reciprocating-engine-hydrogen-pilot-kicks-off-at-michigan-power-plant/.

201 Simpson, Adam, Keith Davidson. 2021. Linear Generation for Combined Heat and Power. California Energy Commission. Publication Number: CEC-500-2021-017. https://www.energy.ca.gov/sites/default/files/2021-05/CEC-500-2021-017.pdf.

reach widespread commercialization and a TRL of 9, technical (performance curve, reliability, and FC lifetime), economic (spark spread), and environmental (NO_x emissions) challenges will need to be largely addressed.

Hydrogen combustion turbines vary since H_2 blending within natural gas turbines is reaching market uptake globally with projects such as the Intermountain Power Plant (IPP) Renewal in Utah and is further along than pure H_2 gas turbines. The electrolytic hydrogen for the IPP Renewal project will be supplied by the Advanced Clean Energy Storage site, located adjacent to the IPP. 100 percent H_2 turbines are still under development, having just passed the verification phase and proceeding to the demonstration phase. In addition to demonstrating pure H_2 gas turbine projects, R&D activities will need to address combustion instabilities that change flame dynamics and further develop dry low NO_x technologies. Industry is committed to enable gas turbines to run entirely on renewable gas fuels by 2030, but European patenting trends indicate that hydrogen turbines lack significant innovation. R&D efforts are essential for this goal to be met and for H_2 combustion turbines to be available to play a significant role in the decarbonization transition.

Hydrogen reciprocating engines are the least developed and demonstrated of the four hydrogen generation technologies discussed. One leading manufacturer, Wärtsilä, has just supported a pilot to test varying levels of H_2 blends with natural gas (up to 25 percent H_2) at a reciprocating engine power plant unit in Michigan. With initial pilots underway, the technology is able to reach an upper bound TRL of 7. However, Wärtsilä is also still developing an engine and plant concept for pure hydrogen which they expect to be ready by 2025. Since the technological concept for pure H_2 units is not fully developed, a lower bound TRL of 5 is reasonable. As H_2 blends increase and ultimately reach 100% H_2, hydrogen injection methods will need to be optimized to prevent premature ignition without resulting in associated side effects such as airflow blockage and engine power reduction or shutdown.

Non-combustion non-fuel-cell (NCNFC) generators[202] are progressing into commercial availability. Currently, Mainspring's linear generator base package offers 250-kW capacity in a shipping container, and is commercially available in behind-the-meter applications but has seen limited use in front-of-the-meter applications in California. To date, their largest generation facility has been a 25 MW site where generator modules are stacked over one acre of land. The company is currently developing a more energy-dense unit that offers 1.5 MW in a 40-foot container, which would likely enable larger-scale projects that exceed 100 MW.[203] Mainspring, a linear generator manufacturer, noted in their comments these systems can be configured to run on hydrogen, RNG, and biogas without major equipment changes or reconfiguration.

Manufacturing and Supply Chain

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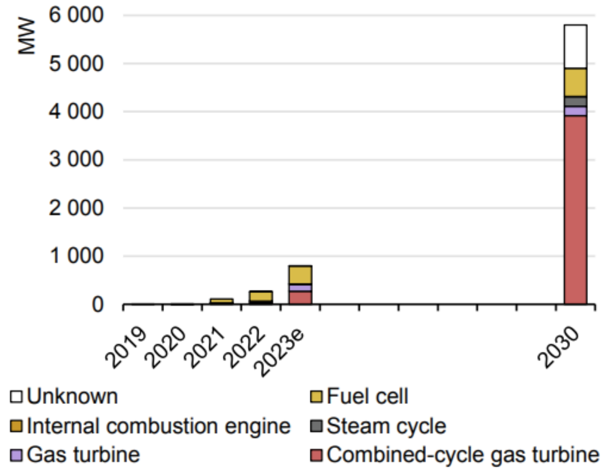
202 Mainspring provided comments with updated data, which will be included in future reports. Mainspring Energy. 2024. Mainspring Energy Comments on Draft SB 423 Emerging Renewable and Firm Zero-Carbon Resources Report. California Energy Commission. Publication Number CEC-200-2024-012-D. https://efiling.energy.ca.gov/GetDocument.aspx?tn=258545&DocumentContentId=94575.

203 Based on industry interviews and comments. Mainspring Energy. 2024. Mainspring Energy Comments on Draft SB 423 Emerging Renewable and Firm Zero-Carbon Resources Report. California Energy Commission. Publication Number CEC-200-2024-012-D. https://efiling.energy.ca.gov/GetDocument.aspx?tn=258545&DocumentContentId=94575.

The industry and manufacturing landscape for hydrogen generation is nascent since many of these technologies are still developing and just beginning to emerge. Nonetheless, there is expected to be significant growth globally within generation capacity for H_2 and ammonia-based resources by 2030 (see Figure 18).

Figure 18: Total Installed Generation Capacity for H_2 and Ammonia[204]



Source: IEA

This forecast from the International Energy Agency (IEA) anticipates about 5,800 MW of power generation capacity using H_2 and ammonia emerging globally by 2030. About 1,300 MW of that capacity is expected to be located within North America. While current installed capacity is predominantly from fuel cells, the majority of deployment capacity in 2030 is expected to come from combined cycle gas turbines or traditional gas turbines (~4,000 MW).[205] As such, of the four types of technologies considered within this analysis, H_2 combustion turbines (including combined cycle) should be the focus area for R&D, demonstrations, and full-scale deployment in the short- to medium-term.

With this projected steep ramp-up in H_2 power generation deployments, even though there is real potential for new companies to emerge within the market, some companies have begun to lead the way as industry players within the sector. For example, General Electric has already deployed >120 combustion turbine units globally that use some percentage of hydrogen. Figure 19 illustrates some of the leading companies for H_2 combustion turbines.

204 IEA staff. 2023. Global Hydrogen Review 2023. IEA. https://iea.blob.core.windows.net/assets/cb9d5903-0df2-4c6c-afa1-4012f9ed45d2/GlobalHydrogenReview2023.pdf.

205 Ibid.

Figure 19: Hydrogen Combustion Turbine Leading Manufacturers

Source: ETN Global

Figure 18 also indicates that there will be some H_2 generation deployment with fuel cells and other technologies, even if the total capacity is marginal in comparison to combined cycle turbines. There might also be some additional synergies with other H_2 end uses such as transportation, where vehicle manufacturers such as Honda and Toyota have used retrofitted FCs from vehicles for stationary power generation. Some of the key companies that are developing projects for FCs, reciprocating engines, and NCNFC generators are detailed in Figure 20.[206]

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206 ETN Global staff. 2020. Hydrogen Gas Turbines. https://etn.global/wp-content/uploads/2020/02/ETN-Hydrogen-Gas-Turbines-report.pdf.

Figure 20: Hydrogen FC, Reciprocating Engine, and NCNFC Generator Leading Manufacturers

Source: ETN Global

Furthermore, most supply chain analysis to date has focused on H_2 production and infrastructure as these are imperative pre-requisites for hydrogen to be used within any end use, not just the power sector. In support of alleviating these challenges, the U.S Department of Energy (DOE) awarded California $1.2 billion through the Alliance for Renewable Clean Hydrogen Energy Systems (ARCHES) for statewide development of H_2 production, transportation, storage, and use at scale.[207] Even if a significant portion of this funding is utilized for other H_2 initiatives than power generation, the funding will help build out the overarching California H_2 supply chain and spur key developments that eliminate barriers to H_2 generation.

Also impacting the H_2 supply chain is the ability to retrofit existing natural gas infrastructure for H_2. This is a significant area for R&D since, according to IEA, "repurposing existing infrastructure for hydrogen would… mitigate the risk of stranded assets, reduce the environmental impact [of] manufacturing and laying new pipelines, and lower investment costs [and project] lead times."[208] These benefits of leveraging natural gas infrastructure for H_2 also hold true for natural gas power plants, and any future supply chain analysis for H_2 generation should consider leveraging existing plants as a starting point when possible.

Current and Expected Costs

Cost projections for hydrogen power generation technologies are sparse, so CAPEX and fixed O&M cost projections in Figure 21 are based on assumptions that use natural gas technology cost data as a baseline. Fixed O&M costs for NCNFC generators were based off of industry interviews.

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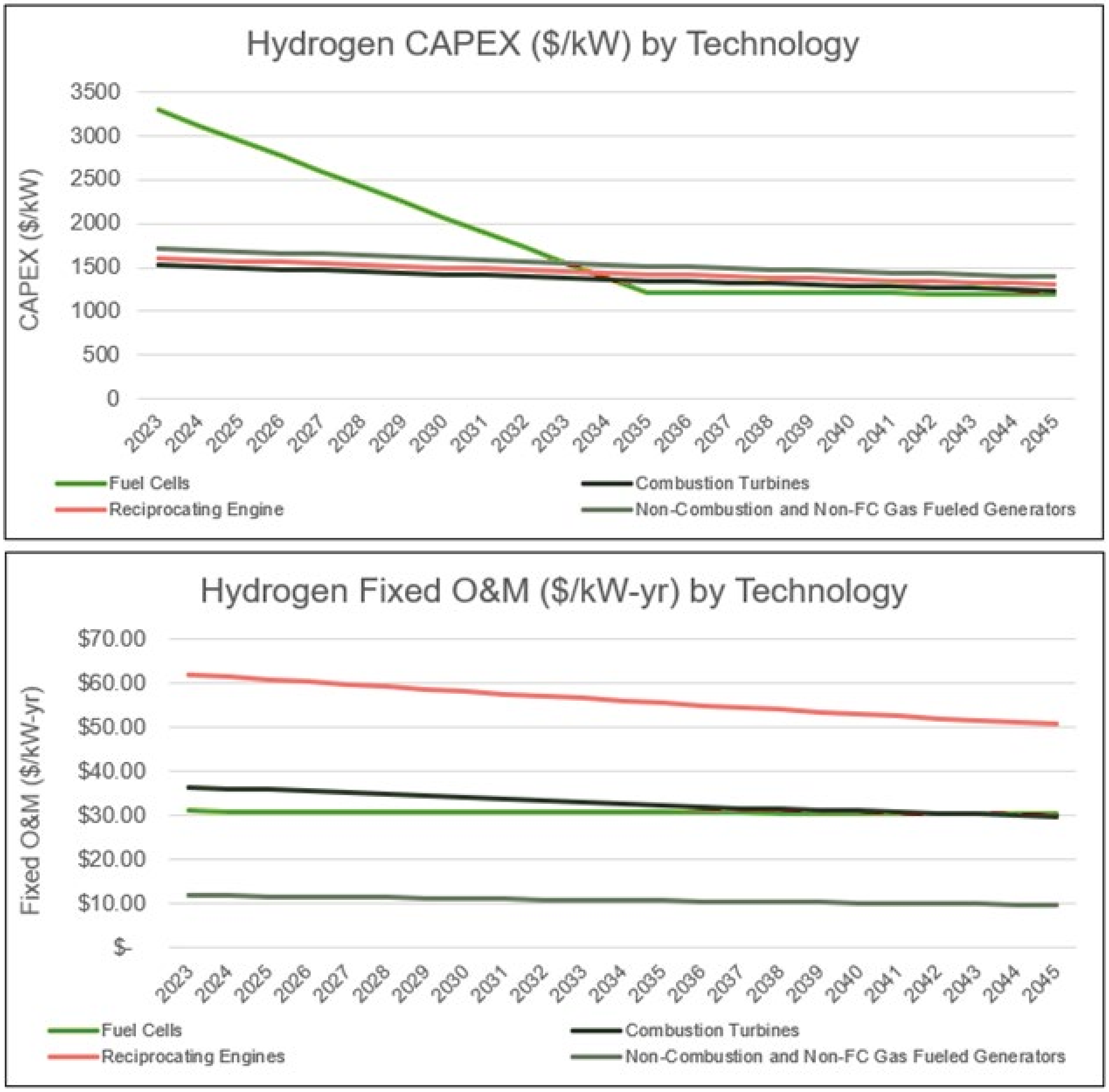
207 2023. "California Selected as a National Hydrogen Hub." Office of Governor Gavin Newsom. https://www.gov.ca.gov/2023/10/13/california-selected-as-a-national-hydrogen-hub/.

208 IEA staff. 2023. Global Hydrogen Review 2023. IEA. https://iea.blob.core.windows.net/assets/cb9d5903-0df2-4c6c-afa1-4012f9ed45d2/GlobalHydrogenReview2023.pdf.

Figure 21: H2 Generation Cost Profiles



Source: Guidehouse-developed figures for this report

Stationary fuel cell capital costs are considerably higher than other technologies in the near term but are expected to reach cost competitiveness by 2035. While fixed O&M costs for reciprocating engines are higher than the other technology types, the example system size for reciprocating engines was significantly lower than for fuel cells and combustion turbines based on the data available. It is possible that the fixed O&M costs for reciprocating engines would have seen economies of scale cost declines with a larger system. Also worth noting is that NCNFC generators typically track O&M costs on a variable basis, where observed variable O&M costs may be around $9-14/MWh. When considering all maintenance up to 170,000 hours of operation, fixed O&M winds up around $10-14/kW-yr.[209]

209 Values are based on industry interviews.

Barriers and Recommendations

The largest barriers to widespread deployment of H_2 generation technologies within California are related to (1) research & development, (2) siting, (3) H_2 production, transport, and storage, and (4) H_2 blending with natural gas. These challenges, more specifically, are described in Table 48 and are paired with associated recommendations.

Table 48: H_2 Generation Barriers and Recommendations

Category	Barriers	Recommendations
Research & Development[210,211]	• Technologies that combust H_2 can result in greater NOx emissions than comparable natural gas combustion technology.H_2 has a broader flammability range and increased laminar flame speeds, increasing safety risks of flashbacks and fuel ignition in the mixing passages within combustion turbine applications. • Patent applications for hydrogen- and hydrogen-based fuels turbines are very low compared to other H_2 end uses such as automotive.	• Further support R&D activities underway to develop dry low NO_x gas turbines that can handle H_2 blends up to 100% H_2 by volume. • Stringent safety protocols and standards must be developed for H_2 combustion prior to operation. • Encourage innovation within hydrogen power generation through regulatory and financial signals.

210 Giacomazzi, Eugenio, Guido Troiani, Antonio Di Nardo, Giorgio Calchetti, Donato Cecere, Giuseppe Messina, Simone Carpenella. 2023. Hydrogen Combustion: Features and Barriers to Its Exploitation in the Energy Transition. https://www.mdpi.com/1996-1073/16/20/7174.

211 IEA staff. 2023. Global Hydrogen Review 2023. IEA. https://iea.blob.core.windows.net/assets/cb9d5903-0df2-4c6c-afa1-4012f9ed45d2/GlobalHydrogenReview2023.pdf.

Category	Barriers	Recommendations
Siting[212]	• Many stakeholders oppose clean hydrogen development, as has been seen with LADWP's Scattergood retrofit. • H_2 FCs, reciprocating engines, and NCNFC generators typically have low power outputs compared with combustion turbines. • Licensing and permitting H_2 infrastructure (e.g., H_2 generation, pipelines, storage) can increase project lead times.	• Prioritize community engagement to address and hopefully alleviate stakeholder concerns with H_2 power generation when pursued. • H_2 turbines should be the focus for large-scale power generation while the other technologies can provide value at smaller scales. • Develop standardized siting practices to balance the efficiency of project deployment and verification of safety and functionality.
H_2 Production, Transport, and Storage[213,214]	• The most significant barrier to widespread H_2 adoption across sectors is its clean and renewable production cost. • Currently, low-emission H_2 accounts for <1% of global H_2 production. • Energy infrastructure projects such as H_2 production and pipelines that are pre-requisite to H_2 generation can typically have long lead times (~6-12 years) and are highly expensive. • H_2 transport and storage technologies are mature but only at small scales.	• Provide regulatory and financial support for electrolysis powered by renewables and other clean H_2 production methods. • Explore technical feasibility and cost impacts of repurposing natural gas infrastructure for H_2 • Innovation must seek to bring these technologies to scale.

212 Gable, Jessica. 2023. "LA City Council Approves Scattergood Hydrogen Motion With Amendments Requiring LADWP to Report on Potential Alternatives." Sierra Club. https://www.sierraclub.org/press-releases/2023/02/la-city-council-approves-scattergood-hydrogen-motion-amendments-requiring.

213 IEA staff. 2023. Global Hydrogen Review 2023. IEA. https://iea.blob.core.windows.net/assets/cb9d5903-0df2-4c6c-afa1-4012f9ed45d2/GlobalHydrogenReview2023.pdf.

214 Giacomazzi, Eugenio, Guido Troiani, Antonio Di Nardo, Giorgio Calchetti, Donato Cecere, Giuseppe Messina, Simone Carpenella. 2023. Hydrogen Combustion: Features and Barriers to Its Exploitation in the Energy Transition. https://www.mdpi.com/1996-1073/16/20/7174.

Category	Barriers	Recommendations
H_2 Blends with Natural Gas[215,216]	• Due to lower energy densities, when blending H_2 and natural gas, CO_2 emissions reduction is smaller than the percentage of H_2 by volume. • When blending H_2 and natural gas, if the gases are not adequately mixed, temperature hotspots can emerge, leading to even greater NO_x formation.	• Hydrogen blending with natural gas for combustion may provide some emissions reductions but cannot be a long-term strategy. • Gas mixture processes must be emphasized and thoroughly validated before operation is allowed.

Source: Guidehouse analysis for this report

215 U.S. Environmental Protection Agency staff. 2023. Hydrogen in Combustion Turbine Electric Generating Units. U.S. Environmental Protection Agency. https://www.epa.gov/system/files/documents/2023-05/TSD%20-%20Hydrogen%20in%20Combustion%20Turbine%20EGUs.pdf.

216 Glanville, Paul, Alex Fridlyand, Brian Sutherland, Miroslaw Liszka, Yan Zhao, Luke Bingham, Kris Jorgensen. 2022. Impact of Hydrogen/Natural Gas Blends on Partially Premixed Combustion Equipment: NOx Emission and Operational Performance. Gas Technology Institute. https://www.mdpi.com/1996-1073/15/5/1706.

APPENDIX H: Additional Information on Small Modular Fission Reactors

Additional information on small modular fission reactors (SMRs) is provided within this section of the appendix. This section is intended to be read in conjunction with the main report and includes further detail on technology characteristics, current deployments, manufacturing and supply chain, performance characteristics, costs, and barriers and recommendations for light water and non-water cooled SMR designs.

Technology Overview

SMRs encompass a class of fission nuclear reactors characterized by a power capacity up to 300 MW electric and the ability of the unit to be factory-assembled and installed on-site. A subclass of SMRs called microreactors refer to reactors with a capacity less than 20 MW which can operate independently from the electric grid; these units are often considered for remote applications and thus are not discussed in this study. Beyond size and modularity, SMR technologies vary widely in the physical design, coolant type, and nuclear process applied. This study focuses on light water-cooled thermal-spectrum fission SMRs, as they are one of the more technologically mature types of SMRs under development and are currently deployed at larger scales as conventional reactors.[217] Other SMR technology under development utilize molten salts, liquid metal, or gas as the coolant and operate with the fast-spectrum neutrons. Table 49 provides a comparison of SMR resources.

Table 49: Small Modular Reactor Resource List

SMR Resources	Characteristics
Pressurized Water Reactor (PWR)	Most widely deployed conventional nuclear reactor. Thermal reactor with light water as the coolant and neutron moderator and low enriched uranium of 3-5% enrichment. Design consists of two loops with primary loop at high pressure to keep the water liquid. Thermal efficiency around 33%.
Boiling Water Reactor (BWR)	Second most widely deployed conventional nuclear reactor. Thermal reactor with water as the coolant and neutron moderator and low enriched uranium of 3-5% enrichment. Design consists of a single loop at lower pressures allowing the water to boil. Thermal efficiency around 33%.
Sodium-cooled Fast Reactor (SFR)	Fast reactor with liquid metallic sodium as the coolant. Requires High-Assay Low Enriched Uranium (HALEU) with enrichments of 5 to 20% or Mixed-Oxide Fuel sourced from spent fuel or previously stockpiled weapons-grade fuel. Operates at atmospheric pressure, removing the need for a large containment shield. Thermal efficiencies of around 40% or greater.

217 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.

SMR Resources	Characteristics
Molten Salt Reactor (MSR)	In development design with molten fluoride salts as a primary coolant. Can operate with thermal or fast neutrons. Fuel arrangements include pebble bed (spheres of fuel coated in graphite moderator and ceramic coating), or fuel dissolved in the coolant. Both arrangements allow for passive safety and proliferation resistance. Requires HALEU with enrichments of 5 to 20%. Operates at atmospheric pressure, removing the need for a large containment shield. Thermal efficiencies of around 40% or greater.
High-temperature gas-cooled reactor (HTGR)	Fast reactor with helium as the coolant at high operating temperatures of 700 to 950°C. Fuel arrangements include prismatic block (similar to a conventional core) or pebble bed. Requires HALEU with enrichments of 5 to 20%. Thermal efficiencies of around 40% or greater.

Source: Science Direct: Engineering Topics.

Current Deployments

Numerous SMR designs are in development worldwide. Table 50 highlights the most mature light water SMR deployments in the United States by technology type, capacity, development status, and key deployment characteristics. In December 2019, the Nuclear Regulatory Commission (NRC) authorized the issuance of an Early Site Permit (ESP) for two or more SMR modules (up to 800 MW electric) at the Tennessee Valley Authority's Clinch River site. Light water SMR designs in development in the U.S. are eligible for the ESP.[218] The permit is valid for up to 20 years from date of issuance and can be renewed for an additional 10 to 20 years.[219] The current NRC licensing and pre-application process requires the developer to hold public meetings of the planning process including site characterization, environmental report, emergency planning, physical security, and operator licensing.

218 2022. Issued Early Site Permit - Clinch River Nuclear Site. U.S. Nuclear Regulatory Commission. https://www.nrc.gov/reactors/new-reactors/large-lwr/esp/clinch-river.html.

219 2019. NRC to Issue Early Site Permit to Tennessee Valley Authority for Clinch River Site. U.S. Nuclear Regulatory Commission. https://www.nrc.gov/reading-rm/doc-collections/news/2019/19-064.pdf.

Table 50: U.S. Light Water SMR Deployment List

Design Name	Power Capacity	Tech. Type	Developer	Status	Deployment Considerations
NuScale	77 MW	PWR	NuScale Power LLC (United States)	Certified for 50 MW design, currently under technical review by the NRC for 77 MW design. If the Carbon Free Power Project is approved, preconstruction activities could start by mid-2025, with the first module expected to be operational in 2029.	NRC is currently reviewing an application to build a six-module NuScale technology SMR plant in Idaho as a part of the Carbon Free Power Project. Site specific characterization at the Idaho National Lab (INL) was conducted August 2021 to January 2022.
AP300	300 MW	PWR	Westinghouse Electric Company (United States)	Submitted pre-application Regulatory Engagement Plan with the NRC.	Eligible to receive Nuclear Regulatory Commission Early Site Permit (ESP). No current agreements for plant siting in the United States.
BWRX-300	300 MW	BWR	GE Hitachi Nuclear Energy (United Status/ Japan)	In licensing process with the NRC.	Eligible to receive Nuclear Regulatory Commission Early Site Permit (ESP). No current agreements for plant siting in the United States. Chosen as technology for the Darlington SMR site in Ontario, Canada, with target online date of 2028.

Source: U.S. Nuclear Regulatory Commission, U.S. Office of Nuclear Energy, Westinghouse Electric Company, GE Hitachi Nuclear Energy, World Nuclear Association.

For reference, Table 51 displays the most mature SMR deployments outside of the United States. China is the current global leader in the development of SMRs with one reactor operational and one under construction.

Table 51: Non-U.S. SMR Deployment List

Design Name	Power Capacity	Tech. Type	Developer	Status
HTR-PM	210 MW	HTGR	China Huaneng (China)	One reactor operational, grid connected December 2021.
ACP100 Linglong One	125 MW	PWR	China National Nuclear Corporation (China)	Under construction.
SMART	100 MW	PWR	KAERI (South Korea)	Licensed.
Rolls-Royce SMR	470 MW	PWR	Rolls-Royce (United Kingdom)	Licensing stage.

Sources: World Nuclear News, Nuclear Engineering International.

Manufacturing and Supply Chain

Compared to conventional nuclear reactors, SMRs have the advantage that they can be fabricated off-site, thus driving down costs. Table 52 compares the manufacturing characteristics for the U.S. based light water technologies previously presented in Table 49.

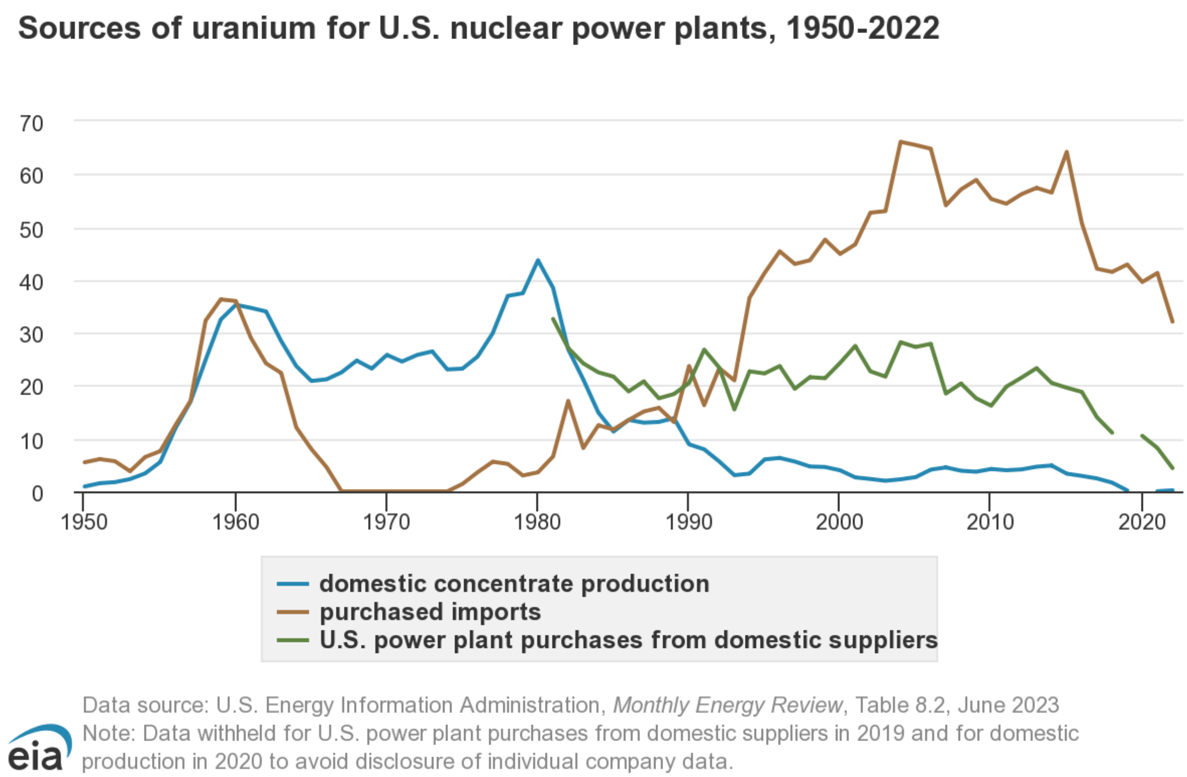
Table 52: SMR Manufacturing by U.S Light Water Design

Design Name	Power Capacity	Tech. Type	Manufacturing
NuScale	77 MW	PWR	Lead manufacturer- Doosan Enerbility (South Korea). Upper reactor pressure vessel will be manufactured by Doosan Enerbility. Upper reactor pressure vessel includes the heavy forgings, steam generator tubes, and weld material for six upper reactor pressure vessels.
AP300	300 MW	PWR	Likely to utilize manufacturers and supply chains established from the Westinghouse AP1000 design and implementation process.
BWRX-300	300 MW	BWR	Lead manufacturer- BWX Technologies (US/ Canada). Main reactor pressure vessel will be manufactured off-site by BWX Technologies. Reactor pressure vessel includes the reactor core and associated internal components.

Sources: NuScale Power, Westinghouse Electric Company, BWX Technologies.

Growing interest and eventual deployment of SMRs in the United States will drive a need for a more robust uranium supply chain. Light water SMRs, like conventional light water reactors, rely on fuel in the form of uranium oxide enriched to 3-5% U-235. The uranium must be mined, enriched, and fabricated to uranium oxide. Uranium oxide for use in U.S. nuclear power plants is historically imported from Canada, Kazakhstan, Russia, Uzbekistan, and Australia as shown in Figure 22.

Figure 22: Sources of Uranium for U.S. Nuclear Power Plants, 1950-2022



Source: U.S. Energy Information Administration.

Advanced nuclear designs like the SFR, MSR, and HTGR rely on High-Assay Low Enriched Uranium (HALEU) fuel with enrichments of 5 to 20%. HALEU is required for non-light water reactor designs due to the neutron-spectrum in which the designs operate.[220] HALEU is currently not available from domestic suppliers, and gaps in the HALEU supply chain could delay the deployment of non-light water SMRs and larger advanced nuclear reactors. In response, the U.S. Department of Energy has launched the HALEU Availability Program to pursue several pathways to secure a domestic supply of HALEU.[221]

Performance Characteristics

Table 53 compares the performance characteristics and requirements for the SMR technologies previously discussed. Non-light water technologies (SFRs, MSRs, and HTGRs) have higher thermal efficiencies—the electric energy output per unit of thermal energy—due to coolant properties allowing for higher temperature operation compared to light water designs. Additionally, PWRs and BWRs require a pressurized system for optimal operation. SFRs and MSRs have the benefit of operating at atmospheric pressure, thus increasing safety by reducing the size of the containment shield. All technologies are expected to have similar

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220 2023. High-Assay Low-Enriched Uranium (HALEU). U.S. Nuclear Regulatory Commission. https://www.nrc.gov/materials/new-fuels/haleu.

221 2022. U.S. Department of Energy HALEU Consortium. Office of Nuclear Energy. https://www.energy.gov/ne/haleu-availability-program.

capacity factors and lifetimes, with variations expected due to site location and other factors external to the design.

Table 53: SMR Performance Characteristics

Criteria	Unit	PWR	BWR	SFR	MSR	HTGR
Capacity Factor (Annual)	%	92%	92%	92%	92%	92%
Thermal Efficiency	%	33%	33%	40%+	40%+	40%+
Operating Pressure	bar	150-160	70	1.013	1.013	70
Maximum Operating Temp.	°C	325	285	550	700+	750+
Lifetime	Years	60-80	60-80	60-80	60-80	60-80

Sources: World Nuclear Association, Idaho National Laboratory.

Current and Expected Costs

SMRs offer cost savings compared to conventional nuclear reactors due to their reduced size thus translating to lower total capital costs and shorter construction periods. Due to the variation in designs, there are large uncertainties associated with estimating the costs of SMRs.

Table 54 displays a comparison between costs for a conventional nuclear reactor, Westinghouse's AP100 PWR, and a Small Modular Reactor from Annual Technology Baseline (ATB) Report published by the National Renewable Energy Laboratory (NREL).[222] The conventional unit is provided for comparison purposes only. The SMR data assumes first available year of 2028 and a lead time of 6 years; all dollar figures are in 2021 USD. NREL ATB assumes an SMR with a thermal output of 600 MW and similar characteristics as the AP1000; these assumptions drive a higher CAPEX cost per kW for the SMR. Other assumptions that account for specifics of the SMR design would likely lead to lower cost assumptions.

Given their smaller size, SMRs offer a lower total cost and are expected to have shorter construction times compared to a conventional reactor. Fixed operation and maintenance (O&M) costs are lower for a small modular reactor due to safety features and less frequent refueling, resulting in lower labor costs.[223]

222 2023. Annual Technology Baseline. National Renewable Energy Laboratory. https://atb.nrel.gov/electricity/2023/index.

223 2018. SMR Roadmap. Economic and Finance Working Group. https://smrroadmap.ca/wp-content/uploads/2018/12/Economics-Finance-WG.pdf.

Table 54: SMR Cost Profile Comparison

Assumptions	Conventional Nuclear (AP1000)	Small Modular Reactor
System Size	1000 MW	75-100 MW
CAPEX Range ($/kW)	7,824 - 8,811	8,546 - 9,459
Fixed O&M ($/kW-year)	152	119

Source: National Renewable Energy Laboratory: Annual Technology Baseline.

Barriers and Recommendations

Table 55 describes the barriers of the siting of SMRs in California and recommendations to the CEC to address the barriers.[224]

Table 55: SMR Barriers and Recommendations

Category	Barriers	Recommendations
Research & Development	• More research and development required in advanced reactor technology (e.g., non-light water cooled SMR designs).	• Support in-state research and development through partnerships with universities, national laboratories, and private sector companies in California.
Siting	• California has a state-wide moratorium on the siting and licensing of new fission reactors until a solution for long-lived radioactive waste is reached. • Concerns of the impacts of seismic activity on the accidental release of radioactive material.	• State-level policy change to allow the siting of SMRs in California. • Community engagement to increase public acceptance and address safety concerns.
Manufacturing	• Limited manufacturing facilities in the United States; risk of delays due to supply chain bottlenecks. • Complex components, coolant, or fuel compositions required specifically for SMRs; may require reliance from international manufacturers. • Transportation by truck, rail, or ship of prefabricated components to California requires coordination and cooperation with neighboring states if contains radioactive material.	• Support partnerships with universities, national laboratories, and private sector companies in California to create a more robust supply chain for SMRs.

224 Mignacca, Benito, Giorgio Locatelli, Tristano Sainati. 2020. Deeds Not Words: Barriers and Remedies for Small Modular Nuclear Reactors. Energy, Volume 206. https://www.sciencedirect.com/science/article/pii/S0360544220312445.

Category	Barriers	Recommendations
Operation	• Shortages of skilled workforce. • Strict regulatory oversight and regulations that increase operating costs.	• Promote nuclear workforce development in California.
End of Life Management	• Reactor decommissioning and long-term waste disposal needs.	• Support research in waste management solutions through partnering with universities, national laboratories, and private sector companies in California. • Promote cross-state collaboration on waste disposal policies.

Source: Science Direct: Energy, Volume 206.

APPENDIX I: Additional Information on Fusion

Additional information on nuclear fusion is provided within this section of the appendix. This section is intended to be read in conjunction with the main report and includes further detail on fusion compared to fission, current deployments, manufacturing and supply chain, costs, and barriers and recommendations.

Nuclear fusion offers a potential long-term energy source. Compared to nuclear fission, fusion could generate four times more energy per kilogram of fuel and future fusion reactors will not produce long-lived nuclear waste.[225] However, significant engineering and logistic barriers must be overcome before nuclear fusion reactor technology can reach the market. Table 56 compares the risks between fission and fusion technology.

Table 56: Fission and Fusion Risk Comparison

	Fission	Fusion
Risk Factors	• Radiation from long-lived isotopes. • Concerns of fuel meltdown due to emergency shutdown (SCRAM). • Geological and seismic safety considerations.	• High energy neutron contamination for deuterium-tritium reactions; no neutron contamination for aneutronic reactions. • High operating temperatures and risk of explosion.
Fuel	• Uranium fuel is only slightly radioactive before fission and can be handled without special shielding.	• Most reactors rely on tritium-deuterium fuel. Tritium is a weak beta emitter but can be harmful to humans if ingested (commonly via contamination of drinking water).
Waste Management	• Fission of uranium leads to high-level highly radioactive waste. Fission product radioactive isotopes have half-lives between ~30 – 200,000 years. Fuel is currently stored on-site in spent fuel pools or dry cask storage.	• The fusion reaction does not produce any long-lived isotopes. • Fusion, however, produces high-energy neutrons that can degrade structural properties and/or produce radioisotopes.
Physical Safety	• Risk of accident due to uncontrolled nuclear chain reaction leading to severe accident. • Containment structure necessary to contain fission products and prevent the release of radioactive materials in the case of an accident.	• Considered inherently safe since fusion is not based on a chain reaction. Loss of power event would cause the reactor to halt with no consequences. • Fusion facilities produce similar risks to particle accelerators or radiological medical facilities.

225 Barbarino, Matteo. 2023. What is Nuclear Fusion? International Atomic Energy Agency. https://www.iaea.org/newscenter/news/what-is-nuclear-fusion.

	Fission	Fusion
Policy	• California has a state-wide moratorium on the siting and licensing of new fission reactors until a solution for long-lived isotopes is reached.	• No present policy regulations against fusion.

Sources: U.S. Nuclear Regulatory Commission, Canadian Nuclear Safety Commission, Oak Ridge National Laboratory.

Current Deployments

The table below displays the three most technologically mature deployments of fusion reactor technology worldwide.

Table 57: Fusion Reactor Deployment List

Design Name	Power Capacity	Tech. Type	Developer	Status	Deployment Considerations
National Ignition Facility (NIF)	N/A	ICF	Lawrence Livermore National Laboratory (LLNL)	In 2022, NIF was the first to demonstrate net energy for a fusion device.	NIF is a single-shot facility. Further development is needed to overcome technical challenges associated with creating a sustained energy source.
International Thermonuclear Experimental Reactor (ITER)	500 MW	MCF	International effort sited in France with collaboration from the U.S., Russia, South Korea, Japan, India, China, and the European Union	Project reached the milestone of 77% completion in June 2022. Has not yet achieved net energy.	Technological issues, supply chain delays and increases in cost have led to concerns about the project's ability to meet the targeted online date of 2025.

Design Name	Power Capacity	Tech. Type	Developer	Status	Deployment Considerations
Soonest/Smallest Possible ARC (SPARC)	50-100 MW	MCF	Commonwealth Fusion Systems in collaboration with the Massachusetts Institute of Technology (MIT)	Reached milestone of successful magnet test of the world's strongest high temperature super conducting magnet in 2021. Has not yet achieved net energy.	SPARC uses high temperature superconducting (HTS) magnets to enable similar performance to ITER at a volume 40 times smaller; progress is reliant on the ability to secure sufficient HTS supply.
Da Vinci	300-500 MW	MCF	TAE Technologies	Reached milestone of successful demonstration of stable plasma operation at 70 million+ degrees Celsius in 2022 with its Norman demonstration. Has not yet achieved net energy.	Commercial design requires operation at 1 billion degrees Celsius. Targeted commercialization by the mid-2030s, barring significant funding or technical hurdles. The first deployment will likely be a ~30 MW demonstration.

Sources: Reuters, Lawrence Livermore National Laboratory, International Atomic Energy Agency, World Nuclear News, Commonwealth Fusion Systems.

Manufacturing and Supply Chain

Most nuclear fusion reactions rely on fuel made up of deuterium and tritium, isotopes of hydrogen. Deuterium is naturally occurring and can separated from seawater while tritium must be produced by nuclear reactors or high energy accelerators.[226,227] As a result, tritium is a scarce resource that will require increased global production and supply chains to meet the fuel needs of fusion reactors. Manufacturing needs by proposed design are shown in Table 58.

Table 58: Fusion Manufacturing by Design

Design Name	Tech. Type	Manufacturing
National Ignition Facility (NIF)	ICF	Specialized fabrication necessary to produce the millimeter-sized deuterium-tritium capsule.

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

227 2005. Fact Sheet: Tritium Production. U.S. Nuclear Regulatory Commission. https://www.nrc.gov/docs/ML0325/ML032521359.pdf.

Design Name	Tech. Type	Manufacturing
International Thermonuclear Experimental Reactor (ITER)	MCF	Containment will require special materials that can sustain wall temperatures at 1000 degrees C for sustained time periods. Material also needs to withstand high-energy neutron activation. Requires a large quantity of high-temperature superconductors for the magnet system. ITER uses Niobium-Tin and Niobium-Titanium and has signed contracts with U.S. manufacturers.
Soonest/Smallest Possible ARC (SPARC)	MCF	Containment will require special materials that can sustain wall temperatures at 1000 degrees C for sustained time periods. Material also needs to withstand high-energy neutron activation. Requires a large quantity of high-temperature superconductors for the magnet system. SPARC uses Yttrium barium copper oxide (YBCO) and will likely contract with Russian and Japanese company, SuperOx.
Da Vinci	MCF	Containment will require special materials that can sustain wall temperatures at 1,000,000 degrees C for sustained time periods. As a aneutronic design, no high-energy neutrons produced, but the material will need to withstand embrittlement from the Helium byproducts.

Sources: Lawrence Livermore National Laboratory, EUROfusion, Materials (Basel), World Nuclear News, Nature.

Current and Expected Costs

Given that fusion technology is still developing, specific cost figures are unknown. Expected capital costs are around $7,000/kW, similar to fission technologies.[228] When commercially viable, fusion technology may be more attractive than fission given the reduced risks.

Barriers and Recommendations

Table 59 describes the barriers of the siting of fusion reactors in California and recommendations to the CEC to address the barriers.[229]

228 Poore, Colton. 2023. Fusion’s Future in the U.S. Could Come Down to Dollars and Cents. Princeton University Andlinger Center for Energy and the Environment. https://engineering.princeton.edu/news/2023/03/16/fusions-future-u-s-could-come-down-dollars-and-cents.

229 Pearson, Richard. 2020. Barriers to Fusion Commercialization: Understanding Innovation. ARPA-E BETHE Kickoff Virtual Workshop. https://arpa-e.energy.gov/sites/default/files/2020-09/Day2_1330_Kyoto_Pearson.pdf.

Table 59: Fusion Barriers and Recommendations

Category	Barriers	Recommendations
Research & Development	• Technical challenges to overcome to reach net energy of a sustained nuclear fusion reaction. • High costs associated with continued research development.	• Supporting in-state research and development through grants and public-private partnerships.
Siting	• Safety concerns of high operating temperatures and high energy neutrons. • Need for public support.	• Development of safety and infrastructure requirements for the siting of nuclear fusion reactors. • Community engagement to increase public acceptance and address safety concerns.
Manufacturing	• Advanced semiconductor materials required; without robust supply chains, may require reliance on international suppliers. • High operating temperatures and neutron fluxes require special materials to withstand sustained high temperatures and irradiation.	• Support California-based companies in the development of special material.
Operation	• Special workforce training required. • Need to comply with regulatory frameworks set by the state/federal government.	• Support workforce training programs at existing California institutions (e.g., Lawrence Livermore National Laboratory). • Determine regulatory framework for fusion reactors.
End of Life Management	• Long-term planning and analysis necessary to understand the impact of decommissioning nuclear fusion.	• Support analysis of the long-term impacts of nuclear fusion reactor operation.

Source: ARPA-E, Breakthroughs Enabling Thermonuclear-fusion Energy (BETHE)

APPENDIX J: Additional Information on Carbon Capture

Additional information on carbon capture is provided within this section of the appendix. This section is intended to be read in conjunction with the main report and includes further detail on technology characteristics, current deployments, manufacturing and supply chain, costs, and barriers and recommendations for carbon capture.

Carbon capture technology classifications are discussed in greater detail in Table 60.

Table 60: Carbon Capture Technology Overview

Carbon capture Technology Classification	Characteristics
Post-combustion capture	• The separation and capture of CO_2 from flue gas produced from fossil fuel combustion in natural gas power generation, coal power generation, and industrial plants (e.g., smelters, cement kilns, steelworks). • Enables a firm zero-carbon resource when paired with legacy natural gas generation systems; it can even be considered a carbon-negative resource when RNG is used instead of natural gas. • Technology types vary in terms of maturity, cost, and suitable application. • Chemical absorption technologies are most mature and have been used for decades in small and large-scale power generation.
Oxy-fuel combustion	• Simplifies post-combustion carbon capture by filtering most of the nitrogen out of air prior to its use in new or retrofitted fossil fuel power plants. • Results in about 75% reduction in flue gas volume which significantly improves CO_2 capture efficiency. • Produces much lower NO_x emissions with nitrogen filtered out early in the process, and enables easier removal of other pollutants (e.g., SO_x, mercury, particulates).

Carbon capture Technology Classification	Characteristics
Pre-combustion capture	• The capture of CO_2 prior to the combustion process within integrated gasification combined cycle (IGCC) power plants.[230] • Likely involves physical or chemical absorption but there are mid to long-term opportunities for membranes and sorbents. • The capture process has the potential to be more cost-effective than post-combustion capture due to much higher CO_2 concentrations in syngas. • However, it is less mature and is tied to the growth of gasification which is currently expensive, reducing the cost-effectiveness of the system as a whole.

Sources: American Chemical Society, DXP Enterprises, U.S. Department of Energy, NETL 1, NETL 2

As briefly touched upon in the body of the report, once CO_2 is captured it must be either utilized in other processes or sequestered. While these processes are not a focus in this report, Table 61 mentions the key options being explored.

Table 61: Carbon Utilization or Sequestration Options

CO_2 Storage Pathway	Approach / Sector
Utilization	Concrete
Utilization	Chemicals & Pharmaceuticals Industry
Utilization	Synthetic Fuels
Utilization	Plastics & Polymers
Sequestration	Biological Carbon Sequestration
Sequestration	Geological Carbon Sequestration

Source: Guidehouse analysis for this report

Specifically with geological carbon sequestration, California has several types of geologic formations that could be conducive to the pathway. However, enhanced oil recovery (EOR), a leading method of geological sequestration, has been effectively banned by SB 1314 (Limón, Chapter 336, Statutes of 2022) to minimize dependence on fossil fuel production.[231]

Current Deployments

In general, carbon capture projects are less developed within the power generation sector. Nonetheless, Table 62 quantifies the total number of projects within power generation at

230 DXP Marketing. 2022. Pre-Combustion vs. Post-Combustion Carbon Capture Technologies. DXP. https://www.dxpe.com/pre-combustion-vs-post-combustion-carbon-capture/.

231 2022. "Senate Bill No. 1314." California Legislative Information. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220SB1314.

varying development stages (e.g., full-scale, demonstration, pilot, on-hold). These projects encompass sites globally, within the U.S., and within California.

Table 62: Current Power Generation Carbon Capture Deployment Overview

Technology Classification	Global Projects	U.S. Projects	California Projects
Post-combustion capture[232]	65	26	5
Oxy-fuel combustion[233]	11	8	2
Pre-combustion capture[234]	20	9	1

Source: Guidehouse analysis for this report

Some of the projects with the most publicly available information are listed below in Table 63.

Table 63: Key Power Generation Carbon Capture Projects

Site Name	Plant Capacity	Tech. Type	Developer	Status
"Project Enterprise" in City of Pittsburg[235]	500 MW Plant with 95% Carbon Capture	Post-combustion Capture, Amine Solvent	Ion Clean Energy	Pilot developed and will last 18 months
Bellingham Energy Center Carbon Capture Plant[236]	40 MW Slipstream Capture Facility	Post-combustion Capture, Amine Solvent	Fluor	Demonstration from 1991-2005
Peterhead Power Station Carbon Capture Plant[237]	900 MW With 90% Carbon Capture	Post-combustion Capture	SSE Thermal / Equinor	Proposed in 2023

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232 2023. "Carbon Capture Utilization and Storage Tracker 4Q23." Guidehouse. https://authoring.guidehouseinsights.com/reports/carbon-capture-utilization-and-storage-tracker-4q23.

233 Ibid.

234 2013. Carbon Capture: A Technology Assessment. Congressional Research Service. https://crsreports.congress.gov/product/pdf/R/R41325

235 Suratos, Pete. 2023. "Pittsburg facility fighting climate change with carbon capture technology project." NBC Bay Area. https://www.nbcbayarea.com/news/local/pittsburg-company-unveils-carbon-capture-technology-project/3273037/.

236 "Carbon Capture Opportunities for Natural Gas Fired Power Systems" U.S. Department of Energy. https://www.energy.gov/fecm/articles/carbon-capture-opportunities-natural-gas-fired-power-systems.

237 "Peterhead Carbon Capture Power Station." Peterhead Carbon Capture. https://www.peterheadcarboncapture.com/project.

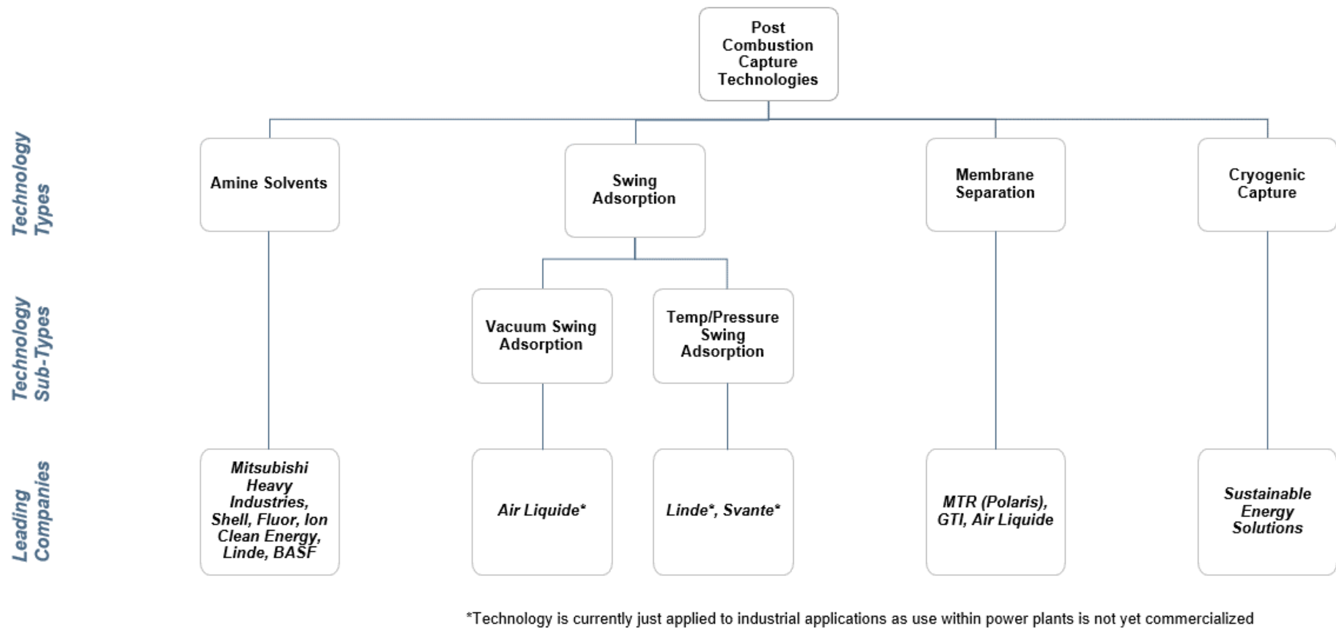
Site Name	Plant Capacity	Tech. Type	Developer	Status
18 Demonstrations[238]	250-1,200 MW	Pre-combustion Capture with Coal-Fired Gasifiers	N/A	Planned Demonstrations
Occidental Permian Basin Oxy-Fuel Combustion Turbine[239]	300 MW	Oxy-Fuel and Supercritical CO_2 Cycle	NET Power	Planned for Deployment in 2026

Source: Guidehouse analysis for this report

Manufacturing and Supply Chain

Figure 23 illustrates the technology types and leading companies for post-combustion capture.

Figure 23: Post Combustion Capture Technology Manufacturers



Source: Guidehouse-developed figure

The supply chain for carbon capture with power plants is relatively nascent, and some of the leading companies listed have historically focused on developing carbon capture solutions within industry, where CO_2 concentrations in flue gas are higher. Nonetheless, many of these companies do emphasize their product offerings can be leveraged within fossil-fuel power generation. Mitsubishi Heavy Industries and Shell have been developing the most power generation carbon capture projects globally, seven projects each.

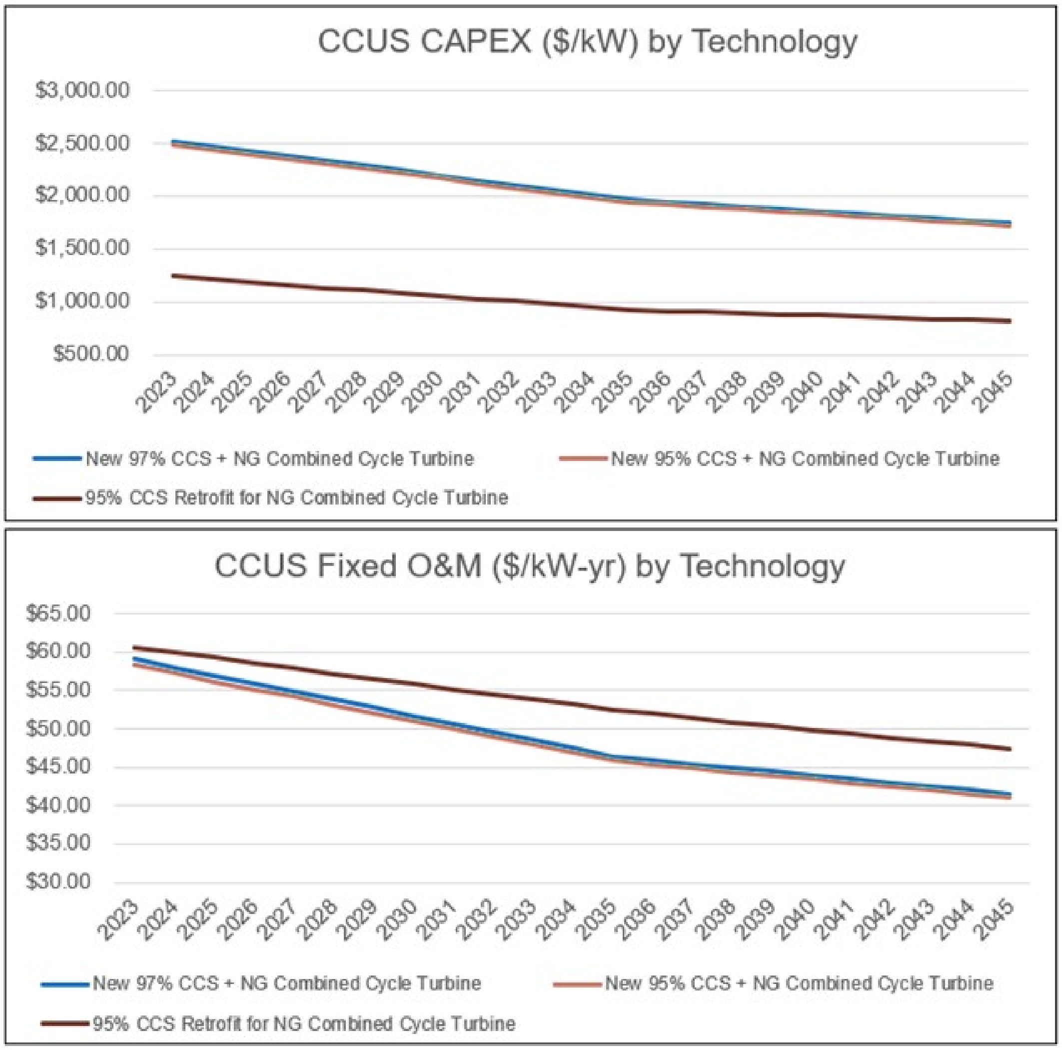
238 2013. Carbon Capture: A Technology Assessment. Congressional Research Service. https://crsreports.congress.gov/product/pdf/R/R41325.

239 2022. "NET Power Announces its First Utility-Scale Clean Energy Power Plant Integrated with CO2 Sequestration." Cision PR Newswire. https://www.prnewswire.com/news-releases/net-power-announces-its-first-utility-scale-clean-energy-power-plant-integrated-with-co2-sequestration-301669970.html.

Current and Expected Costs

Readily available cost data for carbon capture with natural gas combined cycle (NGCC) plants is limited to amine solvent technology for both new and retrofitted plants. Even though there is not a focus on utilization or sequestration technologies within this report, the costs of sequestering captured carbon are included within the following analysis in line with how NREL ATB reported the data.[240] Figure 24 describes the CAPEX and fixed O&M costs per kW of a Solvent CC Carbon Capture system integrated with a NGCC power plant.

Figure 24: Solvent CCS + Combustion Turbine Cost Profiles



Source: NREL

The CAPEX of 95 percent and 97 percent capture efficiency systems was relatively similar, but the upfront cost to retrofit an existing NGCC with 95 percent capture amine solvent technology was expectedly much lower. The fixed O&M costs of retrofitting NGCC plants with 95 percent carbon capture is slightly more expensive than building a new system entirely, and the costs also decline at a slower rate. From a purely economic perspective, carbon capture may be a

240 2023. "Electricity Annual Technology Baseline (ATB) Data Download." NREL. https://atb.nrel.gov/electricity/2023/data.

sound pathway to maintaining sufficient firm generation capabilities, while contributing towards decarbonization.

Barriers and Recommendations

Greater detail on the barriers and recommendations for carbon capture and the key post-combustion carbon capture technologies are described in Table 64.

Table 64: Carbon Capture Barriers and Recommendations

Category	Barriers	Recommendations
All Post Combustion Technologies	• Difficulty of efficient and cost-effective capture carbon is exacerbated with flue gas at lower CO_2 concentrations. • Typical CO_2 concentrations in NGCC plant flue gas are ~4-8%, which is much lower than flue gas from coal plants (~10-14%) and industrial processes (~14-30%).[241]	• Focus R&D efforts on CO_2 capture efficiency at lower CO_2 concentration to enable deployment of this technology at scale. • Encourage carbon capture demonstrations with NGCC plants so learning-by-doing improvements drive down costs and innovation is realized.
Amine Solvents	• Energy input requirements are higher than alternative carbon capture technologies. • Solvents can degrade relatively quickly with repeated heating and cooling.	• Research optimizations to system process design and explore heat integration as a pathway to lower energy requirements. • Explore new solvent compounds and additives with potential to alleviate degradation and reduce costs.
Adsorption	• Adsorption columns are limited in maximum size and do not benefit from economies of scale as much as solvents. • Long cycle time associated with heating and cooling steps can take several hours.[242]	• Focus near-term lab and pilot efforts for smaller-scale generation applications. • Promote research goals to reduce heating and cooling cycle times.
Membranes	• Membrane modules do not benefit from economies of scale as much as solvents. • Membrane modules have relatively low system lifespans (~5-7 years) compared to other solutions.	• Focus near-term lab and pilot efforts for smaller-scale generation applications. • Promote research goals to improve membrane module durability and lifespan.

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241 He, Xuezhong, Danlin Chen, Zhicong Liang, Feng Yang. 2022. Insight and Comparison of Energy-efficient Membrane Processes for CO2 Capture from Flue Gases in Power Plant and Energy-intensive Industry. Carbon Capture Science & Technology. https://www.sciencedirect.com/science/article/pii/S2772656821000208.

242 Mondino, Giorgia, Carlos A. Grande, Richard Blom, Lars O. Nord. 2019. Moving bed temperature swing adsorption for CO2 capture from a natural gas combined cycle power plant. International Journal of Greenhouse Gas Control. https://www.sciencedirect.com/science/article/pii/S1750583618306868?ref=pdf_download&fr=RR-2&rr=81c54a944da213ff.

Category	Barriers	Recommendations
Cryogenic	• Cryogenic carbon capture is nascent compared to other options and has not progressed beyond the economic modeling stage of development.	• Once the technology is developed and optimized at a lab scale, pilots should be conducted.

Source: Guidehouse analysis for this report

In terms of carbon capture at lower CO2 concentrations, specifically with membranes as an example, if CO_2 purity cannot reach ca. 60 vol.% in the first stage of a two-stage membrane, it may not be technically feasible to reach 95 vol.% CO_2 in the final product. This would largely prevent the potential of membranes for NGCC carbon capture.[243] It is a large challenge with NGCC carbon capture plants and must be addressed for any carbon capture technology to be deployed at scale within California.

243 Ibid.