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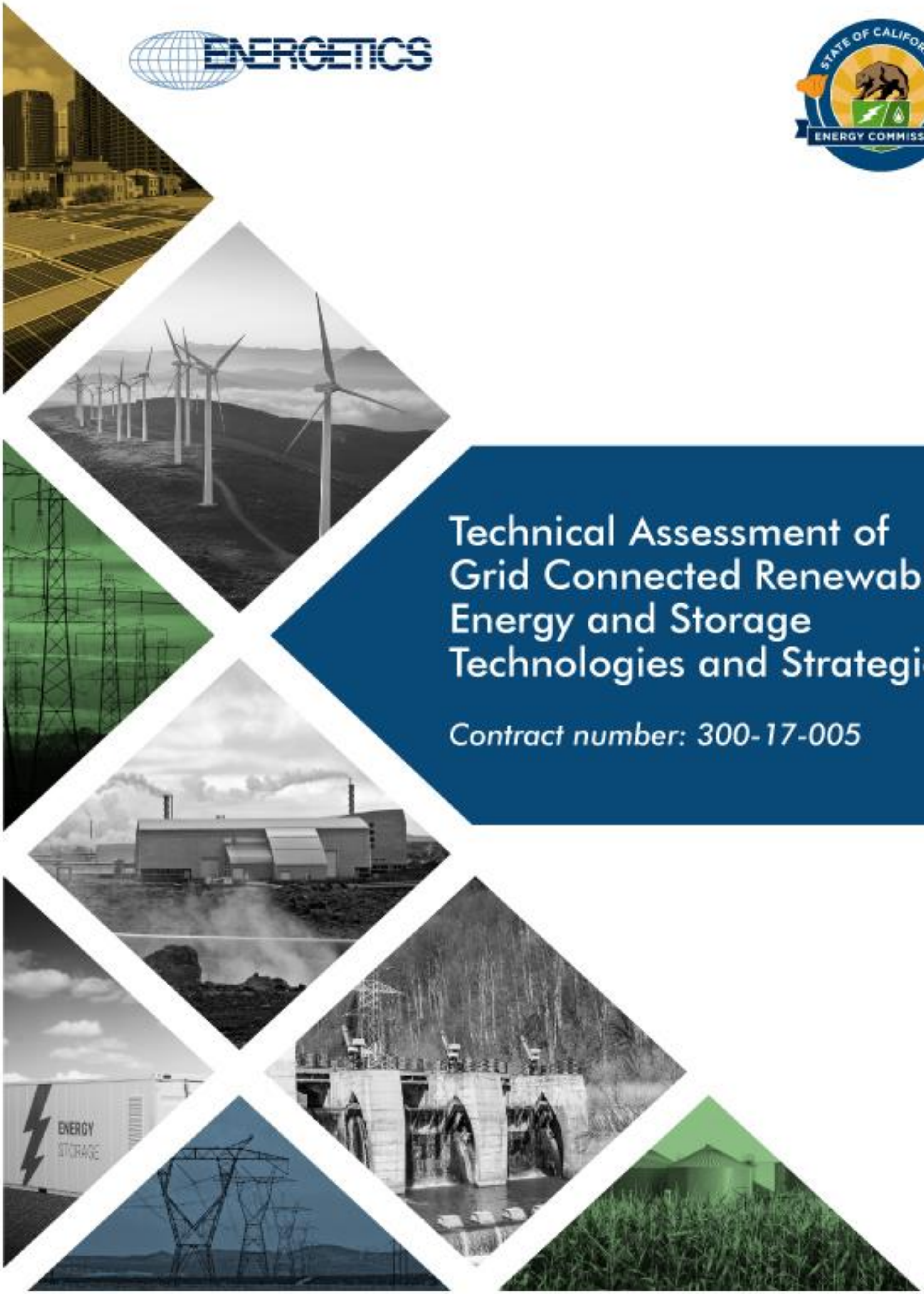

Technical Assessment of Grid Connected Renewable Energy and Storage Technologies and Strategies

Contract number: 300-17-005

Technical Assessment of Grid Connected Renewable Energy and Storage Technologies and Strategies

Prepared for the California Energy Commission

January 2019

Agreement Number: 300-17-005 (Task 2)

Project Title: Research Roadmap for Cost and Technology Breakthroughs for Renewable Energy Generation

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The technologies and strategies in this report were selected based on the best available and most recent literature that could be identified. This report is not expected to be an exhaustive list of technology options. All estimates are intended for guidance at a high level, and those pertaining to cost, performance, and otherwise should not be misconstrued to infer suitability for an individual project.

Executive Summary

This technical assessment represents Task 2 of Agreement 300-17-005, Research Roadmap for Cost and Technology Breakthroughs for Renewable Energy Generation.

- The purpose of the research roadmap is to identify, describe, and prioritize research, development, demonstration, and deployment (RDD&D) on technology opportunities that have potential to achieve high penetration of renewable energy into California's electricity grid.
- The purpose of the technical assessment is to identify the current baseline and best-in-class renewable energy resource technologies and strategies, including cost and performance attributes.

These efforts seek to identify and prioritize research on the most critical RDD&D gaps that need to be addressed to achieve California's goals for integrating high penetrations of renewable energy resources in investor-owned utility (IOU) service territories. Results of the analyses may be used to strategically target future Electric Program Investment Charge (EPIC) investments in a manner that provides optimal benefits to IOU electric ratepayers and maximizes the use of public research and development investments.

California Public Resources Code Section 25711.5(a) requires that EPIC-funded projects benefit electricity ratepayers and lead to technological advancement and breakthroughs to overcome barriers that prevent achievement of the state's statutory energy goals.

Senate Bill 100 (SB 100) has established targets of 60% of electricity production from renewable sources by 2030 and 100% zero-carbon electricity by 2045 in California.[1] As can be inferred from Figure ES-1 California must effectively double its renewable energy capacity in a little over a decade and replace all fossil fuel energy generation (38% of the state's total electricity capacity) in just over 25 years to meet these targets.

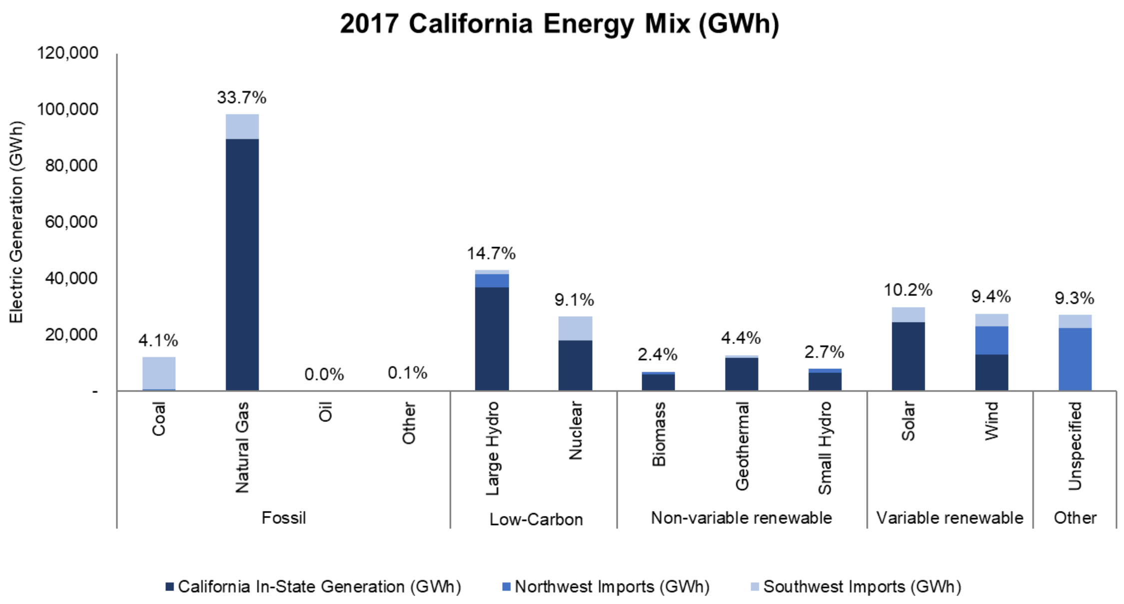

Figure ES-1. 2017 California Energy Mix
energy.ca.gov/almanac/electricity_data/total_system_power.html

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[1] "SB-100 California Renewables Portfolio Standard Program: emissions of greenhouse gases," California Legislative Information, September 10, 2018, accessed December 7, 2018, leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180SB100.

The technical assessment is organized by the technology areas shown in Figure ES-2. These technology areas serve as the foundation for a roadmap of potential EPIC funding initiatives that could allow California to achieve its statutory energy goals.

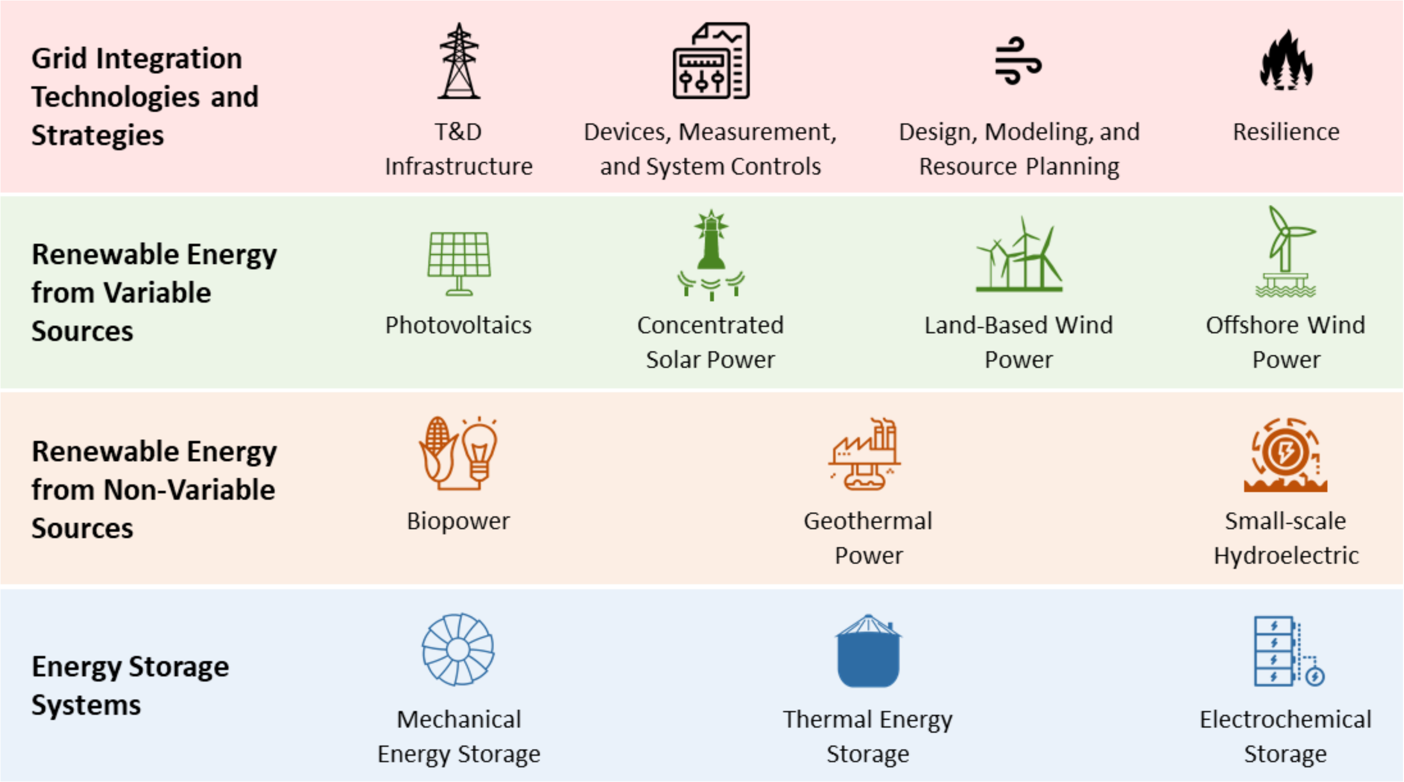

Figure ES-2. Technologies Areas Covered by the Technical Assessment

Analysts identified key cost and performance attributes and characterized research & development (R&D) opportunity areas for each technology area through a detailed review of technology roadmaps, regulatory agency reports, academic literature, and research publications and through numerous expert interviews. The chapters of the tech assessment are organized by the technology areas shown in Figure ES-2 and according to following subsections:

- **Resource Availability.** Characterizes the extent to which the technology type is already deployed in and how that compares with the technical potential for the resource in the state.
- **Technology Overview.** Discusses the use cases, costs, and performance attributes of currently deployed and best-in-class renewable energy and energy storage technologies in California.
- **Research Initiatives.** Provides an overview of ongoing research initiatives from EPIC and other research institutions in the United States. This provides context on the work already being done to advance the technology areas that can inform where additional investment could fill R&D gaps.
- **R&D Opportunity Areas.** Describes key technical, financial, and regulatory considerations that may enable or inhibit growth of a technology area in California. This section also identifies broad categories for R&D that expand beyond those identified in the Energy Commission's 2018–2020 Triennial Investment Plan. Additionally, the section identifies specific breakthrough technologies that could emerge from investments in the R&D opportunity areas.

Investments in grid infrastructure, system controls, and modeling and forecasting systems are necessary for California to effectively integrate more renewables onto the grid. As more renewable energy resources are deployed, additional transmission lines and related infrastructure must be installed, providing an opportunity for the state to implement new technologies and policies. These investments can also increase the resilience of grid infrastructures and operations to mitigate the risks of weather-related hazards resulting from climate change. Improved resource forecasting and modeling efforts can reduce renewable energy curtailment and optimize supply- and demand-side resources.

Table ES-1 compares the currently developed power capacity of each resource with the gross potential capacity of each renewable resource. The technically accessible energy potential for each resource will be lower than the gross potential. However, Table ES-1 provides useful context regarding the current extent of deployment and future opportunity to access a great portion of each resource to meet California's renewable power requirements.

Table ES-1. Resource Availability of Variable Renewable Energy

Resource	Technology Type	Current Capacity (GW)	Estimated Potential Capacity (GW)
Solar	Photovoltaics	9.6	4,120
	Concentrating Solar Power	1.3	2,730
Wind	Land Based	5.6	130
	Off Shore	0.0	160
Bioenergy	From Agriculture, Forestry, and Municipal Solid Waste	1.3	10
Geothermal	Traditional	2.7	20
	With inclusion of Enhanced Geothermal Systems	*0.0*	*50*
Small Hydro	Total smaller than 30 MW capacity	1.7	n/a
	In-Conduit Systems only	0.3	<1

Prices for wind and solar power have surpassed cost parity for most forms of conventional power generation. Variable renewable power generation, namely solar power, has seen a rapid uptake in deployment in California in recent years. Wind and solar offer the highest resource potential in California compared to other renewables. Land based wind development areas in California are currently saturated with older turbines that may require either retrofitting or replacement to access a greater portion of the potentially available wind resource. Offshore wind represents a nascent industry that would require local investments in technology development, meeting supply chain requirements, and operations and maintenance support.

However, wind and solar resources are intermittent, with their time periods of generation often not meeting time periods of high demand. As such, California can invest in technologies and strategies to time shift the availability of renewable resources to meet demand. Some opportunities include investments in concentrated solar power systems with thermal storage, expanded deployments of energy storage systems, or investments in technologies and strategies that enhance the capacity factors and predictability of variable renewable resources.

Non-variable renewable resources lack the same large potential capacity as solar and wind but can provide the flexible generation needed to match the high penetration of intermittent renewables in the grid. Additionally, the capacity available through non-variable renewable resources can provide a significant portion of California's capacity requirements (peak of approximately 50 GW in 2017). Bioenergy systems can provide additional societal value by serving as an energy positive means of organic waste disposal and as a forest management tool to mitigate wildfire risk. California has one of the most productive geothermal resources in the nation. If fully developed, enhanced geothermal systems could meet nearly all of California's baseload energy demand. Additionally, in-conduit hydropower systems can generate power while acting as a pressure management tool for California's extensive irrigation and municipal water systems.

As shown in Figure ES-3, the unsubsidized levelized cost of electricity (LCOE) of alternative energy technologies is comparable, or superior, to that of conventional energy sources as of 2017.[2] Continued investments in the technology areas described in this technical assessment may further enhance the value proposition of renewable energy and energy storage systems. R&D investments may increase the predictability and dispatchability of renewable resources to accommodate grid demands.

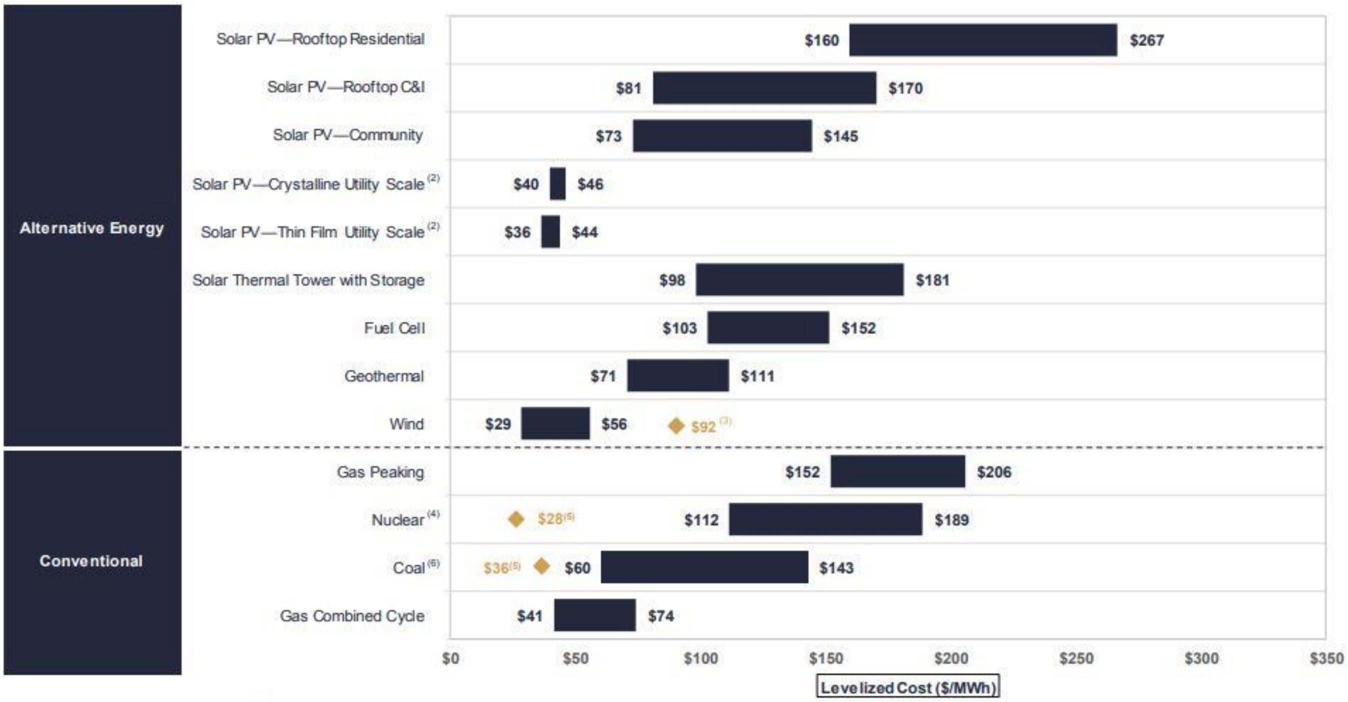

Figure ES-3. Unsubsidized LCOE of various energy sources (Lazard).

Figure from Lazard's Levelized Cost of Energy Analysis 2018 (LCOE 12.0)

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[2] "Levelized Cost of Energy and Levelized Cost of Storage 2018." Lazard. November 8, 2018. lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2018/

Grid-level energy storage at the transmission, distribution, and aggregated customer levels offers unique flexibility for ensuring smooth operation of a renewables-heavy grid. Energy storage systems are becoming an increasingly important grid resource used to complement the variability of wind and solar energy production, avoid demand charges for customers, and even replace generation from natural gas peaker plants. Energy storage technologies can provide multiple types of services and act as both flexible load and generation.

An array of mechanical, thermal, and elecrochemical energy storage systems offer different performance characteristics for rated power, capacity, energy density, and discharge rate that can be used by grid operators to ensure efficient and resilient grid operations. Lithium-ion batteries have emerged as the most popular battery chemistry due to their high energy density and increasingly lower costs. Because of continuing cost declines, technology improvements, and familiarity with the technology among regulatory, utility, and permitting agencies, lithium-ion is likely to dominate both in-front and behind-the-meter energy storage procurement in the near future.

Applying the Tech Assessment to Create an EPIC Roadmap

The technical assessment results constitute a broad assay of the cost and performance baselines for current and best-in-class renewable energy technologies and energy storage systems. The technical assessment also provides useful insights regarding current research initiatives in the United States and identifies a selection of R&D opportunities that could produce valuable emerging and breakthrough technologies that enable California to meet its statutory energy goals.

The priority R&D opportunities will be evaluated according to the EPIC Triennial Investment Plan initiative attributes (Figure ES-4).[3] The roadmapping process will evaluate and prioritize the identified R&D opportunities through consultation with experts in a series of virtual roadmapping webinars, direct engagement with technology developers and grid operators, and continued literature review and analysis. The collective insights of the technical assessment results, inputs from leading technology area experts, and collaboration with the Energy Commission will empower the Energy Commission with an actionable research roadmap to prioritize investments that increase the cost competitiveness, flexibility, and reliability of renewable energy generation and operation to facilitate greater renewable energy penetration in the state's grid.

Figure ES-4. R&D Priority Attributes for Roadmap

- Description
- Impact if Successful
- Primary Users and/or Beneficiaries
- Metrics and/or Performance Indicators
- Topic(s) addressed
- Value Chain
- Program Area(s)
- Ratepayer Benefits

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[3] "Electric Program Investment Charge: 2018–2020 Triennial Investment Plan," California Energy Commission, CEC-500-2017-023-CMF, adopted on April 27, 2017, energy.ca.gov/research/epic/17-EPIC-01/.

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1 | Introduction

California's recent passage of Senate Bill 100 (SB 100) has reaffirmed the state's commitment to achieving a clean-energy-driven and carbon-free electric grid in the near future.[4] To reach the targets of 60% of electricity production from renewable sources by 2030 and 100% zero-carbon electricity by 2045, California must drastically increase its capacity of renewable energy generation and deal with a number of grid integration challenges such as variability of the state's power production portfolio.

1.1 | Objectives

This technical assessment (TA) introduces renewable resources currently operating in California and explores the current state of these technologies, challenges facing their continued growth, new and emerging technologies and processes, and paths forward for future development. The information presented in this document forms the framework of research priorities, potential partnerships, and critical technology milestones. This framework will serve as a basis to prepare a roadmap on utility-scale renewable generation technologies and storage to inform Electric Program Investment Charge (EPIC) research, development, deployment, and diffusion (RDD&D) portfolio decisions and accelerate progress toward more cost-competitive, flexible, and reliable renewable energy generation, operation, and storage.

Figure 1-1. Sector Topics Outline for the Technical Assessment

2. **Grid Integration Technologies and Strategies**
3. **Variable Utility-Scale Renewables**
    - Solar
    - Wind
4. **Non-Variable Utility-Scale Renewables**
    - Bioenergy
    - Geothermal
    - Hydroelectric
5. **Energy Storage**

A series of webinars will explore these takeaways and result in the final roadmap that identifies the RDD&D gaps that can be filled and associated actions that can be taken to integrate high penetrations of renewable energy resources in investor-owned utility (IOU) service territories. The roadmap will also help frame the EPIC research program for utility-scale, transmission-connected renewable energy generation and storage

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[4] "SB-100 California Renewables Portfolio Standard Program: emissions of greenhouse gases," California Legislative Information, September 10, 2018, accessed December 7, 2018, leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180SB100.

that contributes to a balanced electricity supply. The identified breakthroughs will help California achieve its renewable energy goals and meet the needs of California utilities and ratepayers.

1.2 | Overview and Methodology

This TA illustrates the current landscape for renewable energy resources in California. In developing the TA, analysts conducted an extensive literature review, combined with outreach to experts in each sector. These experts included leaders from academia, industry, national laboratories, and corporations. These interviews focus on:

- The current state of technology development
- California's resource potential
- Current issues preventing large-scale deployment of renewables
- Ways to prioritize investment to support future growth

The interviews and literature review provided useful insights into the challenges and opportunities pertaining to expanded penetration of utility-scale renewable energy technology deployment on California's electric grid.

This TA includes a baseline for each renewable resource. These baselines provide context that informs sets of recommended actions for each technology area that will be considered in the project roadmapping phase. Figure 1-2 shows California's energy mix as of 2017, indicating that there is still a long way to go to reach the SB 100 2030 target of 60% of electricity from renewable sources (currently 29.1%) and the 2045 target of 100% carbon-free electricity (currently 52.9%).

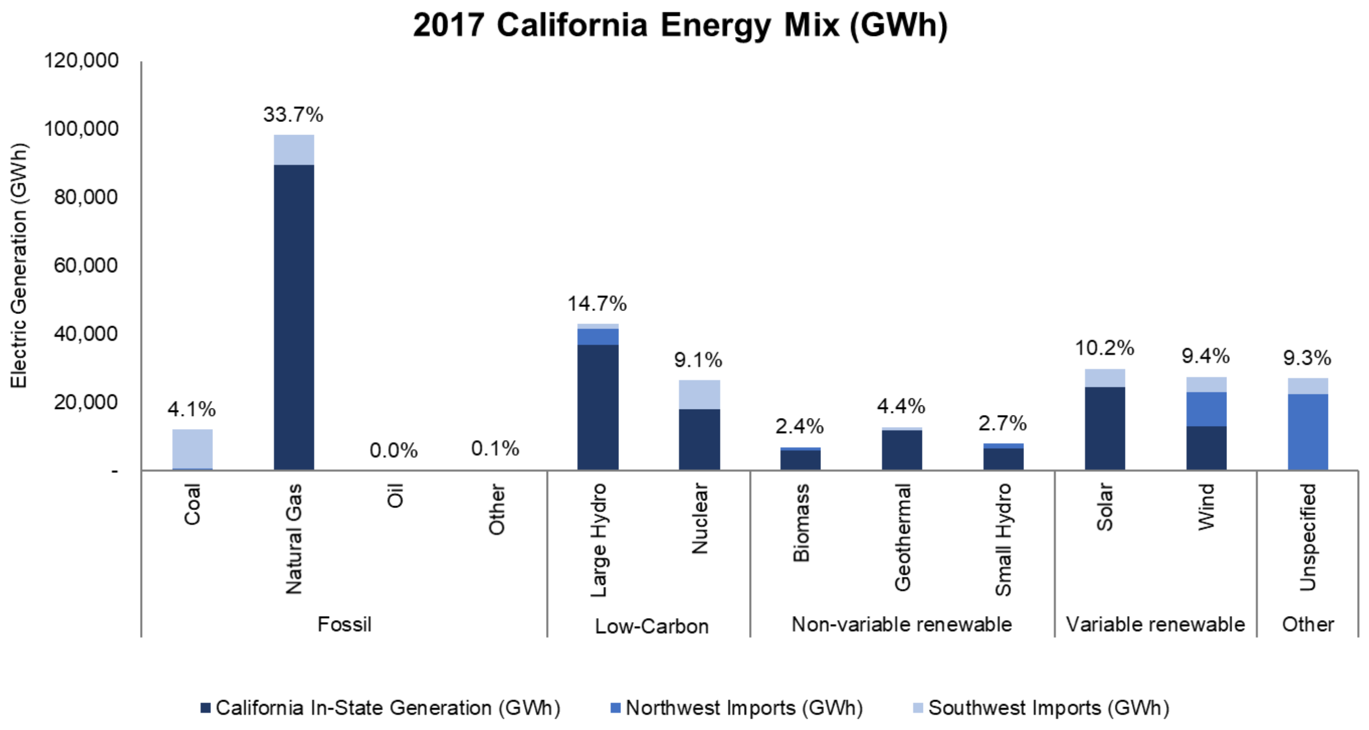

Figure 1-2. 2017 California Energy Mix

energy.ca.gov/almanac/electricity_data/total_system_power.html

Figure 1-3. Cross-Cutting Considerations for the Technical Assessment

- Resource availability
- Ramp rate flexibility
- Planning/permitting and commissioning
- Ease of grid integration
- Forecasting reliability
- Cost
- Environmental impacts
- Social impacts

Each chapter provides an overview of how the renewable resource or technology area contributes to California's current electricity profile and how that contribution has changed over time. There are lessons to be learned from the sectors that have shown growth and from those that have remained stagnant or have contracted. The challenges and opportunities for expansion in each technology area are valuable for providing future recommendations. Figure 1-3 summarizes some of the key factors that are important and comparable across sectors in this TA.

Resource availability attempts to quantify the generation potential of the available resource in California and the geographical locations that can be accessed for near- and/or long-term expansion. Locational information provides insight as to the proximity of renewable resources to load centers. Additionally, resource location may provide unique grid integration challenges or opportunities. The resource availability section in each chapter may also discuss relevant legislation and permitting considerations that are particularly important if a resource is in difficult-to-access terrain or regulated land areas.

Each technology baseline is informed by current deployments that offer insight into the costs, efficiencies, and deployment scale within each renewable technology area. Future priorities and RDD&D gaps are focused on increasing deployment by improving technology performance and reducing costs.

The key reoccurring metrics that were identified and are presented throughout this TA are shown in Table 1-1. In each section, additional metrics are identified that may be technology-specific. The metrics shown below are high-level and intended to provide some useful context for comparison between technology areas and resource types.

Table 1-1. Metrics Considered for Evaluating Progress

Metric	Unit	Description
Renewable Energy Capacity	GW	Installed cumulative capacity of renewable energy plants.
Resource Potential	MW	Amount of energy that can be additionally captured through deployment of a technology (hydro, wind, solar, geothermal, etc.). The overall potential can help show which resources have the most room for growth.
Performance	\$/MW \$/MWh	Levelized cost of energy (LCOE). The net present value of energy over the life of the power generation technology or improvement. For software, the increased capacity or generation enabled by a single application is estimated. Meant to represent a common metric across multiple types of renewable energy and storage.
Cost	$	Cost of a single unit or application. Shows magnitude of investment.
Ease of Integration	Months	Time it takes from starting application to start of life as a generating asset. Long or unknown deployments of technology indicate earlier applications with greater risk profiles. Includes siting and permitting times.
Curtailment	MWh (%)	Measured in either curtailed energy quantity or in percent reduction below what the resource could have otherwise produced, given sufficient demand.

The TA for each renewable energy sector also identifies current research initiatives, including those of the Energy Commission, California Independent System Operator (CAISO), U.S. Department of Energy (DOE), and various state agencies. Understanding the current research initiatives can help inform the Energy Commission as to where additional investment may help to fill RDD&D gaps most effectively.

Each technology section includes a sub-section titled “R&D Opportunity Areas and Technologies” that outlines high-impact opportunity areas for the Energy Commission, incorporating what was learned in the literature review and expert interviews. These opportunity areas include past and present areas of interest from the Energy Commission’s EPIC triennial investment plans.

Each chapter also discusses emerging and breakthrough technologies that fall within a set of identified R&D opportunity areas and parallel research topics (Table 1-2). These breakthroughs represent more targeted opportunities for Energy Commission investment. These include updates and retrofits to existing systems and the development of new technologies that may be necessary if California is to reach its renewable energy targets.

These R&D opportunity areas and technologies will form the basis of the roadmapping effort, in which technology experts will help to prioritize technologies and strategies that the Energy Commission could consider supporting in future investment plans.

Table 1-2. Parallel Research Topics

Parallel Research Topic	Description
Legacy System Improvement	A process or technology improvement to an established and robust technology that is currently in use for the development of renewable energy.
Innovative System Development	A technology or process that represents a new way of generating or accessing renewable energy.
Information Technology	A modeling, computing, or assessment technology relevant to renewable energy development.
Operations and Maintenance Improvement	Ongoing assessment, improvement, or maintenance of a renewable energy generating structure.
Supply Chain	A manufacturing, construction, or installation technology or process that improves renewable energy installations.
Other	New parallel research topic categories as suggested during the roadmapping process.

Chapter 2| Grid Integration Technologies and Strategies

SB 100 accelerates the state's renewable portfolio standard (RPS) to 60% by 2030 and requires that the 100% of electricity come from zero-carbon sources by 2045.

For California to meet these goals and continue to drive down the cost of electricity generation, innovations are needed that will increase the use of low-carbon resources for grid flexibility and stability.

Challenges

- A significant number of California's transmission and sub-transmission lines are being operated at, near, or above their initial design ratings.
- As California increases its reliance on renewable energy resources, the changing electric flow patterns and large flows from concentrated RE resource areas will cause overloading and congestion on existing power lines.

Opportunities

- Infrastructure upgrades, effective planning, and better system modeling and forecasting can help to optimize the existing transmission system and integrate more renewables into the grid.
- System improvements could create a more resilient, reliable electric grid.

Transmission and Distribution (T&D) Infrastructure: As more renewable energy resources are deployed, additional T&D lines and related infrastructure must be installed, providing an opportunity for the state to implement new technologies and policies.

Devices, Measurement, and System Controls: California and other states use a variety of tools and systems for monitoring the electric transmission system. Advanced power electronics and system controls can help increase penetration of renewables in the electric grid and improve reliability.

Design, Modeling, and Resource Planning: Improved resource forecasting and modeling efforts can reduce renewable energy curtailment and optimize supply- and demand-side resources.

Resilience: The State's T&D infrastructure is susceptible to weather-related hazards resulting from climate change or other natural weather events, acts of terrorism, and sabotage.

2.1 | Grid Integration Technologies and Strategies

In 2017, California's total system electricity generation was over 292,000 GWh, up 0.5% from 2016's total generation. The state's energy mix includes conventional generation from fossil fuels, including natural gas and coal, but also includes various non-CO_2-emitting electric generation sources: nuclear, large hydroelectric, and renewable generation. These low-carbon sources accounted for more than 56% of total in-state generation for 2017, up from 50% in 2016.[5] In 2016 alone, the annual average variable renewable energy (VRE) penetration comprised solar photovoltaics (PV) (49.1%), wind (44.2%), and concentrating solar power (CSP) (6.7%).[6]

Figure 2-1 shows California's cumulative installed large-scale renewable energy capacity by technology type from 2010 to 2017.[7]

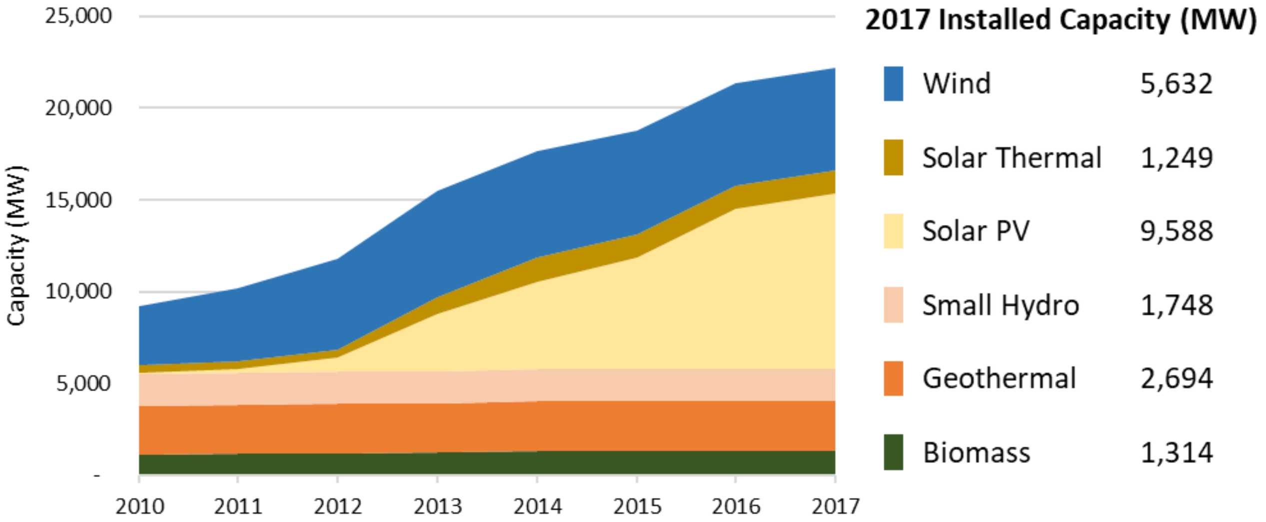

Figure 2-1. Cumulative Installed Large-Scale Renewable Energy Capacity, 2010–2017

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[5] "Total System Electric Generation," California Energy Commission, accessed November 2018, energy.ca.gov/almanac/electricity_data/total_system_power.html.

[6] "2016 Renewable Energy Grid Integration Databook," U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, June 2018, nrel.gov/docs/fy18osti/71151.pdf.

[7] "Electric Generation Capacity & Energy," California Energy Commission, accessed November 2018, energy.ca.gov/almanac/electricity_data/electric_generation_capacity.html.

In addition to the installed large-scale renewable energy capacity quantified above, by the end of 2017, the total renewable capacity in California included nearly 6,800 MW of renewable self-generation capacity (solar, wind, and biomass) from homes and businesses across the state.[8] How best to utilize and monetize the growing fleet of distributed energy resources (DERs) merits consideration for informing future R&D, operations and control systems, and information exchange platforms. Although DERs are integral to the broader electric grid, this TA focuses on utility-scale renewable energy generation.

California's electric grid must deploy new technologies and systems to enable the integration of more renewable power generation in pursuit of 100% carbon-free electricity generation by 2045. Effective planning can help optimize the existing transmission system so that power-handling capacity and energy-transport capabilities are not underutilized. Transmission expansion enables transport and sharing of renewable electricity and reliability responsibilities.

2.1.1 | Technology Overview

2.1.1.1 | Transmission and Distribution Infrastructure

California's transmission and distribution (T&D) infrastructure includes a vast array of high- and low-voltage T&D lines, substations, and an extensive distribution network. This infrastructure facilitates the bulk transfer of electricity from a generating station to a local distribution network and, ultimately, delivers electricity to its various customers in the residential, commercial, and industrial sectors—see Figure 2-2 for an illustrative diagram.[9] In total, California has over 4,400 miles of high-voltage (>230 kV) transmission lines and over 10,300 miles of low-voltage (<230 kV) transmission lines.[10]

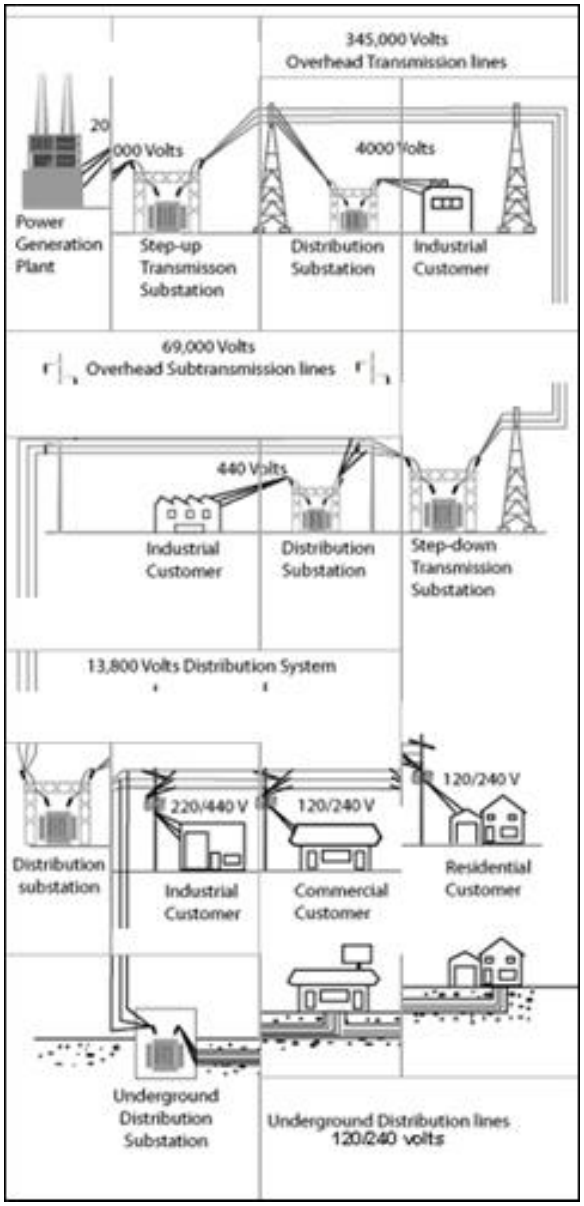

Figure 2-2. Overview of Transmission and Distribution System

As more renewable energy resources are deployed, additional T&D lines and related infrastructure must be installed, providing an opportunity for the state to implement new technologies for power lines, transmission towers, and even control systems. While individual technologies can improve the performance of existing T&D

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[8] "Tracking Progress – Renewable Energy Overview," California Energy Commission, July 2018, energy.ca.gov/renewables/tracking_progress/documents/renewable.pdf.

[9] "Electric Power eTool Webpage," Occupational Safety and Health Administration, accessed November 2018, osha.gov/SLTC/etools/electric_power/scope.html.

[10] "State of California – Energy Sector Risk Profile," U.S. Department of Energy, 2015, energy.gov/sites/prod/files/2015/05/f22/CA-Energy%20Sector%20Risk%20Profile.pdf.

networks, in concert they could achieve significant system-wide benefits.

Transmission Towers

Transmission towers present an opportunity for improvement. Existing steel cross-arms and vertical insulators on existing pylons can de facto limit the transmission capacity of the T&D system. In addition, they are tall structures that require significant resources to build and maintain. Replacing these steel cross-arms with insulating cross-arms can allow for increases in transmission capacity of up to 150% compared to existing infrastructure. New towers built with cross-arms are also 25% shorter and use fewer resources.

Transmission Lines

Transmission lines are another T&D system component whose performance can benefit from technological advances. Technologies such as smart wires could allow for more large-scale renewable energy integration into the grid while deferring the need for significant investments to build new power lines or upgrade existing lines.

Today's standard conductor used in power lines is an aluminum conductor steel reinforced (ACSR) design that is a high-capacity, high-strength stranded conductor. Innovations in the incorporation of carbon fiber have shown promise to reduce sag by providing tensile support, allowing cables to carry more current. Specifically, aluminum conductor composite core (ACCC) could replace the ACSR design; ACCC is a high-temperature, low-sag conductor that is 60% lighter than ACSR cables.

Semiconductor Technology

Other key equipment and components that are integral to the T&D network's architecture and function are ripe for upgrading. New semiconductor technology such as silicon carbine (SiC) power semiconductors can replace conventional silicon semiconductors to reduce the energy losses when electricity is converted before delivery to customers. Specifically, this technology can enable integration of renewable energy such as converting off-shore wind alternating current (AC) to direct current (DC) and solar power inverters for converting DC to AC.

High-Voltage DC Grid System (HVDC)

A high-voltage DC (HVDC) grid system can reduce transmission losses compared to high-voltage AC (HVAC) systems, the commonly used transmission system for off-shore wind farms. Deploying an HVDC transmission system could allow for electricity to be transported in both directions. This would improve off-shore wind transmission architecture and could also reduce transmission losses.

2.1.1.2 | Devices, Measurement, and System Controls

A closer look at the devices and system controls provides another perspective on the opportunities for improving the state of California's electricity grid. For example, advanced power electronics and system controls have enabled wind generating units to achieve performance comparable to, or even superior to, that of conventional thermal or hydro generating units. Most of these capabilities can also be achieved by solar PV generating units since they share several technical characteristics with wind turbine generators (especially inverter-based ones).[11]

Sensors, Controls, and Measurement Systems

Supervisory Control and Data Acquisition (SCADA) and Synchrophasor Technology

California and other states use a variety of tools and systems for monitoring electricity transmission. This includes SCADA, a system of remote control and telemetry used to monitor and control the electric transmission system.[12] Although SCADA underpins the operation of modern power systems, synchrophasor technology could prove a viable alternative that improves grid reliability. Synchrophasors are time-synchronized numbers representing the magnitude and phase angle of the sine waves in electricity and are time-synchronized for accuracy. Measurements are conducted by high-speed monitors called phasor measurement units (PMUs). These PMU measurements record grid conditions with a high level of accuracy and provide insight into grid stability or stress.[13]

Synchrophasor technology can collect 30 to 60 samples per second, roughly 100 times faster than SCADA. This highly granular data enables insights into grid conditions such as:

- Early warning of grid events and dynamic behavior
- Fast identification of failing equipment and asset problems
- Deployment of better models of equipment, generators, and the overall power system

By providing additional visibility into grid performance and operations, deployment of PMUs and synchrophasor technology delivers a redundant, secure operator tool and automated system protection. In addition to its benefits for real-time operations, it also allows for off-line engineering analyses to improve grid reliability, increase efficiency, and lower operating costs.[14,15]

Direct Normal Irradiance (DNI)

More application-specific solutions can also contribute to a more renewable-friendly electricity grid. One example is highlighted in a recent Energy Commission project on a high-fidelity solar power forecasting system. The project sought to design, deploy, and test

Figure 2-3. Wireless Direct Normal Irradiance (DNI) Sensor

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[11] "White Paper: Grid integration of large-capacity renewable energy sources and use of large-capacity electrical energy storage," International Electrotechnical Commission (IEC), 2012, iec.ch/whitepaper/pdf/iecWP-gridintegrationlargecapacity-LR-en.pdf.

[12] "U.S. Electricity Industry Primer," U.S. Department of Energy, July 2015, energy.gov/sites/prod/files/2015/12/f28/united-states-electricity-industry-primer.pdf.

[13] "Synchrophasor Applications in Transmission Systems," SmartGrid.gov, accessed November 2018, smartgrid.gov/recovery_act/program_impacts/applications_synchrophasor_technology.html.

[14] "Synchrophasor Applications in Transmission Systems," SmartGrid.gov, accessed November 2018, smartgrid.gov/recovery_act/program_impacts/applications_synchrophasor_technology.html.

[15] Alison Silverstein, "Synchrophasors and the Grid," North American SynchroPhasor Initiative (NASPI), September 13, 2017, energy.gov/sites/prod/files/2017/09/f36/2_Modern%20Grid-networked%20Measurement%20and%20Monitoring%20Panel%20-%20Alison%20Silverstein%2C%20NASPI.pdf.

low-cost solar instruments and sensors to monitor DNI and improve forecasting models. By optimizing and deploying a network of these sensors—each node of which is solar-powered and wireless—this system could strengthen forecasting models and improve reliability of generation predictions for intermittent solar resources in large-scale plants. By developing hardware and software for forecasting based on high-resolution temporal and spatial local telemetry, very short-term predictions can be improved and could help support grid operations.[16]

Light Detection and Ranging (Lidar)

Currently, controllers on wind turbines may not perform appropriately in the presence of stochastic and unknown wind fields, hence relying on the turbine's response to generate control actions. New technologies such as lidar can allow for sensing of the wind field before it even reaches the rotor. Lidar-assisted control (LAC) has been researched and field-tested to compare the performance of a baseline controller to LAC. Results have shown that measurements from a lidar-based system with multiple range gates can generate rotor average wind speed (RAWS) estimates with higher levels of correlation with wind speed at the rotor, compared to using a single range gate. The use of LAC also shows higher levels of speed control performance with significantly reduced levels of pitch activity and lower levels of tower excitation. This is yet another technology that can help ensure renewable energy resources are utilized most effectively.[17]

Dynamic Line Rating (DLR)

DLR is a more system-level technology that has recently been demonstrated. This technology can improve power system transmission capacity by monitoring system conditions, especially for power plants using intermittent renewables such as solar, wind, tidal, and wave power. Demonstration projects conducted by DOE's Smart Grid Demonstration Program have confirmed the presence of real-time capacity above the static rating, with up to 25% additional usable capacity made available for system operations. DLR technology is inexpensive to install and operationally flexible, which makes it an attractive alternative to costly transmission system upgrades. DLR systems offer a wide array of benefits to transmission owners, customers, and system operators, including congestion relief, greater transmission system reliability, lower costs for consumers, and optimized dispatch of existing and new grid assets.[18]

2.1.1.3 | Design, Modeling, and Resource Planning

Activities associated with designing, modeling and forecasting, and integrated resource planning (IRP) are just as critical as the transmission and distribution infrastructure and hardware that deliver electricity to end-use customers. Although access to transmission is a key cost barrier limiting renewable resource development, complex challenges exist for identifying cost-effective transmission development policies. Given California's drive to increase distributed generation and renewable energy production, research is

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[16] "High-Fidelity Solar Power Forecasting System," California Energy Commission, accessed December 18, 2018, energy.ca.gov/research/notices/2018-02-07_symposium/presentations/06%20Accurate%20Forecasting%20to%20Support%20the%20Modern%20Grid/1.%20Hugo%20Pedro%20UCSD.pdf.

[17] Avishek A. Kumar et al., "Field Testing of LIDAR-Assisted Feedforward Control Algorithms for Improved Speed Control and Fatigue Load Reduction on a 600-kW Wind Turbine," National Renewable Energy Laboratory, November 2015, nrel.gov/docs/fy16osti/65062.pdf.

[18] "Dynamic Line Rating Systems for Transmission Lines," Smart Grid Demonstration Program, April 25, 2014, smartgrid.gov/files/SGDP_Transmission_DLR_Topical_Report_04-25-14_FINAL.pdf.

needed to identify transmission infrastructure improvements that would best support development of mixed renewable technology applications. This can help improve coordination of centralized and distributed power generation. Several existing modeling tools can accomplish optimization analysis, but additional research can improve these tools for use at a range of scales to ensure the best use of available renewable resources.[19]

To identify the optimal resource mix of supply- and demand-side resources, IRP must capture DERs' impact on the T&D system. Examples of impacts not captured in recent IRP modeling include avoided T&D costs and DER integration costs, including both interconnection and renewable integration. These costs and associated benefits can vary significantly and depend on location, load growth, and the associated DER resource mix that is forecasted. Considering the locational value of DERs in IRP can help ensure tariffs and procurement policies appropriately value DERs.[20] Although more progress is needed in this area, improved resource forecasting and modeling efforts can enable better estimation of the locational value of DERs and ensure they are accurately accounted for in IRP modeling. The modeling and forecasting tools discussed below are advancing the state of the art.

Renewable Resource Forecasting

Utilities and grid operators rely on complex modeling and forecasting tools to determine the appropriate resources to be dispatched to meet electricity demand. Similarly, utilities and power generators must plan future resource needs and, in the case of renewable energy resource planning, forecast weather patterns. These functions require thorough models and forecasting tools to inform decisions relating to grid design and planning investments for grid infrastructure upgrades and expansion of service areas.

Weather models have become increasingly sophisticated and include algorithms that provide very short-term predictions of solar power generation by relying solely on past values of solar power data. These univariate time-series prediction tools can generate the forecast output in less than a second. Accurate weather models and renewable resource forecasts are imperative to limiting curtailment of wind and solar energy.[21]

Curtailment is an effective tool for independent system operators (ISOs) to manage oversupply of renewable resources when there is inadequate customer demand, but using this strategy also indicates lost opportunity. Although roughly 2,000 MW of solar capacity has been added in each of the last three years, curtailment is also on the rise in California. In 2015, the California ISO (CAISO) was forced to curtail over 187,000 MWh of solar and wind generation. In 2016, that total rose to over 300,000 MWh.[22]

Deployment of systems such as the High-Fidelity Solar Power Forecasting System, LAC, and even DLR technology could help reduce curtailment and improve the economics of large-scale solar plants. Enhanced forecasts can also help power plants participate in the real-time market and can reduce imbalance with

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[19] Brian Jenkins and Adam Schultz, "Renewable Energy Resource, Technology, and Economic Assessments," California Energy Commission, January 2017, energy.ca.gov/2017publications/CEC-500-2017-007/CEC-500-2017-007.pdf.

[20] "Consideration of Distribution Costs and Benefits of DERs in IRP," California Public Utilities Commission, May 30, 2018, cpuc.ca.gov/uploadedFiles/CPUCWebsite/Content/UtilitiesIndustries/Energy/EnergyPrograms/ElectPowerProcurementGeneration/irp/2018/Consideration%20of%20Locational%20Value%20in%20IRP%205-30-18%20IRP%20MAG.pdf.

[21] Curtailment is the reduction of output of a renewable power plant below what it could have otherwise produced.

[22] "Fast Facts: Impacts of renewable energy on grid operations," California ISO, 2017, caiso.com/documents/curtailmentfastfacts.pdf.

CAISO. Furthermore, there is a need to better understand the behavior of clouds, fog, and aerosols, with corresponding advances in modeling to forecast fog and stratus conditions.

Net Load Forecasting

Net load represents the load that is traded between a microgrid and the utility grid. It is an important concept for resource allocation and electricity market participation at the point of coupling between the interconnected grids.[23] Increased use of net-load forecasting can improve the operation and management of power grids with high renewable energy penetration. The CAISO Baseline Load Forecast Model can also improve forecasts of measured loads for forecast horizons of 15 minutes ahead out to 10 days ahead. Although the modeling framework comprises a set of 193 individual forecast models, none of these models includes the impact of behind-the-meter (BTM) solar PV on measured loads. Integrating BTM forecasting can improve load forecasting accuracy and reduce forecast errors.

Improved net-load forecasting could also benefit the rise in DER aggregation, or virtual power plants, which help distributed PV and other DERs such as battery storage and electric vehicles (EVs) to provide demand response (DR), voltage regulation, and other important grid services. When many DERs are aggregated to provide certain services simultaneously, they can deliver ancillary and other services that enhance grid reliability. This could also open new value streams for renewable generation assets, including PV and emerging DERs and help expand their deployment and transform energy markets.[24]

FASTFarm Wind Turbine Performance Modeling

FASTFarm, a tool developed by the National Renewable Energy Laboratory (NREL), is a multi-physics engineering tool to predict the performance and loads of wind turbines.[25] The tool solves the aero-hydro-servo-elastic dynamics of each individual turbine and accounts for ambient wind in the atmospheric boundary layer, wake deficits, advection, deflection, meandering, and merging.

2.1.1.4 | Grid Resilience to Natural and Other Hazards

According to the National Oceanic and Atmospheric Administration (NOAA), the most frequent natural hazards from 1996 to 2014 were thunderstorms and lightning, which occurred every year. Over that same time, the largest annualized property loss (in millions of dollars per year) due to natural hazards was attributed to wildfires.[26] An NOAA analysis shows that the frequency of billion-dollar disaster events is increasing, highlighting the importance of improving the resilience of grid infrastructure and related systems.[27]

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[23] Amanpreet Kaur et al., "Net load forecasting for high renewable energy penetration grids," *Energy 114* (2016): 1073–1084, semanticscholar.org/f73e/b182180cb897da21ea8d88900e5d396c16c8.pdf.

[24] Jeffrey J. Cook et al., "Expanding PV Value: Lessons Learned from Utility-Led Distributed Energy Resource Aggregation in the United States," National Renewable Energy Laboratory, November 2018, nrel.gov/docs/fy19osti/71984.pdf?utm_source=NREL+Solar+Market+Research+and+Analysis&utm_campaign=66f44ace56-EMAIL_CAMPAIGN_2018_11_12_06_13&utm_medium=email&utm_term=0_7e950366d3-66f44ace56-289284671.

[25] Jason Jonkman, "FAST.Farm," National Renewable Energy Laboratory, May 15, 2017, nwtc.nrel.gov/FASTFarm.

[26] "State of California – Energy Sector Risk Profile," U.S. Department of Energy, 2015, energy.gov/sites/prod/files/2015/05/f22/CA-Energy%20Sector%20Risk%20Profile.pdf.

[27] "Billion-Dollar Weather and Climate Disasters: Overview," National Oceanic and Atmospheric Administration, accessed November 2018, ncdc.noaa.gov/billions/.

The state's T&D infrastructure is susceptible to weather-related hazards resulting from climate change or other natural weather events, such as wildfires and droughts, acts of terrorism, and sabotage. Although most historical fires have had minor impacts on the grid, a few fires have had significant impacts. Wildfire risks are also growing at different rates around the state—risk is now highest along Southern California's coastal mountains, while risk is growing fastest in the mountains of Northern California.[28]

Key equipment such as transformers can vary in size and configuration and is critical for delivering electricity to customers. Because of transformers' size and weight, they are generally difficult to transport, so replacing one is associated with long delivery lead times. In addition, larger, more sophisticated transformers are manufactured abroad.[29] This is but one example of the challenges associated with improving electricity grid resilience to minimize the impact of climate change and other natural disasters on the state's ability to maintain grid operations and effectively and reliably deliver power to its customers. Adaptation options to reduce the risk of wildfire impacts on the grid focus on both transmission and distribution:

- Transmission adaptation options:
    - Eliminate transmission equipment via microgrids.
    - Move transmission assets to low-fire-risk areas.
    - Diversify transmission infrastructure by adding widely spaced lines in high-risk areas or addressing the high concentration of transmission capacity in some high-fire-risk areas.
- Distribution adaptation options:
    - Reduce distribution exposure by purchasing development rights in high-fire-risk zones or encouraging urbanization, limiting sprawl.
    - Underground distribution wires in fire-prone areas.

2.1.2 | Research Initiatives

The following is a brief overview of some of the ongoing R&D initiatives related to integration of new energy sources into the electricity grid and related enabling policies. This summary is not intended to be comprehensive.

2.1.2.1 | EPIC Investment Initiatives

The EPIC 2018–2020 Triennial Investment Plan describes the short-term R&D priorities to increase grid integration of renewable energy in California.[30] Various sections of this EPIC investment plan address key technologies that can facilitate greater integration of utility-scale renewable energy. The following tables consolidate high-level information about California's current and prior initiatives.

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[28] "Assessing the Impact of Wildfires on the California Electricity Grid," Lawrence Berkeley National Laboratory, accessed January 2019, energy.ca.gov/research/notices/2018-02-07_symposium/presentations/03%20Improving%20Power%20System%20Resilience%20to%20Weather-Related%20Events/1.%20Larry%20Dale%20LBNL.pdf.

[29] "U.S. Electricity Industry Primer," U.S. Department of Energy, July 2015, energy.gov/sites/prod/files/2015/12/f28/united-states-electricity-industry-primer.pdf.

[30] "Electric Program Investment Charge: 2018–2020 Triennial Investment Plan," California Energy Commission, CEC-500-2017-023-CMF, adopted on April 27, 2017, energy.ca.gov/research/epic/17-EPIC-01/.

Table 2-1. Grid Integration – Summary of 2018–2020 EPIC Triennial Investment Plan Initiatives

Initiative	Description/Goal	Potential Impact
2018–2020 EPIC Triennial Investment Plan		
Initiative 3.1.2: Assess Performance of Load Control Systems	Build sufficient data on performance to reduce uncertainty and provide confidence in demand response reliability such that telemetry on each load is unnecessary.	Actuate widespread adoption of demand response technologies.
Initiative 3.3.1: Optimize and Coordinate Smart Inverters Using Advanced Communication and Control Capabilities	Develop distributed energy resource management system (DERMS) algorithms to optimize the settings and coordination of advanced smart inverters to maximize the output of solar generation on the grid and improve the ability of solar PV to respond to signals from a utility or other grid operator.	Improve power quality and reduce the chance of electricity outages. Increase the amount of solar PV that can be installed on the distribution grid without upgrades to grid equipment.
Initiative 3.3.3: Provide Visibility into Load and DER Responses to Weather and Other Variables and into the Effects of DER on Gross Load	Establish a database of DER production and gross load data and enhance tools for grid operators to visualize the effects of weather patterns and other events on rooftop solar production, electric vehicle charging, and other DER usage. Improve forecasting tools leveraging the database to better predict the net load that will need to be met through geothermal, natural gas, and other utility-scale generation.	Improve ability of the CAISO and other grid operators to forecast the net load and determine reserves that will need to be scheduled to meet the predicted demand, particularly in cases of heat waves and other atypical events.
Initiative 7.2.1: Improved Understanding of Climate- and Weather-Related Risks and Resilience Options	Improve projections and probabilistic forecasts of hydrological and meteorological parameters needed for operations and seasonal and decadal planning. Develop strategies supported by analysis of projected and historical data for parameters of importance to the energy system: snowpack conditions, stream flows, ambient temperature, precipitation levels, relative humidity, and solar radiation.	Illuminate climate-related risk, potential impacts, and resilience options for the electricity sector and disadvantaged communities that IOUs serve. Integrate projected and/or probabilistically forecasted climate relevant parameters into all aspects of electricity sector planning, operations, and infrastructure investment to prepare for climate change with sufficient lead time and identify ways to implement sound, cost-effective, practical resilience strategies.
Initiative 7.2.3: Integrate Climate Readiness into Electricity System Operations, Tools, and Models	Expand access to vulnerability and resilience tools with region-specific detail that leverage probabilistic forecasts at seasonal and decadal scales to inform utilities' management, planning, and operations, including cost–benefit analyses of resilience investments. Facilitate use of these tools to improve understanding of the electricity system's interconnectedness with other areas (e.g., emergency response, public health, and interconnected infrastructure between sectors) and integrate this information into models.	Enable integration of the best available scientific research on climate change into routine electricity sector planning, operations, and management to bolster electricity sector efforts to improve climate readiness. This initiative will also strengthen IOUs' ability to assess the costs, benefits, and viability of resilience measures and prioritize investments associated with different climate-related hazards.

Table 2-2. Grid Integration – Summary of Pre-2018 and Possible EPIC Initiatives

Previous and Possible EPIC Investments	
Transmission and Distribution	**Demand Response**
1. Smart Inverters a. Assessing the Ability of Smart Inverters and Smart Consumer Devices to Enable More Residential Solar Energy b. Smart Inverter Interoperability Standards and Open Testing Framework to Support High-Penetration Distributed Photovoltaics and Storage c. Demonstration of Integrated Photovoltaic Systems and Smart Inverter Functionality Utilizing Advanced Distribution Sensors d. Solar +: Taking the Next Steps to Enable Solar as a Distribution Asset (GFO-16-309) 2. Communication and Controls a. UniGen Smart System for Renewable Integration 3. Distribution Planning Tools 4. Renewables Forecasting (PON-13-303) a. High-Fidelity Solar Power Forecasting Systems for the 392 MW Ivanpah Solar Plant (CSP) and the 250 MW California Valley Solar Ranch (PV) b. Improving Solar & Load Forecasts: Reducing the Operational Uncertainty Behind the Duck Chart c. Improving Short-Term Wind Power Forecasting through Measurements and Modeling of the Tehachapi Wind Resource Area d. Development, Implementation, and Integration of a Holistic Solar Forecasting System for California	1. Residential Demand Response 2. Commercial Demand Response 3. Vehicle-to-Grid (V2G) with Aggregated Resources a. Next-Generation Grid Communication for Residential Plug-in Electric Vehicles (PEVs) b. Distribution System Aware V2G Services for Improved Grid Stability and Reliability c. Open Source Platform for PEV Smart Charging in California 4. Transactive Energy

Select EPIC Projects

The Energy Commission has recently funded several innovative grid integration projects that are featured on the Energy Commission Innovation Showcase website.[31] The following table summarizes projects that describe emerging technologies that are relevant to the integration of utility-scale renewables.

Table 2-3: Grid Integration – Select EPIC Projects

Project Name	Technology Type	Description
Improving Hydrological Snowpack Forecasting for Hydropower Generation Using Intelligent Information Systems (Active until 12/2018)	Modeling and Forecasting	This project develops improved snowpack forecasts within a representative Sierra Nevada watershed to bolster the hydrographic data network that supports hydropower planning and operations. The project is expected to reduce uncertainty in water forecasts in a changing climate, and assist in the development of reliable and flexible operations of hydropower dams that will also bring economic benefits to utilities and ratepayers.

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[31] California Energy Commission Innovation Showcase, innovation.energy.ca.gov/.

Project Name	Technology Type	Description
Improving Short-Term Wind Power Forecasting through Measurements and Modeling of the Tehachapi Wind Resource Area (Active until 12/2017)	Modeling and Forecasting	This project comprises coordinated atmospheric field measurements and computational modeling improvements to improve the accuracy of prediction of short-term wind ramps (i.e., large, rapid changes in wind power production). The Tehachapi Pass Wind Resource Area is the focus of the project. Since the area features complex terrain and meteorology, the findings can be readily adapted and applied to many other regions.
Advanced VGI Control to Maximize Battery Life and Use of Second-Life Batteries to Increase Grid Service and Renewable Power Penetration (Active until 12/2020)	Control Systems	This project is developing and implementing an optimization and control algorithm that includes impacts on battery health expressed as an economic cost, using models and parameters derived from actual battery measurements.
Development of New Technologies for Agricultural Loads to Participate in Renewables Integration, RTP Programs, and/or New Time-of-Use Rates (Active until 12/2020)	Control Systems	This project addresses the direct electricity cost of irrigation for agricultural customers and the indirect cost to all electricity ratepayers of procuring sufficient resources to meet marginal peak demand, integrating variable renewable energy generation, and building sufficient infrastructure to support agricultural pumping load peaks.
UniGen Smart System for Renewable Integration (Active until 3/2019)	Systems Integration	This project is developing the UniGen Smart Software System to smooth energy output from a combination of variable energy resources (VERs). VER generation often deviates from forecasts and schedules because of variations in weather. This uncertainty can be alleviated by a fast-acting control system that automatically compensates for deviations from projected generation using a dedicated mix of energy resources (e.g., a PV system and an energy storage system). Onset's UniGen control system couples these resources with a primary power plant using proprietary algorithms in a software application in real time so that the combined output corresponds to the committed output. Any deviation is solved at the project or distributed level, making it easier for the ISO to manage grid performance.

2.1.2.2 | Research Initiatives from Other Funding Entities

Current research initiatives from DOE also seek to advance the current state of grid integration technologies.

Table 2-4. Grid Integration – Summary of DOE Research Initiatives

Initiative	Description/Goal	Potential Impact
U.S. Department of Energy		
Systems Integration Subprogram (Solar Energy Technologies Office)	Funds early-stage grid integration R&D with focus on power variability, voltage regulation, frequency control, unintentional islanding, protection coordination, and two-way power flow.	Enables safe, reliable, and cost-effective integration of hundreds of gigawatts of solar power into the electricity grid.
Mitigate Market Barriers Subprogram (Wind Energy Technologies Office)	Funds R&D in wind energy grid integration, such as how to effectively operate the power grid under high penetrations of wind energy.	Enables reliable incorporation of wind energy into the power system, particularly for the four states that have 25% greater wind electrical generating capacity compared to their total installed capacity.

Initiative	Description/Goal	Potential Impact
Federal Energy Management Program	Assists federal agencies in energy savings and reliability projects by providing a two-way grid interface.	Enhances grid reliability while facilitating resilience and reducing the load on the grid.

"Department of Energy FY 2019 Congressional Budget Request." DOE. March 2018. energy.gov/sites/prod/files/2018/03/f49/FY-2019-Volume-3-Part-2.pdf.

DOE Grid Modernization Multi-Year Program Plan

In November 2015, DOE released the Grid Modernization Multi-Year Program Plan (MYPP), which outlines the Department's vision for a modern grid and identifies key challenges and opportunities.[32] The Grid Modernization MYPP identifies the six technical areas that need to be the focus of future projects to achieve grid modernization. The following table states the technical areas listed in the report and the research, development, and demonstration (RD&D) activities corresponding to each technical area.

Table 2-5. Grid Integration – Grid Integration Roadmap Areas of Need (DOE)

Technical Area	Relevant Activities
TA 1: Devices and Integrated Systems Testing	• Develop advanced storage system, power electronics, and other grid devices • Develop precise models of emerging components and controllers • Develop standards and test procedures • Build capabilities and conduct device testing and validation • Conduct multi-scale systems integration and testing
TA 2: Sensing and Measurements	• Develop a roadmap for achieving full electric system observability • Improve sensing for devices, buildings, and end-users • Enhance sensing for distribution systems • Enhance sensing for the transmission system • Develop data analytic and visualization techniques • Demonstrate unified grid-communications network
TA 3: Systems Operations, Power Flow, and Control	• Develop grid architecture and control theory • Develop coordinated system controls • Improve analytics and computation for grid operations and control • Develop enhanced power flow control device hardware
TA 4: Design and Planning Tools	• Scale tools for comprehensive economic assessment • Develop and adapt tools for improving reliance and reliability • Build computation technologies and high-performance computing capabilities to speed up analyses
TA 5: Security and Resilience	• Improve ability to identify threats and hazards • Increase ability to protect against threats and hazards • Increase ability to detect potential threats and hazards • Improve ability to respond to incidents • Improve recovery capacity time
TA 6: Institutional Support	• Provide technical assistance to states and tribal governments • Support regional planning and reliability organizations • Develop methods and resources for assessing emerging technologies, valuation, and new markets • Conduct research in future electric utility regulations

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[32] Grid Modernization Initiative – Multi-Year Program Plan. energy.gov/sites/prod/files/2016/01/f28/Grid%20Modernization%20Multi-Year%20Program%20Plan.pdf

2.1.3 | R&D Opportunity Areas and Technologies

To identify and prioritize R&D opportunity areas and technologies for grid integration, analysts relied on state and federal government reports, industry reports, and peer-reviewed research articles. Results were also informed by phone interviews with several experts from government and other research institutions across the United States.

Together, these sources provided detailed insights into the state of existing technologies, key challenges, R&D opportunity areas, and emerging and potential breakthrough grid integration technologies.

Figure 2-4. Grid Integration Experts Interviewed

- Gerry Braun, Founder,
  Integrated Resource Network (IRESN)
- Dave Bryant, Director of Technology,
  Composite Technology Corporation
- Jake P. Gentle, Power Systems Engineer,
  Idaho National Laboratory
- Roger Salas, Engineering Manager,
  Southern California Edison
- Kristin Sampayan, Chief Executive Officer,
  Opcondys
- Dave Townley, Director of Public Affairs,
  Composite Technology Corporation

2.1.3.1 | Key Considerations

Expert interviews and literature review identified several factors worth consideration when dealing with assessment, investment, or construction of grid infrastructure in California. These areas are broadly categorized into technical, financial, and regulatory considerations, as discussed below.

Technical Considerations

- **Energy storage systems are needed to address issues with intermittent generation from variable renewables.** The costs of storage systems and availability of their materials will dictate future growth of these systems. Advancements in control systems, smart inverters, and other power electronics will be crucially important for the integration of energy storage systems.
- **Forecasting of wind and solar resources has improved management of renewable resources.** Accurate forecasting helps grid operators mitigate the intermittency of wind and solar generation, which in turn lowers curtailment. Weather models now include algorithms that provide short-term predictions of renewable power generation. These prediction tools can generate the forecast output in less than a second. However, these models and tools and their outputs can be better integrated into utility and system operator resource planning activities.
- **Improved grid data availability and control, such as through the use of smart inverters and advanced meters, can increase grid reliability.** Smart inverters, meters, and DERMS can help determine the timing and location of loads so utilities can manage the grid effectively and deliver electricity in a reliable and accurate manner.
- **Power lines must handle new power flows that are shifting because of changes in generation and demand.** As new renewables are added to the system and load centers shift, the direction of power flow and the capacity required through certain power lines changes. These changes can be exacerbated by the proliferation of community choice aggregators (CCAs) that can quickly change the make-up of grid systems. California can upgrade existing T&D infrastructure and/or find ways to effectively manage existing interconnections. Advanced conductors are one way to allow more power to flow through existing power lines.

Financial Considerations

- **Upgrades to grid infrastructure and system management can reduce liabilities from wildfires and other risks exacerbated by a changing climate.** The increased loading of power onto transmission lines causes unforeseen increased wire sag, and sagging lines contacting trees can cause wildfires. Adding more transmission infrastructure and reducing congestion on existing power lines limits this wildfire risk. Reducing the cost of undergrounding wires and improving the ease of maintenance could also help reduce wildfire risk in fire-prone communities. Wildfire prevention is just one form of system preparedness and resilience that carries the benefit of reducing utilities' risk of financial penalties. Modeling and planning for other disasters allows utilities to be more proactive in their preparation and further eliminate risk.
- **The value proposition of grid infrastructure improvement costs must be presented clearly to ratepayers and regulators**. Capital improvements in grid infrastructure will ultimately have a cost that is carried over to ratepayers. The most substantial cost increases may be attributable to T&D infrastructure improvements and the addition of smart devices and system controls. Investment and innovation in devices and non-wire alternatives could help reduce future needs for additional grid infrastructure.

Regulatory Considerations

- **Additional grid-integrated renewable energy assets and communications devices require data collection and connectivity that introduce cybersecurity risks.** Standards for integrating new generation assets and devices and sending information are necessary at the state and national levels, and two-way communication is key to maximizing the operational efficiency of existing infrastructure and appropriately dispatching renewable generation. California can work with utilities, technology vendors, and regulatory agencies to ensure that grid-connected devices are secure and that cybersecurity measures align with federal requirements.
- **Permitting new power lines and grid corridors may be more difficult than upgrading existing systems.** Environmental and social considerations, as well as land management and associated permitting, prevent power lines from being built in new locations quickly. With expansion to the grid happening rapidly, changes to permitting processes are needed. Upgrades to existing power lines can help to support new load and generation, but ultimately new power lines may need to be built. This may help connect to new renewable resource areas and/or regions without sufficient infrastructure to handle growth in renewable energy generation. In addition, it highlights the need to balance cost-effective T&D upgrades with system expansion to ensure system reliability, reduce network congestion, and improve resilience to enable additional renewable energy penetration in the state. Incorporating the prospect of future utility-scale renewable generation assets into transmission policy planning could help ensure there are effective pathways to deploying new renewable energy projects.

2.1.3.2 | R&D Opportunity Areas

The R&D opportunity areas in Table 2-6 expand beyond those identified in the Energy Commission's 2018–2020 Triennial Investment Plan and are based on an extensive literature review and conversations with experts.

Table 2-6. Grid Integration – Technology R&D Opportunity Areas

ID	Opportunity Areas	Description
O.I.1	**Climate-Based Risk and Resilience Tools**[4,5]	Projections and probabilistic forecasts of hydrological and meteorological parameters to improve planning and operations and help understand risks and resilience options for grid infrastructure and electricity system operations.
O.I.2	***Load Control Systems**[1]	Performance assessments of technical system needs such as specific ancillary services, balancing renewable variability, and meeting local needs to facilitate a portfolio approach to managing different loads when available and when the opportunity cost of responding falls below the value to the system.
O.I.3	**Load Models**[3]	Models that reduce power system operational uncertainty.
O.I.4	**Sensors**	Data acquisition systems designed for solar monitoring applications, including solar power efficiency checks and selection of solar power sites.
O.I.5	****Smart Inverters**[2]	Devices that enable more elaborate monitoring and communication of grid status, ability to receive operation instructions from a centralized location, and capability to make autonomous decisions to improve grid stability, support power quality, and provide ancillary services (e.g., spinning reserves, load following, voltage support, ramping, frequency response, variability smoothing, and frequency regulation.
O.I.6	**Telemetry**	Improvements to the cost and efficiency of high-density ground telemetry.
O.I.7	**Transmission Architecture**	Hardware and materials that allow for greater transmission capacity while reducing energy losses.
O.I.8	**Weather Models**[3,4,5]	Models to predict power production from weather-dependent energy sources.

Several research areas overlap with EPIC investment interests. Those overlaps are given the following identifiers:
* Mentioned in EPIC Investment Plan: Previous and Planned EPIC Investments on Demand Response
** Mentioned in EPIC Investment Plan: Previous and Planned EPIC Investments on Transmission and Distribution
1 Relevant to Initiative 3.1.2 Assess performance of load control systems
2 Relevant to Initiative 3.3.1 Optimize and coordinate smart inverters using advanced communication and control capabilities
3 Relevant to Initiative 3.3.3 Provide visibility into load and DER responses to weather and other variables and into the effects of DER on gross load
4 Relevant to Initiative 7.2.1 Improved understanding of climate- and weather-related risks and resilience options
5 Relevant to Initiative 7.2.3 Integrate climate readiness into electricity system operations, tools, and models

2.1.3.3 | Emerging and Breakthrough Technologies

The emerging and breakthrough technologies in Table 2-7 represent more targeted investment opportunities for the Energy Commission and fall within the aforementioned R&D opportunity areas.

Table 2-7. Grid Integration – Emerging and Breakthrough Technology Matrix

ID	Name	Parallel Research Topic	R&D Opportunity Areas	Potential Impact
Transmission and Distribution				
I.1	**Aluminum Conductor Composite Core (ACCC)**	Legacy System Improvement	Transmission Architecture	This high-temperature, low-sag conductor replaces the standard aluminum conductor steel reinforced (ACSR) design. Carbon fiber core reduces sag by providing tensile support, which allows cables to carry more current. ACCC cables are 60% lighter than ACSR cables.
I.2	**Offshore HVDC Grid**	Innovative System Development	Transmission Architecture	Transmission losses are lower than those of HVAC, which is the commonly used transmission system for offshore wind farms. The electricity can be transported in both directions.
I.3	**Silicon Carbine (SiC) Power Semiconductors**	Legacy System Improvement	Transmission Architecture	These devices replace conventional silicon semiconductors and reduce the amount of energy lost when electricity is converted before it is delivered to the customer. Integration with renewable energy includes (1) offshore wind AC-to-DC conversion and (2) solar power inverters for DC-to-AC conversion.
I.4	**Smart Wires and SmartValve**	Legacy System Improvement	Transmission Architecture	SmartValve adjusts the reactance of a transmission line to transfer power from an overloaded circuit to parallel lines with spare capacity. Allows for more large-scale renewable energy integration into the grid without the need to build new power lines or upgrade existing lines.
I.5	**Transmission Towers with Insulating Cross-Arms**	Legacy System Improvement	Transmission Architecture	This advanced design replaces the steel cross-arms and vertical insulators on existing pylons, allowing for greater transmission capacity of up to 150%. New towers built with cross-arms are 25% shorter and use fewer resources.
Devices, Measurement, and System Controls				
I.6	**Dynamic Line Rating**	Information Technology	Sensing and Controls	This tool improves power system transmission capacity by monitoring system conditions, particularly for power plants that use intermittent renewables such as solar, wind, tidal and wave power.
I.7	**Lidar-Assisted Controls**	Information Technology	Sensors, Sensing and Controls	Turbine-mounted lidars, or light detection and ranging systems, improve wind turbine control systems by providing accurate updates on turbine inflow before it reaches the blades.

ID	Name	Parallel Research Topic	R&D Opportunity Areas	Potential Impact
Modeling and Forecasting				
I.8	**EnergyForecaster: Mathematical Model**	Information Technology	Weather Models	This model produces improved PV and wind farm power forecasts every 15 minutes, showing how much electricity will be generated over the next few hours and days.
I.9	**High-Fidelity Solar Power Forecasting System**	Information Technology	Weather Models, Telemetry, Sensors	This tool monitors and forecasts direct normal irradiance (DNI) and plane of array (POA) and the corresponding power generation, as well as improves power generation forecasts via resource-to-power modeling.
I.10	**Improved Net-Load Forecasting**	Information Technology	Load Models	Behind-the-Meter (BTM) solar PV generation is incorporated into grid forecasting, reducing errors. These forecasts are applied to reduce scheduling uncertainty for utilities and the CAISO. Suggested methods include direct modeling and reconstituted load.
I.11	**NREL FASTFarm**	Information Technology	Weather Models	This multi-physics engineering tool predicts the performance and loads of wind turbines. It uses software called FAST to solve the aero-hydro-servo-elastic dynamics of each individual turbine. The tool also accounts for ambient wind in the atmospheric boundary layer, wake deficits, advection, deflection, meandering, and merging.
I.12	**GOES-17 Imagery and Data**	Information Technology	Weather Models	The latest Geostationary Operational Environmental Satellite-17 (GOES-17) system can provide infrared images with enhanced refresh rates and spatial resolution compared to previous satellite systems.
I.13	**WRF-CMAQ Two-Way Coupled Model**	Information Technology	Weather Models	The two-way coupled meteorology and air quality model is composed of the Weather Research Forecasting (WRF) model and the Community Multiscale Air Quality (CMAQ) model. This system enables two-way communication between the WRF and CMAQ components to incorporate aerosol information from CMAQ into the meteorological model WRF.
I.14	**Univariate Time Series Prediction of Solar Power**	Information Technology	Weather Models	This algorithm provides super-short-term predictions of solar power generation by relying solely on past values of solar power data. The algorithm is able to generate the forecast output in less than a second.

Chapter 3| Variable Renewable Energy

Prices for wind and solar power have surpassed cost parity for most forms of conventional power generation. Variable renewable power generation, namely solar power, has seen a rapid uptake in deployment in California in recent years.

Challenges

- The current characteristics of wind- and solar-generated electricity in California, including variability, uncertainty, and non-synchronous generation, present challenges to large-scale, cost-effective grid integration.
- Development of land-based wind power faces several non-technical barriers such as wildlife, siting, and permitting issues and competition with solar.

Opportunities

- Wind and solar offer the highest resource potential in California compared to other renewables.
- State policies encourage development of wind and solar power, which are also among the cheapest to deploy.

Solar Power

Photovoltaics: California leads the nation in deployed PV systems, and will continue to do so due to low costs and favorable state policies.

Concentrated Solar Power: California has multiple CSP stations located in the southern portion of the state. CSP could become an important technology to time shift the availability of solar power to meet demand.

Wind Power

Land-Based: California has some of the oldest turbines still in operation in the United States. New turbines could replace or be sited on top of existing tower structures and bases.

Offshore: California has the opportunity to become a leader in offshore wind by investing in manufacturing facilities and demonstration areas.

3.1 | Solar Power

In 2002, California established a renewable standard portfolio (RPS) requiring that a significant share of retail electricity be produced with renewable resources.[33] Combined with improved solar technology, the RPS has driven rapid growth in solar capacity and enabled solar to become an important source of energy for the state. Recent modifications to the RPS have increased the required share of energy from renewable resources, ensuring a continued expansion of solar generation in the coming decades.

Solar energy is now the largest source of renewable energy in the state and provides a significant portion of total electricity generation. In 2017, the solar energy generated within California totaled 24,324 GWh from generating units with more than one megawatt of capacity, with 21,860 GWh coming from solar PV installations and 2,463 GWh from solar thermal facilities.[34] These solar units accounted for roughly 12% of the in-state total power generation and 40% of in-state renewable power generation. This increase in solar capacity and generation was strongly associated with the increased PV deployment shown in Figure 3-1.

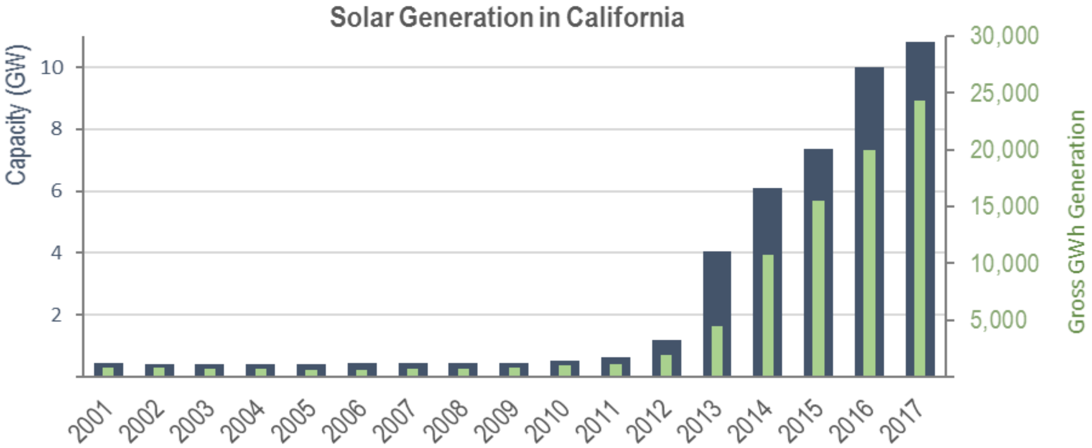

Figure 3-1. Solar Energy Generation and Capacity in California (facilities >1 MW capacity)

Data from energy.ca.gov/almanac/renewables_data/solar/

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[33] "Renewables Portfolio Standard Eligibility Guidebook, Eighth Edition," California Energy Commission, 2015, https://www.energy.ca.gov/2015publications/CEC-300-2015-001/CEC-300-2015-001-ED8-CMF.pdf.

[34] "2017 Total System Electric Generation." California Energy Commission. Data as of June 21, 2018. energy.ca.gov/almanac/electricity_data/total_system_power.html

Looking forward, current projections indicate that 14,037 MW of added solar capacity will be available in the next five years across California, in response to market and policy factors. [35]

Further deployments and investment in R&D will continue to decrease prices and improve the performance of solar power technologies. Figure 3-2 shows the rapid price decline in LCOE for crystalline silicon (c-Si) solar cells.[36] The DOE FY 2019 budget request establishes cost performance targets, summarized in Table 3-1. The most recent of these targets have already been exceeded for some installations in California. DOE's goal is to make solar power one of the least expensive forms of electricity. Key areas of research include grid reliability, PV efficiency, energy yield and storage, material durability, power electronics, microgrid integration, and next-generation CSP.

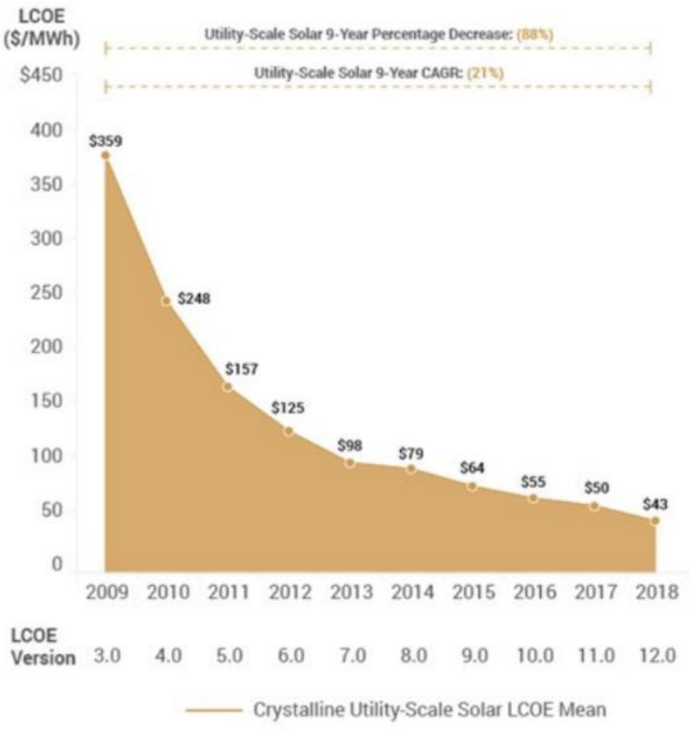

Figure 3-2. Unsubsidized Solar PV LCOE (Lazard)

Figure from Lazard's Levelized Cost of Energy Analysis 2018 (LCOE 12.0)

Table 3-1. Solar Power Cost Performance Targets (DOE)

	FY 2017	FY 2018	FY 2019	Endpoint Target
Concentrating Solar Power	10 cents/kWh	n/a	8 cents/kWh	5 cents/kWh
Photovoltaic (PV)	7 cents/kWh (exceeded, 6)	6 cents/kWh	5.5 cents/kWh	3 cents/kWh
Solar + Storage	$1.96/Wdc	n/a	$1.65/Wdc	$1.45/Wdc

Concentrating Solar Power: The CSP energy cost target is an unsubsidized cost of energy at utility scale including 14 hours of thermal storage in the U.S. Southwest.

Photovoltaics: The PV solar energy cost target is an unsubsidized cost of energy at utility scale.

Solar + Storage: The solar + energy storage cost target is an unsubsidized cost of energy at utility-scale array with 4 hours of battery storage, actual installed costs in Watts direct current (Wdc). Model assumptions based on NREL analysis: 2017 NREL PV Benchmark Report, the Annual Technology Baseline, and PV-plus-storage analysis.

Source: "Department of Energy FY 2019 Congressional Budget Request." Volume 3–Part 2: 22. DOE. March 2018. energy.gov/sites/prod/files/2018/03/f49/FY-2019-Volume-3-Part-2.pdf.

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[35] "Solar Spotlight – California," Solar Energy Industries Association (SEIA), September 2018, accessed November 7, 2018, seia.org/sites/default/files/2018-09/Factsheet_State_California_2018Q2.pdf.

[36] "Levelized Cost of Energy and Levelized Cost of Storage 2018," Lazard, November 8, 2018, lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2018/.

3.1.1 | Resource Availability

California encompasses some of the largest areas of high irradiance in the country. While irradiance is particularly intense in the deserts of southern California, most of California is suitable for solar energy generation, as can be seen in Figure 3-3.

Table 3-2 shows NREL estimates of technical availability of tracked PV and CSP resources in California. Figure 3-4 provides links to additional publicly available resources that provide data on current and future solar thermal and PV facilities across California and the United States.

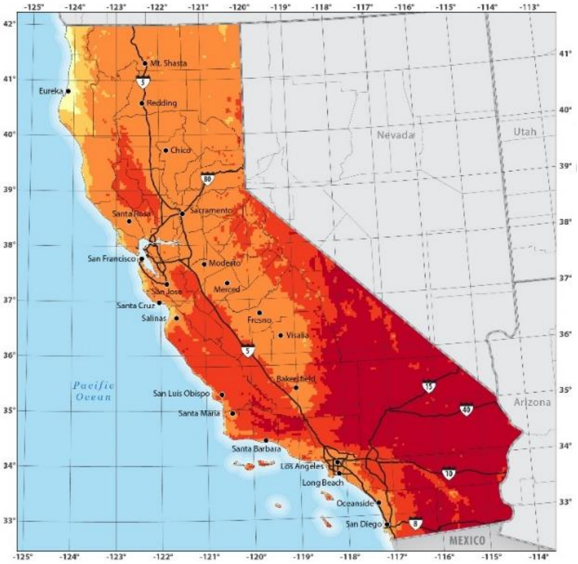

Figure 3-4. Solar Project Databases

NREL's Open PV Project features open source data and reporting of PV projects in the United States. Available at openpv.nrel.gov/

Argonne National Laboratory (ANL) maintains a solar database that lists all U.S. solar thermal and PV installations over 10 MW. Available at solarprojects.anl.gov/

ANL's "Solar Energy Environmental Mapper" is a geospatial tool that can be used to map solar energy environmental data. Available at solarmapper.anl.gov/

Figure 3-3. Direct Normal Irradiance Map of California (NREL)

NREL provides maps measuring annual average daily Direct Normal Irradiance (shown in the figure) and Global Horizontal Irradiance throughout the United States. These maps contain average data from 1998-2016 and were published in 2017.

Available at: nrel.gov/gis/solar.html

Table 3-2. NREL Estimates of Technical Availability of California Solar Resource Potential[37]

System Type	Area (KM^2)	Capacity (GW)	Production (GWh)
Urban Utility-Scale PV	2,321	111	246,008
Rural Utility-Scale PV	83,549	4,010	8,855,917
CSP	82,860	2,726	8,490,916

3.1.1.1 | Solar Variability

The supply of electricity must always meet the demand. This requirement, coupled with the fact that solar radiation varies significantly across several timescales, has created operational challenges as solar capacity increases. Continued efforts to tap into California's plentiful solar resources must overcome challenges such as those presented by the variable nature of solar radiation and insufficiencies with existing transmission infrastructure.

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[37] Lopez, Roberts, Heimiller, Blair, and Porro, "U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis," National Renewable Energy Laboratory, July 2012, nrel.gov/docs/fy12osti/51946.pdf.

Seasonal and Diurnal Cycles

Seasonal and daily cycles of the solar resource are entirely predictable but create challenges for grid operators. The periods of maximum solar energy generation do not necessarily overlap with demand. Solar power generation reduces the power requirements from other generating sources during the middle of the day. However, decreasing solar energy generation in the late afternoon coincides with increased electricity demand and forces other energy sources to ramp up quickly. This creates a pattern in the net system load widely known as the "duck curve,"[38] as shown in Figure 3-5.

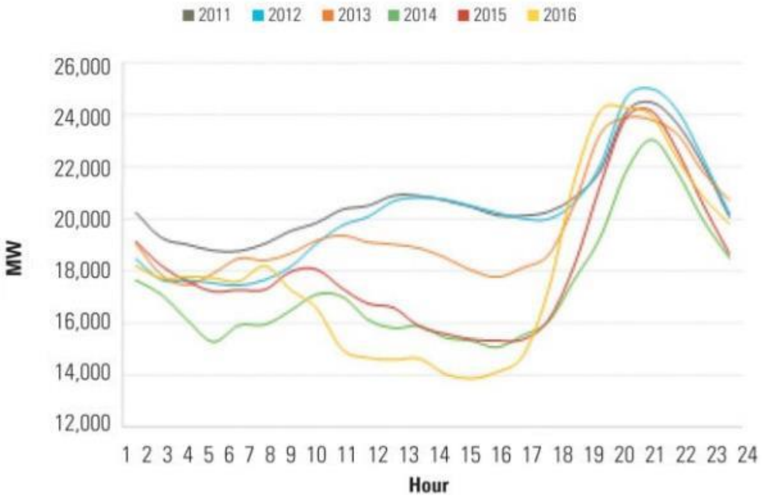

Figure 3-5. Yearly Changes in the Duck Curve

The system loads shown above represent the day of the lowest system load in March in California of that year. The duck curve proceeds to get deeper over time, representing increasing amounts of solar power generation during the day.

Learn more at: scottmadden.com/wp-content/uploads/2016/10/Revisiting-the-Duck-Curve_Article.pdf

In addition to the difficulty associated with ramping up generators to meet demand, the grid operators must rely heavily on fossil fuel generators. This effect can get particularly severe in the spring and lead to over-generation (i.e., electricity supply that exceeds demand), ultimately resulting in the curtailment of solar generators during the day. Indeed, over 300 GWh of renewable energy was curtailed in California during 2016, almost all of it through decremental bids.[39,40] CAISO has been attempting to mitigate curtailments, including working with other utilities to transfer excess energy to where it is needed.

Most of this energy transfer between CAISO and other western utilities is happening during peak solar production. Without the ability to time-shift solar, more gigawatt-hours of renewable energy will be curtailed as renewable penetration increases.[41] Strategies to time-shift (i.e., storing electricity during periods of high supply and consuming it during periods of high demand) using improved storage technologies could reduce the need for curtailment in the future.[42] CSP with thermal energy storage can address the variability of solar resource availability and help to mitigate the duck curve. CSP systems can time-shift energy collected during the day, dispatching it in the evening as PV output decreases.

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[38] Vlahoplus, Litra, and Quinlan, "Revisiting the California Duck Curve," Scott Madden, 2016, scottmadden.com/wp-content/uploads/2016/10/Revisiting-the-Duck-Curve_Article.pdf.

[39] "Impacts of renewable energy on grid operations," CAISO, 2017, caiso.com/documents/curtailmentfastfacts.pdf.

[40] J. John, "California's Flood of Green Energy Could Drive a Record 8GW of Curtailment This Spring," *Greentech Media*, March 21, 2017, greentechmedia.com/articles/read/californias-flood-of-green-energy-could-drive-a-record-6-to-8-gigawatts-of#gs.TZoUXo5T.

[41] Jeff St. John, "California's Flood of Green Energy Could Drive a Record 8GW of Curtailment this Spring," *Greentech Media*, 2017, greentechmedia.com/articles/read/californias-flood-of-green-energy-could-drive-a-record-6-to-8-gigawatts-of#gs.nQHlK04U.

[42] Denholm, O'Connell, Brinkman, and Jorgenson, "Overgeneration from Solar Energy in California: A Field Guide to the Duck Chart," National Renewable Energy Laboratory, 2015, nrel.gov/docs/fy16osti/65023.pdf.

Weather

In addition to seasonal and daily cycles, weather has a large influence on solar generation. Passing clouds can decrease irradiance by more than 60% in a matter of seconds.[43] The effects on solar power generation depend on the size, depth, and speed of the passing cloud, as well as the size and type of solar plant.[43] Further, high temperatures can reduce the efficiency of PV technologies by 10%–15%.[44] Weather forecasting and solar power predictions are produced through advanced mathematical simulation and statistical approaches using weather data, satellite imagery, ground telemetry, sky images, and historical power generation data. Continued advancements in short-term weather forecasting are needed to improve grid operations, including real-time dispatch, load forecasting, ramp event prediction, day-ahead scheduling, and hour-ahead scheduling.

3.1.1.2 | Transmission

Although many locations across California have favorable conditions for solar generation plants, there are many environmental, social, and regulatory factors that place limitations on potential sites. These restrictions typically force utility-scale solar plants to be in relatively remote areas of the state, but the viability of these locations depends the existence (or construction) of long-distance transmission infrastructure connecting the generators with load centers. Transmission lines can be prohibitively expensive ($200,000 to >$2,000,000 per mile), and approval for these projects can take more than a decade.[45] As such, the location of existing transmission infrastructure and the costs of new transmission currently limit California's ability to efficiently leverage the solar resources available in the state. Planning and developing appropriate transmission infrastructure for solar and other renewable energy resources will require coordination between utilities, grid operators, and regulators.

3.1.2 | Technology Overview

Utility-scale solar technology deployments across California have changed rapidly over the last decade. The oldest sources of solar power in California are CSP plants, or solar thermal plants, which were first installed over 30 years ago. In 2007, CSP plants accounted for approximately 99% of solar capacity in California (0.4 GW). Utility-scale photovoltaic (PV) generation has grown more quickly in recent years and surpassed CSP plants in generating capacity in 2012.[46] By 2017, solar generating capacity had increased by 36 times to 10.8 GW, and PV accounted for 90% of state solar capacity. The technology continues to change, and there are new types of CSP and PV plants, already operational, that have greater efficiency and new capabilities such as energy storage.

3.1.2.1 | Solar Photovoltaic (PV) Trends and Performance Attributes

The high insolation across California has allowed the state to benefit greatly from decreasing PV costs. Figure 3-6 shows the trends in installed solar capacity and power purchase agreement (PPA) costs.[46,47] It is

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[43] Mills et al., "Understanding Variability and Uncertainty of Photovoltaics for Integration with the Electric Power System," Lawrence Berkeley National Laboratory, December 2009, emp.lbl.gov/sites/all/files/lbnl-2855e.pdf.

[44] Woodhouse et al., "The Role of Advancements in Solar Photovoltaic Efficiency, Reliability, and Costs," National Renewable Energy Laboratory, May 2016, www.nrel.gov/docs/fy16osti/65872.pdf.

[45] "Electricity Transmission: A Primer," National Council on Electric Policy, 2004, energy.gov/sites/prod/files/oeprod/DocumentsandMedia/primer.pdf.

[46] "California Solar Energy Statistics & Data," California Energy Commission, 2018, energy.ca.gov/almanac/renewables_data/solar/index.php.

[47] "Utility-Scale Solar," Lawrence Berkeley National Laboratory, 2018, emp.lbl.gov/capex-lcoe-and-ppa-prices-pv-projects.

interesting to note a surge in development from 2015 to 2016. These investments could be attributed to the pending expiration of the federal investment tax credit (ITC), a 30% federal tax credit for investments in renewable generation, in 2016.[48] Continued increases in development can also be attributed to significant cost reductions for PV systems. These cost reductions span all PV system components, including soft, hardware, and module costs, as shown in Figure 3-7.[49]

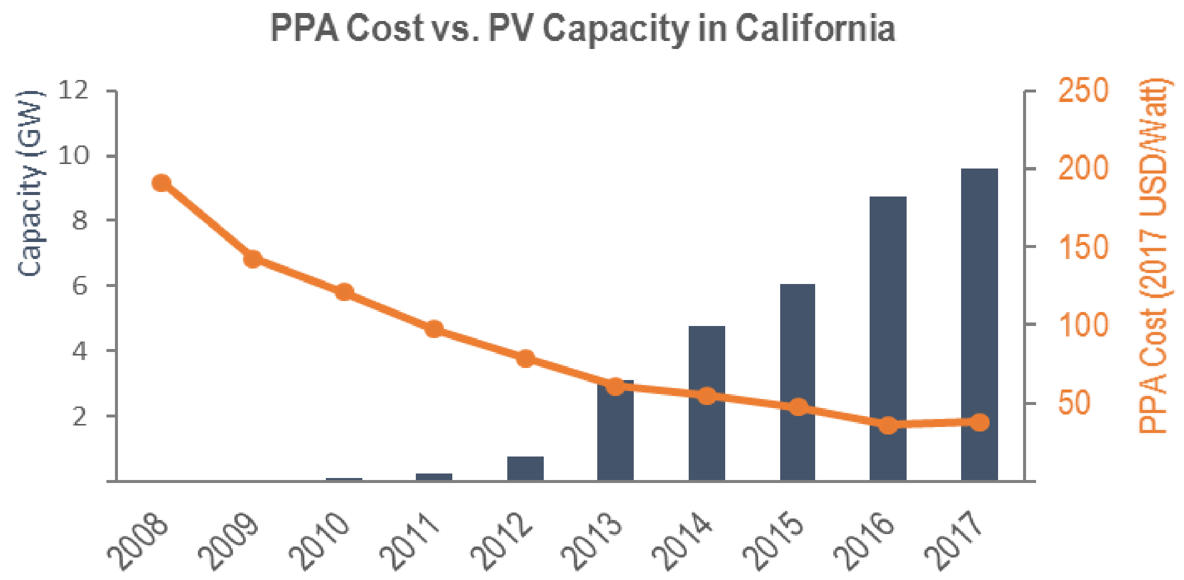

Figure 3-6. PPA Cost vs. PV Capacity Installed in California

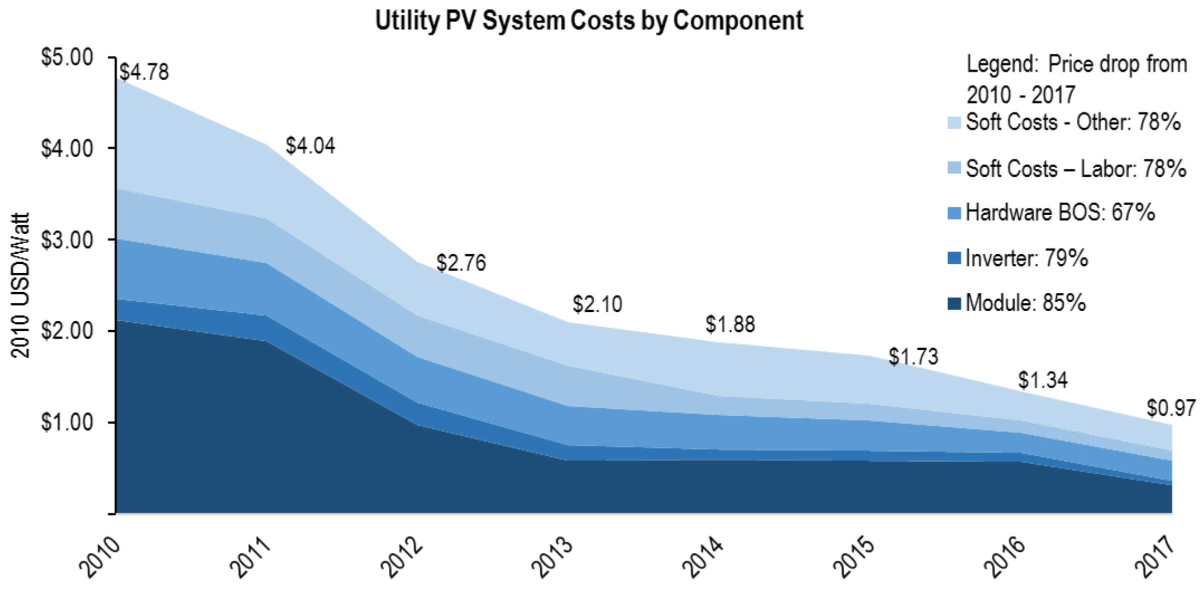

Figure 3-7. Nationwide Average Costs for Utility PV Systems

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[48] "Solar Investment Tax Credit," Solar Energy Industries Association, June 2018, seia.org/sites/default/files/inline-files/SEIA-ITC-101-Factsheet-2018-June.pdf.

[49] Fu et al., "U.S. Solar Photovoltaic System Cost Benchmark: Q1 2017," National Renewable Energy Laboratory, September 2017, www.nrel.gov/docs/fy17osti/68925.pdf.

There are two primary types of PV technologies that are used in utility-scale plants: c-Si and thin film solar cells. Table 3-3 provides a comparative look at the performance characteristics of two of California's largest solar PV farms.

Table 3-3. Performance Attributes for Two of California's Largest Solar PV Farms (2018)

Attribute	Topaz Solar Farm	Solar Star
Capacity	550 MW	579 MW
Year Fully Operational	2014	2015
Type	Fixed Tilt	Single-Axis Tracking
Developer	First Solar	Sunpower
Solar Cell	Cadmium Telluride	Crystalline Silicon
Number of Modules	9,000,000	1,720,000
California County	San Luis Obispo	Kern
Acreage	4,700	3,200
Capacity Weighted Land Use (Acre/MW)	8.54	5.53
Net Production (MWh) (2017)	1,237,530	1,637,872
Capacity Factor	25.6%	32.3%

Crystalline Silicon Solar Modules

The solar market is currently dominated by c-Si solar modules, which are the most mature form of PV technology. In 2017, they accounted for 93% of solar modules produced [50] and 77% of total U.S. added PV capacity (3.03 GW).[51] Additionally, c-Si modules account for 90% of installed PV capacity worldwide. The advantages of c-Si technologies include relatively high efficiencies, low costs, environmental abundance compared to other materials used in PV modules, and a well-developed supply chain.[51] On the other hand, c-Si module manufacturing processes can be complex and must adhere to high purity standards.

Thin Film Solar Modules

Thin film cadmium–telluride (CdTe) cells are the most competitive thin film solar cells on the market. CdTe cells boast the highest efficiency of thin film PV chemistries, as well as low module costs and low material requirements. High temperatures affect CdTe cell efficiency less than that of other solar cells. Thin film cells have a much less intensive manufacturing process than c-Si modules. Thin film cells can be printed on flexible substrates and do not require the same high temperatures and heating requirements as c-Si wafer production. However, CdTe solar modules face material challenges in the future. Tellurium (Te) is not an environmentally abundant material, and cadmium is environmentally harmful.[52]

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[50] "Photovoltaics Report," Fraunhofer Institute for Solar Energy Systems, ISE, August 2018, ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf.

[51] M. Bolinger and J. Seel, "Utility-Scale Solar: Empirical Trends in Project Technology, Cost, Performance, and PPA Pricing in the United States," Lawrence Berkeley National Laboratory, 2018, emp.lbl.gov/sites/default/files/lbnl_utility_scale_solar_2018_edition_report.pdf.

[52] "The Future of Solar Energy," MIT, 2015, energy.mit.edu/wp-content/uploads/2015/05/MITEI-The-Future-of-Solar-Energy.pdf.

Other types of thin film solar cells in development include copper–indium–gallium–selenide (CIGS), gallium arsenide (GaAs), amorphous silicon (a-Si), organic PV, quantum-dot cells, and perovskite solar cells. Each of these cells has seen efficiency improvements and cost reductions in recent years.[52]

Domestic vs. International Production

Most of the silicon solar modules deployed in the United States are imported. Nearly 10 GW of the 10.6 GW (94%) of solar capacity installed in 2017 was from imported solar modules.[53] New tariffs instituted in early 2018 have increased costs of imported PV modules, leading to a 10% growth in utility-scale solar projects.[54] Some companies are responding by building new manufacturing facilities in the United States,[55] but domestic manufacturers are unable to meet U.S. demand.

Time-Shifting PV Generated Resources

Battery storage has emerged as the primary means to time-shift PV power plants. A 65% decrease in battery storage costs from 2010 to 2017 has allowed PV-plus-storage systems to become cost-competitive in some markets.[56] Several PV-plus-storage projects are in operation or underway in Hawaii, Florida, Arizona, and Colorado.[57] The PPA price in these projects varies from $139/MWh (Hawaii) to $45/MWh (Arizona). The costs of energy from PV-plus-storage continues to decrease, with Xcel Energy in Colorado reporting median solar-plus-storage bids for $36/MWh in 2017. [52] The capabilities of each storage system vary, but systems can supply 3–50 MW of energy for 4–5 hours. It is important to note that these project PPAs begin in 2021. The utilities and developers have priced the PPAs with the expectation that battery prices will continue to decrease.**Error! Bookmark not defined.** Deployments of solar-plus-storage plants are likely to r ise in the future as battery costs continue to fall and the need and value of time-shifting renewable power grows.[58]

Solar Trackers

Solar trackers increase the energy yield of PV systems by orienting the panel toward the sun throughout the day. For example, single-axis tracking can increase an array's energy output by 25%–30%.[59] Dual-axis trackers can further improve energy yields by ensuring the optimum orientation for panels. However, solar developers must weigh the added costs of tracking systems with the benefits of increased energy production. The overall costs, including increased efficiencies, of PV projects with single-axis trackers have decreased to a point where they can be cheaper than fixed-tilt projects. Continued innovation in solar tracking will decreases costs related to both installation and maintenance. Examples include the Nevados

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[53] "Annual Solar Photovoltaic Module Shipments Report," U.S. Energy Information Administration, 2018, www.eia.gov/renewable/annual/solar_photo/pdf/pv_full.pdf.

[54] Michaela Platzer, "Domestic Solar Manufacturing and New U.S. Tariffs," Congressional Research Service, February 2018, fas.org/sgp/crs/misc/IF10819.pdf.

[55] Feldmen, Hoskins, and Margolis, "Q4 1027/Q1 2018 Solar Industry Update," National Renewable Energy Laboratory, May 2018, nrel.gov/docs/fy18osti/71493.pdf.

[56] Ericson et al., "Hybrid Storage Market Assessment," Joint Institute for Strategic Energy Analysis, October 2017, nrel.gov/docs/fy18osti/70237.pdf.

[57] "U.S. Battery Storage Market Trends," U.S. Energy Information Administration, May 2018, eia.gov/analysis/studies/electricity/batterystorage/pdf/battery_storage.pdf.

[58] Denholm, Eichman, and Margolis, "Evaluating the Technical and Economic Performance of PV Plus Storage Power Plants," August 2017, nrel.gov/docs/fy17osti/68737.pdf.

[59] Alan Goodrich et. al., "Residential, Commercial, and Utility-Scale Photovoltaic (PV) System Prices in the United States: Current Drivers and Cost-Reduction Opportunities," National Renewable Energy Laboratory, 2012, nrel.gov/docs/fy12osti/53347.pdf.

Engineering project, which is developing a PV tracking system capable of working on sloped terrain, and the Sunfolding project, which is developing air-driven solar tracking systems.[60,61] Last year, approximately 80% of all new solar capacity included solar tracking systems, nearly all of which were single-axis trackers.

3.1.2.2 | Concentrating Solar Power (CSP) Overview

CSP systems work by using mirrors to concentrate solar radiation to a receiver to produce heat at temperatures ranging from 250°C–1000°C. The heat is used to create steam that then drives conventional turbines to generate electricity. Importantly, since CSP generates thermal energy, it is relatively straightforward and cost-effective to add thermal storage to these systems, which enables CSP plants to be dispatchable sources for grid operators.

The primary disadvantages of CSP systems are their susceptibility to lower efficiencies due to cloud cover and the land and water requirements necessary for economically viable systems.[52] However, thermal storage coupled with CSP can mitigate efficiency losses from cloud coverage and allows the system to act more like a dispatchable resource. Although there was a burst of CSP projects from 2013–2015 in California, Arizona, and Nevada, there are currently no plans for new CSP plants in the United States. This domestic paucity in CSP projects may be because CSP project costs have not decreased at the rate of utility-scale PV project costs.[51] However, as solar market penetration increases, the value of CSP plants may increase because of their intrinsic thermal storage capacity and dispatchability.[52]

Table 3-4 provides a comparative look at the performance characteristics of two of California's CSP facilities.

Table 3-4. Attributes of CSP Facilities in California

Attribute	Genesis Solar Energy Project	Ivanpah Solar Energy Station
Capacity	250 MW	386 MW
Year Fully Operational	2014	2013
Developer	Genesis Solar LLC	Solar Partners I II VIII LLC
System	Parabolic Trough	Solar Tower
California County	Riverside	San Bernardino
Acreage	1,920	3,238
Capacity Weighted Land Use (Acre/MW)	7.68	8.38
Net Production (MWh) (2017)	627,886	719,421
Capacity Factor	28.7%	21.3%

There are two types of CSP technologies that are primarily used in utility-scale plants: parabolic troughs and solar towers.

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[60] "Installations and Soft Cost Reduction for Horizontal Single Axis Trackers (Stage II)," California Energy Commission, accessed December 2018, innovation.energy.ca.gov/SearchResultProject.aspx?p=31483&tks=636827154418527750.

[61] "Mass Manufactured, Air Driven Trackers for Low Cost, High Performance Photovoltaic Systems," California Energy Commission, accessed December 2018, innovation.energy.ca.gov/SearchResultProject.aspx?p=30065&tks=636827154744037058.

Parabolic Troughs

Parabolic trough systems are the most mature form of CSP technology. Indeed, the majority of CSP systems in California use parabolic troughs, accounting for 857 MW of the 1,249 MW (69%) capacity from CSP plants.[62] The newest parabolic trough systems in the state are the Genesis Solar Energy Project and the Mojave Solar Project. Both systems have 250 MW of capacity and became fully operational in 2014.[62,63] There are several other parabolic trough CSP systems in California, such as SEGS, which is currently divided into seven subsystems with capacities from 34–92 MW (357 MW total).

Parabolic troughs use long rows of solar reflectors to concentrate light onto receivers that typically contain synthetic thermal oil. This fluid is then either transported directly to the heat transfer system, which creates steam to generate electricity with conventional turbines, or transported to thermal storage. These designs generally have about a 15% solar-to-electric efficiency.[62] However, parabolic trough designs are currently limited, as the synthetic thermal oil used is restricted to operating temperatures below 400°C, which lowers the efficiency of the systems. Alternatives to synthetic thermal oils, such as steam and molten salt, are under development but introduce new challenges.[63]

Solar Towers

Solar tower CSP consists of an array of mirrors with a tracking system that focuses solar radiation toward a receiver on a central tower. The Ivanpah Solar Facility is the only solar tower CSP system in California. Ivanpah consists of three solar towers with a total rated capacity of 386 MW.[64] Solar towers can operate at much higher temperatures than parabolic trough designs, which increases system efficiency. The higher temperatures are also beneficial for thermal storage since they lower the size of storage per unit of energy, reducing costs and heat losses. However, CSP towers have several disadvantages: the need for dual-axis tracking mirrors, increased maintenance costs, and environmental concerns due to increased air temperatures around the sites.[52]

Time-Shifting CSP-Generated Resources

One of the primary advantages of CSP technology is that it generates thermal energy, which can be stored significantly more efficiently and cheaply than PV with battery storage. There are two CSP thermal storage systems currently operating in the United States: Crescent Dunes in Nevada and Solana in Arizona. Crescent Dunes is a tower CSP system with a capacity of 110 MW and 10 hours of storage.[51] The Solana facility is a parabolic trough CSP with a capacity of 250 MW and 6 hours of thermal storage.[65] These projects cost an estimated \$9/W and \$7/W, respectively. Historically, CSP with solar thermal storage costs approximately \$2–\$3/W more than similar-sized CSP projects without storage.[51]

Alternative Financing for CSP with Thermal Energy Storage

A main barrier to CSP systems with storage is the high capital cost, even though CSP-plus-storage decreases LCOE through greater electricity production. U.S. electricity markets have not yet created conditions that adequately incentivize the dispatchability of CSP-plus-storage systems. Innovative financing methods and

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[62] Pitz-Paal, "Concentrating Solar Power Systems," EPJ Web of Conferences, July 2017, epj-conferences.org/articles/epjconf/pdf/2017/17/epjconf_eps-sif2017_00008.pdf.

[63] "Genesis Solar Energy Projects," California Energy Commission, 2018, energy.ca.gov/sitingcases/genesis_solar.

[64] "Ivanpah Solar Electric Generating System," California Energy Commission, 2018, energy.ca.gov/sitingcases/ivanpah/index.html.

[65] "Solana Generating Station," National Renewable Energy Laboratory, 2015, solarpaces.nrel.gov/solana-generating-station.

updated market structures could help to overcome the high capital cost barrier and increase the number of CSP-plus-storage deployments.

In Australia, a 2017 bid by Solar Reserve to build a new CSP facility utilizing a solar tower design was signed with a PPA of $0.06 per kWh. While the new facility, Aurora, has a lower-than-average technology cost owing to continued technology development, that alone does not explain the low PPA. The planned Aurora CSP facility will have a capacity of 150 MW, but the PPA agreement secures access only to 125 MW of Aurora's capacity. With 8 hours of storage, Aurora sells most of its power at the fixed PPA price when demand is low and then taps into higher-value market prices in the evenings to respond to a ramp-up in demand as PV generation decreases. The hybrid PPA is an innovative solution to match renewable energy availability with demand. It allows the plant to operate profitability by providing a steady revenue stream during the day and access to peak demand prices that can exceed 1000 AUD.[66]

3.1.3 | Research Initiatives

The following is a brief overview of some of the ongoing R&D initiatives related to solar power. This summary is not intended to be comprehensive.

3.1.3.1 | EPIC Investment Initiatives

The EPIC 2018–2020 Triennial Investment Plan describes the short-term R&D priorities to increase utility-scale solar capacity in California. Under the first and second EPIC investment plans, the EPIC program concentrated on technologies that would reduce costs and improve CSP efficiency, in addition to improving solar forecasting. The latest plan broadly aims to increase the economic potential of solar, enable solar to compete in grid-level service markets, and develop solar technologies that can create novel uses and markets.

Table 3-5. Solar Power – Summary 2018–2020 EPIC Triennial Investment Plan Initiatives

Initiative	Description/Goal	Potential Impact
2018–2020 EPIC Triennial Investment Plan		
Initiative 4.1.1: Advance the Material Science, Manufacturing Process, and In Situ Maintenance of Thin Film PV Technologies	This initiative will advance the materials science associated with emerging thin film PV technologies by exploring the advantages of changes in materials composition, substituting non-toxic and abundant alternatives for toxic and/or rare elements.	Combining advancements in materials science of thin film PV materials, demonstration of high efficiencies, and utilization of abundant and non-toxic materials with effective low-cost encapsulating strategies to increase module lifetime could lead to a greater acceptance and large-scale adoption of thin film PVs.
Initiative 4.3.1: Making Flexible-Peaking Concentrating Solar Power with Thermal Energy Storage Cost-Competitive	This initiative will conduct comprehensive research, technology development and demonstration, and studies that will advance the technology readiness of CSP with thermal energy storage (TES), bring it closer to the market, and make CSP-TES cost-competitive compared to fossil fuel power generation and conventional (battery) energy storage systems.	Financially viable CSP-TES will increase future deployment, which will provide a significant contribution to California's RPS goal while providing a dispatchable form of renewable energy ready to support non-synchronous renewables.

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[66] Johan Lilliestam and Robert Pitz-Paal, "Concentrating Solar Power for Less than USD 0.07 KWh: Finally the Breakthrough?," *Renewable Energy Focus*, September 2018, sciencedirect.com/science/article/pii/S1755008418300309.

Table 3-6. Solar Power – Summary of Other California Initiatives

Initiative	Description
Previous EPIC Investment Plans	
Previous/Planned/Possible EPIC Investments in Solar Technologies	1. Enhance Efficiency and Environmental Performance in Low-Cost PVs a. PON-14-308: High-Performance Cu Plating for Heterojunction Silicon Cells, Based on Ultra-Low-Cost Printed Circuit Board (PCB) Technology b. GFO-16-032: Scaling Reliable, Next-Generation Perovskite Solar Cell Modules c. PON-14-303: Develop Advanced Distributed Photovoltaic Systems 2. Cost-Effective Large-Scale Manufacturing of Emerging PVs a. GFO-16-302: Scaling Reliable, Next-Generation Perovskite Solar Cell Modules 3. High-Value Applications for Thin Film PV 4. In Situ Upgrade Methods and Strategies for Thin Film PV 5. Efficient and Low-Cost Thermal Energy Storage and Heat Transfer Fluid a. Low-Cost Thermal Energy Storage for Dispatchable CSP b. Systems Integration of Containerized Molten Salt Thermal Energy Storage in Novel Cascade Layout 6. Low-Cost and Improved Receivers and Absorbers (CSP) 7. Component Integration and System Requirements for Flexible Operation (CSP) 8. Low-Cost Alternatives to Conventional CSP a. Dairy Waste-to-Bioenergy via the Integration of Concentrating Solar Power and a High-Temperature Conversion Process b. Commercializing a Disruptively Low-Cost Solar Collector
California, Multi-Agency Initiative	
Go Solar California	Go Solar California combines three program components from separate entities in California. The California Public Utilities Commission's (CPUC's) California Solar Initiative (CSI), Energy Commission's New Solar Homes Partnership, and various programs from California's publicly owned utilities (POUs) comprise the Go Solar California program.

Select EPIC Projects

The Energy Commission has recently funded several innovative solar projects through the EPIC program that are featured on the Energy Commission Innovation Showcase website.[67] The following table summarizes projects that describe emerging solar technologies that are relevant to utility-scale solar generation.

Table 3-7: Solar – Select EPIC Projects

Project Name	Technology Type	Description
PV		
Improving Solar & Load Forecasts: Reducing the Operational Uncertainty Behind the Duck Chart (Completed 6/2018)	Solar Forecasting	Improves solar forecasts for grid-connected PV in California, uses those improved forecasts to create enhanced net-load forecasts, and quantifies the value of improved forecasts for utilities and grid operators.
Mass-Manufactured, Air-Driven Trackers for Low-Cost, High-Performance Photovoltaic Systems (Active until 3/2019)	Tracking	Installs and tests a PV system with air-driven trackers that uses mass manufacturing for the drive and remove requirements for outdoor wiring or individual control hardware.

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[67] California Energy Commission Innovation Showcase, innovation.energy.ca.gov/.

Project Name	Technology Type	Description
Self-Tracking Concentrator Photovoltaics for Distributed Generation	Tracking	Develops, tests, and demonstrates a self-tracking concentrator PV system that does not require a precision mechanical tracker to remain aligned with the sun. There is potential to cut installed system cost for distributed PV systems in half.
Installation and Soft Cost Reduction for Horizontal Single Axis Trackers (Stage II) (Active until 12/2019)	Tracking	Demonstrates a single-axis solar PV tracking system that can fit on sloped and rolling terrain at lower costs to help solar developers build projects on land closer to load centers and interconnection points.
High-Performance Cu-Plating for Heterojunction Silicon Cells, Based on Ultra-Low-Cost Printed Circuit Board (PCB) Technology (Stage II) (Active until 12/2019)	Manufacturing	Develops a next-generation manufacturing tool for low-cost, high-performance copper patterning on PV cells using technologies from PCB manufacturing.
Scaling Reliable, Next-Generation Perovskite Solar Cell Modules (Active until 12/2020)	Materials Science	Integrates new materials into the perovskite absorber layer, the solar cell’s contact layers, and the encapsulation of the module to improve perovskite solar cell reliability and scaling.
CSP		
Low-Cost Thermal Energy Storage for Dispatchable CSP (Completed 3/2018)	Thermal Storage	Develops and demonstrates a robust and low-cost TES fluid, elemental sulfur that will enable overall low system costs, long lifetime, and scalability for a wide range of CSP applications and temperatures.
Cross-Cutting		
High-Fidelity Solar Power Forecasting Systems for the 392 MW Ivanpah Solar Plant (CSP) and the 250 MW California Valley Solar Ranch (Completed 3/2018)	Solar Forecasting	Develops a high-density network of irradiance sensors that will improve solar forecasting methods. Short-term forecasts using sky imagers and distributed data from the sensor network improves forecasted data.
Carbon Balance with Renewable Energy: Effects of Solar Installations on Desert Soil Carbon Cycle (Active until 8/2019)	Environmental Management	Quantifies the impacts of large-scale solar arrays and long-term climate change on desert soil conditions to yield fundamental insights into the terrestrial carbon budget in arid environments.
Optimizing Solar Facility Configuration Effects on Habitat, Managed Plants, and Essential Species Interactions (Active until 9/2019)	Environmental Management	Develops methods to decrease adverse environmental impacts of solar energy facilities, enhance the ability to predict and overcome costly invasions of non-native plants, improve mitigation measures, reduce impacts, and overcome barriers to facility siting and design.
Development of a Genoscape Framework for Assessing Population-Level Impacts of Renewable Energy Development on Migratory Bird Species in California (Active until 9/2019)	Environmental Management	Develops high-resolution maps of population structure and migration routes and applies this information to assess population-level impacts by screening carcasses collected from renewable energy facilities to improve siting recommendations for new facilities.
Connecting Emerging Energy Technologies and Strategies to Market Needs and Opportunities (Active until 3/2021)	Market Integration	Provides market analysis that addresses the barriers that hamper commercial development of emerging energy technologies. The deliverables from this project will help prioritize future Energy Commission funding toward technologies that solve the addressed issues.

3.1.3.2 | Research Initiatives from Other Funding Entities

DOE focuses on R&D to reduce the cost and improve the performance of solar technologies; efforts span from early-stage materials research to initial demonstration projects. Current initiatives and funding opportunities are aimed at improving the efficiency, resilience, and costs of PV and CSP technologies. There is an additional focus on improving the integration of solar on the grid, including a specific initiative to improve solar forecasting. Finally, DOE is investing in projects that are aimed at developing solar-relevant skills in the workforce.

Table 3-8. Solar Power – Summary of DOE Research Initiatives

Initiative/Program	Description/Goal	Potential Impact
U.S. Department of Energy		
Advanced Systems Integration for Solar Technologies (ASSIST)	Strengthen the integration of solar on the electricity grid, especially critical infrastructure sites, and improve grid resilience.	Develop tools that enhance the situational awareness of solar systems on both the distribution and transmission grid and validate technologies that improve grid security and resilience.
Solar Energy Technologies Office (SETO): Concentrating Solar-Thermal Power	Advance components found in CSP sub-systems including collectors, power cycles, and thermal transport systems.	Develop new technologies and solutions capable of lowering solar electricity costs for CSP.
Solar Energy Technologies Office (SETO): Photovoltaics	Support early-stage research that increases performance, reduces materials and processing costs, and improves reliability of PV cells, modules, and systems. In addition, develop and test new ways to accelerate the integration of emerging technologies into the solar industry.	Develop new technologies and solutions capable of lowering solar electricity costs for PV.
Solar Energy Technologies Office (SETO): Workforce	Support projects that seek to prepare the solar industry and workforce for a digitized grid. Increase the number of veterans in the solar industry.	Improve workforce training that will manage a modern grid.
Solar Forecasting 2	Support projects that generate tools and knowledge for grid operators to better forecast how much solar energy will be added to the grid.	Improve the management of solar power's variability and uncertainty, enabling more reliable and cost-effective integration onto the grid.

DOE SunShot Vision Study

In February 2012, DOE released the SunShot Vision Study,[68] which includes a roadmap of recommended actions aimed at pursuit of the vision. The progress toward these goals has been tracked and updated in a more recent set of eight research papers collectively called "On the Path to SunShot."[69] Table 3-9 provides actions identified in these follow-up research papers as areas that are critical for increasing solar capacity in the United States.

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[68] "Sunshot Vision Study," National Renewable Energy Laboratory, 2012, www.energy.gov/eere/solar/sunshot-vision-study.

[69] "On the Path to SunShot," National Renewable Energy Laboratory, 2016, www.energy.gov/eere/solar/path-sunshot.

Table 3-9. Actions to Achieve SunShot Vision

Action	Description
PV	
Decrease Production Costs (c-SI)	Use kerfless wafering techniques to reduce material waste, lower energy consumption, and eliminate other factory costs.
Increase c-Si Efficiency	Increase cell efficiency using known technology improvements such as passivated emitter and rear cells (PERCs).
Decrease Production Costs (Thin Film)	Implement less expensive deposition methods, use different material precursors, and increase substrate reuse for exitaxial lift-off methods.
Increase Reliability and Durability	Improve control of the process window, and prevent the shipment of products with latent defects. Develop high-resistivity encapsulant materials and other materials that result in fewer cracked cells, broken ribbons, and failed solder bonds; develop new processes that reduce delamination and chemical erosion.
Decrease Balance of System Hardware Costs	Improve efficiency of modules; develop new racking and installation materials, new types of inverters, and use-integrated PV; and improve modular construction.
Decrease BOS Soft Costs	Improve software for designing systems, streamline planning/permit processes, introduce robotic-based installations, reduce the complexity of electrical connections to reduce labor, and standardize systems to reduce design and construction time.
CSP	
Reflectivity and Mirror Cleaning	Improve the initial reflectivity and long-term durability of mirrors; develop new materials and strategies that minimize labor and water usage for cleaning mirrors.
Alignment, Focusing, and Tracking	Improve the alignment and focusing of the mirror facets to improve collector performance in optimal and diffuse-sky conditions.
Manufacturing and Installation	Improve on-site manufacturing and installation processes to reduce complexity and cost.
Salt Solar Receiver	Develop lower-cost and thermodynamically compatible salt receivers.
Thermal Energy Storage	Develop containment options that can use lower-cost containment alloys, including internal insulated salt tanks or frozen salt barrier tanks.
Material Selection/Compatibility	Identify appropriate materials for containment that can resist salt corrosion and have the requisite tensile strength at the desired operating temperatures.
Solid Particles	Identify or continue to develop low-cost particles that increase solar absorbance and decrease particle loss and reduce abrasiveness to structural materials.
Salt Chemistry	Develop new salt chemistries that can be used at representative operational temperatures.
Salt-to-sCO_2 Heat Exchanger	Develop heat exchangers with very low pressure drop on the CO_2 side, and develop strategies to avoid thermal shock and freeze recovery.
Cross-Cutting	
Environmental Management	Develop new strategies to reduce glare. Assess the effect of the solar plants on bird mortality.

3.1.4 | R&D Opportunity Areas and Technologies

Figure 3-8. Solar Experts Interviewed

- Jan Kleissl, Associate Director, UCSD Center for Energy Research
- Sarah Kurtz, Professor, UC Merced
- Cara Libby, Senior Technical Leader, Electric Power Research Institute
- Avi Shultz, CSP Program Manager, DOE/SETO
- Lenny Tinker, PV Program Manager, DOE/SETO

To identify and prioritize R&D opportunity areas and technologies for solar energy, technical assessment analysts relied upon over 30 state and federal government reports, industry reports, and peer-reviewed research articles. Research also included phone interviews with five solar energy experts from government and other research institutions across the United States. The interviews consisted of a series of questions that covered three broad topics: industry trends and drivers, technical attributes of existing and breakthrough technologies, and recommendations for future Energy Commission investments and metrics.

Together, these sources provided detailed insights into the state of existing technologies, key challenges, R&D opportunity areas, and emerging and potential breakthrough solar technologies.

3.1.4.1 | Key Considerations

Expert interviews and literature review identified a number of factors worth consideration when dealing with assessment, investment, or construction of solar generation in California. These areas are broadly categorized into technical, financial, and regulatory considerations, as discussed below.

Technical Considerations

- **The intermittent nature of solar energy poses integration issues for the grid to be addressed.** The intermittent nature of solar radiation complicates the smooth integration of solar energy onto the grid. CSP with thermal storage and PV-plus-storage systems offer ways to time-shift solar generation to better match resource availability and energy demand. Time-shifting solar energy will allow for more reliable energy and most likely lead to more installations.
- **New tracking hardware can increase solar efficiency.** Innovations in solar tracking equipment, such as the air-powered systems developed with EPIC funds, can reduce the cost and complexity of tracking systems.
- **New materials can increase PV and CSP system efficiencies.** Improved contact layers, cell structures, and materials offer the potential for higher-efficiency collection of solar energy for PV technologies. These materials can drive down system costs and increase production in a smaller amount of land. CSP has similar opportunities for improving the materials for thermal energy storage. Increased efficiency could enhance the return on investment of CSP systems and add value to the grid as a dispatchable renewable resource.
- **CSP grid integration modeling assessments could enhance understanding of the value proposition for future development in California.** Understanding the overall effect of CSP on the California grid requires that modeling efforts look at grid penetration. California has taken steps to understand CSP as a resource by looking at CSP production from the Ivanpah plant. Potential CSP development sites could be modeled to identify those of the greatest value. Resource integration studies should not be limited

to CSP systems and should include PV and other renewables, storage, and grid infrastructure/ management systems as well.

- **New models are needed to explore the impacts of high solar PV generation growth and portion of load share in California.** There is a risk that an over-reliance on solar PV in California could exacerbate the duck curve, which will result in a greater need for fast-ramping systems to deal with the decline in energy production when the sun goes down. While renewables can fill ramping requirements, typically natural gas plants are used for fast-ramping applications. New market structures or technologies, such as more operationally flexible CSP systems, may be needed to complement increased PV production with the ability time-shift the availability of those resources.

Financial Considerations

- **PV costs per kilowatt-hour have declined rapidly over the past decade, but markets are likely to adjust to value the time of resource availability more appropriately.** Solar PV costs have decreased rapidly in past decades. However, future energy costs may need to be reduced further and may need to incorporate a cost component for storage systems or the ability to more effectively time-shift resources. This is particularly important, as the increase in solar PV generation can drive markets into negative values. These market drivers may incentivize CSP-plus-thermal-storage and PV-plus-battery-storage systems.

Regulatory Considerations

- **Regulations, incentives, and market updates could help to shift the state's load profile and reduce solar integration issues.** Introducing time-of-use (TOU) rates and incentives for consumers to shift demand to peak solar generation periods can help create more of a market for solar energy during hours when the sun is shining. Greater demand during those periods can signal that the grid can accept more solar generation. Generators may also be encouraged to look at ways to provide electricity outside of peak solar windows that would encourage installation of dispatchable CSP systems or solar PV plus storage.

3.1.4.2 | R&D Opportunity Areas

There are several R&D opportunities that can help continue the expansion of solar capacity in California. The R&D opportunity areas are listed in Table 3-10 and expand beyond those identified in the Energy Commission's 2018–2020 Triennial Investment Plan. They are based on an extensive literature review and conversations with experts. This table is intended to be a broad sampling of categories where continued R&D is required for further deployment of solar power generation. Table 3-11 shows more targeted and specific technologies that could benefit or emerge from investment in the R&D opportunity areas.

Table 3-10. Solar Power – Technology Research & Development Opportunity Areas

ID	Opportunity Areas	Description
PV		
O.S.1	***Building- and Community-Scale PV and Storage**	PV in combination with storage to provide power to communities and buildings when the sun is not shining. This smooths the production from solar, allowing the resource to become non-variable for as long as the storage lasts.

O.S.2	**Innovative Technologies**	New technologies, materials, chemistries, and designs that increase the efficiency and/or lower costs of solar PV.
O.S.3	**Improving, Predicting, and Quantifying PV Durability**	PV modules that are more durable to weather hazards, reducing maintenance and financing costs as well as LCOE.[70]
O.S.4	***Large-Scale Manufacturing of Emerging Technologies**	Technologies and processes that reduce the cost of manufacturing and increase throughput, so California-based manufacturers can be cost-competitive with other countries and states.
O.S.5	***Traditional PV Improvements**	Improvements to traditional PV solar designs and chemistries that can lower costs and increase efficiency. Research to improve the ability to quantify, predict, and improve outdoor PV durability, which would reduce financing costs and lower LCOE.
O.S.6	***Thin Film Technologies[2]**	Specific PV technology that is more adaptable and easier to manufacture and install.
CSP		
O.S.7	***Alternatives to Conventional CSP**	Current CSP projects are large-scale, expensive, and land-intensive. Approaches that look at using alternative materials, working fluids, manufacturing, and/or designs can lower costs of systems and reduce their footprints.
O.S.8	***Efficient TES and Heat Transfer Fluid**	Technologies, processes, and innovative materials that reduce failure and lower maintenance costs associated with TES. The handling and storage of the TES medium for CSP plants is critical for providing delayed energy generation from solar.
O.S.9	***Improved Receivers and Absorbers for CSP**	Improvements to the receiver tower and absorbing materials for CSP, which are important for increasing the amount of heat collected and transferred to the heat transfer material.
O.S.10	***TES[3]**	Technologies and processes that deal with CSP with a medium that provides TES. This area covers integration and operation of the system and also includes technologies not handled by other opportunity areas that bring CSP with TES closer to market.
Cross-Cutting		
O.S.11	**Environmental and Social Improvements[4]**	Investments in technologies or processes that reduce negative environmental or social impacts from solar technologies.
O.S.12	**Testing Methods and Facilities**	Test beds for PV and CSP systems to assist in lowering costs and proving a technology is ready before going to market.

Several research areas overlap with EPIC investment interests. Those overlaps are given the following identifiers:
* Mentioned in EPIC Investment Plan: Previous and Planned EPIC Investments related to Solar Technologies
2 Relevant to Initiative 4.1.1 Advance the Material Science, Manufacturing Process, and In Situ Maintenance of Thin Film PV Technologies
3 Relevant to Initiative 4.3.1 Making Flexible-Peaking Concentrating Solar Power with Thermal Energy Storage Cost-Competitive
4 Relevant to Initiative 7.3.1 Find Environmental and Land Use Solutions to Facilitate the Transition to a Decarbonized Electricity System

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[70] Alex Bradley, “Materials can be key to Differences in Module Durability,” DuPont, dupont.com/content/dam/dupont/products-and-services/solar-photovoltaic-materials/solar-photovoltaic-materials-landing/documents/PV-Tech-article.pdf.

3.1.4.3 | Emerging and Breakthrough Technologies

The emerging and breakthrough technologies in Table 3-11 represent more targeted opportunities for Energy Commission investment and fall within the aforementioned R&D opportunity areas.

Table 3-11. Solar Power – Emerging and Breakthrough Technology Matrix

ID	Name	Parallel Research Topic	R&D Opportunity Areas	Potential Impact
PV				
S.1	**Alternative to Rare Earth**	Supply Chain	Large-Scale Manufacturing of Emerging PVs	Rare earth elements such as those in CIGS and cadmium–telluride solar cells are in high demand and will increase costs. Alternatives to these need to be identified.
S.2	**Gallium Arsenide Solar Cells**	Legacy System Improvement	Traditional Thin Film PV Improvements, Large-Scale Manufacturing of Emerging PVs	The ability to mass-produce low-cost gallium arsenide solar cells, which have efficiencies 50% greater than that of silicon solar cells, would significantly increase the amount of power per unit area solar can generate.
S.3	**Organic Photovoltaics**	Innovative System Development	Innovative Thin Film PV Technologies	These photovoltaics consist of earth-abundant materials, which would make collecting the materials low-cost. While currently expensive because of inefficient fabrication processes, improvements in manufacturing can make organic PV more affordable.
S.4	**Perovskite Solar Cells**	Innovative System Development	Thin Film PV Technologies	Perovskite cells have achieved lab efficiencies comparable to incumbent PV technologies, and being able to stabilize the material defects could allow for higher-efficiency and lower-cost solar modules to enter the market.
S.5	**Tandem PV**	Innovative System Development	Innovative PV Technologies	Tandem PV cells use multiple PV cells tuned so that one absorbs higher-energy photons while others absorb lower-energy ones. Optimizing solar cells for specific bandgaps can increase the system efficiency.
CSP				
S.6	**Brayton Cycle**	Operations and Maintenance Improvement	Alternatives to Conventional CSP	A Brayton cycle for power generation uses air or supercritical carbon dioxide instead of water and can operate at a higher temperature than a standard steam turbine, increasing the efficiency of the system.
S.7	**Beam Down CSP**	Innovative System Development	Alternatives to Conventional CSP	This CSP system, which beams light down toward a secondary collector below a central tower, may allow for higher operating temperatures and higher system efficiency.
S.8	**Direct Solar to Salt Receiver**	Operations and Maintenance Improvement	Improved Receivers and Absorbers for CSP, Efficient TES, and Heat Transfer Fluid for CSP	Removing a heat transfer medium between the reflected solar energy and the molten salt allows for the salt to operate at a higher temperature, improving efficiency.

ID	Name	Parallel Research Topic	R&D Opportunity Areas	Potential Impact
S.9	**Containment Alloys**	Supply Chain	CSP-TES	Alloys that resist corrosion and high temperatures can allow for more efficient CSP designs and make CSP more reliable by minimizing events such as leaks.
S.10	**Gas Phase Receiver**	Legacy System Improvement	Alternatives to Conventional CSP	Using a gas phase heat transfer fluid instead of a liquid offers a lower cost than molten salt and can be built with modular storage to ensure long-term reliability.
S.11	**Insulation of Molten Salt**	Operations and Maintenance Improvement	Efficient TES and Heat Transfer Fluid for CSP	Minimizing the amount of heat the molten salt loses will allow CSP to store more energy for longer periods of time.
S.12	**Linear Fresnel**	Innovative System Development	Alternatives to Conventional CSP	This design of having slightly curved stationary mirrors reflect light onto a stationary tube similar to a parabolic trough is a simpler and more cost-effective method of CSP, although it does have a lower efficiency.
S.13	**Molten Salts**	Legacy System Improvement	Efficient TES and Heat Transfer Fluid for CSP	Molten salts that can be heated to higher temperatures (>700°C) can allow for a more efficient system and more power generation.
S.14	**New Materials for Reflection and Absorption**	Supply Chain	Improved Receivers and Absorbers for CSP	Materials that can increase the amount of light reflected by heliostats and absorbed by the receiving tower can increase efficiency by allowing the plant to operate at a higher temperature.
S.15	**Particle Receiver System**	Legacy System Improvement	Alternatives to Conventional CSP	Using solid particles instead of a heat transfer fluid can allow for operation above 1000°C, being more efficient while lowering costs by using less materials.
S.16	**Pumps for Molten Salt**	Operations and Maintenance Improvement	CSP-TES	The ability to pump high-temperature molten salt without damaging the system improves efficiency and plant reliability.
S.17	**Stirling Dish Engine**	Innovative System Development	Alternatives to Conventional CSP	By using a dish to focus light onto a Stirling engine, this technology is a modular form of CSP that would have an efficiency higher than other alternatives.
Cross-Cutting				
S.18	**Sensory Systems**	Operations and Maintenance Improvement	CSP-TES; Traditional PV Improvements	Sensory measures for the tracking systems of PV modules and heliostats will improve their efficiencies. Sensory systems will also be needed in CSP flow systems to ensure system reliability.
S.19	**Test Facilities**	Information Technology	Testing Methods and Facilities; Efficient TES and Heat Transfer Fluid for CSP	Testing of all individual PV and CSP components is necessary to ensure systems will operate appropriately.

3.2 | Wind

In 2017, wind energy generated within California totaled 12,858 GWh, accounting for roughly 6.2% percent of the in-state total power generation and 21.0% of in-state renewable power generation.[71] Wind energy power plants generating in California during at least part of the year had a total capacity of 5,632 MW.[72]

Figure 3-9 shows how wind energy generation in California has grown in gross generation (GWh) and capacity from 2001 to 2017. The number of gigawatt-hours represents more than a tripling of wind energy capacity since California's RPS law was adopted. California turbines span an age range of more than three decades and vary from early fixed-speed, fixed-pitch machines of tens of kilowatts in capacity to modern power-electronic variable-speed, variable-pitch machines of more than 3 MW. While many early turbines were installed on lattice towers, newer ones are installed on tubular towers. The composition of the turbine fleet has been dynamic as operators repower or retire older turbines and start new projects. [73]

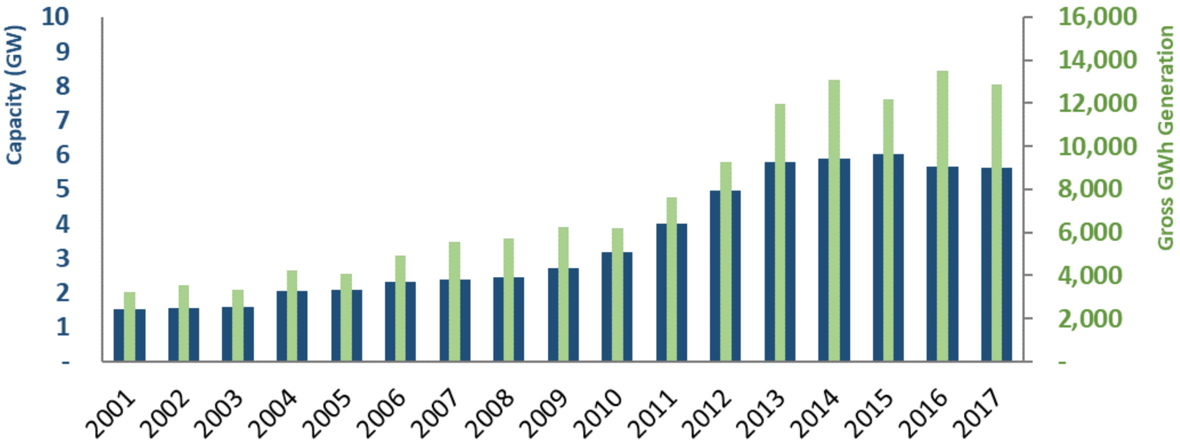

Figure 3-9. Wind Energy Generation in California from 2001 to 2017

Data from energy.ca.gov/almanac/renewables_data/wind/

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[71] "2017 Total System Electric Generation," California Energy Commission, data as of June 21, 2018, energy.ca.gov/almanac/electricity_data/total_system_power.html.

[72] "Electricity from Wind Energy Statistics & Data," California Energy Commission, accessed October 8, 2018, energy.ca.gov/almanac/renewables_data/wind/.

[73] J. Hingtgen, M. Prindle, and P. Deaver, "Wind Energy in California: 2014 Description, Analysis, and Context," California Energy Commission, CEC-200-2017-001, February 2017, energy.ca.gov/2017publications/CEC-200-2017-001/CEC-200-2017-001.pdf.

Continued deployments and investment in R&D will help to continue to drive down the price and improve the performance of wind power technologies. Figure 3-10 shows the decline in LCOE for wind power from 2009 to 2018.[74]

Looking forward, the DOE FY 2019 budget request establishes cost performance targets, summarized in Table 3-12. The most recent of these targets have already been exceeded. DOE focuses on science and early-stage innovations to optimize the design and operation of future wind plants. The aim is to strengthen the body of knowledge that industry can utilize to develop the taller towers, larger rotors, lower-weight components, plant-level control strategies, and technologies that reduce environmental and community impacts, achieve necessary cost reductions, improve grid reliability, and reduce regulatory burdens.[75]

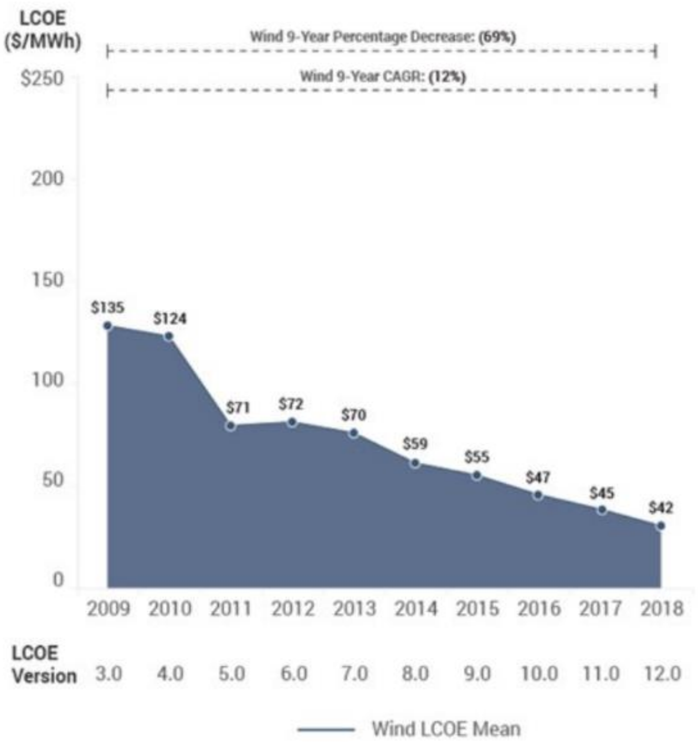

Figure 3-10. Unsubsidized Wind LCOE (Lazard)

Figure from Lazard's Levelized Cost of Energy Analysis 2018 (LCOE 12.0)

Table 3-12. Wind Power Cost Performance Targets (DOE)

	FY 2017	FY 2018	FY 2019	Endpoint Target
Offshore Target	17.2 cents/kWh (target met)	16.2 cents/kWh	15.7 cents/kWh	14.9 cents/kWh by 2020 9.3 cents/kWh by 2030
Land-Based Target	5.5 cents/kWh (exceeded at 5.2)	5.4 cents/kWh	5 cents/kWh	3.1 cents/kWh by 2030

Offshore assumptions: The offshore wind energy cost target is an unsubsidized cost of energy at utility scale. Discount rate is derived from empirical European installations; capacity weighted average installed capital and operating expenditures (CapEx and OpEx) values derived from European Installations in 2016; 8.4 m/s wind speed @50 m hub height; and 20-year plant life.

Land-based assumptions: The land-based wind energy cost target is an unsubsidized cost of energy at utility scale. Real market weighted average cost of capital (WACC) of 5.6%; national capacity weighted average installed CapEx and OpEx values; 7.25 m/s wind speed @50 m hub height; and 25-year plant life.

Source: Department of Energy FY 2019 Congressional Budget Request. Volume 3–Part 2: 23. DOE. March 2018. energy.gov/sites/prod/files/2018/03/f49/FY-2019-Volume-3-Part-2.pdf.

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[74] "Levelized Cost of Energy and Levelized Cost of Storage 2018," Lazard, November 8, 2018, lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2018/.

[75] Department of Energy FY 2019 Congressional Budget Request, Volume 3–Part 2: 23, DOE, March 2018, energy.gov/sites/prod/files/2018/03/f49/FY-2019-Volume-3-Part-2.pdf.

3.2.1 | Resource Availability

The state has six designated wind resource areas (WRAs) that are specific zones containing many installed wind generation projects. A larger map of the California wind resources areas can be shown by following the link listed in the caption of Figure 3-11. In order from north to south, the wind resource areas are:

- Solano
- Altamont
- Pacheco
- Tehachapi
- San Gorgonio
- East San Diego County

The WRAs were identified as having high wind resources and being close to grid-access points. The largest wind resource area is Tehachapi in Kern County, which is also the county with most wind generating capacity. With more than 4,000 turbines and more than 3,000 MW of capacity, the Tehachapi wind resource area produced more than half of California's net wind energy in 2014. The WRAs do not represent all the available wind resources in the state, and they do not represent limits for future expansions of the electric grid.

Figure 3-11. Wind Projects and Wind Resource Areas
CEC provides maps of California wind projects and wind resource areas. The webpage also provides a link to an interactive mapping tool from NREL to measure wind energy across the state and country.

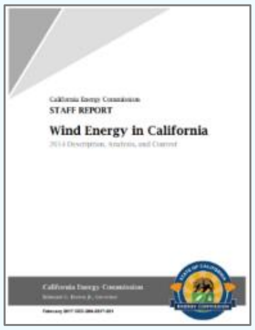
Available at energy.ca.gov/maps/renewable/wind.html

The Renewable Energy Transmission Initiative (RETI) is a proactive, statewide, non-regulatory forum to identify the constraints and opportunities for new transmission to access and integrate new renewable resources and help meet the state's GHG and renewable energy goals. Effective planning can help to optimize use of the existing transmission system, ensuring that power-handling capacity and energy-transport capabilities are not underutilized and transmission expansion enables transport and sharing of renewable electricity and reliability responsibilities.

The Tehachapi Renewable Transmission Project is an ongoing SCE project in Kern, Los Angeles, and San Bernardino Counties that connects roughly 3,800 MW of new wind capacity. This project includes new and upgraded transmission infrastructure along roughly 170 miles of new and existing right-of-way from the Tehachapi WRA in southern Kern County south through Los Angeles County and east to Ontario.[76]

Figure 3-12. Wind Energy in California

The “Wind Energy in California” report, released by the Energy Commission in February 2017, is the first to address the state of wind energy in California since reinstatement of the California Energy Commission’s Wind Performance Reporting System in 2014.



California Energy Commission
STAFF REPORT
Wind Energy in California

California Energy Commission

Available at energy.ca.gov/2017publications/CEC-200-2017-001/CEC-200-2017-001.pdf

Estimates of the wind energy resource over the land area of California were developed by NREL in a series of studies.[77] NREL evaluates exclusion of potential areas for reasons of the environment, national defense, land use, and topography. The data provide an estimate of annual average wind resources for states and regions. The datasets are geographic shapefiles generated from original raster data, which varied in resolution from 200 m to 1,000 m cells. Additionally, NREL published a study in 2010 that includes annual average offshore wind speeds at a 90 m height within 50 nautical miles of the California coast.[78]

The California Wind Energy Association (CalWEA) makes estimates of the current, near-term potential for further wind energy development. Considering current constraints on wind development in California, the association estimates that the state’s near-term additional developable potential is approximately 2,000 MW.[79] If wind technologies can reach higher hub heights and offshore locations, potential wind generation can be increased dramatically. The taller towers and larger blades of advanced land-based wind energy technologies access more consistent and stronger winds higher above the ground. NREL estimates that at a 140 m hub height, California’s wind energy potential can be increased by almost 25,000 square miles to unlock an additional capacity of 128 GW.[80]

The ocean waters of California also hold wind resources that may be accessed in the future. Offshore resources are estimated to offer several advantages over land-based locations, including higher capacity factors, closer correspondence of generation profiles to demand, steadier winds, proximity to coastal areas with high populations, and a need for shorter transmission infrastructure by comparison to other western wind resources. Wind generation in deep water using floating platforms will help enable access to much greater offshore wind resources. Including all locations with water depths less than 1000 m and wind speeds greater than 7 m/s, California’s technical resource capacity for offshore wind is roughly 160 GW; however, the capacity that is realistically accessible may be far lower.[81] Future offshore developers will

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[76] “Wind Energy in California,” California Energy Commission, February 2017, page 14, energy.ca.gov/2017publications/CEC-200-2017-001/CEC-200-2017-001.pdf.

[77] “Wind Data,” National Renewable Energy Laboratory, accessed December 2018, nrel.gov/gis/data-wind.html.

[78] M. Schwartz, D. Heimiller, S. Haymes, W. Musial, “Assessment of Offshore Wind Energy Resources for the United States,” National Renewable Energy Laboratory, Technical Report NREL/TP-500-45889, June 2010, nrel.gov/docs/fy10osti/45889.pdf.

[79] N. Rader, “Repowering 1980s-Vintage Turbines: Benefits & Barriers,” presentation at California Energy Commission, Sacramento, January 28, 2016.

[80] Wind Exchange, accessed December 2018, windexchange.energy.gov/maps-data/14.

[81] Walt Musial, “Offshore Wind Energy Briefing,” National Renewable Energy Laboratory, presentation at California Energy Commission Integrated Energy Policy Workshop Offshore Renewable Energy, May 25, 2016.

have work with state and federal agencies and be aware of areas that may be off-limits because of federal jurisdiction.

3.2.2 | Technology Overview

3.2.2.1 | Land-Based Technology Trends and Performance Attributes

California hosts a wide variety of wind turbines within the state borders. Turbines started operating in the state in the early 1980s and continue to be installed today. Over three decades, turbine technology has advanced greatly. While early turbines were fixed-speed and fixed-pitch, current turbines include power-electronic variable speed, variable pitch, and computer controllers. Current turbines are self-monitoring, provide condition status to operators over a distance, and contain software to regulate power output.[82]

The most common turbine size in California is 100 kW, followed by 65 kW, exemplifying that much of the state's fleet consists of older technology. The largest turbines in the state are 3.3 MW with a rotor diameter of 112 m. Analysis of reported turbine models in California by number shows that the Kenetech KCS 56-100 is the most common model, with 2,600 turbines in use. These early technology turbines were installed in the late 1980s, and they continue to produce energy. Other common turbine models include the Vestas V-17 (with more than 800), the Vestas V-15 (with more than 700), and the Bonus 250 (with almost 600). On a capacity basis, the most used turbine models are the Vestas V 90 3.0 (with 1,500 MW in use), the GE 1.5 (with almost 800 MW), the Siemens SWT 2.3 (with almost 600 MW), and the REpower 92 MM (with almost 500 MW).[83]

Figure 3-13. The U.S. Wind Turbine Database (USWTDB)

The USWTDB is a comprehensive dataset that includes the location, installation year, capacity, and turbine and manufacturing specifications for each wind turbine in the United States. An accompanying visualization tool that allows users to explore a U.S. map of wind turbines is part of this resource.

Available at: eerscmap.usgs.gov/uswtdb/

Table 3-13. Performance Attributes of 100 kW Turbine from 1990 and 3.3 MW Turbine from 2014

Attribute	Example of 100 kW Turbine, 1990	Example of 3.3 MW Turbine, 2014
Capacity	100 kW	3.3 MW
Installation Year	1990	2014
Manufacturer	Kenetech	Vestas
Model	56-100	V112-3.3
California Project Name	EDF Renewable V Project	Rising Tree North
California County	Solano	Kern
Hub Height	18 m	84 m
Rotor Diameter	17 m	112 m
Total Height	27 m	140 m
Swept Area	227 m^2	9852 m^2
Estimated Capacity Factor	21.6% (1991)[*]	25.8% (2014)[**]

[*] Data from 1991 Wind Performance Reporting System Summary. Production of 56-100 turbines divided by capacity and 8,760 hours.

[**] Weighted average of monthly capacity factors reported for large wind turbines in Tehachapi in Wind Energy in California: 2014 Description, Analysis, and Context Report.

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[82] "Wind Energy in California," 2017.

[83] "Wind Energy in California," 2017, page 24.

Table 3-13 compares a common turbine installed in 1990 with one from 2014 and demonstrates the vast change in characteristics that has occurred in the interim. The dominance of older technology, especially at high wind resource sites, represents an opportunity to modernize the fleet with resulting benefits in efficiency, grid compatibility, reduced impacts on avian species, and increased renewable energy production. Current-market technology offers considerable advantages over much of the installed equipment in the state. A broader comparison of wind technologies in the United States and California is presented below.

Table 3-14. Average Performance for Newly Installed Wind Turbines in the United States in 2017

Attribute	2017 Average U.S. Value	2017 Average California Value	Notes and Trends
Technology and Performance Attributes			
Nameplate Capacity	2.32 MW	2.26 MW	Up 8% from 2016 and 224% since 1998–1999
Capacity Factor[1]	32% (2016)	29% (2016)	Based on U.S. Energy Information Administration (EIA) data from 2016 and USWTDB
Curtailment	2.5%	0.4%	Data from 2017 Wind Technologies Market Report
Rotor Diameter[2]	113 m	113 m	Nationally, up 4% from 2016 and 135% since 1998–1999
Hub Height	86 m	80 m	Nationally, up 4% from 2016 and 54% since 1998–1999
Specific Power[3]	231 W/m^2	380 W/m^2	Nationally, down from 394 W/m^2 in 1998–1999
Long-Term Average Wind Speed at Deployment Site	7.7 m/s at 80m height	n/a	Nationally, 2017 deployments were in lower-wind-speed sites than in the previous three years
Configuration	Nearly a quarter of the larger wind power projects built in 2016 and 2017 utilized turbines with multiple hub heights, rotor diameters and/or capacities—all supplied by the same original equipment manufacturer (OEM).		
Costs and Power Prices			
Price by Capacity	$750–950/kW	n/a	Down from $1,600/kW in 2008
Installed Project Costs	$1,610/kW	$2,157/kW	Capacity weighted average
Operations and Maintenance (O&M)	n/a	n/a	Limited data availability
PPA Price	$20/MWh	n/a	Down from around $70/MWh in 2009
LCOE	$42/MWh	n/a	Interior region
Energy Market Value	$19/MWh	$28/MWh	The energy market value of wind was lowest in the Southwest Power Pool, at $14/MWh, whereas the highest-value market was California at $28/MWh.
Cost of Integration[4]	Range from $5/MWh to $20/MWh	n/a	For wind power capacity penetrations of up to or exceeding 40% of the peak load of the system

Data from eerscmap.usgs.gov/uswtdb/ and energy.ca.gov/2017publications/CEC-200-2017-001/CEC-200-2017-001.pdf

[1] Capacity factor was calculated by dividing the total wind energy production in the state and country, reported by EIA, by the installed capacity that was present before 2017 according to the USWTDB and 8760 hours.

[2] In 2008, no turbines employed rotors that were 100 meters in diameter or larger; in contrast, by 2017, 99% of newly installed turbines featured rotors of at least that diameter, with 80% of newly installed turbines featuring rotor diameters of greater than 110 meters and 14% greater than or equal to 120 meters.

[3] There has been a decline in the average "specific power" as growth in swept rotor area has outpaced growth in nameplate capacity. Turbines originally designed for lower-wind-speed sites have rapidly gained market share and are being deployed in a range of resource conditions.

[4] Grid system operators and others continue to implement a range of methods to accommodate increased wind energy penetrations. Just over 500 miles of transmission lines came online in 2017—less than in previous years. The wind industry has identified 26 near-term transmission projects that, if completed, could support considerable amounts of wind capacity.

Recent wind capacity additions were driven in part by the industry's primary federal incentive—the production tax credit (PTC)—as well as myriad state-level policies. Wind capacity additions have also been driven by improvements in the cost and performance of wind power technologies, yielding low-priced wind energy for utility, corporate, and other power purchasers. However, California is experiencing saturation of its wind resource areas, and installed land-based wind power capacity decreased by 39.6 MW between 2016 and 2017. The prospects for growth beyond the current PTC cycle remain uncertain, given declining tax support, saturation of suitable development areas, and modest electricity demand growth.[84]

Figure 3-14. 2017 Wind Technology Market Report

The 2017 Wind Technologies Market Report summarizes the major trends in the U.S. wind power market in 2017:

- Installation Trends
- Industry Trends
- Technology Trends
- Performance Trends
- Cost Trends
- Wind Power Price Trends
- Policy and Market Drivers
- Outlook

Available at emp.lbl.gov/wind-technologies-market-report

The expansion of manufacturing capabilities over the past decade has supported domestic technology growth. However, there is currently a conflicting incentive for new manufacturing growth; after the PTC expires, near-term demand for rapid growth will likely decline to more tempered demand. In addition, several original equipment manufacturers (OEMs) consolidated, which resulted in the closure of some manufacturing facilities. California has limited wind manufacturing capabilities and even saw the shutting of a plant near Tehachapi in 2014.[85] The lack of local manufacturing increases transportation costs for new turbines and therefore raises the capital costs associated with new turbine installations in California. In addition, the lack of manufacturing capabilities in California means the majority of the over 105,000 workers in wind-related jobs are not located in the state.

3.2.2.2 | Offshore Wind Energy Overview

The 2017 Offshore Wind Technologies Market Update provides a detailed discussion of key offshore wind market trends regarding technology, cost and pricing, developments, and more. The following highlights were selected from this report.[86]

The U.S. offshore wind industry took a large leap forward as commercial-scale projects were competitively selected in Massachusetts (800 MW), Rhode Island (400 MW), and Connecticut (200 MW). As of June 2018, the U.S. market has 1,906 MW of capacity that, according to developers, will commence operations by 2023 and 25,464 MW of potential capacity in the aggregate pipeline.

The U.S. pipeline continues to be led by projects along the U.S. eastern seaboard. As shown in Table 3-15, there are two projects being considered in California. The California projects, unlike those on the eastern seaboard, are still in initial planning and outreach phases and will likely be years in the making.

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[84] R. Wiser and M. Bolinger, "2017 Wind Technologies Market Report," Lawrence Berkeley National Laboratory, prepared for DOE, August 2018, emp.lbl.gov/wind-technologies-market-report.

[85] Jack Bramwell, "GE shutting down wind manufacturing in Tehachapi," *Tehachapi News*, October 22, 2014, bakersfield.com/archives/ge-shutting-down-wind-manufacturing-in-tehachapi/article_e5a8105c-7ccc-55fe-855f-b00b339d4a94.html.

[86] "2017 Offshore Wind Technologies Market Update," DOE Office of Energy Efficiency and Renewable Energy, September 2018, energy.gov/sites/prod/files/2018/09/f55/71709_V4.pdf.

Table 3-15. Offshore Wind Projects Being Considered in California

Project Name	Developer	Status	Project-Specific Capacity (MW)	Foundation Type
Morro Bay Offshore[1]	Trident Wind	Planning	765	Floating
Humboldt Bay[2]	Principle Power/EDPR/ RCEA	Planning	100–150	Floating

[1] At this time, nothing has been permitted, and the project is still in initial planning and outreach phases. A memorandum of cooperation was approved by the City Council on October 13, 2015, outlining the potential use of the outfall and requests from the City for Trident Winds to engage in significant public outreach on the project. morro-bay.ca.us/897/Trident-Winds-Offshore-Wind-Energy-Proje

[2] The Redwood Coast Energy Authority (RCEA) proposed a project off the coast of Humboldt Bay, California, and signed a public–private partnership with an industry consortium led by Principle Power LLC. redwoodenergy.org/offshore-wind-energy/

During 2017 and the first half of 2018, offshore wind auctions were held in Germany, the Netherlands, and the United Kingdom for projects with commissioning dates from 2021 to 2025. The auction results support a trend of continuing price reductions over time and resulted in awards that were termed “zero-subsidy” in Germany and the Netherlands.

The expected cost reductions driving recent record-low winning auction bids for future European projects are reported to include a combination of increased turbine and project size; continued optimization of technology and installation processes; improved market, regulatory, and auction design structures; increased competition within the supply chain; favorable macroeconomic trends; and strategic market behavior.[87]

Although many cost reductions are generally expected to be transferrable to a U.S. context,[88] their full magnitude may not be exhibited in the first tranche of full-scale commercial U.S. projects, in part because of both physical differences (e.g., water depth, distance from shore, wind resource, geotechnical, marine life) and the risks associated with deploying in a new market.

- Capital expenditures (CapEx) are the single largest contributor to the lifecycle costs of offshore wind plants and include all

Figure 3-15. State Offshore Wind Prodcurement Targets

U.S. offshore wind development is driven primarily by state procurement mechanisms, such as offshore wind renewable energy credits (ORECs) employed in New Jersey and Maryland and competitive solicitations employed in Massachusetts, Rhode Island, and Connecticut.

- **Massachusetts’ target:** 1,600 MW by 2027. Massachusetts will hold competitive solicitations at least every two years to meet the target.
- **Connecticut’s target:** 825,000 MWh/yr. Offshore wind projects will be acquired via requests for proposals (RFPs).
- **New York’s target:** 2,400 MW by 2030. New York’s Public Service Commission opened a docket to receive public comment on the optimal offshore wind procurement mechanism.
- **New Jersey’s target:** 3,500 MW by 2030. The state will obtain offshore wind capacity by issuing RFPs and offering the winners New Jersey ORECs.
- **Maryland’s target:** 2.5% of the state’s total retail electric sales. Capacity will be acquired by issuing RFPs and offering the awardees Maryland ORECs.

Please refer to the 2017 Offshore Wind Technologies Market Update for more information: energy.gov/sites/prod/files/2018/09/f55/71709_V4.pdf

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[87] W. Musial, P. Beiter, P. Schwabe, T. Tian, T. Stehly, and P. Spitsen, “2016 Offshore Wind Technologies Market Report,” U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, 2017, energy.gov/sites/prod/files/2017/08/f35/2016%20Offshore%20Wind%20Technologies%20Market%20Report.pdf.

[88] For instance, some European developers (Dutch and German) are not responsible for the costs of transmission infrastructure, as these are the financial obligation of the grid operator. It is currently expected that in the United States, the developer may have to pay for a larger share of the transmission infrastructure than in some European jurisdictions.

expenditures incurred prior to the commercial operation date (COD).

  - CapEx values have stabilized and are estimated to decline over the next few years, as shown in Figure 3-16.
  - Hornsea One (1,218 MW) in the United Kingdom, the largest offshore wind farm currently under development, has a reported CapEx of $4 billion ($3,280/kW).
- Operational expenditures (OpEx) cover all costs incurred after the COD—but before decommissioning—that are required to operate the project and maintain turbine availability to generate power.
  - Industry-wide OpEx estimates for offshore wind projects are subject to considerable uncertainty because of limited publicly available empirical data.[89] Major O&M cost drivers include the distance from the project to maintenance facilities and the prevailing metocean climate at a project site.[90]

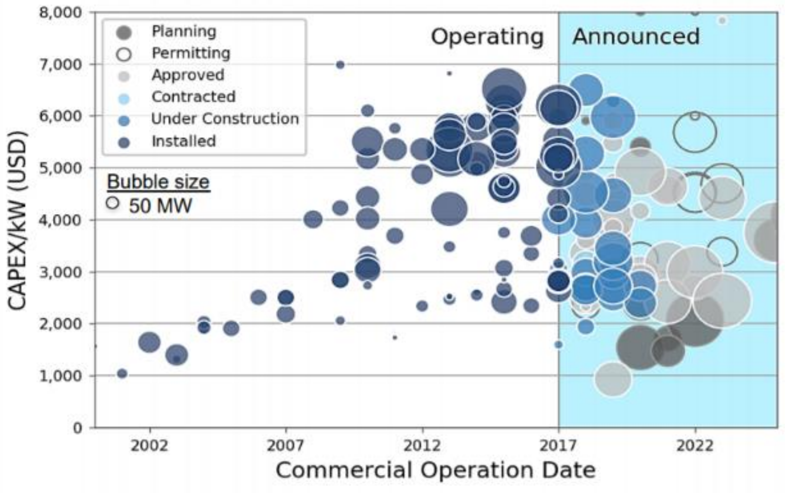

Figure 3-16. Capital Expenditures of Global Offshore Wind Projects

Although CapEx increased between 2000 and 2015, this trend is expected to reverse based on announced costs for future projects, which suggest a considerable decline between 2015 (observed) and 2025 (announced). The lowest CapEx of <$2,700/kW for projects installed in 2017 was reported for the Jiangsu Luneng Dongtai (200 MW) in China.

The global capacity-weighted average turbine rating installed in 2017 was 5.3 MW, with an average rotor diameter of 141 m and a 98 m hub height. Based on the collected sample, average turbine rating is anticipated to approach 10 MW by the mid-2020s, with the potential to exceed 11 MW later in the decade, as informed by initial data for projects with an expected COD in the period of 2023–2025. Turbine sizes in the 12–15 MW range are anticipated to be a key enabler of cost reductions that are driving the recent record-low auction results observed over the past 12–18 months. Table 3-16 provides an overview of the performance attributes of the GE 12 MW Haliade-X offshore wind turbine.

Table 3-16. Performance Characteristics for GE 12 MW Haliade-X Offshore Wind Turbine

Attribute	Value	Notes
Rated Power	12 MW	
Power Production	65 GWh per year	
Capacity Factor	63%	For typical German North Sea Sites
Rotor Diameter	220 m	With 107 m blade
Total Height	260 m	From transition piece to blade tip
CapEx	Savings of $26 million per turbine per 100 MW	When compared with previous Haliade model (rated power of 6 MW and rotor diameter of 150 m)

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[89] Although wind project owners commonly report CapEx, they rarely report OpEx. Uncertainty from the lack of available data is further amplified because it is standard practice in the offshore wind industry for turbine OEMs to offer five-year warranties.

[90] T. Stehly, D. Heimiller, and G. Scott, “2016 Cost of Wind Energy Review,” 2017, nrel.gov/docs/fy18osti/70363.pdf.

Attribute	Value	Notes
Deployment		
Timeline	First nacelle for demonstration in 2019 with first units expected to ship in 2021	
Competition	Siemens Gamesa and Senvion have both announced that they are planning to develop 10+ MW turbines	

Focusing on the operating fleet, Siemens Gamesa holds a dominant position with a market share of more than 68% of installed turbine capacity, and MHI Vestas maintains a significant minority share at 15%. Looking ahead, Siemens Gamesa, MHI Vestas, and General Electric (GE) are expected to capture more than 85% of the known pipeline.

Additional trends in offshore wind technology are shown in Table 3-17.

Table 3-17. Offshore Wind – Site Characteristics, Substructures, Logistics, and Infrastructure Trends

Offshore Wind Technology Trends

Site Characteristics

- Most installed projects around the world are located in water depths of <40 m and <50 km from shore.
- While most developers still prefer to build projects in shallow water close to shore to minimize cost, some developers have been able to build bankable projects that are in deeper waters further from shore.

Substructure Technology

- Nearly 80% of globally installed substructures are monopiles.
- As the industry has begun to expand beyond Northern Europe and into locations with more diverse site characteristics, the announced project pipeline indicates increasing penetration for floating substructures as well as increasing diversity among fixed-bottom substructures.
    - Floating technology solutions took continued significant steps to large-scale commercialization with Equinor commissioning its Hywind project, the world’s first commercial floating offshore wind farm, in October 2017 off of Peterhead, Scotland.
- Semi-taut angled mooring lines are being pioneered by companies such as SBM and GICON to provide the ability to reduce the length and size of moorings for floating platforms with larger turbines.

Vessel and Marine Logistics

- As the U.S. market matures, pressure is increasing for companies to build Jones-Act-compliant turbine installation vessels capable of installing 12 MW turbines.
    - Zentech/Renewable Resources International, AllCoast/AK Suda, and Aelous Energy Group have announced plans to deploy U.S.-flagged turbine installation vessels for projects with CODs around 2022 but have not yet initiated construction of these vessels.
- There is a persistent push to improve the U.S. port infrastructure and manufacturing capabilities supporting offshore wind components, installation, and maintenance.
- In Spain, a consortium led by Esteyco is preparing to test a self-installing turbine prototype called the Elican project; the approach is anticipated to eliminate the need for specialized installation vessels.

Electrical Infrastructure Advancements

- According to Siemens, using 66 kV cables rather than 33 kV cables can reduce the cost of offshore collector systems by up to 15%.
    - ABB, JDR, Prysmian Group, and Siemens have developed or are developing transformer technology, intra-array cables, switchgears, and equipment to enable 66 kV systems.
- Advancement of storage technology is driving an increased interest in coupled offshore wind and storage projects; in response to the Massachusetts solicitations, Deepwater Wind proposed a potential partnership with Tesla for a 40 MW/144 MWh battery, and Bay State Wind proposed a partnership with NEC for a 55 MW/110 MWh battery system.

3.2.3 | Research Initiatives

The following is a brief overview of some of the ongoing R&D initiatives related to wind power. This summary is not intended to be comprehensive.

3.2.3.1 | EPIC Investment Initiatives

The EPIC 2018–2020 Triennial Investment Plan describes the short-term R&D priorities to increase wind capacity in California.[91] Under the first and second EPIC investment plans, the EPIC program concentrated on the challenge of repowering wind energy. The latest plan recognizes the technical resource capacity for additional advanced land-based wind in California. Offshore wind is also discussed as an R&D need, particularly in deep water, where floating platform technology is needed to support wind turbines.

Table 3-18. Wind Power – Summary of Select Investment Initiatives

Initiative	Description/Goal	Potential Impact
2018–2020 EPIC Triennial Investment Plan		
Initiative 4.2.1: Advanced Manufacturing and Installation Approach for Utility-Scale Land-Based Wind Components	Support advanced manufacturing techniques of wind turbine components and introduce new composite material for wind towers and blades.	Improve the performance of wind technology and explore untapped areas with lower wind speeds. Bring new manufacturing facilities and jobs to California that will lower associated transportation costs.
Initiative 4.2.2: Real-Time Monitoring Systems for Wind	Reduce maintenance costs by introducing a proactive maintenance system (preventive approach) that avoids unexpected failures that lead to expensive repair and generation loss, minimizes downtime, and maximizes technology performance.	Provide performance monitoring for operation and condition-based maintenance, with the potential to reduce O&M costs by more than 20% for offshore turbines and more than 10% for land-based turbines.
Initiative 7.3.1: Find Environmental and Land Use Solutions to Facilitate the Transition to a Decarbonized Electricity System	Proactively find solutions to potential environmental issues tied to deployment of renewable energy systems (long permitting delays, post-construction monitoring and mitigation).	Allow deployment of offshore wind in areas with sensitive marine environmental considerations.

Table 3-19. Wind Power – Summary of Pre-2018 EPIC Initiatives

Initiative	Description
Previous EPIC Investment Plans	
Previous/Planned/Possible EPIC Investments in Wind Technologies	1. Wind turbine improvements a. GFO-16-301: Improving Performance and Cost Effectiveness of Small Hydro, Geothermal, and Wind Technologies b. GFO-16-310: Improving Performance and Cost Effectiveness of Wind Energy Technologies 2. High-elevation wind 3. Offshore wind 4. Real-time monitoring for wind

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[91] "Electric Program Investment Charge: 2018–2020 Triennial Investment Plan," California Energy Commission, CEC-500-2017-023-CMF, adopted on April 27, 2017, energy.ca.gov/research/epic/17-EPIC-01/.

Select EPIC Projects

The Energy Commission has recently funded several innovative wind projects that are featured on the Energy Commission Innovation Showcase website.[92] The following table summarizes projects that describe emerging wind technologies that are relevant to utility-scale generation.

Table 3-20: Wind – Select EPIC Projects

Project Name	Technology Type	Description
		Onshore Wind
Improving Short-Term Wind Power Forecasting Through Measurements and Modeling of the Tehachapi Wind Resource Area	Wind Forecasting	This project is coordinating atmospheric field measurements and computational modeling to more accurately predict short-term wind ramps in the Tehachapi Wind Resource Area.
Rotor-Mounted Bat Impact Deterrence System Design and Testing	Environmental Management	To mitigate the impact of wind turbines on wildlife, this project is designing and testing a bat deterrence system utilizing ultrasound transmitters mounted on a wind turbine's rotor blades.
21st Century Solutions for 20th Century Wind Projects	Retrofitting	This project seeks to design inexpensive standardized turbine upgrades to retrofit aged turbines. These low-cost updates will allow older turbines to behave like modern ones.
High-Performance, Ultra-Tall, Low-Cost Concrete Wind Turbines Additively Manufactured	Manufacturing	This project seeks to build ultra-tall towers for wind turbines on-site by using additive manufacturing with concrete materials, lowering costs of assembly while accessing more wind potential through the use of taller towers.
		Cross-Cutting
Learning from Real-World Experience to Understand Renewable Energy Impacts to Wildlife	Environmental Management	This project is using real-world data to correlate wildlife fatalities pre- and post-construction to improve predictive accuracy about the impact future renewable energy projects will have on sensitive wildlife.
Understanding and Mitigating Barriers to Wind Energy Expansion in California	Wind Forecasting	By using global re-analysis datasets, sets of observations, and high-resolution global climate simulations, this project is helping to identify the extent to which regions in California may have new vulnerabilities or opportunities as wind resources change in magnitude and availability.

3.2.3.2 | Research Initiatives from Other Funding Entities

DOE investments seek to optimize the design and operation of future wind plants to develop taller towers, larger rotors, lower-weight components, plant-level control strategies, and technologies that can benefit the industry.[93]

New York State has identified offshore wind energy as a major source of affordable renewable power for the state.[94] NYSERDA is leading the coordination of offshore wind opportunities in New York State. Offshore wind will support the state's ambitious Clean Energy Standard, which requires that 50% of New York's electricity needs be met by renewable sources by 2030. NYSERDA led the development of the New York Offshore Wind Master Plan by conducting studies and engaging with stakeholders and the public to ensure

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[92] California Energy Commission Innovation Showcase, innovation.energy.ca.gov/.

[93] "Department of Energy FY 2019 Congressional Budget Request," DOE, March 2018, energy.gov/sites/prod/files/2018/03/f49/FY-2019-Volume-3-Part-2.pdf.

[94] "New York State Offshore Wind," New York State (website), nyserda.ny.gov/All%20Programs/Programs/Offshore%20Wind.

that offshore wind is developed responsibly and transparently.[95] The state has set a 2030 offshore wind goal of 2,400 MW of power.

Table 3-21. Wind Power – Summary of DOE and State Research Initiatives

Initiative	Description/Goal	Potential Impact
U.S. Department of Energy		
Atmosphere to Electrons (A2e) Initiative	Investigate systems-level interactions influenced by atmospheric conditions, variable terrain, and machine-to-machine wake interactions.	Reduce unsubsidized wind energy cost of energy by up to 50% by 2030, compared to a $46/MWh national average in 2015.
Design and Manufacturing of Low Specific Power Rotors (Large Swept Area) for Tall Wind Applications	Strengthen the body of knowledge necessary for industry to mitigate aerodynamic loads, deploy new materials and approaches to structural design, and apply novel methods of fabrication and transportation, including evaluation of the potential for onsite manufacturing.	Overcome barriers to achieving a 10% improvement in wind plant capacity factor.
Wind Energy Grid Integration and Grid Infrastructure Modernization Challenges	Focus on the tools and technologies to measure, analyze, predict, protect, and control the impacts of wind generation on the grid as it evolves with increasing amounts of wind power.	Enable incorporation of increasing amounts of wind energy into the power system, while maintaining economic and reliable operation of the national transmission grid.
Minimize Radar Interference and Wildlife Impacts from Domestic Wind Energy Development	Support projects that evaluate proof-of-concept mitigation measures in operational settings and ready them for broad deployment.	Address the impacts of wind development on critical radar missions.
Grid Modernization Initiative (GMI)	Evaluate and refine essential reliability services (such as voltage control, frequency response, and ramp rate control) provided by wind power plants.	Utilize renewable integration studies to evaluate various power system scenarios with ever-increasing amounts of wind energy to better understand impacts on reliability of the electric power network.
Beyond Batteries Initiative	Conduct laboratory-based R&D on adaptable, wind-based, energy storage alternatives. Focus on advances in controllable loads, hybrid systems incorporating generation from all sources, and new approaches to energy storage.	Develop advances that allow for loads to be combined with generation from all sources, optimizing use of existing assets to provide grid services and increasing grid reliability.
NYSERDA		
New York State Offshore Wind Master Plan	Conducted 20 studies and engaged with stakeholders and the public to ensure the responsible and cost-effective development of offshore wind.	Generate 2,400 MW of offshore wind energy generation by 2030.
Cross-Cutting		
National Offshore Wind Research and Development Consortium	Lead the formation of a nationwide R&D consortium for the offshore wind industry, beginning with a collaboration between DOE, NYSERDA, the Renewable Consulting Group, and the Carbon Trust.	Fill the long-term vision for offshore wind under the current U.S. policy and based on the 2015 DOE Wind Vision Report, which calls for 86 GW of offshore wind capacity, representing 7% of all U.S. electricity generation, by 2050.

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[95] "NYS Offshore Wind Master Plan." NYSERDA Report 17-25. nyserda.ny.gov/All-Programs/Programs/Offshore-Wind/Offshore-Wind-in-New-York-State-Overview/NYS-Offshore-Wind-Master-Plan

DOE Wind Vision Roadmap

In March 2015, DOE released Wind Vision: A New Era for Wind Power in the United States, which explores a scenario in which wind provides 10% of U.S. electricity in 2020, 20% in 2030, and 35% in 2050. The Wind Vision report includes a roadmap of recommended actions aimed at pursuit of the vision.[96] This roadmap includes 33 high-level actions addressing nine specific action areas, such as Wind Technology Advancement, Wind Electricity Delivery and Integration, and Workforce Development. For many of the actions, a second level of detail is included. In 2016–2017, DOE updated this roadmap to reflect recent developments and experience.[97] While most of the originally identified actions are still considered relevant and important, the update effort identified several actions that either need increased emphasis or were not included in the original roadmap. These are described in Table 3-22.

Table 3-22. Wind Vision Roadmap, Areas of Need

Action	Description
Action 1.1: Improve Wind Resource Characterization	Develop long-term, high-quality public wind resource data sets for model development and validation. Extend wind forecasting—both land-based and offshore—to include seasonal and interannual variations and extreme storms, thereby reducing wind-plant financing risks and increasing wind energy value.
Action 2.1: Develop Next-Generation Wind Plant Technology; Action 2.5: Develop Revolutionary Wind Power Systems	Conduct R&D with a sustained focus on fundamental science promising major reductions in wind energy costs and development risks.
Action 3.1: Increase Domestic Manufacturing Competitiveness	Conduct full-scale demonstration of promising new manufacturing techniques to reduce commercial investment risks. Document public-domain, wind-specific manufacturing knowledge; include design codes and standards; identify manufacturing knowledge gaps.
Action 3.2: Develop Transportation, Construction and Installation Solutions	Evaluate trade-offs between large component transport and on-site manufacturing. Develop transportation best practices and a national policy on interstate transport of wind equipment.
Action 4.1: Improve Reliability and Increase Service Life	Optimize decision making for maintenance to reduce turbine downtimes and increase energy generation.
Action 5.1: Encourage Sufficient Transmission	Facilitate transmission expansion to enable transport and sharing of renewable electricity and reliability responsibilities. Optimize use of the existing transmission systems so that power-handling capacity and energy-transport capabilities are not underutilized.
Action 5.2: Increase Flexible Resource Supply	Develop electricity markets that value and encourage overall power system flexibility to aid in the integration of all energy sources. Conduct a wind integration study for the entire North American electricity network to examine opportunities and challenges associated with sharing energy services over very large regions. Proactively engage in design of electricity markets that recognize and equitably compensate all energy and reliability services.
Action 6.2: Develop Strategies to Mitigate Siting and Environmental Impacts.	Form an expanded public–private fund pool for wildlife research to reduce uncertainties of impacts from wind plant development. Expand development of wildlife-deterrent technologies to reduce harmful impacts on wildlife and reduce wind turbine curtailment.
Action 6.3: Develop Information and Strategies to Mitigate the Local	Compile extensive available information on the public impacts of wind development, conducted by an authoritative body such as the National Academy of Sciences.

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[96] "Wind Vision: A New Era for Wind Power in the United States," DOE, 2015, energy.gov/sites/prod/files/2015/03/f20/wv_full_report.pdf.

[97] E. DeMeo and R. Tusing, "2016-2017 Status Assessment and Update on the *Wind Vision* Roadmap," NREL/SR-6A20-69026, October 2017, nrel.gov/docs/fy18osti/69026.pdf.

Impact of Wind Deployment and Operation	
Action 7.1: Provide Information on Wind Power Impacts and Benefits	Conduct expanded outreach on wind benefits, costs, and other impacts. Conduct proactive outreach to policymakers and educators to promote balanced, objective information on wind energy costs, benefits, and other impacts, as well as attractive career opportunities in wind power.
Action 8.1: Develop Comprehensive Training, Workforce, and Educational Programs	Expand certified education and training programs aimed at wind careers at all levels. Pursue workforce diversity to expose wind opportunities more broadly to minorities and across the gender spectrum.
Action 9.1: Refine and Apply Energy Technology Cost and Benefit Evaluation Methods	Conduct comprehensive comparative evaluation of all sources of electricity.

3.2.4 | R&D Opportunity Areas and Technologies

To identify and prioritize R&D opportunity areas and technologies for wind power, analysts relied on state and federal government reports, industry reports, and peer-reviewed research articles. Several wind power experts were interviewed to help develop a holistic perspective on current and future wind deployment in California. Interviews focused specifically on California and aspects of its wind industry that are unique and areas for improvement. Interviewees addressed technological and non-technical factors of wind energy, as well as provided targets and metrics for wind deployment.

3.2.4.1 | Key Considerations

Expert interviews and literature review identified a number of factors worth consideration when dealing with assessment, investment, or construction of wind generation in California. These areas are broadly categorized into technical, financial, and regulatory considerations, as discussed below.

Figure 3-17. Wind Experts Interviewed

- Clyde Loutan, Principal, Renewable Energy Integration, CAISO
- Walt Musial, Offshore Wind Technology Lead, National Renewable Energy Laboratory
- Brian Naughton, Technical Project Manager, Sandia National Laboratories
- Joshua Paquette, Principle Member of the Technical Staff in Wind Energy Technologies, Sandia National Laboratories
- Nancy Rader, Executive Director, California Wind Energy Association (CalWEA)
- Mike Robinson, Deputy Director, National Wind Technology Center at the National Renewable Energy Laboratory
- Mark Rothleder, Vice President of Market Quality and Renewable Integration, CAISO
- Robert Thresher, Research Fellow, National Renewable Energy Laboratory
- Jim Walker, Co-Founder, American Wind Wildlife Institute, and past senior executive of several wind companies
- Ryan Wiser, Group Leader, Lawrence Berkeley National Laboratory

Technical Considerations

- **Investors are being drawn to other regions with higher capacity factors and greater development opportunity.** Capacity factors in California tend to be lower than in the rest of the country, especially the Plains states. The combination of older technologies and a limited number of permitted land-based wind resource areas contributes to California's lower capacity factor. Exclusion of several high-wind resource areas through state policies has also limited wind development opportunities.
- **California has a unique opportunity to repower old turbines to increase production from existing wind sites.** Repowering turbines involves installing new turbines on top of existing tower structures or completely replacing existing turbines and bases with new technologies. This opportunity area is currently receiving attention in California and was encouraged by multiple experts as an important

consideration in California. The state has some of the oldest turbines and can become a leader and expert in repowering and on-site manufacturing techniques.

- **California could establish a robust offshore wind economy**. Offshore wind installations lack a mature supporting supply chain, such as vessels for laying power lines and erecting turbines. There is also a lack of manufacturing plants for the large offshore turbines in the Pacific and around the world. California could create accessible demonstration areas and invest in the infrastructures, vessels, manufacturing facilities, and workers necessary to support an offshore wind industry. The East Coast and other parts of the world has seen substantial interest from developers, and California can become a leader on the West Coast.
- **California can become a test bed for floating offshore wind since much of the state's offshore resource requires floating turbines.** Because of the generally deep water off the coast of California, most of the offshore wind resource can be accessed only with floating turbines. As an emerging technology, California has an opportunity to become a host for floating offshore wind companies. There is also an opportunity to become a hub for international investment in floating technologies, as no country has taken the lead in this area. U.S. port infrastructure would be needed to handle offshore and floating offshore installations to comply with the Jones Act.
- **Wind assessment studies can point to new areas, both onshore and offshore, that are attractive for future development.** California can invest in assessment studies on higher wind resources and offshore resources to further refine deployment timelines and cost estimates.
- **Larger turbines can be dispatched as individual, controllable grid assets.** Larger wind turbines have enough to capacity to be dispatched as independent assets on the grid. The plant-based approach to multiple turbines is no longer necessary. Individual turbine control will allow for more grid flexibility.

Financial Considerations

- **Wind turbines can add value through ancillary services.** Thanks to their inertial rotors, wind turbines can provide ancillary services such as spinning reserves. Some wind turbines can also provide frequency regulation by controlling how the power from individual turbines is added to the grid. Accounting for these additional services for wind can make it a more attractive option when compared to other renewables in California.

Regulatory Considerations

- **There is limited and difficult terrain available for new turbine installations in the state.** Most of California's best and easiest-to-access wind resources are filled, as much California wind infrastructure is long-standing and the state does not have an abundance of great wind resource areas. Preventing some further installations is the Desert Protection Act, which keeps several remaining wind resource areas off the table for new developments. The remaining wind resource areas in the state are on complex and difficult terrain, which presents installation challenges and increases capital costs.
- **Installation of offshore wind would involve first-of-its-kind installations that have social and environmental impacts.** Siting wind turbines offshore will have impacts on local wildlife that are not well understood. Other concerns include visual obstruction of the ocean, which will affect the public. The military also has concerns about offshore structures that affect radar systems.

- **Wildlife issues have blocked wind installations in the past and will continue to limit and delay new onshore and offshore projects.** Wildlife detection and deterrence will remain an important issue, especially for sites that are not currently developed. Offshore wind will have to worry about underwater considerations as well. Smart curtailment is one way to respond when wildlife is detected.
- **Importing power from lower-cost regions may be the lowest-cost way to increase wind's contribution to the state's electricity needs, but this strategy reduces the share of power obtained locally.** Neighboring states can provide wind resources with higher capacity factors and lower costs than wind power generated in California. However, importing power from outside the CAISO has its own challenges. Additionally, there are ongoing discussions about whether CCAs should be able to purchase power from wind farms outside the ISO.

3.2.4.2 | R&D Opportunity Areas

The R&D opportunity areas in Table 3-23 expand beyond those identified in the Energy Commission's 2018–2020 Triennial Investment Plan and are based on an extensive literature review and conversations with experts.

Table 3-23. Wind Technology Research & Development Opportunity Areas

ID	Opportunity Areas	Description
O.W.1	***Aging Wind Turbines[2]**	Technologies and retrofits that support continued use of older wind turbines.
O.W.2	**Blade Improvements[2]**	Materials, installations, manufacturing, and design improvements to blades that can increase their power output.
O.W.3	**Distributed Wind Systems**	Small and low-height wind turbines that produce smaller amounts of energy but allow for lower-speed wind collection.
O.W.4	**Electrical Systems**	Systems that support the flow of electricity from individual wind turbines to substations and the grid.
O.W.5	**Environmental and Social Improvements[4]**	Processes and technologies that minimize sound, wildlife, and other environmental impacts.
O.W.6	**Floating Wind Turbines**	Offshore wind turbines that float on a stable base that is moored to the seafloor.
O.W.7	**Forecasting and Assessment**	Technology that provides better quality data and models to forecast wind speeds.
O.W.8	***High-Elevation Wind**	Higher towers and other designs that allow current popular wind structures to access higher-elevation wind.
O.W.9	**Manufacturing[2]**	Any process or technology that lowers the cost of manufacturing.
O.W.10	**Non-Traditional Wind Energy Designs**	Innovative and revisited designs for wind generation technologies.
O.W.11	**Other Monitoring and Measurement Technologies**	Monitoring and measurement technologies that deliver higher quality data.
O.W.12	***Offshore Wind**	Non-floating wind turbines and related technologies.
O.W.13	***Real-Time Monitoring Systems[3]**	Monitoring systems that report data at short intervals, allowing for adjustment and control of systems to improve power output.
O.W.14	**Testing Methods and Facilities**	Test beds, wind tunnels, and other advanced testing structures that can help lower costs and raise generation through comprehensive testing before a design goes to market.
O.W.15	**Tower and Structure Design**	Materials or design improvements to the tower that holds the blades or the substructure that supports both the tower and upper section.
O.W.16	**Transportation and Assembly[2]**	Technologies and processes that lower costs and installation time.
O.W.17	**Turbine and Nacelle Improvements[2]**	Technologies that improve the generation or lower the cost of the turbine and nacelle of traditional wind structures.
O.W.18	**Turbine and System Control**	Processes and technologies that increase wind generation by optimizing energy capture while minimizing maintenance requirements.

Several research areas overlap with EPIC investment interests. Those overlaps are given the following identifiers:
* Mentioned in EPIC Investment Plan: Previous and Planned EPIC Investments on Wind Technologies
2 Relevant to Initiative 4.2.1 Advanced manufacturing and installation approach for utility-scale land-based wind components
3 Relevant to Initiative 4.2.2 Real-time monitoring systems for wind
4 Relevant to Initiative 7.3.1 Find environmental and land use solutions to facilitate the transition to a decarbonized electricity system

3.2.4.3 | Emerging and Breakthrough Technologies

The emerging and breakthrough technologies in Table 3-24 represent more targeted opportunities for Energy Commission investment and fall within the aforementioned R&D opportunity areas.

Table 3-24. Emerging and Breakthrough Technology Matrix

ID	Name	Parallel Research Topic	R&D Opportunity Areas	Potential Impact
Onshore Wind				
W.1	**Airborne Wind Power Systems**	Innovative System Development	Distributed Wind Systems; Non-Traditional Wind Energy Designs	Wind turbines with no fixed tower base that typically float with an inflatable air casing. The project could enable wind turbines located in areas where land-based and offshore locations do not support the tower base.
W.2	**High Towers**	Legacy System Improvement	High-Elevation Wind; Tower and Structure Design	Higher structural towers to unlock the 140-meter-and-above wind resources on land in the United States.
W.3	**Land Wind Transportation**	Supply Chain	Transportation and Assembly	Reducing travel time and complications with on-land transportation to decrease installation costs. In addition, advanced transportation has the potential to enable the use of larger-capacity on-land turbines.
W.4	**Onsite Assembly**	Supply Chain	Transportation and Assembly	Advanced onsite assembly to increase the modularity of parts for transportation and enable the use of larger turbines for land applications.
W.5	**Retrofitting Existing Turbine Structures**	Legacy System Improvement	Aging Wind Turbines	Aging turbine structures that can be retrofitted to reduce total new installation cost by reusing the tower structure, thereby improving performance with up-to-date turbines.
W.6	**Shrouded Horizontal Axis Turbines**	Legacy System Improvement	Non-Traditional Wind Energy Designs	Turbine designs that feature an external tube structure. These turbines are meant to increase power production for low-wind speed applications.
W.7	**Turbines for Lower-Wind-Speed Sites**	Legacy System Improvement	Distributed Wind Systems; Turbine and Nacelle Improvements	Different turbine designs that enable more distributed wind capture at lower wind sites, which can increase total wind power generation and potentially allow consumers to install their own systems.
Offshore Wind				
W.8	**Alternative Underwater Pile Driving Operations**	Supply Chain	Environmental and Social Improvements; Offshore Wind	New methods for pile driving to address noise reduction techniques and initial installation costs, which are some of the largest upfront costs for offshore installations. Advanced techniques can lower these costs while improving environmental externalities.
W.9	**Floating Installations**	Innovative System Development	Floating Wind Turbines	Advancements to the bases of wind turbines that are floating in water to enable long system life without continued maintenance.

ID	Name	Parallel Research Topic	R&D Opportunity Areas	Potential Impact
W.10	**Floating Lidar**	Information Technology	Offshore Wind; Floating Offshore Wind; Real-Time Monitoring Systems; Other Monitoring and Measurement Systems; Forecasting	Floating lidar to allow offshore wind and floating offshore wind systems to monitor wind speeds at a number of different heights, enabling prediction of performance of existing structures and resource assessment and forecasting in undeveloped areas.
W.11	**Ice Prevention Systems**	Operations and Maintenance Improvement	Blade Improvements; Environmental and Social Improvements; Offshore Wind	Advanced systems to prevent ice accumulation that can slow or stop operation of turbines, especially offshore turbines. Such systems can keep wind turbines operational and raise capacity factors.
W.12	**Offshore High-Voltage Inter-Array Cables**	Legacy System Improvement	Electrical Systems; Offshore Wind; Floating Offshore Wind	Deployment of higher-voltage inter-array cables to lower material costs and improve efficiency of power transportation. This will improve cost, performance, and ease of integration.
W.13	**Substructure Design for Offshore Wind**	Legacy System Improvement	Offshore Wind	Selecting an optimal design for the substructure design of offshore wind resources. Results could have a significant impact on initial project cost and affect long-term performance.
W.14	**Time-Saving Assembly and Installation of Offshore Wind**	Supply Chain	Offshore Wind; Transportation and Assembly	Reduced time of assembly and installation to decrease upfront costs, improving the payback period for offshore systems.
Cross-Cutting – Information Technology				
W.15	**Advanced Simulation and System Design Tools**	Information Technology	Forecasting and Assessment	A multitude of assessment and forecasting tools that can optimize substation placement, analyze aeroelastic properties, enhance O&M data analytics, and perform many other tasks.
W.16	**Aerodynamic Devices along Blade**	Information Technology	Blade Improvements; Real-Time Monitoring Systems	Sensors located on blades that provide real-time data. These sensors are aerodynamic, so they do not affect blade speed or power production.
W.17	**Control Systems**	Information Technology	Turbine and System Control	Control systems that allow wind towers to capture more wind resources. Advanced systems work to optimize many aspects of the system, such as management of aerodynamic and mechanical loads.
W.18	**Flow Control on Grids**	Information Technology	Electrical Systems; Real-Time Monitoring Systems	Controlling power flow on the grid to allow wind turbines to provide more resilience services and smooth their power outflow. These systems make wind energy more desirable for the grid.
W.19	**Forecasting of Site-Specific Wind Resources**	Information Technology	Forecasting and Assessment	More accurate assessment of wind resources for optimal placement of wind structures. Improved forecasting increases wind's value to the electric power system.

ID	Name	Parallel Research Topic	R&D Opportunity Areas	Potential Impact
W.20	**Pitch Control**	Information Technology	Turbine and System Control	Optimal pitch-control strategies that increase energy capture and improve control of blade and drivetrain loads.
W.21	**Next-Generation Lidar**	Information Technology	Other Monitoring and Measurement Systems; Real-Time Monitoring Systems	Improved understanding of wind conditions at the turbine to improve operations and optimize wind generation.
W.22	**Radar Interference Mitigation**	Information Technology	Offshore Wind	Mitigation of offshore wind turbines' interference with radar in shipping areas or sensitive military zones. This interference prevents installation, so mitigation can open potential sites.
W.23	**Test Facilities**	Information Technology	Testing Methods and Facilities	Rigorous testing of all wind system components to identify potential issues and optimize operation before installation.
Cross-Cutting – System Improvement				
W.24	**Advanced Multi-Stage Geared Approaches**	Legacy System Improvement	Turbine and Nacelle Improvements	Improvements to conventional wind turbine design to lower the weight and cost.
W.25	**Aeroelastic Techniques to Shed Load**	Legacy System Improvement	Blade Improvements	Mitigation of high dynamic loading to improve wind system efficiency. Both active and passive load alleviation technologies are included.
W.26	**Direct-Drive Systems**	Legacy System Improvement	Electrical Systems; Turbine and Nacelle Improvements	Direct drive systems that rely on permanent magnet generators (PMGs) to operate. These systems currently exist and are more efficient at lower weights than traditional gear box designs. The system's lower weight and complexity can reduce costs, especially for higher-megawatt turbines. The gearbox-free design lowers the chance of breakdown later in the turbine life. These systems can be difficult to install, which lowers their ease of integration.
W.27	**Downwind Rotor Turbines**	Innovative System Development	Non-Traditional Wind Energy Designs	Revisiting downwind turbines with modern techniques. These systems do not require a yaw mechanism, which could theoretically lower costs. The idea was tested when wind turbines were first being deployed; applying more up-to-date knowledge could result in more efficient systems.
W.28	**Flexible Blades**	Legacy System Improvement	Blade Improvements	Using materials that allow blades to be more flexible, which has shown potential to increase system efficiency.
W.29	**High-Temperature Superconducting (HTS) Generators**	Innovative System Development	Electrical Systems; Turbine and Nacelle Improvements	Low-weight, zero-resistivity superconducting generators that can pave the way for larger offshore direct-drive systems.

ID	Name	Parallel Research Topic	R&D Opportunity Areas	Potential Impact
W.30	**Medium-Speed Systems**	Legacy System Improvement	High-Elevation Wind; Turbine and Nacelle Improvements	Hybrid systems that typically use multiple gears but a larger initial magnetic system. These systems enable larger-capacity generation but use a fraction of the rare earth metals as standard generators, which lowers cost of production.
W.31	**Permanent Magnet Generators (PMGs)**	Legacy System Improvement	Electrical Systems; Turbine and Nacelle Improvements	Essential components for enabling medium and direct-drive systems that allow for larger-megawatt systems.
W.32	**Power Converters**	Legacy System Improvement	Electrical Systems	Methods to lower power converter weight. This component is typically located at the turbine, so lowering its weight decreases installation time and costs.
W.33	**Reducing Nacelle Mass**	Legacy System Improvement	Offshore Wind; Floating Offshore Wind; Turbine and Nacelle Improvements; High-Elevation Wind; Transportation and Assembly	Methods to lower the mass of the nacelle, which would reduce material and transportation costs. These factors directly affect the cost, performance, and ease of integration of the wind turbine. In addition, taller towers may not be able to support, or have cranes that can install, nacelles that are too heavy.
W.34	**Silicon Carbide for Power Conversion Electronics**	Legacy System Improvement	Electrical Systems	Using silicon carbine in power conversion electronics to eliminate the need for complex liquid cooling systems that increase installation and operating costs.
W.35	**Wind Turbine Noise Reduction**	Legacy System Improvement	Environmental and Social Improvements	Methods to address noise issues with wind turbines that prevent siting in some locations and negatively affect the public. Lowering noise can improve the public standing of wind resources and open new development sites.
Cross-Cutting – Operations and Maintenance				
W.36	**Blade Repair Solutions**	Operations and Maintenance Improvement	Aging Wind Turbines	Advanced UV systems and other innovations to reduce repair time and allow for easier in-place blade repair. Reducing man-hours and preventing blade replacement will lower long-term O&M costs and allow turbines to operate longer.
W.37	**Coatings for Corrosion and Erosion**	Operations and Maintenance Improvement	Blade Improvements	Coatings that reduce leading-edge corrosion to reduce future O&M needs, which lowers cost of operation.
W.38	**Laminate Layouts**	Operations and Maintenance Improvement	Blade Improvements	Improved laminate layouts to increase efficiency.
W.39	**Nondestructive Inspection of Blades**	Operations and Maintenance Improvement	Blade Improvements	Drones and virtual reality assisted assessment tools to eliminate the need to send people up wind towers. This will improve the overall safety of installation and maintenance.

ID	Name	Parallel Research Topic	R&D Opportunity Areas	Potential Impact
W.40	**Protecting Turbines against Extreme Events**	Operations and Maintenance Improvement	Environmental and Social Improvements; Offshore Wind; Floating Offshore Wind; Turbine and Nacelle Improvements	Offshore and on-land turbine systems that can survive a weather event. In areas where extreme weather events are likely, failure fears prevent systems from being sited, so resilient systems are essential for deployment in certain areas.
Cross-Cutting – Supply Chain				
W.41	**Alternatives to Rare Earth Technologies**	Supply Chain	Environmental and Social Improvements; Turbine and Nacelle Improvements	Alternatives to rare earth metals used in permanent magnet synchronous generator (PMSG) wind turbines. Rare earth metals are in high demand and will increase in cost as deployments increase. Finding substitutes will allow for less expensive turbines with no material restrictions.
W.42	**Automated Component Manufacturing**	Supply Chain	Manufacturing	Removing manual labor to lower costs and allow for more precision in manufacturing. The lower initial costs will improve lifetime performance. The enhanced precision will make it easier to integrate parts as well.
W.43	**Concrete Structure Fabrication**	Supply Chain	Manufacturing; Tower and Structure Design	Changing the mix of concrete and metal in the tower structure of wind turbines to decrease installation time, improve structural stability, and enable construction of taller towers.
W.44	**Metal Component Production**	Supply Chain	Manufacturing	Improving the efficiency of metal component production to lower initial costs and improve the payback period of the wind system.
W.45	**New Materials for Blades**	Supply Chain	Blade Improvements	New blade materials to reduce drag and increase efficiency of wind power production.
W.46	**New Materials for Towers**	Supply Chain	Tower and Structure Design	New lower-weight tower materials to decrease installation time and lower initial installation costs.
W.47	**Reduce Dependence on Heavy Lift Systems**	Supply Chain	Transportation and Assembly	Methods to reduce use of heavy lift systems, which are expensive and time-consuming to operate. Reducing their use can decrease installation costs.

Chapter 4| Non-Variable Renewable Energy

California has significant resources for expansion of non-intermittent renewable capacity, including high-temperature geothermal resources, enhanced and low-temperature geothermal technologies, millions of tons of biomass resources, and underdeveloped in-conduit hydropower from irrigation and municipal water systems.

Non-variable renewable energy resources can provide the flexible generation needed to match the high penetration of intermittent renewables in the grid.

Challenges

- Despite known value to the grid, the environment, and society, cost remains a major barrier for power from non-variable renewable resources.

Opportunities

- Non-variable renewables could offer advantages over energy storage technology as a complement to intermittent renewables.
- Bioenergy is critical in the portfolio of options to address issues caused by the enormous number of dead trees in California's drought-stricken forests.

Biopower

Bioenergy projects can provide grid services, such as flexible generation and energy storage. In spite of known value to the grid, to the environment (including forest, agriculture, and urban organic wastes) and society, the costs of bioenergy systems remain a major barrier.

Geothermal

Geothermal power has long been considered as a baseload resource. Advancements in the technology make it possible for it to provide ancillary and on-demand services, such as load-following, spinning reserves, non-spinning reserves, and replacement or supplemental reserves.

In-Conduit Hydropower

Small-scale hydroelectric power can tap into existing municipal water and irrigation infrastructure to increase renewable power generation and offset water system energy requirements. Many in-conduit installations can use turbines and equipment that are readily available.

4.1 | Bioenergy

In 2017, gross bioenergy generation in California totaled 6,565 GWh (not including production from publicly owned treatment works). Since bioenergy requires energy inputs to generate power, the resulting net generation in 2017 was 5,767 GWh, which accounted for roughly 2.8% of in-state total power generation and 9.5% of in-state renewable power generation.[98] In 2017, the 93 operating biomass plants in California had a total capacity of 1,305 MW.[99]

Bioenergy is produced from two major pathways: direct combustion of biomass and combustion of biogas, which is produced from digesters, landfills, and municipal solid waste (MSW). Different types of gas are also produced by putting waste through processes such as gasification and pyrolysis. Of the 5,767 GWh of net generation in 2017, 3,595 GWh was from direct combustion (891 MW capacity), and 2,172 GWh was from biogas combustion (414 MW capacity).

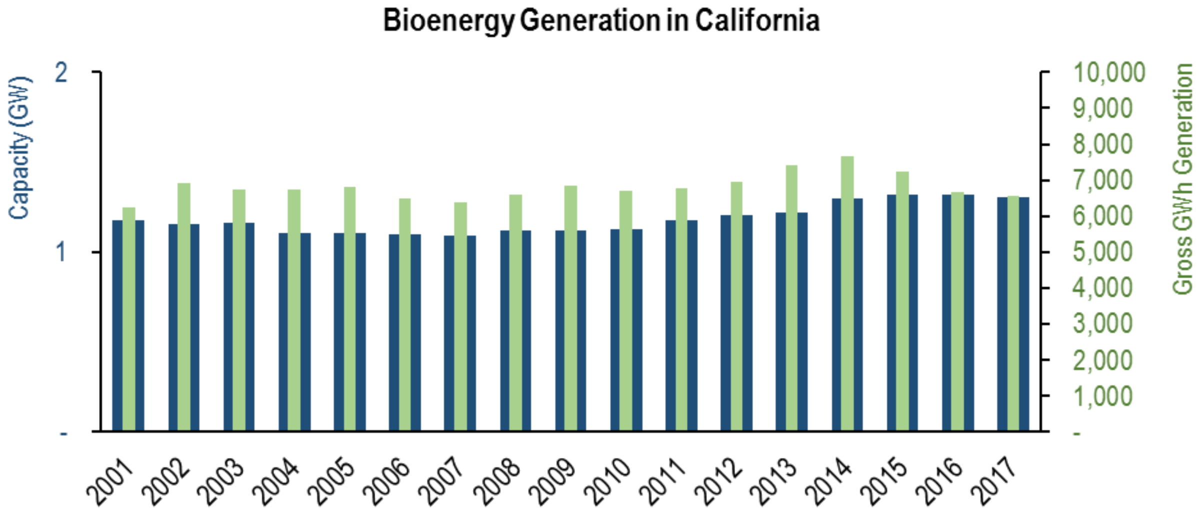

Figure 4-1. Bioenergy Generation in California from 2001 to 2017

Data from energy.ca.gov/almanac/renewables_data/biomass/

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[98] "2017 Total System Electric Generation," California Energy Commission, data as of June 21, 2018, energy.ca.gov/almanac/electricity_data/total_system_power.html.

[99] "California Biomass and Waste-To-Energy Statistics and Data," California Energy Commission, accessed December 6, 2018, energy.ca.gov/almanac/renewables_data/biomass/.

Figure 4-1 shows how bioenergy generation in California has grown in gross generation (GWh). California bioenergy production dates back before 1980, with the technology becoming an essential part of the state's renewable energy mix in the late 1980s. Early biomass plants were in the range of 2–10 MW in capacity, while later builds reached closer to 50 MW.[100] There has been growth in the number of landfill gas and digester gas facilities in California, particularly in recent years. However, that growth has been counteracted by a decrease in woody biomass facilities as their PPAs expire and are not renewed. This has resulted in small fluctuations in the number of gigawatt-hours produced from bioenergy since 1990.

DOE efforts in biomass conversion to energy focus on biofuels. DOE research and cost projections are therefore focused on pricing comparisons to gasoline and oil. International development of biomass-to-electricity systems is more prolific because of different market structures and regulations in place globally. The International Renewable Energy Agency (IRENA) estimated a range of LCOE in 2014 and projected costs to 2025 for four biomass-to-electricity systems: stokers, gasification, co-firing, and anaerobic digestion (AD). These results are shown below.

Table 4-1. International Biomass to Electricity Cost Projections (IRENA)

	2014 (Low Range)	2014 (High Range)	2025 (Low Estimate)	2025 (High Estimate)
Stoker	6 cents/kWh	21 cents/kWh	5 cents/kWh	19 cents/kWh
Gasification	7 cents/kWh	23 cents/kWh	6 cents/kWh	20 cents/kWh
Anaerobic Digestion	6 cents/kWh	14 cents/kWh	5 cents/kWh	12 cents/kWh
Co-Firing	4 cents/kWh	12 cents/kWh	4 cents/kWh	11 cents/kWh

Source: "Renewable Power Generation Costs in 2014." IRENA. January 2015. irena.org/DocumentDownloads/Publications/IRENA_RE_Power_Costs_2014_report.pdf.

4.1.1 | Resource Availability

Bioenergy is produced from a variety of feedstocks in California. The feedstocks can be grouped into three overarching types: agricultural residue biomass, forest residue and thinnings, and municipal wastes. A list of some of the biomass feedstocks used in California is given in Table 4-2 below. The use of these biomass resources typically provides a dual benefit: producing electricity and avoiding landfilling or other non-beneficial disposal of the feedstocks.

Table 4-2. Types of Biomass Feedstocks Used in California

Agricultural Residue Biomass	Forest Residues and Thinnings	Municipal Wastes
• Orchard and Vineyard Crops • Field and Seed Crops • Vegetable Crops • Food Processing Residues • Animal Manures	• Forest Thinnings and Slash • Shrubland Treatment Biomass (Chaparral) • Mill Residues	• Biomass (organic) Fraction of Municipal Solid Waste (MSW) • Source Separated Food Waste • Biosolids from Wastewater Treatment Operations • Landfill Gas • Sewage Digester Gas • Wood Component of Construction and Demolition Debris • Greenwaste

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[100] "Biomass Energy Production in California: The Case for a Biomass Policy Initiative," National Renewable Energy Laboratory, November 2000, nrel.gov/docs/fy01osti/28805.pdf.

Biomass electricity in California is produced by combusting or decomposing the above materials as illustrated in Figure 4-2. The electricity generation potential for biomass is tied to the available waste streams and their quantity. Given the large variety of landscapes and agricultural activities in California, along with the state's large population and numerous large urban areas, the resource and generation potential from biomass is extremely high.

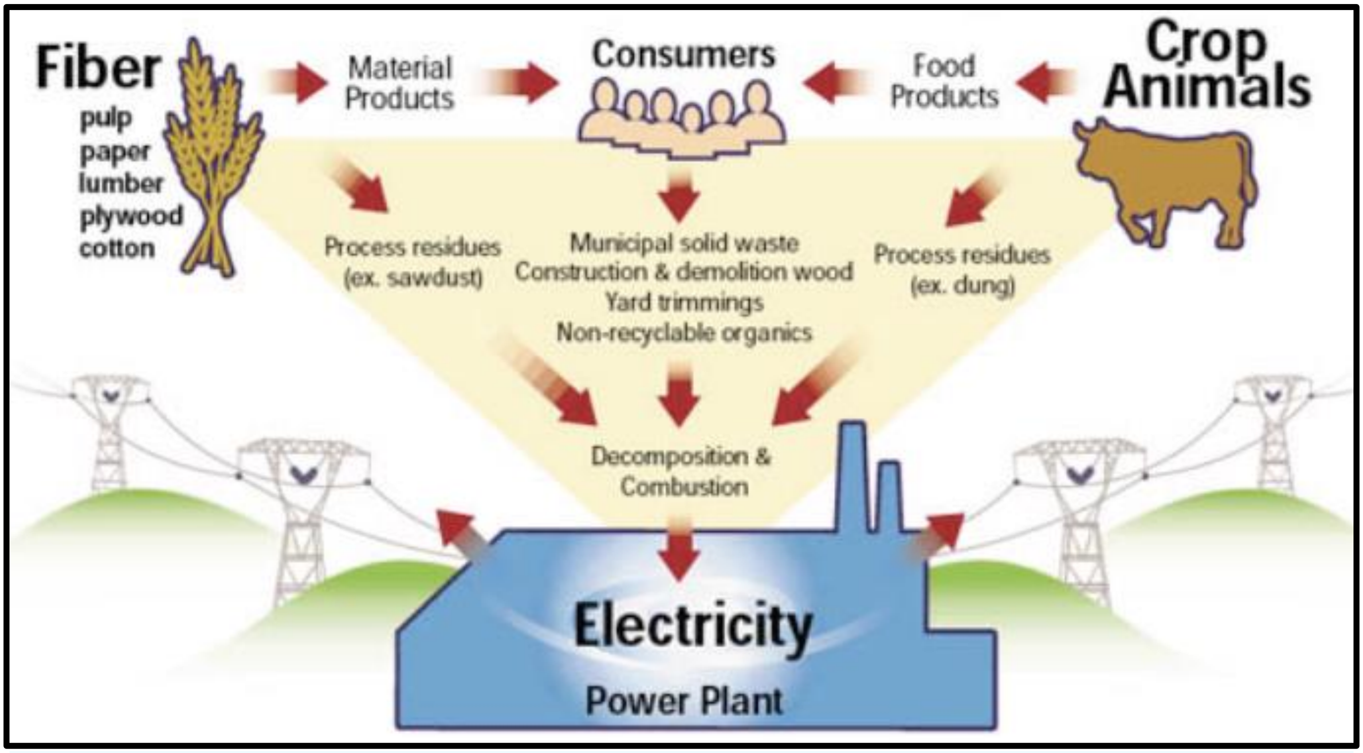

Figure 4-2. Biomass-to-Electricity Pathways

Source: California Energy Commission (energy.ca.gov/biomass/index.html)

Table 4-3 contains estimates of biomass resource potential in California. It should be noted that the potentials are divided between gross and technically available biomass resources; differences may be due to agronomic and ecological requirements, environmental requirements, limitations to collection due to topography and locations, inefficiencies in biomass collection and handling, and other constraints. These conditions limit how much of the "gross" biomass resources can be collected, as indicated in "technical" resource availability. The technical resource potential includes biomass materials currently used in existing bioenergy, feed, mulch, compost, bedding, and other markets.

Table 4-3. Resources and Generation Potentials from Biomass in California

	Resource Availability (Million BDT/y)		**Electrical Capacity** (MWe)		**Electrical Energy** (TWh)	
Category	Gross	Technical	Gross	Technical	Gross	Technical
Agriculture	25	12.1	2,360	990	15	7.4
Forestry	27	14.3	3,580	1,910	27	14.2
MSW	26	9.0	3,957	1,749	29	13
Total	**78 Million BDT/yr**	**35 Million BDT/yr**	**9,897 MWe**	**4,650 MWe**	**71 TWh**	**35 TWh**

Source: An Assessment of Biomass Resources in California, California Biomass Collaborative, March 2015, CEC (CEC-500-11-020).

California currently uses five million bone-dry tons (BDT) of woody biomass a year.[101] Most of this biomass is not provided by the forest but instead comes from agricultural residues, urban wood waste, and sawmill residues.

The current number of large wildfires in California requires economical and climate-sensitive ways to lower the risk of starting new wildfires. One of the largest causes of new wildfires is the number of dead trees that are part of the tree mortality crisis. Many new technologies could benefit from reducing wildfire risk and using downed and dead trees. It is estimated that 129 million trees have died in California's forests because of climate change, drought, bark beetle infestation, and high tree densities, among other factors. The tree resource alone could provide an additional three million BDT a year. Woody biomass use for bioenergy presents a way to address renewable and clean energy goals while mitigating wildfire risks.

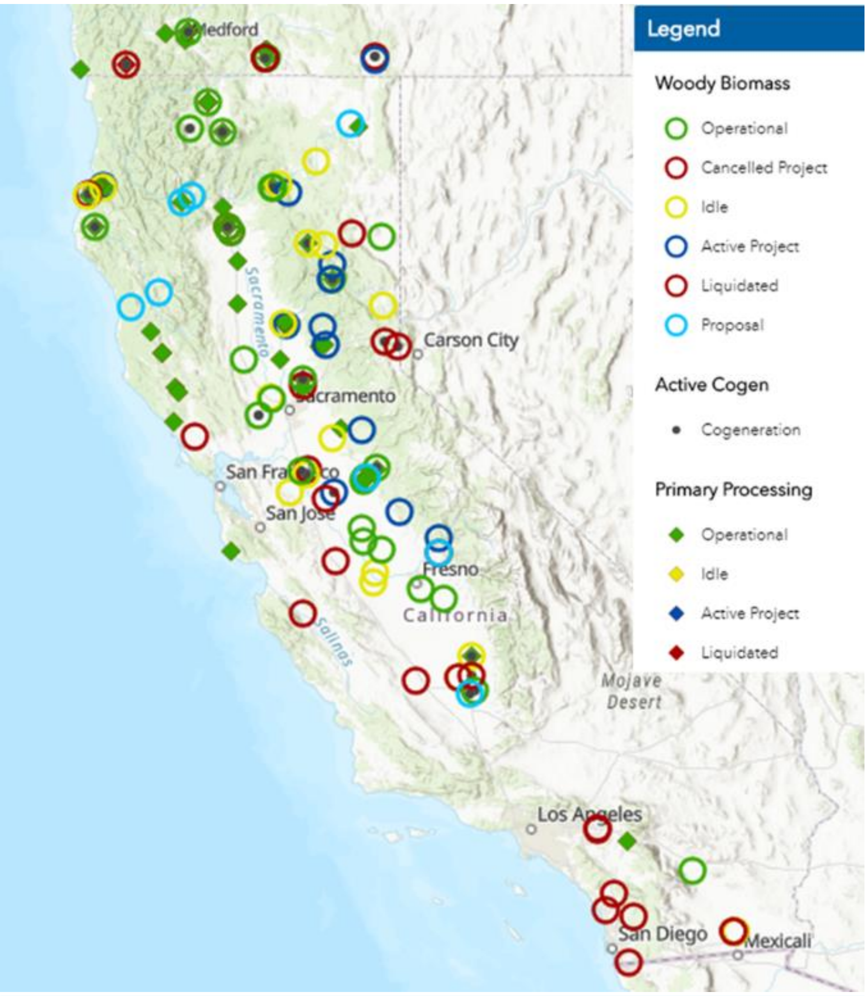

Figure 4-3. Woody Biomass Utilization Infrastructure

The University of California Cooperative Extension maintains a database of operating and idled woody biomass processing, gasification, and combustion facilities. This data is presented graphically in the image above. The website also contains information on national forest biomass flow with an equally impressive accompanying image. These materials provide context to the state of woody biomass collection and use in California.

Available at ucanr.edu/sites/WoodyBiomass/Technical_Assistance/California_Biomass_Power_Plants/

However, it is not currently economical to collect woody biomass from forests without a subsidy or value-added byproduct such as saw logs. Transportation costs typically make forest-sourced biomass the most expensive woody feedstock. About half of collectable woody biomass is typically left on the forest floor or piled and burned onsite at forest operations. Collection and transportation to centralized facilities remains a problem for all types of biomass.

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[101] Stephen Kaffka et al., "Biomass Energy in California's Future: Barriers, Opportunities, and Research Needs. Draft Report," UC Davis, December 2013, biomass.ucdavis.edu/wp-content/uploads/Task-5-FINAL-DRAFT-12-2013.pdf.

While woody and forestry resources experience problems with collection and transportation, MSW facilities, wastewater treatment plant (WWTP) facilities, and agricultural producers can experience issues with grid interconnection. Many of these facilities do not produce enough power to require export to the grid. In cases where generation is high enough to export to the grid, a lack of appropriate grid equipment can restrict integration, especially for smaller-capacity installations (<3 MW). To aid in bioenergy use, guaranteed purchasers operating with PPAs are useful.

MSW and WWTP plants do have an alternative for their renewable natural gas, landfill gas, and biogas in the form of pipeline injection. By combining a lower-quality gas resource with traditional natural gas, these facilities can receive revenue strictly for biogas production without worrying about local electricity generation. Pipeline injection does require capital investment to install the piping and injection facilities, which can limit deployment at smaller-scale facilities.

The availability of the biomass resources specifically for bioenergy applications is further dependent on economic factors, conversion technology, permitting/regulatory compliance costs, and competition with other end uses and markets. However, if all these obstacles were overcome and the entire biomass technical resource was captured, 35 TWh could provide roughly 17% of the total electricity produced in-state (206 TWh) in 2017 and would be a 500% increase over 2017 biomass generation levels.[102]

4.1.1.1 | Small-Scale Bioenergy SB-1122

Small-scale California bioenergy sector development has been enhanced by the passage of Senate Bill (SB) 1122 in 2012. This legislation directed the three major IOUs[103] to procure at least 250 MW of small-scale biomass-derived electricity (3 MW or smaller) from three basic categories of urban, agriculture, and forest. Landfill gas conversion to electricity is not covered by SB 1122.

SB 1122 directed the CPUC to conduct proceedings for the procurement of small-scale bioenergy power. As part of the proceeding, a study was prepared that contained the electrical generation potential for small-scale bioenergy in California. Table 4-4 below lists the potential generation per the BioMAT categories. From a resource perspective, the estimates indicate that there is roughly four times more material technically available to meet SB 1122's procurement requirements.

Table 4-4. Small-Scale Bioenergy Systems Potential by Category and Utility

Utility	Category 1 – Urban (MW)	Category 2 – Agriculture (MW)	Category 3 – Forest (MW)	Total Potential (MW)	SB 1122 Targets (MW)
Pacific Gas & Electric	101	340	277	718	**109**
Southern California Edison	115	118	15	249	**118**
San Diego Gas & Electric	26	1	2	29	**23**
Total Potential	**241**	**460**	**295**	**996**	**250**
SB 1122 Targets	**110**	**90**	**50**	**250**	

Source: "Draft Consultant Report: Small-Scale Bioenergy Resource Potential, Costs, and Feed-in-Tariff Implementation Assessment." Prepared by Black & Veatch for the California Public Utilities Commission. April 2013. ftp2.cpuc.ca.gov/PG&E20150130ResponseToA1312012Ruling/2013/04/SB_GT&S_0874313.pdf.

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[103] Pacific Gas & Electric, Southern California Edison, and San Diego Gas & Electric

Small-scale facilities' (3 MW or less) LCOE has been the subject of review because of the implementation of SB 1122 and the BioMAT program. The LCOE of the new systems to be built exceeds that of other sources of renewable power. Nonetheless, the purpose of SB 1122 is to incentivize this higher-priced power with higher electricity prices to be obtained from the utilities. As of December 2018, BioMAT PPAs can garner \$127.72/MWh for Category 1, \$187.72/MWh for Category 2, and \$199.72/MWh for Category 3.[104]

4.1.2 | Technology Overview

4.1.2.1 | Combustion Technology Trends and Performance Attributes

Biomass electricity is commonly generated using direct combustion methods. These processes are renewable because their feedstocks can be continuously generated at short time scales. Developers in California built numerous biomass-fired power plants in forested regions in Northern California. The predominant biomass utilization of these 1980s era plants was to produce biomass power to generate both heat and electricity.

However, biomass electricity generation still generates GHG emissions that affect the environment and human health, such as ash, solid particles (e.g., PM10) and condensable compounds, and compounds in the gaseous phase (e.g., CO_2, CO, NO_x, and SO_x). The lifecycle GHG emissions of biomass are typically considered to be close to zero because the emissions are offset by avoiding non-beneficial end-uses and during growth of the biomass (e.g., trees that end up as forestry residue). Stoker boilers and fluidized bed boilers are the primary combustion technologies in use in California today.

Many of the first-generation biomass power plants developed in California use stoker boilers. Known for their fairly simple design (many were converted coal furnaces) and long history of commercial deployment, these boilers are designed to combust biomass fuel as it rests on a grate. Stokers are known for their rather simple operations, relatively low O&M cost, and low parasitic power load.

As more types of economical wood waste (e.g., agricultural byproducts such as nut shells and pits) became available and contained a broader array of material characteristics (e.g., moisture content, high heat value, chemical makeup, and smaller particles), combustion engineers began deploying fluidized bed boilers. The boilers use an inert medium (sand) that is heated and suspended so that biomass combustion is conducted in suspension, ensuring more complete combustion. The two types of fluidized bed are bubbling and circulating.

Table 4-5. Characteristics of a Typical Biomass Power Plant in California

Attribute	Typical California Biomass Power Plant
Electricity Generation Method	Combustion/steam turbine
Technology Type	Grate stoker
Capacity	20 MW
Construction Cost	\$60–\$80 million
Material Processed	160,000–200,000 tons per year

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[104] PG&E BioMAT Participant Platform. pgebiomat.accionpower.com/biomat/home.asp

Biomass Transportation Distance	Up to 50 miles
Value of Delivered Biomass	\$15–\$60 per BDT
Average Electricity Production Cost	\$0.07–\$0.10 per kWh
2010 California PPA Prices	\$0.11 per kWh or higher

Source: Gareth J. Mayhead. “Biomass to Electricity.” University of California, Agriculture and Natural Resources. October 21, 2010. ucanr.edu/sites/WoodyBiomass/files/78993.pdf.

Co-firing biomass in a coal-burning power plant is a near-term, low-cost option for efficiently and cleanly converting biomass to electricity by adding biomass as a partial substitute fuel in high-efficiency coal boilers. However, there are no longer any coal-burning power plants in California, nor are any ever expected to operate in the state again, so this option is no longer viable in California.

4.1.2.2 | Gasification Energy Overview

Gasification systems generate electricity through transformation of biomass into a synthesis gas, also known as syngas. This syngas is then combusted in an internal combustion engine generator set. Gasification is the thermochemical conversion of carbon-containing biomass, such as woody biomass, into a syngas under controlled temperature and oxygen conditions. It is difficult to obtain high-quality syngas using current gasification technologies. These processes currently result in a producer gas with more contaminants than syngas because the technologies use air as a process medium instead of steam or oxygen.

Table 4-6. Size and Generation Capacity of Combustion and Gasification Plants in California

	Current-Generation Biomass Combustion Power Plant	Current-Generation Integrated Gasification/Combustion Power Plant	Next-Generation Thermo-Chemical Conversion Power Plant
Plant Size (BDT/day)	450	450	450
Electricity Conversion (kWh/BDT)	1000	1200	1400
Total Electricity (MWh/day)	450	540	630
Average Net Energy Efficiency	20%	22%	28%

Source: Marc Carreras-Sospedra et al. “Assessment of the Emissions and Energy Impacts of Biomass and Biogas Use in California.” California Air Resources Board. February 27, 2015. arb.ca.gov/research/apr/past/11-307.pdf.

Syngas is composed of hydrogen (H_2), carbon dioxide (CO_2), methane (CH_4), and carbon monoxide (CO) and has a heating value that ranges typically from one-fourth to one-half that of natural gas. Table 4-7 contains information on different syngas compositions that were obtained from different starting raw materials. Gasification also produces a biochar byproduct, which can be used as a fertilizer and soil amendment and serves as a carbon sequestration medium.

Table 4-7. Syngas Composition Obtained from Gasification of Different Raw Materials

Feedstock	H_2 (mol %)	CO (mol %)	CH_4 (mol %)	CO_2 (mol %)	HHV (MJ/m^3)
Coal	25–30	30–60	0–5	5–15	7–15
Petcoke	22–30	39–48	0–1	18–34	8–11
Biomass	5–16	10–22	1–6	8–20	4–7
MSW	8–23	22–24	0–3	6–15	3–7

Source: Juan Camilo Solarte-Toro et al. “Evaluation of biogas and syngas as energy vectors for heat and power generation using lignocellulosic biomass as raw material.” *Electronic Journal of Biotechnology*. Vol. 33, May 2018: 52–62. sciencedirect.com/science/article/pii/S0717345818300101.

Modular gasification technologies are also being developed and exist as community-scale biomass-to-electricity systems. These systems are an important part of the state's solution to the tree mortality crisis, and they help maintain critical operations and services during grid outages. Currently, there are four community-scale facilities in early-stage development in California. Biomass gasification technologies reduce carbon dioxide equivalent (CO_2e) emissions by 30% compared to biomass combustion technology.

4.1.2.3 | Pyrolysis

Pyrolysis uses the same processes as gasification but operates in a temperature range of 300°C–600°C. Unlike gasification, pyrolysis involves heating biomass material in the absence of air. The result is a liquid bio-oil, as well as a syngas and solid char material. All three phase elements produced by this process can be used for energy; however, the bio-oil, which is similar to crude oil, must be processed to remove contaminates such as acids before it can be used as fuel.

Pyrolysis is typically performed either quickly or over longer time periods (hours to days) in processes known as fast pyrolysis and slow pyrolysis, respectively. The slow pyrolysis process results in more solid material and takes place at lower temperatures (~300°C). This process has been used in various forms for thousands of years. Fast pyrolysis takes place over a matter of seconds and at higher temperatures (~500°C), with the resulting stream containing much more liquid bio-oil (~65% of product stream).

4.1.2.4 | Anaerobic Digestion

The biological decomposition of solid biomass into a gaseous form is completed by several different technologies and processes. Unlike gasification, these processes occur naturally but are centralized and driven by technologies and processes to increase efficiency, which raises the amount of energy captured from biomass feedstocks. Currently, anaerobic digesters are the primary way to generate biogas from organic waste in California. Waste inputs to anaerobic digesters include food wastes, WWTP sludges, dairy waste, and other organics.

There are three primary types of anaerobic digesters: covered lagoon digesters, complete mixed digesters, or plug flow digesters. AD systems are often characterized as wet and dry technologies. Wet AD systems are designed for high-moisture-content feedstock types and typically include covered lagoon and complete mix digesters. Dry AD systems are designed for relatively low-moisture-content feedstock (e.g., yard waste) and are typically plug flow digesters.

The U.S. Environmental Protection Agency maintains a database of livestock AD projects in the United States. The website currently lists 20 operational livestock AD projects in California, all of which operate with dairy cows. Of those, 14 provide their annual electricity production numbers. They are summarized in Table 4-7. AgSTAR estimates that a typical on-farm anaerobic digester costs between $400,000 and $5,000,000, depending on the size of operation, with an average cost of $1.2 million.[105]

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[105] "Anaerobic Digesters," *Exploring Energy Efficiency & Alternatives*, accessed December 6, 2018, e3a4u.info/energy-technologies/anaerobic-digesters/economics/.

Table 4-7. List of Livestock Anaerobic Digesters in California with Reported Electricity Generation

City	Digester Type	Year Operational	Number of Dairy Cows	Biogas Generation (ft^3/day)	Electricity Generation (MWh/yr)	Biogas End Use
Bakersfield	Covered Lagoon	2013	15,500	600,000	16,206	Electricity
Bakersfield	Covered Lagoon	2013	1,700	50,000	4,205	Electricity
Bakersfield	Covered Lagoon	2018	9,700	270,000	7,600	Cogeneration; Refrigeration
Bakersfield	Covered Lagoon	2018	7,000	360,000	6,700	Electricity; Compressed Natural Gas
Buttonwillow	Covered Lagoon	2018	7,000	n/a	7,600	Electricity
Galt	Complete Mix	2013	1,700	90,000	1,830	Electricity
Galt	Covered Lagoon	2013	1,810	n/a	2,190	Cogeneration
Hanford	Covered Lagoon	2016	14,500	n/a	7,600	Electricity
Lindsay	Covered Lagoon	2004	1,500	n/a	5,072	Electricity; Compressed Natural Gas
Lodi	Covered Lagoon	2004	3,213	89,148	2,233	Electricity
Madera	Covered Lagoon	2017	4,800	n/a	4,800	Electricity
Marshall	Covered Lagoon	2004	417	14,832	346	Cogeneration
Modesto	Complete Mix	2009	2,513	165,000	3,324	Cogeneration
Riverdale	Covered Lagoon	2016	4,000	n/a	6,400	Electricity

Source: "Livestock Anaerobic Digester Database." AgSTAR, U.S. Environmental Protection Agency. Accessed December 6, 2018. epa.gov/agstar/livestock-anaerobic-digester-database.

Wastewater Treatment Plants/Publicly Owned Treatment Works

WWTPs, also referred to as publicly owned treatment works (POTWs), operate some of the largest anaerobic digesters in the state. There are roughly 150 POTWs that utilize AD as an inherent component of their treatment process. Biogas produced at POTWs is roughly 60% methane and 40% carbon dioxide. These digesters can handle more material than just what is available from wastewater inputs. Food waste, much of which is currently discarded in landfills, is a high-energy organic feedstock that can be co-digested in an AD facility. A 10% volumetric increase in food waste can double the biogas produced. This increase in biopower can lead to the export of electricity, storage of electricity for on-site use during periods of peak demand, use as a power source for electric vehicles under the low-carbon fuel standard, or direct on-site use.

4.1.2.5 | Biogas, Landfill Gas, and Producer Gas Combustion

Unlike gasifiers' producer gas, the resulting product of AD processes is called biogas, which consists of methane (CH_4) and carbon dioxide (CO_2) with very small amounts of water vapors and other gases. The carbon dioxide and other gases can be removed from this mixture, resulting in only methane, which is the primary component of natural gas. Another product with similar composition is landfill gas, which is produced by the degradation of organic compounds that were disposed of in landfills. The collection of landfill gas requires covers and other diversion methods at the landfill since their emission is spread out. All these gases can be used to produce renewable electricity through internal combustion engines, microturbines, traditional gas turbines, or fuel cells. Many electricity generators are not designed to be used with producer gas, biogas, and landfill gas. These bio-derived gases can be combined with natural gas to raise the overall energy content for use in gas turbines or require the use of specially tuned equipment and contaminant removal, such as sulfur, before combustion.

4.1.2.6 | Cost Considerations

The contract price for large-scale woody biomass facilities in California currently ranges from $80/MWh to $120/MWh.[106] Nearly all these facilities were built in the 1980s and 1990s and received Public Utility Regulatory Policies Act of 1978 (PURPA) Standard Offer #4 contracts. Most of those PPAs have expired, or are about to, and these facilities are closing if they are unable to negotiate new PPAs with the utilities. Some have been successful in negotiating new contracts within the range mentioned above.

The LCOE of large-scale woody biomass facilities has also been estimated by the U.S. Energy Information Administration.[107] Biomass LCOE is estimated at $95.30/MWh (2017 $/MWh) for new biomass generation entering service in 2022. The LCOE for biomass generation entering service in 2014 (2017 $/MWh) is estimated at $84.80/MWh. It should be noted that anecdotal information in the bioenergy industry suggests that the LCOE for new woody biomass facilities may be more in the order of $140 to $150/MWh.

Feedstock costs for woody biomass facilities are the biggest variable affecting the costs to produce electricity. Woody biomass plants must pay for feedstock, and different types of feedstock sources have variable prices. For example, forest-sourced biomass can be $45 to $60+ per BDT, whereas agricultural and urban feedstock can come in under $25 and $15 per BDT, respectively. Feedstock costs are important to the bottom line; every $10 increase per BDT of feedstock effectively results in an increase of $10/MWh in electricity generation costs. Thus, feedstock at $60 per BDT adds $60 to the generation cost.

4.1.3 | Research Initiatives

The following is a brief overview of some of the ongoing R&D initiatives related to bioenergy. This summary is not intended to be comprehensive.

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[106] "Small-Scale Bioenergy Resource Potential, Costs, and Feed-in-Tariff Implementation Assessment," prepared by Black & Veatch for the California Public Utilities Commission, October 2013.

[107] "Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2018," U.S. Energy Information Administration, prepared March 2018.

4.1.3.1 | EPIC Investment Initiatives

The Energy Commission EPIC 2018–2020 Triennial Investment Plan presents R&D priorities to increase bioenergy use and capacity in California.[108] This current effort is again focused on woody biomass utilization to address the significant forest tree mortality issue in California, as well as the significant reduction in operations of previously constructed biomass plants. Additionally, reduced operations at biomass power plants is affecting agricultural waste management, particularly in the Central Valley.

Special emphasis is being placed on technologies and strategies that will reduce the LCOE, along with O&M costs to bring bioenergy into cost parity with fossil fuels. The EPIC investment plan includes developing and demonstrating lower-cost emissions controls and lower-cost, low-emission generation technologies, as many AD biogas projects are smaller and do not have the economies of scale to use commercially available emissions control systems. The EPIC 2018–2020 Triennial Investment Plan describes the short-term R&D priorities to increase bioenergy in California by addressing key technical and market challenges.

Table 4-8. Bioenergy – Summary of 2018–2020 EPIC Triennial Investment Plan Initiatives

Initiative	Description/Goal	Potential Impact
2018–2020 EPIC Triennial Investment Plan		
Initiative 4.4.1: Tackling Tar and Other Impurities: Addressing the Achilles Heel of Gasification	The focus is on research to help eliminate the reliability risks of biomass gasification to electricity systems due to problems caused by tars and other impurities produced during the gasification process. Additional R&D is also being conducted on the disposal of wastes that may be derived from the removal of tars and impurities.	Cost-effectively solving the tar and other impurity issues will assist in making biomass gasification to electricity more reliable, mitigating risks to downstream equipment such as the internal combustion engine generator set, and lowering costs of biomass gasification electricity systems.
Initiative 4.4.2: Demonstrating Modular Bioenergy Systems and Feedstock Densifying and Handling Strategies to Improve Conversion of Accessibility-Challenged Forest Biomass Resources	This demonstration initiative is to generate critical in-field data and address technological challenges needed for broader deployment and commercialization of biomass-to-electricity systems in the forest–urban interface. Challenges include integration of multiple units, feedstock handling and loading, grid interconnection, produced gas quality improvement, air/water emission and waste management, and co-products. This initiative is to advance needed methods and strategies to bring the abundant, yet many times accessibility-challenged, forest biomass waste resources to the power generation facilities in a more economic manner.	The initiative demonstrates improvements to conversion efficiency, emissions, and emissions control, and mitigates solid and liquid waste byproducts to safe environmental levels. Such projects could lead to wider adoption of small-scale biomass electricity facilities using forest biomass that has been removed to reduce catastrophic wildfires. Demonstration projects involving feedstock transportation cost reduction would provide better economics for biopower projects.
Initiative 4.4.3: Demonstrate Improved Performance and Reduced Air Pollution Emissions of Biogas or Low-Quality Biogas Power Generation Technologies	The aim is to reduce the cost of pollution controls for small-scale biogas-to-electricity systems and develop more cost-effective off-the-shelf, low-emission electricity generation technologies that use biogas. There is also a need for new and/or improved technologies to utilize low-quality biogas, such as is generated at landfills and wastewater treatment facilities. More economic cleanup and	Improved air quality would better meet permitting requirements and lead to wider use of biogas that is otherwise emitted or flared.

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[108] "Electric Program Investment Charge: 2018–2020 Triennial Investment Plan," California Energy Commission, CEC-500-2017-023-CMF, adopted on April 27, 2017, energy.ca.gov/research/epic/17-EPIC-01/.

Initiative	Description/Goal	Potential Impact
	emissions controls are needed for these low-quality-biogas producing facilities.	

Table 4-9. Bioenergy – Summary of Pre-2018 and Possible EPIC Initiatives

Previous and Possible EPIC Investments

1. Advanced Pollution Control Equipment and Low-Emission Generators
    a. Pollution Control and Power Generation for Low-Quality Renewable Fuel Streams
    b. GFO-15-325 – Group 2: TD&D: Demonstrate and Evaluate Environmentally and Economically Sustainable Woody Biomass-to-Electricity Systems
2. Develop Modular Bioenergy Systems for Forest–Urban Interface Areas
    a. Modular Biomass Power Systems to Facilitate Forest Fuel Reduction Treatments
    b. Reciprocating Reactor for Low-Cost and Carbon-Negative Bioenergy
    c. Cleaner Air – Cleaner Energy: Converting Forest Fire Management Waste to On-Demand Renewable Energy
    d. GFO-15-325 – Group 1: AR&D: Efficient, Sustainable and Lower-Cost Bioenergy: Innovations to Improve Woody Biomass-to-Electricity Systems
3. Develop Waste-to-Energy Bioenergy Systems
    a. Robust, Low-Cost, Real-Time, NOx Sensor for Optimization of Dispatchable Distributed Generation Systems
    b. Advanced Recycling to 1 MW Municipal Solid Waste of Electricity Generation
    c. The SoCalGas Waste-to-Bioenergy Applied R&D Project
    d. Paths to Sustainable Distributed Generation through 2050: Matching Local Waste Biomass Resources with Grid, Industrial, and Community Needs
    e. Low-Cost Biogas Power Generation with Increased Efficiency and Lower Emissions
4. Thermochemical Conversion Technologies or Deployment Strategies
    a. North Fork Community Power Forest Bioenergy Facility
    b. GFO-15-325 – Group 2: TD&D: Demonstrate and Evaluate Environmentally and Economically Sustainable Woody Biomass-to-Electricity Systems
5. Biochemical Conversion Technologies or Deployment Strategies
    a. The Lakeview Farms Dairy Biogas-to-Electricity Project
    b. The West Star North Dairy Biogas-to-Electricity Project
    c. Enabling Anaerobic Digestion Deployment for Municipal Solid Waste-to-Energy
    d. Lowering Food-Waste Co-Digestion Costs through an Innovative Combination of a Pre-Sorting Technique and a Strategy for Cake Solids Reduction
    e. Community-Scale Digester with Advanced Interconnection to the Electrical Grid
    f. Installation of a Lean Burn Biogas Engine with Emissions Control to Comply with Rule 1110.2 at a Wastewater Treatment Plant in South Coast Air Quality Management District
    g. GFO-15-325 – Group 3: TD&D: Demonstrate and Evaluate Environmentally and Economically Sustainable Food Waste Biomass-to-Electricity Systems
6. Demonstrating Clean Energy Solutions that Support California's Industries, the Environment and the Electrical Grid
    a. Advancing Biomass Combined Heat and Power Technology to Support Rural California, the Environment, and the Electrical Grid
    b. ABEC #4 Renewable Combined Heat and Power Project

Select EPIC Projects

The Energy Commission has funded several innovative bioenergy-related projects that are featured on the Energy Commission Innovation Showcase website.[109] The following table summarizes projects that demonstrate emerging bioenergy and relevant technologies that could potentially be used for grid-scale biomass electricity.

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[109] California Energy Commission Innovation Showcase, innovation.energy.ca.gov/.

Table 4-10. Bioenergy – Select EPIC Projects

Project Name	Technology Type	Description
Community-Scale Digester with Advanced Interconnection to the Electrical Grid	AD Power Production	This project is installing and operating an innovative AD system using high-rate biodigester technology that will process both food waste and a high-strength slurry from a concentrated wastewater stream. Estimated LCOE is $122/MWh.
Advancing Novel Biogas Cleanup Systems for the Production of Renewable Natural Gas	Biogas Cleanup	This project is developing and demonstrating a novel biogas cleanup system for the separation and removal of hydrogen sulfide, siloxanes, CO_2, nitrogen and oxygen to generate renewable natural gas (RNG). The result is biogas cleanup systems that are reliable, effective, and not overly costly to aid growth of the RNG market in California.
Pre- and Post-Combustion NOx Control for Biogas Engines	Bioenergy Emissions Controls	The project is development and demonstration of an integrated microwave system that will address the current inability of biogas engines to meet the South Coast AQMD Rule 1110.2 and California Air Resources Board NOx emissions standard.
Paths to Sustainable Distributed Generation Through 2050: Matching Local Waste Biomass Resources with Grid, Industrial, and Community Levels	Bioenergy Feedstock	This analytical project identifies high-priority California area and feedstock types, highlights promising geographic areas and available technologies, and improves efficiency by lowering feedstock transportation distances. Integrated use of waste biomass (from municipal wastes, agricultural residues, and food processing wastes) for distributed generation in California has the potential to produce 4.2 TWh of biomass electricity per year.
Demonstrating the Potential for On-Site Electricity Generation from Food Waste Using Containerized Anaerobic Digestion Units	Modular Anaerobic Digestion	This project is to assess the potential for highly standardized and rapidly deployable decentralized AD systems. With such systems, it is possible to reduce/avoid non-renewable electricity, transmission and distribution losses over longer distances and to lower feedstock transportation costs. The pilot distributed generation unit is expected to reduce the host facility net peak demand of 60 kW, with an annual savings of $72,246 or $152/MWh.
Dairy Waste-to-Bioenergy via the Integration of Concentrating Solar Power and a High-Temperature Conversion Process	CSP and Bioenergy	The project is to integrate CSP and bioenergy into a single integrated system. The project anticipates proving it possible to store the energy contained in dairy manure waste in a manner that enables natural gas plants to produce readily dispatchable, ultra-low-emissions renewable electricity. A renewable electricity production cost of $69/MWh is estimated.
Demonstrating a Commercial-Scale Gasification Facility for Converting Forest Wood Waste to Electricity	Modular Woody Biomass Power	This project developed and tested a modular biomass gasification system that can be deployed rapidly to forested communities to promote and support fire-safe management activities. This project aims in part to reduce direct costs of utility-caused wildfires and protect utility infrastructure.

4.1.3.2 | Research Initiatives from Other Funding Entities

The DOE Bioenergy Technologies Office (BETO), along with the Biomass Research and Development Board, promotes bioenergy RD&D at the national level. However, it must be noted that nearly all current and future BETO activities have a very high emphasis on conversion of biomass to biofuels (to substitute for petroleum-derived transportation fuels) and bioproducts (again, to lessen dependence on petroleum- and natural-gas-derived chemicals and products). BETO even states in its Multi-Year Program Plan (2016) that biomass-to-power electricity generation facility technology is considered commercially mature, and therefore not in need of additional R&D support. However, BETO does work with other DOE offices that continue RD&D work on biomass conversion into electricity:

- Office of Fossil Energy – Examine technology development improvements to increase efficiency, environmental performance, and economic viability of utility-scale biopower and carbon reuse.
- Advanced Manufacturing Office – Research and develop biomass-based technologies to produce electricity, among other biomass conversion technologies.
- Fuel Cell Technologies Office – Coordinate research efforts on gasification and renewable hydrogen production for use in fuel cell electricity generation.

Table 4-11. Bioenergy – Summary of DOE Research Initiatives

Initiative	Description/Goal	Potential Impact
U.S. Department of Energy		
Conversion Research and Development	R&D to improve the conversion of biomass to biopower.	Increasing conversion efficiency will lower biomass feedstock costs, a critical cost factor in the production of electricity from biomass.
Feedstock Supply and Logistics	R&D to improve the harvesting, handling/processing, and transportation of biomass feedstocks.	Technology improvements in processing and logistics that enter the market over time can reduce the unit cost of biomass supply.

"Department of Energy FY 2019 Congressional Budget Request." DOE. March 2018. energy.gov/sites/prod/files/2018/03/f49/FY-2019-Volume-3-Part-2.pdf.

NYSERDA funded biomass-to-electricity studies and projects in the past, but now nearly all the bioenergy R&D is focused on the use of biomass for direct heating applications.

4.1.4 | R&D Opportunity Areas and Technologies

To identify and prioritize R&D opportunity areas and technologies for bioenergy, analysts relied on state and federal government reports, industry reports, and peer-reviewed research articles. Findings were also informed by phone interviews with six bioenergy experts from government and other research institutions across the United States.

Figure 4-4. Bioenergy Experts Interviewed

- Robert Baldwin, PhD, Principal Scientist, National Renewable Energy Laboratory
- Greg Kester, Renewable Resource Program, California Association of Sanitation Agencies
- Tom Miles, Principal, T.R. Miles Technical Consultants, Inc.
- Valentino Tiangco, Biomass Program Manager, Sacramento Municipal Utility District
- Steve Tourigny, Principal, SPT Services
- Robert Williams, Engineer, California Biomass Collaborative Development

4.1.4.1 | Key Considerations

Expert interviews and literature review identified a number of factors worth consideration when dealing with assessment, investment, or construction of bioenergy generation in California. These areas are broadly categorized into technical, financial, and regulatory considerations, as discussed below.

Technical Considerations

- **Generating more biogas from biomass resources offers a way to increase bioenergy use.** The decommissioning of stoker boilers and other biomass combustion systems in California has limited their production over the past decade. Biogas production from both MSW plants and WWTPs provides a diversion pathway. Biogas can be burned onsite to generate power for those same MSW and WWTP facilities, and in some cases, these biogas turbines produce enough power to feed back to the grid.

- **Modeling of organic waste diversion from landfilling to electric power generation can make bioenergy's valuation more attractive**. As recent California legislation, regulations, and policies are emphasizing a significant diversion of organic waste from landfills, the full lifecycle costs/benefits need to be investigated in depth.
- **More modularization of bioenergy systems can lower manufacturing and capital costs.** Wind and solar currently benefit from manufacturing economies of scale and faster and lower-cost installation compared to bioenergy systems. Research and demonstration of modularization, principally with more fabrication of standardized bioenergy components in manufacturing facilities, is needed for proof of concept.
- **Using bioenergy in conjunction with solar and wind power at hybrid facilities is a way to increase power from biomass.** Biomass energy can be produced at any time of the day and in any season, essentially functioning as a form of physical energy storage. The dispatchability of bioenergy could complement the intermittency of solar or wind systems. Coupling these systems could result in a cost-competitive hybrid system that assists in the reduction of the "duck curve" of electricity prices.
- **Bioenergy can be configured to supply baseload or dispatchable power.** Bioenergy systems should be compared to natural gas generation rather than variable renewables such as wind and solar.

Financial Considerations

- **The cost of biopower is high when compared to other forms of renewable generation.** Bioenergy costs are affected by significant labor needs, compared to other renewables, and high feedstock costs.
- **Monetizing the non-electricity benefits of biopower could lower bioenergy costs.** Biopower can provide numerous non-electricity benefits and value streams, such as waste disposal and forest management. Appropriately considering and quantifying these additional benefits could increase the value proposition for biopower.
- **Market certainty for byproducts would lower risks for investors.** Byproducts of biopower generation, such as biochar, biosolids, and fertilizer supplements, could create additional revenue streams to bring down overall system costs. However, markets for biochar (from gasification of woody biomass) and fertilizer products (from AD) are small and immature.
- **Repurposing older large-scale biomass power plants to generate electricity for electric vehicles (EVs) can open a new revenue stream.** The large existing fleet of large-scale woody biomass plants is winding down as their PPAs are expiring. However, the California Low Carbon Fuel Standard program provides significant monetary value for renewable electricity used to power EVs. Biomass plants could increase their value by supplying electricity to electric charging stations or EV vehicle fleets.

Regulatory Considerations

- **SB 1122 is incentivizing small-scale bioenergy production in California.** The small-scale California bioenergy sector development was enhanced by the passage of SB 1122 in 2012. The bill directed the major IOUs to procure 250 MW of power from small-scale bioenergy units (3 MW or less) that used woody, agricultural, or forestry wastes.
- **Emissions standards can limit or even prevent siting for bioenergy facilities.** Unlike most other renewables, bioenergy systems produce air emissions from direct combustion of woody biomass or through the production of syngas or biogas and combustion of those gases in an internal combustion

engine generator or boiler systems to generate electricity. California has some of the most stringent air quality regulations in the United States, and some of the California air districts assume worst-case emissions scenarios for bioenergy systems.

- **Bioenergy from woody biomass can be used as a forest management and wildfire mitigation strategy.** A critical issue facing California is the increased wildfire risk due to drought conditions and increased wood residue in forests. Bioenergy can reduce wildfire risk through the beneficial use of forest residues. In addition, biosolids produced through AD can be used to reclaim fire-ravaged land and reduce the potential severity of future fires through improved soil health and increased biomass production. However, this application is inhibited by cost barriers such as material collection and transportation.
- **Diverting waste to bioenergy systems lowers the overall GHG emissions from waste control systems.** The beneficial use of biogas, instead of leaking methane and leaching carbon, is not well quantified and valued by the public. GHG emission reductions should be captured through the diversion of biogas-to-energy systems.

4.1.4.2 | R&D Opportunity Areas

The R&D opportunity areas in Table 4-12 expand beyond those identified in the Energy Commission's 2018–2020 Triennial Investment Plan and are based on an extensive literature review and conversations with experts.

These identified R&D opportunities consider the bioenergy needs to assist California in meeting policy and legislative goals regarding biomass and organic waste utilization, diversion from landfilling, and potential reduction of catastrophic wildfire. Subject matter experience, "lessons learned" from existing and failed bioenergy projects, and bioenergy expert feedback were used in determining these opportunities.

Table 4-12. Bioenergy Technology Research & Development Opportunity Areas

ID	Opportunity Area	Description
Combustion and Gasification		
O.B.1	**Convert Direct Combustion Biomass Facilities to Gasification Facilities**	This conversion could result in more efficient use of purchased biomass feedstocks and lower air pollutant emissions.
O.B.2	**Existing and Idle Biomass Plant Retrofits**	This area examines technologies and retrofits that support continued use of the existing biomass power plant fleet.
O.B.3	**Improved Pressurized Biomass Gasification and Gas Cleaning**	This process can be improved to allow the use of gas-turbine applications and for other high-efficiency power systems.
O.B.4	**Integrating Biopower into Biorefineries**	This area would develop integrated biorefinery concepts involving large-scale power (and heat) plants.
O.B.5	**Large-Scale Biomass Gasification Systems**	Current gasification systems proposed in California are all 3 MW or less; no utility-scale woody biomass gasification systems are proposed.
O.B.6	**Tar and Other Impurity Management**[2]	There is a need to economically and environmentally handle and process tar and other contaminants removed from the cleanup of syngas from biomass gasification.
O.B.7	***Thermochemical Conversion Technologies**	Advanced technologies could lower costs of gasification reactor vessels and pyrolysis processes.
Digestion		

ID	Opportunity Area	Description
O.B.8	***Advanced Wastewater Treatment Plants**	Increasing AD efficiencies in future wastewater treatment will produce higher biogas volumes for energy production or injection into the natural gas pipeline system.
O.B.9	***Biochemical Conversion Technologies**	Technologies are needed to continue to lower the cost of biochemical conversion through increasing biogas production through various means such as enzymes, specialty microbes, and other potential chemical and biological supplements.
O.B.10	**Codigestion of Wastes**	Low-energy yielding manures can be augmented with higher-energy yielding food waste to increase AD system efficiency.
O.B.11	**Enhanced Anaerobic Digestion with Enzymes**	A potential significant increase in methane production in AD systems would increase electricity production.
O.B.12	**Processing of MSW to Economically Remove the Organic Component**	Organic waste feedstock in AD systems must be contaminant-free.
Other and Cross-Cutting Opportunity Areas		
O.B.13	**Biogas Power Generation Technologies**[4]	Biogas use can be further integrated with fuel cell technologies.
O.B.14	***CSP Integration with Bioenergy Systems**	This area seeks to evaluate the technical and economic benefits of blending solar electricity and biomass electricity production at collocated sites.
O.B.15	**Environmental and Social Benefits Analysis**	There is a need for quantification of societal and environmental benefits from biomass utilization.
O.B.16	***Modular Bioenergy Systems**[3]	Modularization can lower Capex and Opex. There is a need for small-scale biopower systems (<3 MW) with over 80% biomass utilization efficiency and at least 35% electrical efficiency.
O.B.17	***Pollution and Emissions Controls**	Continued improvement in air pollution control devices for emissions will allow bioenergy systems to meet California's continuing refinement of air emissions standards.
O.B.18	**Ultra-Clean Biogas**	Use of ultra-clean biogas from AD can be used in fuel cells.
O.B.19	***Waste-to-Energy Bioenergy Systems**	Processes generate electricity and/or heat directly through combustion or produce a combustible fuel commodity such as methane, methanol, ethanol, or synthetic fuels.

Several research areas overlap with EPIC investment interests. Those overlaps are given the following identifiers:

* Mentioned in EPIC Investment Plan: Previous and Planned EPIC Investments on Bioenergy Technologies

2 Relevant to Initiative 4.4.1 Tackling Tar and Other Impurities: Addressing the Achilles Heel of Gasification

3 Relevant to Initiative 4.4.2 Demonstrating Modular Bioenergy Systems and Feedstock Densifying and Handling Strategies to Improve Conversion of Accessibility-Challenged Forest Biomass Resources

4 Relevant to Initiative 4.4.3 Demonstrate Improved Performance and Reduced Air Pollution Emissions of Biogas or Low-Quality Biogas Power Generation Technologies

4.1.4.3 | Emerging and Breakthrough Technologies

The emerging and breakthrough technologies in Table 4-13 represent more targeted opportunities for Energy Commission investment and fall within the aforementioned R&D opportunity areas.

Table 4-13. Emerging and Breakthrough Technology Matrix

ID	Name	Parallel Research Topic	R&D Opportunity Areas	Potential Impact
B.1	**Bioenergy with Carbon Capture and Storage (BECCS)**	Legacy System Improvement	Existing and Idle Biomass Plant Retrofits	BECCS produces negative carbon emissions by capturing CO_2 produced during power production and storing it, preventing it from reentering the atmosphere.
B.2	**Cleaner Combustion Technologies**	Legacy System Improvement	Pollution and Emissions Controls	Combustion technology converts biogas to bioenergy while complying with local air district regulations.
B.3	**Food Waste Integration into WWTPs**	Legacy System Improvement	Codigestion of Wastes	Food waste contains organics that can be digested in the same anaerobic digesters that are used for WWTPs. This saves new installation costs and can increase AD biogas production.
B.4	**Improved Pyrolysis Processes**	Innovative System Development	Thermochemical Conversion Technologies	Improving the cost and yields of pyrolysis processes, especially slow pyrolysis, would provide a pathway to utilizing more biomass for electricity production.
B.5	**Integrated Gasification Combined Cycle (IGCC)**	Legacy System Improvement	Convert Direct Combustion Biomass Facilities to Gasification Facilities	IGCC systems can improve power plant efficiency while decreasing the amount of CO_2 released from biomass.
B.6	**Microbial Fuel Cells**	Innovative System Development	Biogas Power Generation Technologies; Waste-to-Energy Bioenergy Systems	Microbial fuel cells can take carbon-rich bio-waste and convert it into stored electricity.
B.7	**Modular Gasification Systems**	Innovative System Development	Thermochemical Conversion Technologies	Gasification systems can lower costs and be more transportable and installable if they are smaller and modular.
B.8	**Pipeline Injection**	Legacy System Improvement	Biogas Power Generation Technologies	Utilizing biogas by injecting it into existing natural gas pipelines allows the biogas to be put to beneficial use. While lowering the overall quality of the gas in the system, the degradation is not enough to affect power plant operations.
B.9	**Thermal Hydrolysis at WWTPs**	Legacy System Improvement	Advanced Wastewater Treatment Plants	Thermal hydrolysis can be used as a precursor to AD to increase biogas production and increase breakdown of organic material.

4.2 | Geothermal Power

In 2017, geothermal energy generated within California totaled 11,745 GWh. As the largest source of renewable energy in the state, geothermal accounted for roughly 5.7% percent of the in-state total power generation and 19.2% of in-state renewable power generation.[110] Geothermal energy in California during 2017 was supplied by 43 operating geothermal plants accounting for around 2.7 GW of capacity with an additional 64.7 MW of import capacity available.[111]

Figure 4-5 shows how geothermal energy generation in California has changed in terms of gross generation (GWh) and capacity (GW) since 2001. The number of gigawatt-hours produced from geothermal power is relatively unchanged since California's RPS law was adopted. California's first source of geothermal power was developed at the Geysers in 1960. The newest in-state installations of geothermal energy came online in 2004. Since 2001, less than 100 MW of geothermal capacity has been added in California.

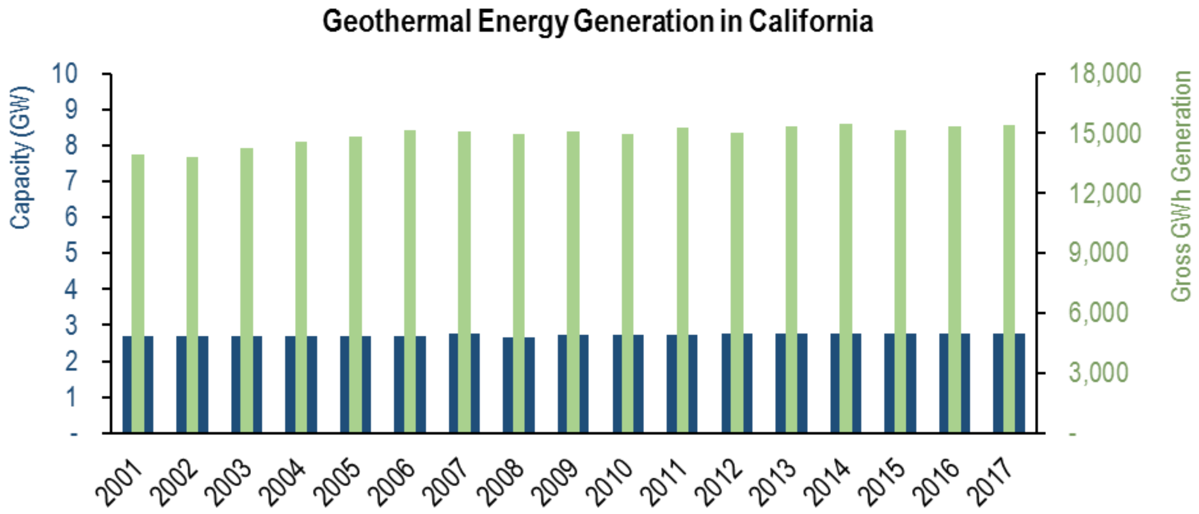

Figure 4-5. Geothermal Energy Generation in California from 2001 to 2017

Data from energy.ca.gov/almanac/renewables_data/geothermal/

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[110] "2017 Total System Electric Generation," California Energy Commission, data as of June 21, 2018, energy.ca.gov/almanac/electricity_data/total_system_power.html.

[111] "California Solar Energy Statistics & Data," California Energy Commission, accessed November 7, 2018. energy.ca.gov/almanac/renewables_data/solar/.

Looking forward, the DOE FY 2019 budget request establishes cost performance targets, summarized in Table 4-14. DOE research efforts focus on subsurface stress measurement and simulation to enable the collection of stress data at reservoir scale to understand fracture propagation, permeability distribution, reservoir management, fluid production, and wellbore integrity. Advances would support enhanced grid reliability and resilience through analyses focused on improving the ability for geothermal power to be operated flexibly and provide essential grid reliability services.

Table 4-14. Geothermal Power Cost Performance Targets (DOE)

	FY 2017	FY 2018	FY 2019	Endpoint Target
Geothermal Systems	22 cents/kWh (target met)	21.8 cents/kWh	21.7 cents/kWh	6 cents/kWh by 2030

The geothermal energy cost target is an unsubsidized cost of energy at utility scale. The Geothermal Electricity Technology Evaluation Model (GETEM) estimates the representative costs of generating electrical power from geothermal energy. The estimated costs are dependent upon several factors specific to the scenario being evaluated, with most of these factors defined by inputs provided.

Source: "Department of Energy FY 2019 Congressional Budget Request." Volume 3–Part 2: 25. DOE. March 2018. energy.gov/sites/prod/files/2018/03/f49/FY-2019-Volume-3-Part-2.pdf.

4.2.1 | Resource Availability

California is one of nine states with operating or planned geothermal power resources and has more than three times the installed capacity of the rest of the country combined. The geothermal resource in California is considered one of the largest in the country, with estimates of additional capacity ranging from 4,000 MW–20,000 MW for conventional geothermal generation and estimates as high as 50,000 MW with the inclusion of enhanced geothermal systems (EGS).[112] The U.S. Geological Survey (USGS) and NREL are two U.S. government organizations that developed assessments of the country's geothermal resources.[113,114]

California has 25 known geothermal resource areas (KGRAs), of which 14 have temperatures above 300°F.[115] Currently, geothermal capacity in California is concentrated around five regions, but future development is planned in the northeast of the state for the first time.

Geothermal resource potential is assessed based on several factors such as the heat, water content, and permeability of a given reservoir. Accessing the geothermal resources requires drilling activities like those undertaken during oil and gas exploration. The exploration and discovery of geothermal resources is the most capital-intensive part of the process. Modeling efforts help identify areas that are more probable for geothermal generation and save costs. This part of resource assessment focuses on the areas that are already identified as good geothermal resources.

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[112] Colin F. Williams et. al., "Assessment of Moderate- and High-Temperature Geothermal Resources of the United States," USGS 2008, pubs.gov/fs/2008/3082/pdf/fs2008-3082.pdf.

[113] "Western U.S. Geothermal Assessment Summary," USGS, accessed November 28, 2018, certmapper.cr.usgs.gov/data/energyvision/?config=config_Geothermal.json.

[114] "Geothermal Maps," National Renewable Energy Laboratory, accessed November 28, 2018, nrel.gov/gis/geothermal.html.

[115] "Geothermal Energy in California," California Energy Commission, accessed November 28, 2018, https://www.energy.ca.gov/geothermal/background.html.

Geothermal facilities also have the potential to capitalize on more than energy production through the extraction of material from subsurface brines. Lithium, boron, and other valuable materials are present in certain brines located in areas like the Salton Sea of California. There is overlap with other renewable projects, as the extracted lithium can be used for energy storage battery products. In any case, the extraction of materials will increase the revenues of a project, which will help pay back the capital investments in geothermal projects.

Owing to the nature of geothermal facilities, another resource component that must be considered in development is water use. California has a constrained water resource due to common drought conditions and other earmarked uses such as agriculture. The best geothermal resources for the state will rely primarily on water that is captured from the geothermal drilling operations themselves or by using non-potable resources that cannot be used in the state for other reasons. One example of creative water use in California is the pipeline transporting treated water straight from a WWTP to a geothermal plant in the Geysers.

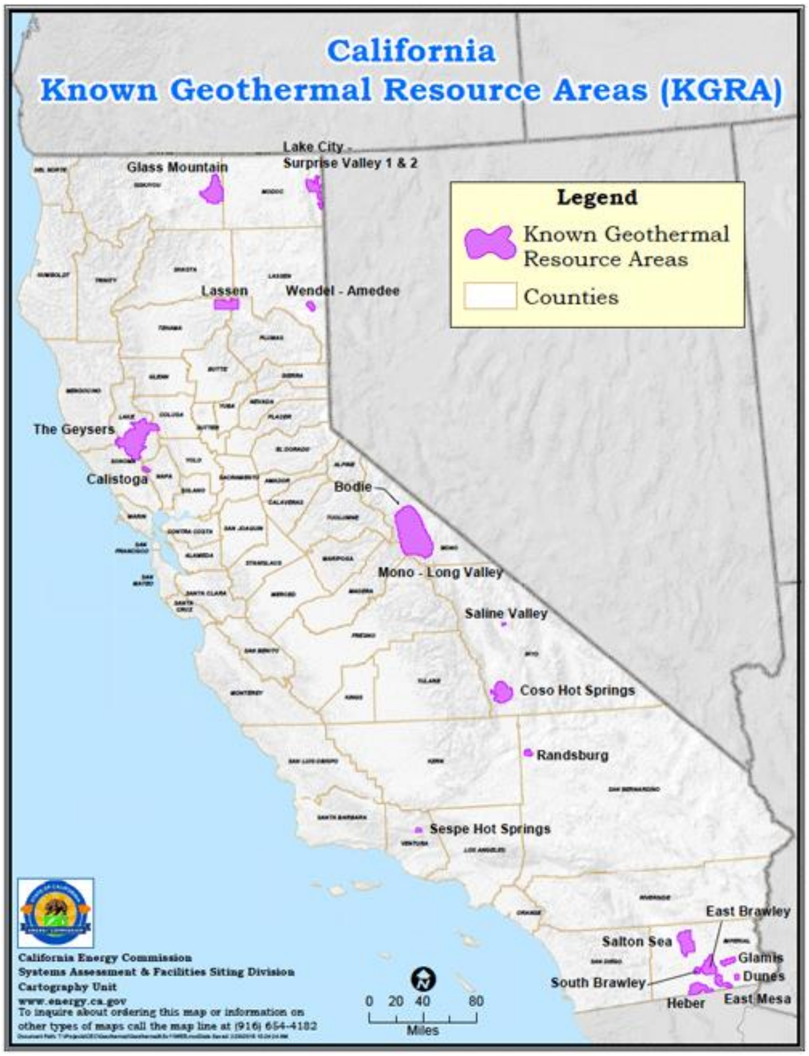

Figure 4-6. Known Geothermal Resource Areas

The Energy Commission's System Assessment & Facilities Siting Division Cartography Unit generates a map of all known geothermal resource areas in the state. These areas have to be assessed and explored to understand the true geothermal resource potential and possible generating plant siting locations.

Available at energy.ca.gov/maps/renewable /geothermal_areas.html

4.2.2 | Technology Overview

There are three ways energy is conventionally produced from geothermal resources:[116]

- **Dry steam** designs directly utilize hot steam that emanates from the ground to directly power an electric generator. In some cases, such as the Geysers, this used to occur naturally. However, over time, the water in the geothermal reservoir was depleted, and steam generation declined. The

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[116] "Electricity Generation." Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy. Accessed November 28, 2018. energy.gov/eere/geothermal/electricity-generation.

geothermal reservoirs at the Geysers are now recharged with treated wastewater. Approximately 20 million gallons per day of reclaimed water is injected into the Geysers reservoir to mitigate steam production decline. California has 15 power plants currently operating that use dry steam design and produce 800 MW of capacity.

- **Flash steam** geothermal plants utilize hydrothermal fluids over 360°F from geothermal wells. This liquid is pumped up into a tank that is kept at much lower pressure then the geothermal fluid. When that fluid is released, it vaporizes, creating steam that then powers the electric generator. Some designs incorporate a second tank that can flash any fluid that remains from the first tank to generate more energy. The selection of a single-flash, dual-flash, or dry steam design is determined by the characteristics of the geothermal system. Three plants in California utilize the dual-flash design and provide 112 MW of capacity. The single-flash design accounts for 22 plants in the state and, with 892 MW, contributes the most capacity of any design.
- **Binary cycle** plants are common for geothermal resources that are below 400°F. Water from the subsurface is pumped up into a heat exchanger, which passes heat to a fluid with a much lower boiling point. A common working fluid is isopentane. This working fluid is flashed to vapor in the heat exchanger, and that vapor is used to drive an electrical generator. These are closed-loop systems, so nothing is vented to the atmosphere. The water that comes from the geothermal wells is pumped back down the injection well to replenish the reservoir. Binary plants range from 2 MW–50 MW in capacity.[117] Five plants in operation in California utilize the binary cycle design and provide 62.9 MW of capacity.

Geothermal power by its nature provides baseload power because the generation of steam from the subsurface is not slowed or controlled. The capacity factors of geothermal technologies are very high (>90%) because the steam supply is constant. This characteristic distinguishes geothermal power from other types of renewables. However, there is ongoing research into ways to make geothermal power more flexible so it can help deal with the large swings in production that have accompanied the installation of more solar projects in California.

4.2.2.1 | Cost Trends and Performance Attributes

In general, the LCOE for geothermal designs ranges from \$0.04/kWh to \$0.14/kWh, assuming a 25-year plant life.[118] Installed costs for geothermal systems range from \$1000/kW to \$9000/kW. Binary steam plants are typically more expensive than dry steam and flash plants. Figure 4-7 presents a comparison of the costs of binary plants and flash plants, plotted by the temperature of the geothermal resource.[119]

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[117] "Geothermal Electric Power Production," UC Davis, accessed November 28, 2018, cgec.ucdavis.edu/resources/learn/geothermal-electric-power-production/.

[118] "Geothermal Power: Technology Brief," International Renewable Energy Agency, September 2017, irena.org/-/media/Files/IRENA/Agency/Publication/2017/Aug/IRENA_Geothermal_Power_2017.pdf.

[119] Geothermal Summary Charts, International Renewable Energy Agency, accessed November 28, 2018, irena.org/costs/Charts/Geothermal.

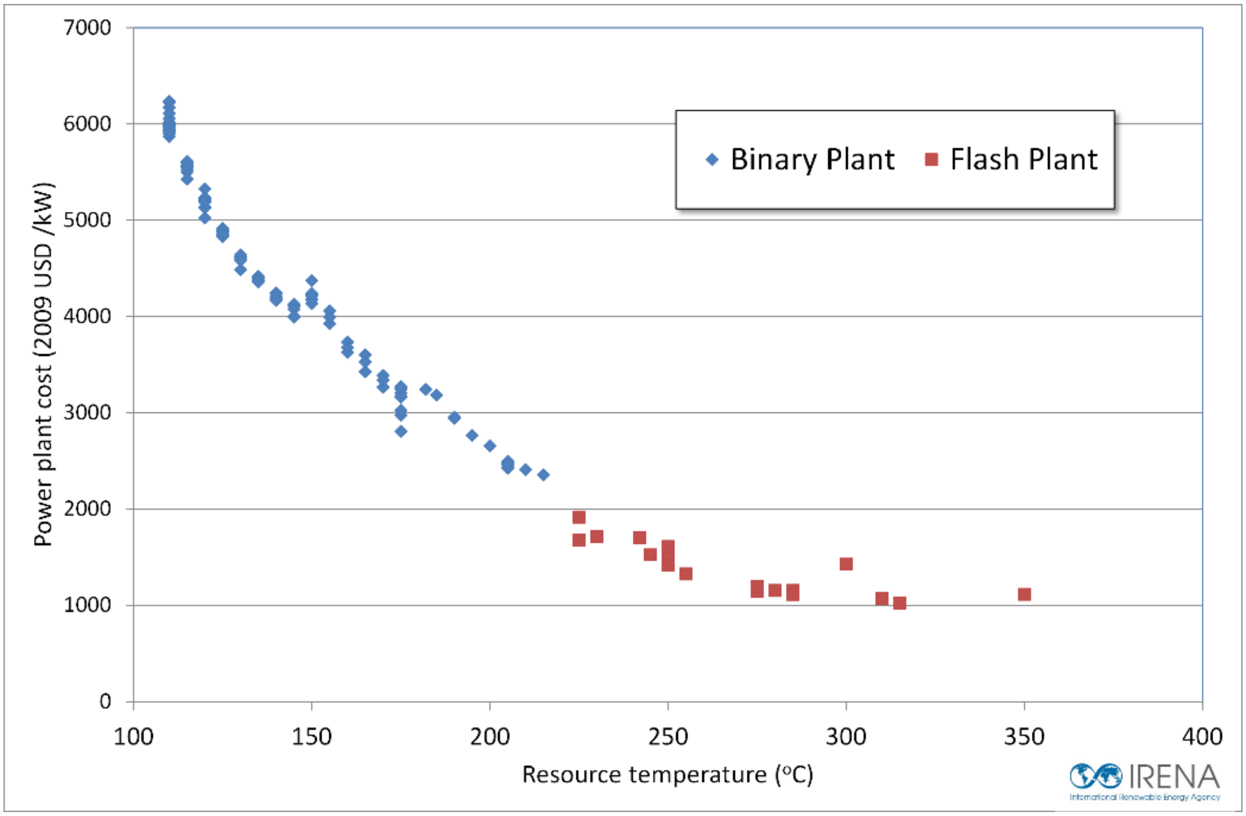

Figure 4-7. Installed Cost of Binary and Flash Plants by Geothermal Resource Temperature

Geothermal costs vary heavily even within technology types, mostly because of ranging development costs. Factors such as temperature, pressure, depth, permeability, fluid chemistry, location, local drilling market, and size of development all play a role. A major cost differentiator can be whether the new plant is an expansion near an existing plant or a greenfield plant. New development areas have added risks that can increase costs substantially.

4.2.2.2 | Enhanced Geothermal Systems (EGSs)

An emerging area of interest for geothermal technologies exists for enhanced geothermal systems. These systems can enable new geothermal generation in areas where the subsurface temperature is high but little steam or hot water exists and permeability is low. The process for creating an enhanced geothermal system involves drilling and assessing a potential heat reservoir. The drilled holes can range from four to ten kilometers below the surface.[120] Once the reservoir is selected, water is pumped down the hole and pressurized to create fractures in the rock. This process may be compared to hydraulic fracturing but does not carry the same risks and should not be assessed with the same stigma as "fracking" for oil development.

Once the formation contains large enough fractures, a production well is drilled with the intent of intersecting enough fractures to provide water a pathway back to the surface. The system can involve multiple production wells. The injection well is used to pump down cold water, which is heated in the

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[120] C. Augustine, "Updated U.S. Geothermal Supply Characterization and Representation for Market Penetration Model Input," NREL, 2011, nrel.gov/docs/fy12osti/47459.pdf.

subsurface and then transported to the surface as hot water or steam, which can be used to generate electricity through one of the conventional generation methods. EGS demonstration plants have been developed, and commercial facilities are targeted for deployment in 2030. The estimated costs for EGSs range from 0.10 $/kWh to 0.30 $/kWh.[121]

4.2.3 | Research Initiatives

The following is a brief overview of some of the ongoing R&D initiatives related to geothermal power. This summary is not intended to be comprehensive.

4.2.3.1 | EPIC Investment Initiatives

The EPIC 2018–2020 Triennial Investment Plan describes the short-term R&D priorities to increase geothermal power in California.[122] Under the first and second EPIC investment plans, the EPIC program concentrated on the challenge of characterizing and assessing geothermal resources, designing flexible systems, and reducing costs. The latest plan recognizes geothermal energy's ability to provide reliable renewable energy to the grid.

Table 4-15. Geothermal – Summary of California Investment Initiatives

Initiative	Description/Goal	Potential Impact
2018–2020 EPIC Triennial Investment Plan		
Initiative 4.3.2 Geothermal Energy Advancement for a Reliable Renewable Energy System	Addresses flexible generation issues such as corrosive material build-up to allow geothermal to operate in a non-baseload setting. Explores the economic values of capturing build-up from condensates and looks at ways to boost geothermal power from declining or idling geothermal plants.	Will accelerate penetration of total renewable generation on the grid by decreasing reliance of non-renewable generation for ramping and ancillary services. Could make geothermal more attractive to investors as well.
Previous EPIC Investment Plans		
Previous/Planned/Possible EPIC Investments in Geothermal Technologies	1. Flexible Geothermal Energy Generation a. Comprehensive Physical–Chemical Modeling to Reduce Risks and Costs of Flexible Geothermal Energy Production 2. Exploration, Resource Characterization, and Resource Development a. Improving Performance and Cost-Effectiveness of Small Hydro, Geothermal, and Wind Technologies b. High-Resolution Imaging of Geothermal Flow Paths Using a Cost-Effective Dense Seismic Network 3. Increasing Cost-Effectiveness and Economic Opportunities of Geothermal Power Generation a. Recovery of Lithium from Geothermal Brines	
Other		
Geothermal Grant and Loan Program	Seeks to promote the development of new or existing geothermal technologies. Commonly known as the Geothermal Resources Development Account (GRDA) program (after its funding source).	Provides millions of dollars for funding project developers operating on federal land in California. These grants and loans can provide vital funding to emerging technologies such as lithium recovery.

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[121] "Technology Roadmap: Combined Heat and Power," International Energy Agency, 2011, iea.org/publications/freepublications/publication/Geothermal_Roadmap.pdf.

[122] "Electric Program Investment Charge: 2018–2020 Triennial Investment Plan," California Energy Commission, CEC-500-2017-023-CMF, adopted on April 27, 2017, energy.ca.gov/research/epic/17-EPIC-01/.

Select EPIC Projects

The Energy Commission has recently funded several innovative geothermal projects that are featured on the Energy Commission Innovation Showcase website.[123] The following table summarizes projects that are working on emerging geothermal technologies that are relevant to utility-scale generation.

Table 4-16. Geothermal – Select EPIC Projects

Project Name	Technology Type	Description
Comprehensive Physical-Chemical Modeling to Reduce Risks and Costs of Flexible Geothermal Energy Production	Grid Integration	This project is working with a geothermal model to further understand well bore and reservoir integrity, scaling, and corrosion at geothermal facilities operating as both baseload and in a flexible mode, which puts significant stress on the plant.
High-Resolution Imaging of Geothermal Flow Paths Using a Cost-Effective Dense Seismic Network	Site Assessment	This project will develop an advanced, low-cost, automated tomographic imaging system that uses micro-earthquakes and a network of portable, low-cost seismic sensors to form high spatial and temporal resolution images of subsurface fluid flow.
Investigating Flexible Generation Capabilities at the Geysers	Grid Integration	This project is investigating how the operation of Geysers geothermal facilities may be modified in order to address the greater demands imposed on the grid by the significant addition of intermittent resources.
Low-Cost High-Reliability Thermoelectrics for Waste Heat Conversion	Thermoelectric Generators	This project is developing a thermoelectric material for high-temperature operation. This thermoelectric material would capture waste heat to produce energy.
Recovery of Lithium from Geothermal Brines	Material Reuse	This project is developing a laboratory-scale, cost-effective method of recovering lithium from geothermal brines.
Thermoelectric Generator Application and Pilot Test in a Geothermal Field	Thermoelectric Generators	This pilot geothermal facility uses thermoelectric generators, which can generate electricity at a smaller scale than traditional geothermal plants.

4.2.3.2 | Research Initiatives from Other Funding Entities

DOE's Geothermal Technologies Office (GTO) focuses on cost and risk reduction through innovative technologies. GTO is focused on development of four areas: hydrothermal resources, enhanced geothermal systems, low-temperature and co-produced resources, and systems analysis. The office is also working on a GeoVision report, due for release in 2019, that will detail economic, social, and environmental impacts of geothermal power. This report will also include information on desalination, mineral recovery, and hybridization with other technologies. GTO has already developed several useful tools and reports including an EGS roadmap, exploration roadmap, geothermal regulatory roadmap, geothermal prospector, and geothermal data repository.[124]

Table 4-17. Geothermal – Summary of DOE Research Initiatives

Initiative	Description/Goal	Potential Impact
U.S. Department of Energy		
Frontier Observatory for Research in Geothermal Energy (FORGE)[1]	Dedicated site where scientists and engineers can test, develop, and accelerate breakthroughs in EGS technologies.	Providing a site for EGS development will push the technologies toward commercialization.

[1] "FORGE: U.S. Department of Energy." DOE Office of Energy Efficiency and Renewable Energy. Accessed November 28, 2018. energy.gov/eere/forge/forge-home.

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[123] California Energy Commission Innovation Showcase, innovation.energy.ca.gov/.

[124] "2017 Annual Report: Geothermal Technologies Office," U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, January 2018, energy.gov/sites/prod/files/2018/01/f47/GTO%202017%20Annual%20Report.pdf.

4.2.4 | R&D Opportunity Areas and Technologies

To identify and prioritize R&D opportunity areas and technologies for geothermal power, analysts relied on state and federal government reports, industry reports, and peer-reviewed research articles. Findings were also informed by phone interviews with five experts from government and other research institutions across the United States.

Figure 4-8. Geothermal Experts Interviewed

- Pat Dobson, Geothermal Systems Program, Lawrence Berkeley National Laboratory
- Bill Glassley, Geologist, California Geothermal Energy Collaborative
- William Pettitt, Executive Director, Geothermal Resources Council
- Jefferson William Tester, Professor, Cornell University
- Jim Turner, Chief Operating Officer, Controlled Thermal Resources

4.2.4.1 | Key Considerations

Expert interviews and literature review identified a number of factors worth consideration when dealing with assessment, investment, or construction of geothermal generation in California. These areas are broadly categorized into technical, financial, and regulatory considerations, as discussed below.

Technical Considerations

- **California has the highest potential for geothermal energy in the nation.** Existing infrastructure near known resources makes it easier than other states to integrate geothermal power. However, the Salton Sea region has known power connection issues, and new steam from new wells requires long pipes to reach existing plants, lowering efficiency.
- **EGSs could increase capacity in the state by 40,000–50,000 MW.** The technically accessible geothermal resources in California can provide 50%–100% of the state's baseload power needs.
- **New materials can make geothermal systems more flexible.** There is a need for systems that address corrosion issues associated with geothermal fluids. Additionally, new materials are needed to store thermal energy above ground more effectively. These materials could also benefit CSP systems.
- **Downhole heat exchangers could leverage existing assets to lower the cost of geothermal systems.** Downhole heat exchangers could take advantage of existing oil and gas wells. These exchanges present a new, potentially lower-cost method of capturing geothermal energy.
- **Improved resource assessment of geothermal resources and EGSs is needed.** Outside of existing fields, the geothermal resource in California is difficult to quantify and qualify. Underground modeling is difficult even for established industries like oil and gas, and geothermal production has many of the same issues. A commitment to modeling high-probability geothermal areas could reduce risk and installation costs of systems.

Financial Considerations

- **Lithium extraction from geothermal brines could provide an added value stream.** Geothermal operations can increase value through the recovery of lithium, metals, agricultural products, or other beneficial minerals from highly mineralized geothermal brines.
- **Exploration and drilling costs must be reduced to increase the competitiveness of geothermal systems in California.** Lowering the costs of exploration and drilling, the most expensive parts of geothermal development, is necessary to lower capital costs.
- **PPAs and market pricing do not compensate for the added value of predictable power production from geothermal resources.** Pricing does not consider the baseload nature of geothermal power, which

puts it at a disadvantage when compared to lower-cost, but intermittent, generation from solar and wind.

Regulatory Considerations

- **Geothermal regulations can be burdensome for developments over 50 MW.** To avoid the additional permitting processes, no new large-scale geothermal is being built in California.

4.2.4.2 | R&D Opportunity Areas

The R&D opportunity areas in Table 4-18 expand beyond those identified in the Energy Commission's 2018–2020 Triennial Investment Plan and are based on an extensive literature review and conversations with experts.

Table 4-18. Geothermal Technology Research & Development Opportunity Areas

ID	Opportunity Areas	Description
O.G.1	**Corrosive Material Reduction**[2]	Moving geothermal systems from baseload to flexible generators presents issues with buildup of corrosive materials. Mitigating these issues is important to enabling flexible geothermal generation.
O.G.2	**Energy Storage Integration**[2]	Integrating energy storage systems can help geothermal plants operate in more traditional baseload settings while providing flexible electricity to the grid.
O.G.3	**Enhanced Geothermal Systems**	Enhanced geothermal systems take advantage of natural heat that exists in non-permeable rock. The rock is opened to form fissures that can then carry water or another working fluid from an injection well to a production well. The working fluid is pumped down the wells and comes up hotter from the production well, allowing the heat to be used for energy.
O.G.4	***Exploration, Resource Characterization, and Resource Development**	High costs and barriers are associated with the exploration and discovery of new geothermal resources. Tools and processes that decrease risk and expenses of these activities are essential for new resource characterization and discovery.
O.G.5	***Flexible Geothermal Energy Generation**	There are issues associated with flexible generation, such as added stresses on the system and high costs that are not lowered with lower power generation.
O.G.6	**Improving Aging Facilities**[2]	Boosting geothermal electricity production from declining fluid production and idling facilities can keep geothermal an important part of California's renewable energy mix.
O.G.7	**Innovative Geothermal Systems**	General geothermal systems take advantage of existing heat below the earth's surface to provide energy.
O.G.8	***Increasing Cost-Effectiveness**	Lowering maintenance costs and increasing efficiency of geothermal systems will increase their output and help pay back plant investments faster.
O.G.9	**Material Reuse**[2]	Exploring and extracting value from materials such as condensates that build up during geothermal production will help pay back the facilities and make them more economically viable.

Several research areas overlap with EPIC investment interests. Those overlaps are given the following identifiers:
* Mentioned in EPIC Investment Plan: Previous and Planned EPIC Investments related to Solar Technologies
[2] Relevant to Initiative 4.3.2 Geothermal Energy Advancement for a Reliable Renewable Electricity System

4.2.4.3 | Emerging and Breakthrough Technologies

The emerging and breakthrough technologies in Table 4-19 represent more targeted opportunities for Energy Commission investment. These individual technology advancements merit consideration based on the potential to lower costs, increase performance, enhance integration, and access a greater resource potential.

Table 4-19. Emerging and Breakthrough Technology Matrix

ID	Name	Parallel Research Topic	R&D Opportunity Areas	Potential Impact
G.1	**Improved Fluid Injection**	Innovative System Development	EGSs	For EGS, the fluid that is injected needs to be non-corrosive and limit losses to downhole formations. Also, in areas with tight water supplies, using fluids other than potable water may be desired.
G.2	**Characterizing and Modeling EGS Reservoirs**	Information Technology	EGSs	EGSs can be expensive because of massive drilling and exploration costs. Properly characterizing the wells can prevent initial spending and make EGSs more economical.
G.3	**Carbon Dioxide as a Working Fluid**	Innovative System Development	Innovative Geothermal Systems	Using CO_2 instead of water as a working fluid offers a method to permanently sequester carbon that would have entered the atmosphere, and using CO_2 generates steam more efficiently than using water.
G.4	**Improved Well Connectivity in EGS**	Innovative System Development	EGSs	Increasing the fractures and their openness in EGSs allows them to transport more water and be more efficient.
G.5	**Corrosion-Resistant Geothermal Piping**	Operations and Maintenance Improvement	Corrosive and Toxic Material Reduction	Polyethylene and plastics can be used instead of metal to avoid corrosion from impurities in geothermal brines. Certain metal alloys also limit corrosion. These improvements help extend system life and lower O&M costs.
G.6	**Material Recovery from Geothermal Brines**	Innovative System Development	Material Reuse	Recovering valuable materials such as lithium from geothermal resources can provide a secondary value stream, which lowers the overall cost of geothermal energy.
G.7	**Downhole Heat Exchangers**	Innovative System Development	Innovative Geothermal Systems	Existing oil and gas wells or non-productive discovery wells can have heat exchangers placed in them to allow fluid to go down and collect geothermal heat. The heated water can be used to power geothermal systems.
G.8	**Heat Recovery**	Legacy System Improvement	Innovative Geothermal Systems	Maximizing the heat recovery of a geothermal system increases its overall efficiency.

G.9	**Oil–Gas Well Reuse**	Innovative System Development	Increasing Cost-Effectiveness	Oil and gas wells that are located at sites with some geothermal potential can be reused, eliminating new drilling costs and therefore lowering the long-term cost of geothermal energy.
G.10	**Lower Drilling Costs**	Supply Chain	Increasing Cost-Effectiveness	Drilling costs are the highest single cost for geothermal systems. Lowering these costs by using improved processes or by selecting better sites for development can reduce the overall costs of geothermal energy.
G.11	**Water Reinjection**	Legacy System Improvement	Improving Aging Plants	Water can be piped to a geothermal location to increase liquid injection and resulting steam and heated water that is produced from geothermal wells. This can increase the production of wells without a strong water resource.
G.12	**Integration with CSP Systems**	Innovative System Development	Energy Storage Integration	CSP can be integrated with geothermal systems to pump molten salt down in geothermal wells for additional thermal storage and to increase the heat of a geothermal system.
G.13	**Combination with Desalination**	Innovative System Development	Improving Aging Plants	Geothermal power is typically a baseload generation technology. When power is not needed on the overall grid, desalination can be performed locally to limit how much of the required water resource needs to be brought in from elsewhere.
G.14	**Geophysical Methods**	Information Technology	Exploration, Resource Characterization, and Resource Development	Geophysical methods such as seismic sensors, remote sensing with lidar, and magnetic sensing can improve the characterization of underground resources for geothermal development.
G.15	**Modeling for Flexible Generation**	Information Technology	Flexible Geothermal Energy Generation	Flexible generation is not commonly performed by geothermal systems because of stresses on the system. Modeling of ramp-up and ramp-down for geothermal systems can explore whether future flexible systems are possible with new technologies.

4.3 | Small Hydro (<30 MW)

In 2017, hydropower generated 45,394 GWh of electricity in California. The state's hydro facilities are broken down into two categories: facilities with more than 30 MW of generation capacity are called "large" hydro, and facilities with less than 30 MW of generation capacity are considered "small" hydro and qualify as renewable under the Renewables Portfolio Standard. California's small hydro facilities generated 6,443 GWh of electricity in 2017, accounting for approximately 3% of California's total energy production.[125]

Small hydro facilities are typically either dam-based or in-conduit hydro systems. For in-conduit hydropower, existing tunnels, canals, pipelines, aqueducts, and other manmade structures that carry water are fitted with electric generating equipment. In-conduit projects can extract power from water without the need for a large dam or reservoir. The majority of hydroelectric development occurred in the late 20th century, and there has been little development since. As shown in Figure 4-9, small hydro capacity in

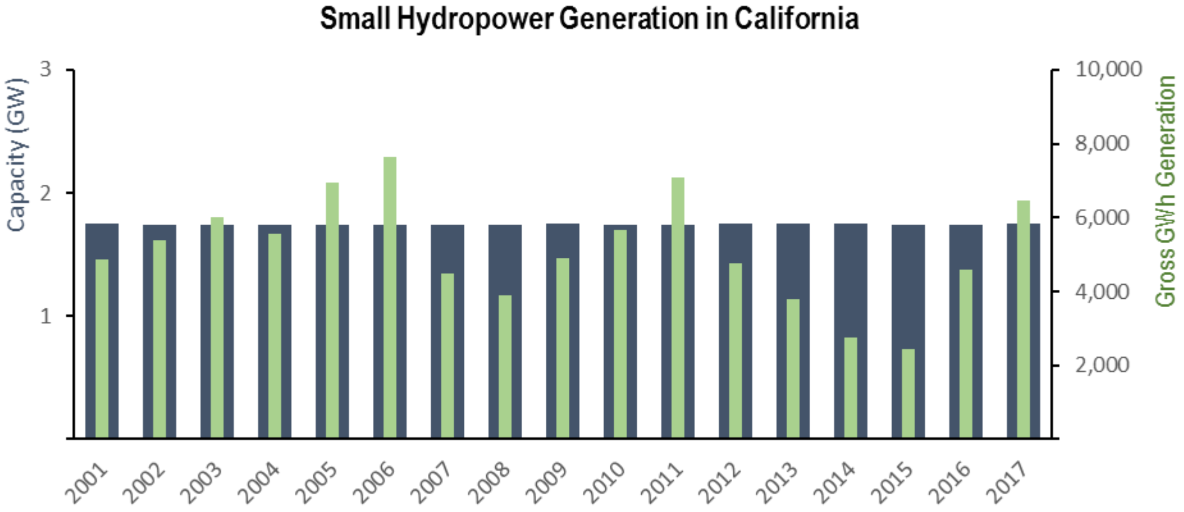

Figure 4-9. Small Hydropower Generation in California from 2001 to 2017

Data from energy.ca.gov/almanac/renewables_data/hydro/index.php

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[125] "California Hydroelectric Statistics & Data," California Energy Commission, energy.ca.gov/almanac/renewables_data/hydro/index.php.

California has remained nearly constant since 2001, although generation from these resources has fluctuated.

Thousands of miles of canals, pipelines, and other conduits send water to and from various locations across California. New conduit hydropower deployments could tap into this existing infrastructure to increase renewable power generation and offset the energy requirements of water transportation.[126] Other forms of small hydro development exist in the forms of retrofitting non-powered dams with hydropower capabilities and run-of-river or water diversion systems.

Looking forward, the DOE FY 2019 budget request establishes cost performance targets for small hydro systems from streams, summarized in Table 4-20. DOE research efforts support early-stage R&D exploring novel concepts and approaches to capturing hydropower and marine hydrokinetic energy resources.

Table 4-20. Small Hydro Cost Performance Targets (DOE)

	FY 2017	FY 2018	FY 2019	Endpoint Target
Small Hydro (streams)	11.5 cents/kWh (target met)	11.4 cents/kWh	11.15 cents/kWh	10.9 cents/kWh by 2020 8.9 cents/kWh by 2030

The new stream developments energy cost target is an unsubsidized cost of energy at utility scale. The target is for small, low-head developments.

Source: "Department of Energy FY 2019 Congressional Budget Request." Volume 3–Part 2: 24. DOE. March 2018. energy.gov/sites/prod/files/2018/03/f49/FY-2019-Volume-3-Part-2.pdf.

While stream-based systems and the development of site-specific non-powered dams show promise for the future, this report focuses on the potential of in-conduit systems.

4.3.1 | Resource Availability

In the United States, 14% of hydropower installations are in-conduit, but these installations account for only 2% of the country's total hydropower capacity. California contains 320 MW of in-conduit hydropower.[127] Installed capacity in California includes a 20 kW LucidPipe™ in Riverside's municipal system, as well as a 4.5 MW turbine in place of a pressure reduction valve in San Diego.[128,129] In both cases, in-conduit systems act as a form of pressure reduction, reducing excess pressure in the municipal water system while generating usable power.

Despite several examples of economically viable deployments of in-conduit hydropower systems in the United States and California, there has not been a national assessment of the potential for in-conduit resources. California conducted a small hydropower resource assessment in 2006, but this was limited to 43 of the states' water purveyors, accounting for only 65% of the state's water entitlements.[130] Of the 128 sites the report analyzed with estimated capacities over 100 kW, 67% had capacities that were 1 MW or less. The report identified a total potential of undeveloped in-conduit hydropower of 255 MW, with

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[126] "Hydropower Vision: A New Chapter for America's 1st Renewable Electricity Source," DOE, 2016, energy.gov/sites/prod/files/2018/02/f49/Hydropower-Vision-021518.pdf.

[127] N.M. Samu et al., "National Hydropower Plant Dataset, Version 1, Update FY18Q2 (2018). Existing Hydropower Assets [series] FY18Q2," Oak Ridge National Laboratory, National Hydropower Asset Assessment Program, nhaap.ornl.gov/submission-id/eha-3224.

[128] "LucidPipe Power System Case Study: Riverside Public Utilities," Lucid Energy, accessed December 2018, lucidenergy.com/wp-content/uploads/2016/10/LucidEnergy-RiversideCaseStudy-2016-10-lr.pdf.

[129] "Conduit," National Hydropower Association, accessed December 2018, hydro.org/policy/technology/conduit/.

[130] Laurie Park, "Statewide Small Hydropower Resource Assessment," Navigant Consulting, prepared for California Energy Commission, energy.ca.gov/2006publications/CEC-500-2006-065/CEC-500-2006-065.PDF.

capacity split evenly between irrigation and municipal water systems. In comparison, developing small hydropower by retrofitting non-powered dams offers a potential capacity of 195 MW in California.[131]

Figure 4-10. California's Canals

Through the State Water Project and the Central Valley Project, California has thousands of miles of canals to transport water from across the state.

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[131] Boualem Hadjerioua et al., "An Assessment of Energy Potential at Non-Powered Dams in the United States," Oak Ridge National Laboratory, 2012, energy.gov/sites/prod/files/2013/12/f5/npd_report_0.pdf.

In-conduit hydropower can be located at a canal or irrigation drop in agricultural systems, in existing pipelines using water diverted for municipal and industry use. Southern California has the highest potential, thanks to the proximity of large municipal systems such as Los Angeles and large irrigation systems for farming further inland. Central California shows the lowest potential because of the slower flow rate of its canal system. Northern California has large municipal water systems and canals that go through hills in that region of the state, increasing the height difference and flow rate of water in the conduit.[132]

Seasonal and weather variations play an important role in power availability. The energy output of hydropower in irrigation systems is skewed toward the summer months, in accordance with the growing season, and increases with municipal water usage and increased residential use for outdoor irrigation. Hydropower also sees a spring boost due to both increased rains and snowmelt, but drought conditions can decrease production. Droughts in 2007–2009 and 2011–2016 reduced hydropower production; Figure 4-9 shows the decreases in gross generation. According to the 2018 National Climate Assessment, increased temperatures due to climate change have reduced the winter snowpack, which, coupled with the temperature rise, has amplified California’s recent droughts. Continued rising temperatures increase the probability of droughts lasting over a decade that could severely cut hydroelectric power generation.[133]

4.3.2 | Technology Overview

4.3.2.1 | Small Hydro Performance Attributes

Hydropower has been used throughout the United States for centuries. In-conduit hydropower benefits from the technical maturity of hydro, as many installations can use equipment that is readily available. All forms of hydropower require the use of turbines to generate electricity from the potential and kinetic energy in water. In-conduit hydropower can serve a dual purpose of generating power through a turbine while reducing pressure in the water system. The two main kinds of turbines in use are reaction and impulse turbines. Reaction turbines react to the change in pressure of water flow, requiring them to be fully submerged, while impulse turbines rotate in response to a change in speed as they contact flowing water.[134]

In the United States, Francis turbines are the most common type of in conduit reaction turbines; however, 54% of all new turbines installed in the last decade are Kaplan turbines. Kaplan turbines are primarily deployed in low-head sites. The median size of all new installations since 2006 is around 10 MW.

Table 4-21compares the performance attributes of turbines used in low-head applications.

Table 4-21. Examples of In-Conduit Hydropower Turbines Used in Low-Head Applications

Turbine	Francis[1]	Kaplan[1]	PowerPipe[2]	Archimedes Screw[2]
Type	Reaction	Reaction	Reaction	Impulse
Head Range (m)	0–400	1.5–20	0–4	0–10

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[132] “Statewide Small Hydropower Resource Assessment,” Navigant Consulting, prepared for the California Energy Commission, June 2006, https://www.energy.ca.gov/2006publications/CEC-500-2006-065/CEC-500-2006-065.PDF.

[133] P. Gonzalez et al., “Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II,” US Global Change Research Program, 2018, nca2018.globalchange.gov/.

[134] Michael J. Sale et. al., “Opportunities for Energy Development in Water Conduits,” Oak Ridge National Laboratory, info.ornl.gov/sites/publications/files/Pub50715.pdf.

Flow Range (m^3/s)	0.05–40	1.5–60	1.0–5.6	0.1–10
Capacity	0–20,000 kW	20 kW–3500 kW	14–100 kW	1–500 kW

[1]Data from wrc.org.za/Knowledge%20Hub%20Documents/Research%20Reports/TT%20597-14.pdf
[2]Data from energy.ca.gov/2017publications/CEC-500-2017-007/CEC-500-2017-007-APL.pdf

4.3.2.2 | Cost Attributes and Barriers to Development

There has been little development of new hydropower in recent decades, despite the maturity of hydropower. The limited development that has taken place has mostly been small hydropower, although small hydropower still faces development barriers. Capital costs for in-conduit systems are variable and dependent on site-specific factors such as the availability of existing infrastructure, hydraulic head, and system capacity.[135] Additionally, most in-conduit designs are custom-engineered, which can add costs.

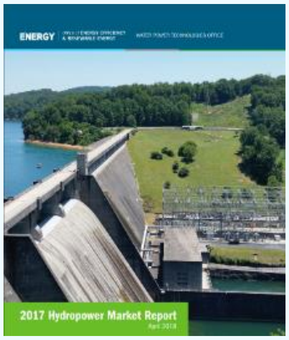
Conduit systems may also be perceived as unproven, as deployments are fewer than with other system types. Water system owners are highly risk-averse owing to the necessity of water for their operations, be it irrigation, municipal use, or otherwise.[136]

Recent regulatory changes and incentive programs attempt to mitigate some of the barriers to hydropower deployment. The Hydropower Regulatory Efficiency Act of 2013 and the Promoting Conduit Hydropower Facilities Act of 2017 helped to accelerate permitting for conduit hydropower projects. California offers state-level incentives for in-conduit hydropower projects. California's Self-Generation Incentive Program offers eligible projects an incentive of $.60/watt and a feed-in tariff program of 8.9 cents/kWh for systems smaller than 3 MW.[137] However, ongoing permitting challenges at the state and local levels can cause small projects to stall and face cancellation despite the regulatory changes and incentive programs.[138]

Figure 4-11. 2017 Hydropower Market Report

The 2017 Hydropower Market Report discusses the major trends in the U.S. hydropower market in 2017:

- Installation Trends
- Industry Trends
- Technology Trends
- Performance Trends
- Cost Trends
- Policy and Market Drivers
- Outlook



Available at energy.gov/sites/prod/files/2018/04/f51/Hydropower%20Market%20Report.pdf

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[135] Rocio Uria-Martinez et. al., "2017 Hydropower Market Report," Oak Ridge National Laboratory, April 2018, energy.gov/sites/prod/files/2018/04/f51/Hydropower%20Market%20Report.pdf.
[136] "Pumped Storage and Potential Hydropower from Conduits," DOE, February 2015, energy.gov/sites/prod/files/2015/06/f22/pumped-storage-potential-hydropower-from-conduits-final.pdf.
[137] Kurt Johnson et. al., "Energy Recovery Hydropower: Electricity Costs for Agricultural, Municipal, and Industrial Water Providers and Users," NREL/TP-6A20-70483, January 2018, nrel.gov/docs/fy18osti/70483.pdf.
[138] Kurt Johnson et. al., "Small Hydropower in the United States," ORNL/TM-2018/999, October 2018, files.constantcontact.com/397893ca301/a989fb6f-138a-4c4f-bfe9-18def6786555.pdf.

4.3.3 | Research Initiatives

4.3.3.1 | EPIC Investment Initiatives

The EPIC 2018–2020 Triennial Investment Plan does not mention R&D priorities to increase small hydropower deployment in California.[139]

Select EPIC Projects

The Energy Commission's EPIC Program funds applied R&D, technology demonstration and deployment, and market facilitation that promote the development of new energy solutions and their introduction into the marketplace. The following EPIC-funded projects focus on in-conduit hydropower technology and innovation.[140]

Table 4-22. Select EPIC Hydropower Projects

Project	Description/Goal	Potential Impact
Comprehensive Assessment of In-Conduit Hydropower Generation Potential in California to Assist Municipal, Agricultural, and Industrial Water Purveyors	Site Assessment; Market Integration	Conduct a comprehensive assessment of in-conduit hydropower in California and produce materials outlining cost-effective development of this resource for water purveyors in California.
Cost-Effective and Climate-Resilient In-Conduit Hydropower and Civil Works Innovation	Modular Turbines	Design a scalable, standardized powerhouse and plant design that can be replicated for multiple irrigation drops in California.
Improving Hydrologic and Energy Demand Forecasts for Hydropower Operations with Climate Change	Climate Change Mitigation; Hydropower Forecasting	Use sensors to create grid-wide forecasts of inflow and electricity demand, incorporating data on temperature, hydrologic conditions, and grid performance.
San Gabriel Valley Water Company "Plug and Play" In-Conduit Hydropower Development Project	Modular Turbines	Develop a modular "plug-and-play" sub-100 kW in-conduit water system that can take the place of pressure-reducing stations in the state's municipal water system.
The Amador Water Agency In-Conduit Hydropower Development Project	Pressure Reducing Turbine	Develop an in-conduit Pelton turbine runner at an existing pressure-reducing station, capturing lost energy with a higher-efficiency design.

4.3.3.2 | Research Initiatives from Other Funding Entities

DOE Hydropower Vision Roadmap

In July 2016, DOE released Hydropower Vision: A New Chapter for America's 1st Renewable Electricity Source, which discusses how U.S. hydropower can add 40 GW of capacity from 2015 to 2050. The Hydropower Vision report includes a roadmap of recommended actions aimed at pursuit of the vision. Table 4-3 lists actions of interest for the continued growth of in-conduit hydropower.[141]

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[139] "Electric Program Investment Charge: 2018–2020 Triennial Investment Plan," California Energy Commission, CEC-500-2017-023-CMF, adopted on April 27, 2017, energy.ca.gov/research/epic/17-EPIC-01/.

[140] California Energy Commission Innovation Showcase, innovation.energy.ca.gov/.

[141] "Hydropower Vision: A New Chapter for America's 1st Renewable Electricity Source," DOE, 2015. energy.gov/sites/prod/files/2018/02/f49/Hydropower-Vision-021518.pdf.

Table 4-23. Hydropower Vision Road Map, Areas of Need

Action	Description
Action 1.1: Develop Next-Generation Hydropower Technologies	Continue development and research on new designs and methods for hydroelectric power generation to make it competitive with other energy sources.
Action 1.3: Validate Performance and Reliability of New Hydropower Technologies	Demonstrate the reliability of new technologies, minimizing risk and promoting continued development.
Action 2.1: Increase Hydropower's Resilience to Climate Change	Continue assessment of climate-driven weather events, how they affect hydropower generation, and how to mitigate their effects.
Action 3.1: Improve Valuation and Compensation of Hydropower in Electricity Markets	Develop market systems that promote the positive characteristics of hydropower generation.
Action 3.3: Remove Barriers to the Financing of Hydropower	Expand opportunity for financing low-capacity hydropower through standardized documentation and outreach about small hydro.
Action 5.2: Compile, Disseminate, and Implement Best Practices and Benchmarking in Operations and Research and Development	Continue communication of innovation, development, and fleet performance to inform stakeholders of performance and effects of new technology developments.
Action 5.3: Develop and Promote Professional and Trade-Level Training and Education Programs	Encourage training in the field from the high school to trade levels to replace an aging workforce.

4.3.4 | R&D Opportunity Areas and Technologies

To identify and prioritize R&D opportunity areas and technologies for small hydropower, technical assessment analysts relied on state and federal government reports, industry reports, and peer-reviewed research articles. Research also included phone interviews with several experts from government and other research institutions across the United States.

Figure 4-12. Small Hydro Experts Interviewed

- Kurt Johnson, Chief Executive Officer, Telluride Energy
- Brennan Smith, Program Manager, Oak Ridge National Laboratory, Water Technologies
- Sandra Walker, Chief Operating Officer and Co-Founder, Oceanus Power and Water
- Tim Welch, Program Manager, DOE Hydropower Program

4.3.4.1 | Key Considerations

Expert interviews and literature review identify a number of factors worth consideration when dealing with assessment, investment, or construction of small-hydropower generation in California. These areas are broadly categorized into technical, financial, and regulatory considerations, as discussed below.

Technical Considerations

- **A conduit hydro resource assessment is needed to obtain information to support resource development**. The last assessment in California was done in 2005 but was limited in scope. Compared to other states, California has an outsized potential for in-conduit hydropower and a strong incentive to understand the full extent of this resource potential, which can be more clearly demonstrated through combined study of resources, irrigation and municipal systems data, and information about water rights.

- **Standardized and modular components for hydropower systems would enable broader deployment.** Standardized components can decrease costs and enhance system feasibility. Standard turbines that can operate in a variety of flow conditions could be installed in a variety of locations instead of being custom-designed.
- **Improved conduit system monitoring and controls could enable greater value.** Smart conduit systems could add value streams such as water monitoring and lead to more accurate forecasting of power generation and water delivery.

Financial Considerations

- **The custom design and configuration of conduit hydropower systems increases capital costs.** Every site for in-conduit hydropower is unique, with different flow rates, pressure heads, and civil structures in place, as well as varying water rights of water purveyors and customers. Custom-engineered systems drive costs up.
- **Project financing can be hard to secure because of the perceived high risk of small hydro systems**. Small hydro projects can face high costs in permitting, engineering, and interconnection. Current permitting regulations favor smaller systems, but small systems typically having higher relative soft costs.

Regulatory Considerations

- **Small hydropower is typically not dispatchable because of the highly controlled nature of water delivery in California.** In-conduit hydro relies on the service of water purveyors to generate power. While water is constantly flowing in municipal systems, energy production will be tied to seasonal irrigation in California’s farming regions.

4.3.4.2 | R&D Opportunity Areas

The R&D opportunity areas in Table 4-24 expand beyond those identified in the Energy Commission’s 2018–2020 Triennial Investment Plan. They are based on an extensive literature review and conversations with experts.

Table 4-24. Small Hydro – Technology Research & Development Opportunity Areas

ID	Opportunity Areas	Description
O.H.1	**Alternative Materials for Turbine Components**	Materials improvements that improve efficiency and/or bring materials costs down as a result of simplified manufacturing.
O.H.2	**Electrical and Control Systems**	Systems that support the flow of electricity from hydro turbines to interconnection points.
O.H.3	**Environmental and Societal Improvements**	Processes and technologies that improve sound, effects on wildlife, and other environmental externalities.
O.H.4	**Forecasting and Assessment**[1]	Technologies that provide better-quality data to predict power generation because of precipitation, snowpack, runoff, and stored water in reservoirs.
O.H.5	***Integrate Climate Readiness into Electricity System Operations, Tools, and Models**	Technologies that mitigate the effects of climate change on power generation and transmission capabilities.
O.H.6	**Low-Head Application**	Technologies that allow for small hydro to be more feasible in conduits that have a low head.

ID	Opportunity Areas	Description
O.H.7	**Real-Time Monitoring Systems**	Monitoring systems that report data at short intervals, allowing for adjustment and control of systems to improve power output.
O.H.8	**Site and Energy Assessment of Existing Conduits**	Technology that can accurately assess the capacity and generation capabilities of existing conduits.
O.H.9	**Testing Methods and Facilities**	Test facilities to verify power production, test new technologies and designs, and lower costs.
O.H.10	**Turbine Improvements**	Technologies that improve the efficiency and performance of turbines.
O.H.11	**Turbine Standardization**	Innovations that simplify turbine design and make it replicable in a variety of locations.

Research areas do overlap with EPIC investment interests. Those overlaps are given the following identifiers:
* Mentioned in EPIC Investment Plan: Previous and Planned EPIC Investments on Demand Response
[1] Relevant to Initiative 7.2.1 Improved Understanding of Climate and Weather-Related Risks and Resilience Options

4.3.4.3 | Emerging and Breakthrough Technologies

The emerging and breakthrough technologies in Table 4-25 represent more targeted opportunities for Energy Commission investment and fall within the aforementioned R&D opportunity areas.

Table 4-25. Emerging and Breakthrough Technology Matrix

ID	Name	Parallel Research Topic	R&D Opportunity Areas	Potential Impact
H.1	**Cavitation Analysis**	Information Technology	Testing Methods and Facilities; Real-Time Monitoring Systems	Preventing cavitation in turbines is necessary to ensure efficiency and minimize damage due to blade erosion.
H.2	**Composite Materials**	Supply Chain	Alternative Materials for Turbine Components	Composite materials make hydropower components more lightweight, decreasing costs related to manufacturing, transport, installation, and maintenance.
H.3	**Dead Level Turbine Efficiency**	Legacy System Improvement	System Standardization	Turbines that can maintain a high efficiency over a variety of flows will generate more power and generate power reliably as flow rates change.
H.4	**Hydrokinetic Turbines**	Innovative System Development	Low-Head Application; Turbine Standardization	Submerged turbines that rely on water velocity instead of pressure head are an ideal fit for locations with a stable elevation but fast-flowing water.
H.5	**Inflatable Weirs**	Innovative System Development	Low-Head Application	Inflatable structures that alter the head can increase the number of sites eligible for small hydro.
H.6	**Modular Systems**	Supply Chain; Operations and Maintenance improvement	System Standardization	Producing components off-site that can easily be connected on-site will reduce civil and installation costs while making small hydro scalable to a variety of sites.
H.7	**Standardized Site Assessment Tool**	Information Technology	Site and Energy Assessment of Existing Conduits; Forecasting and Assessment	Consistent methods that can be used for site assessments of all potential in-conduit hydropower locations improve understanding of resource availability.
H.8	**Test Facilities**	Information Technology	Testing Methods and Facilities	Testing new components and designs can minimize the risk to developers and lower costs.
H.9	**Water and Self-Lubricated Turbines**	Legacy System Improvement	Turbine Improvements	Avoiding oil-based lubricants can maintain turbine efficiency while mitigating risk of water supply contamination.
H.10	**Induction Generator**	Legacy System Improvement	Electrical Systems	Induction generators can operate at lower cost while operating and being able to withstand potential overspeed if the water flow increases.
H.11	**Permanent Magnet Generator**	Legacy System Improvement	Electrical Systems	A permanent magnet generator can operate at a variety of speeds, being able to consistently generate power no matter how water flow increases or decreases.

Chapter 5| Energy Storage

Grid-level (utility- or ISO-controlled) energy storage at the transmission, distribution, and aggregated customer levels offers unique flexibility for ensuring smooth operation of a renewables-heavy grid.

Locating storage at transmission-constrained points can reduce grid congestion, defer or avoid costly investments in new transformers, and make the grid more secure, reliable, and responsive.

Challenges

- Although front-of-the-meter energy storage is growing quickly, utilities are hesitant to procure large-scale energy storage systems unless required to do so or in response to emergencies.
- There is a lack of comparable information and standards regarding energy storage system performance.

Opportunities

- AB 2514 has established energy storage procurement requirements for California’s largest three IOUs.
- Energy storage prices, particularly for electrochemical storage, continue to decline as performance increases. Some experts indicate that storage systems have already surpassed cost parity with conventional gas peaker plants.

Mechanical

Mechanical storage systems use mechanical components to store energy in the form of potential or kinetic energy. When desired, the potential or kinetic energy is released and used to generate electricity.

Thermal

At the utility scale, thermal energy storage systems often accompany concentrating solar plants. These installations can shift electricity from solar power away from the times that traditional PV solar operates.

Electrochemical

Battery materials and chemistries impact cost and performance and result in batteries that are suited for certain uses. Lithium-ion batteries have emerged as the most popular battery chemistry due to their high energy density and increasingly lower costs.

5.1 | Energy Storage Systems

California has the largest energy storage market in the United States and continues to increase in capacity, thanks to requirements by California legislature, grid reliability needs, and incentive programs. Energy storage systems are becoming an increasingly important grid resource used to complement the variability of wind and solar energy production, avoid demand charges for customers, and even replace generation from natural gas peaker plants. Behind-the-meter, distribution, and transmission-tied systems are being installed in California.

Energy storage capacity in California stayed relatively constant for several decades after the early 1980s, when the largest projects, pumped hydropower, began implementation. The recent installation of new battery systems and some thermal energy systems has increased the total generation of California projects. However, as Figure 5-1 demonstrates, electro-chemical and thermal systems remain a small part of California's total storage capacity.

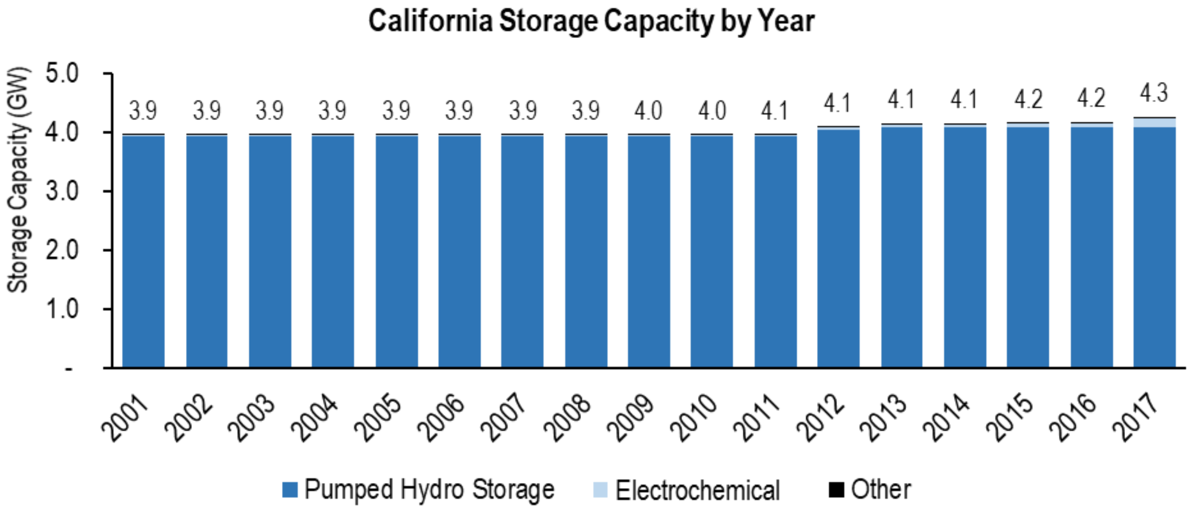

Figure 5-1 Energy Storage Capacity in California from 2001 to 2017

Data from DOE Energy Storage Database (energystorageexchange.org/)

In 2017, California added 68 MW of new energy storage capacity, of which 62 MW was battery storage systems. Overall, California had 4.16 GW of energy storage capacity at the end of 2017: 95.3% (3.97 GW) was pumped hydro storage, 4.2% (173 MW) was electrochemical storage systems, and .04% (18 MW) was thermal storage systems. The rest of the storage capacity was minimal (2 MW) and provided by mechanical systems, such as flywheels.

The recent increase in energy storage systems can be attributed partially to the California Public Utilities Commission (CPUC) 2013 decision[142] requiring the state's largest three IOUs to procure 1,325 MW of storage capacity by 2020, with installation by 2024. However, utility storage procurement to meet reliability needs, such as gas shortages from the Aliso Canyon leak or the San Onofre Nuclear Generating Station (SONGS) retirement, has outpaced the storage mandate procurement.[143] Developers of new solar and wind systems are also finding that certain renewable installations can compete with fossil generating assets by packaging their systems with storage and offering power at a blended price. [144]

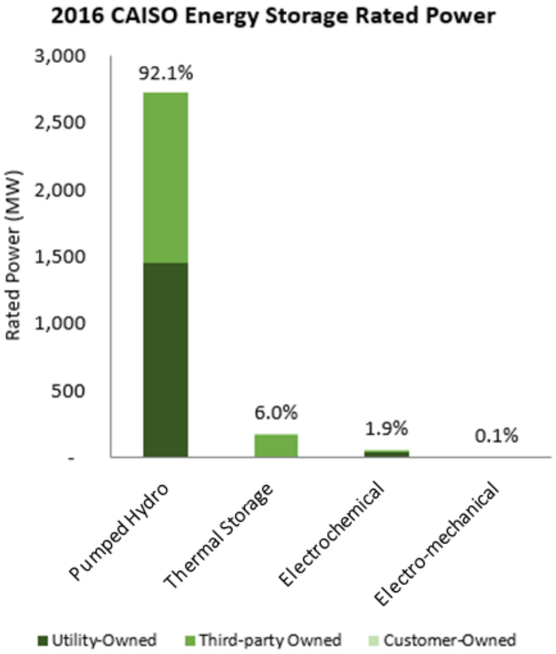

Figure 5-2. 2016 CAISO Energy Storage Rated Power

The DOE Office of Electricity maintains a database of reported energy storage projects across the globe.

The database contains links and information on the project and can be sorted by multiple criteria including storage type and location.

energystorageexchange.org/projects/data_visualization

Looking forward, the DOE FY 2019 budget request establishes cost performance targets, summarized in Table 5-1. DOE research efforts focus on new materials and device technologies that can lead to significant improvements in the cost and performance of utility-scale energy storage systems.

Table 5-1. Energy Storage Cost Performance Targets (DOE)

	FY 2017	FY 2019	Endpoint Target
Grid-scale (>1 MW) aqueous soluble organic electrolyte (redox flow battery system)	$350/kWh for a 4-hour aqueous soluble organic flow system	$225/kWh for a 4-hour aqueous soluble organic flow system; projected 1 MW/4 MWh system operating at 150 mA/cm^2	By the end of FY 2025, the cost of a prototype redox flow battery system will be $100/kWh

Source: "Department of Energy FY 2019 Congressional Budget Request." Volume 3–Part 1: 32. DOE. March 2018. energy.gov/sites/prod/files/2018/03/f49/DOE-FY2019-Budget-Volume-3-Part-1_0.pdf.

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[142] This decision stemmed from Assembly Bill 2514.

[143] "Energy Storage Market Survey and Recommendations," CPUC Commissioner Briefing, October 24, 2018: 3, cpuc.ca.gov/uploadedFiles/CPUC_Public_Website/Test_Calendar/CPUC%20Energy%20Storage%20Market%20Survey%20and%20Recommendations%2010.22.18(1).pdf.

[144] "Xcel to Replace 2 Colorado Coal Units With Renewables and Storage," *Greentech Media*, August 29, 2018, https://www.greentechmedia.com/articles/read/xcel-retire-coal-renewable-energy-storage#gs.8tdIe3c.

5.1.1 | Resource Availability

Numerous economic, technological, and locational constraints and considerations affect when energy storage systems are available for use. This section will analyze the impacts of physical location, use cases, technology type, and raw materials on system availability.

Figure 5-3. Tracking Progress of Energy Storage in California

The Energy Commission releases sector-specific summaries that are updated regularly for several renewable energy topic areas. The "Tracking Progress" report for Energy Storage was released in August 2018.

Tracking Progress reports are available here: energy.ca.gov/renewables/tracking_progress/.

5.1.1.1 | Physical Location

Most energy storage systems are not restricted by the same resource limitations as renewables that rely on a natural source of power (e.g., wind or sunlight). The exception is pumped hydropower plants that require specific sites with a low- and a high-height water reservoir nearby. The lack of new pumped hydropower plant installation in California and the United States can be partially attributed to a lack of available sites. In addition, there are several environmental considerations that impede development of these projects. DOE's Hydropower Vision report estimates that 650–1,075 MW of potential pumped hydro power capacity is available in California.[145]

Other energy storage projects, especially lithium-ion batteries, can be sited and deployed almost anywhere. This is truer for behind-the-meter and smaller energy storage deployments than for utility-scale projects. When energy storage systems are providing arbitrage or other grid services, there is a benefit to placing them near transmission lines and junctions to limit losses and to ease integration onto the system. However, utility-scale battery energy storage systems are large enough that environmental and social issues associated with installation may warrant consideration.

Utility-scale energy storage (especially batteries) can be installed at existing substations, taking up far less land than conventional generation; therefore, system installation effects a significantly smaller physical imprint, as well as reductions to the cost and time associated with land procurement. Examples of storage systems located at existing substations include San Diego Gas and Electric's (SDGE's) 30 MW/120 MWh battery system installed at its Escondido substation[146] and Pacific Gas and Electric's (PG&E's) recently approved 182.5 MW Moss Landing substation energy storage project.[147]

5.1.1.2 | Use Cases

An energy storage system's use cases, or the services the system is intended to provide, will have an impact on resource availability. Unlike many types of generation that provide a single specific service (such as energy, capacity, frequency regulation, etc.), energy storage technologies can provide multiple types of

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[145] "Hydropower Vision Chapter 3: Assessment of National Hydropower Potential," U.S. Department of Energy, Water Power Technologies Office, energy.gov/eere/water/downloads/hydropower-vision-chapter-3-assessment-national-hydropower-potential

[146] "Project of the Year: SDG&E's Escondido energy storage project," *Utility Dive*, December 4, 2017, utilitydive.com/news/project-of-the-year-aes-escondido-energy-storage-project/511157/.

[147] "PG&E Proposes Four New Cost-effective Energy Storage Projects to CPUC," June 29, 2018, pge.com/en/about/newsroom/newsdetails/index.page?title=20180629_pge_proposes_four_new_cost-effective_energy_storage_projects_to_cpuc; CPUC Resolution E-4949, November 8, 2018, docs.cpuc.ca.gov/PublishedDocs/Published/G000/M240/K050/240050937.PDF.

services and act as both flexible load and generation. However, as storage systems attempt to provide multiple services, they run the risk of receiving simultaneous and/or conflicting instructions on how to operate. In this event, a storage system may not be available to perform certain use cases if others take precedent.

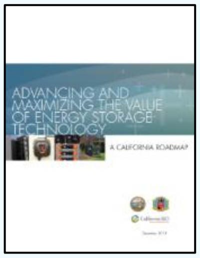
Additionally, storage systems operate differently and have variant availability to provide multiple use cases, depending on which services the systems are designed to provide. For example, a system designed for bulk energy arbitrage may charge and subsequently discharge for multiple hours at a time, leaving it unavailable to provide other services for several hours. However, a system designed to perform frequency regulation may charge and discharge for only a few minutes or hours at a time and has greater availability to provide other services. Batteries can also vary the services they are intended to perform on longer-term weekly, monthly, and seasonal cycles.

The CPUC recently defined multiple use cases that energy storage systems can provide at the customer, distribution, and transmission levels, established guiding principles on when and how a single system can provide multiple use cases, and instituted a working group to refine the use cases and guiding principles.[148] Future CPUC decisions may further affect resource availability by establishing rules around use cases that storage systems can provide. Additionally, California agencies have produced an energy storage roadmap that discusses use cases for storage,[149] and organizations such as the Rocky Mountain Institute have explored multiple value streams and developed a list of services that energy storage systems can provide.[150] Understanding the value of the resource is important for encouraging continued development and deployment of energy storage systems in California.

Figure 5-4. 2014 CAISO Energy Storage Roadmap

The 2014 CAISO roadmap, “Advancing and Maximizing the Value of Energy Storage Technology,” provides guidance for CPUC, the Energy Commission, and CAISO related to the following energy storage actions:

- Planning
- Procurement
- Rate Treatment
- Interconnection
- Market Participation


ADVANCING AND MAXIMIZING THE VALUE OF ENERGY STORAGE TECHNOLOGY
A CALIFORNIA ROADMAP

The roadmap is available here: caiso.com/informed/Pages/CleanGrid/EnergyStorageRoadmap.aspx.

A 2018 Lazard report examines the cost of energy storage on a subset of use cases that are the most identifiable and common in the context of its specific applications on the grid and behind the meter.[151] Each use case is described in Figure 5-5. The use cases represent applications of energy storage that market participants are utilizing now or will be utilizing in the near future.

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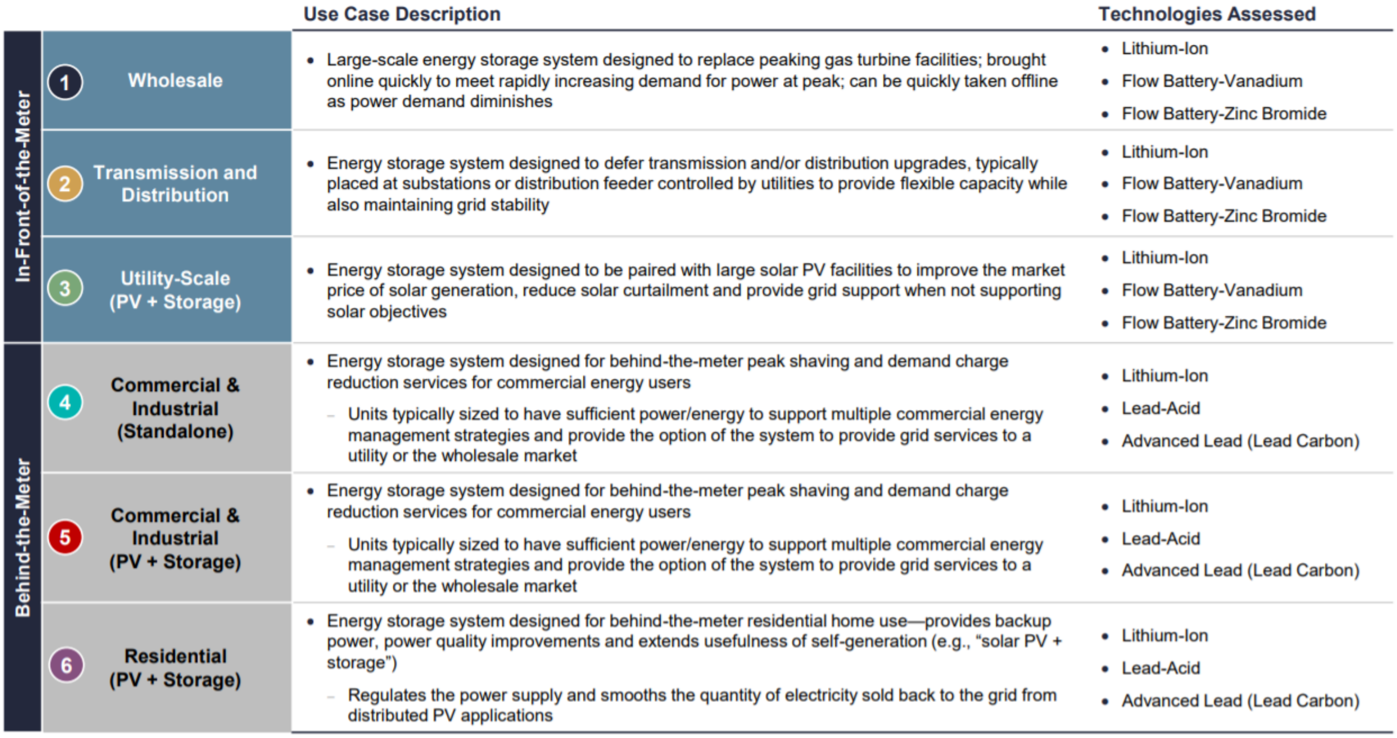
[148] Decision 18-01-003, January 11, 2018, http://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M206/K462/206462341.pdf.

[149] “Advancing and Maximizing the Value of Energy Storage Technology,” CAISO, December 2014, caiso.com/Documents/Advancing-MaximizingValueofEnergyStorageTechnology_CaliforniaRoadmap.pdf.

[150] “The Economics of Battery Energy Storage,” Rocky Mountain Institute, October 2015, rmi.org/wp-content/uploads/2017/03/RMI-TheEconomicsOfBatteryEnergyStorage-FullReport-FINAL.pdf.

[151] “Lazard’s Levelized Cost of Storage Analysis – Version 4,” Lazard, November 2018, lazard.com/media/450774/lazards-levelized-cost-of-storage-version-40-vfinal.pdf.



			Use Case Description	Technologies Assessed
In-Front-of-the-Meter	1	Wholesale	Large-scale energy storage system designed to replace peaking gas turbine facilities; brought online quickly to meet rapidly increasing demand for power at peak; can be quickly taken offline as power demand diminishes	Lithium-Ion Flow Battery-Vanadium Flow Battery-Zinc Bromide
	2	Transmission and Distribution	Energy storage system designed to defer transmission and/or distribution upgrades, typically placed at substations or distribution feeder controlled by utilities to provide flexible capacity while also maintaining grid stability	Lithium-Ion Flow Battery-Vanadium Flow Battery-Zinc Bromide
	3	Utility-Scale (PV + Storage)	Energy storage system designed to be paired with large solar PV facilities to improve the market price of solar generation, reduce solar curtailment and provide grid support when not supporting solar objectives	Lithium-Ion Flow Battery-Vanadium Flow Battery-Zinc Bromide
Behind-the-Meter	4	Commercial & Industrial (Standalone)	Energy storage system designed for behind-the-meter peak shaving and demand charge reduction services for commercial energy users – Units typically sized to have sufficient power/energy to support multiple commercial energy management strategies and provide the option of the system to provide grid services to a utility or the wholesale market	Lithium-Ion Lead-Acid Advanced Lead (Lead Carbon)
	5	Commercial & Industrial (PV + Storage)	Energy storage system designed for behind-the-meter peak shaving and demand charge reduction services for commercial energy users – Units typically sized to have sufficient power/energy to support multiple commercial energy management strategies and provide the option of the system to provide grid services to a utility or the wholesale market	Lithium-Ion Lead-Acid Advanced Lead (Lead Carbon)
	6	Residential (PV + Storage)	Energy storage system designed for behind-the-meter residential home use—provides backup power, power quality improvements and extends usefulness of self-generation (e.g., "solar PV + storage") – Regulates the power supply and smooths the quantity of electricity sold back to the grid from distributed PV applications	Lithium-Ion Lead-Acid Advanced Lead (Lead Carbon)

Figure 5-5. Energy Storage Use Cases – Overview (Lazard 2018)

5.1.1.3 | Raw Materials

Related to the growing demand for lithium batteries in California and elsewhere, there is an expanding interest in developing and extracting lithium resources. As of 2018, only one lithium production facility existed in the United States, a brine operation in Nevada. Known lithium reserves in the United States currently total 6.8 million tons.[152] In California, geothermal brines are expected to be the largest potential source of lithium in California. A 2015 NREL report looks at the lithium resource near the Salton Sea in southern California and estimates geothermal brines at that location could provide 54,000–122,000 metric tons of lithium by 2030.[153] This development depends on improvements in lithium recovery technologies and processes. The Salton Sea is one of a limited number of areas in California with lithium brine resources. Future lithium extraction from brines could provide revenues, expand local economies, and secure a source of battery-grade lithium within state boundaries.

In addition to lithium, lithium-ion batteries require different materials for the anode and cathode. There are numerous lithium-ion battery chemistries, each using different combinations of materials with differing levels of resource availability. Some common cathode materials, such as cobalt and nickel, are relatively rare, are expensive, come from conflict zones that deploy child labor and environmentally hazardous practices, have potentially unreliable supply chains, and may not meet future energy storage demands.[154] Consequently, developing lithium-ion batteries that use more abundant minerals could greatly improve the

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[152] "Mineral Commodity Summaries 2018," U.S. Department of the Interior, U.S. Geological Survey, January 2018, minerals.usgs.gov/minerals/pubs/mcs/2018/mcs2018.pdf.

[153] Douglas Gagne et al., "The Potential for Renewable Energy Development to Benefit Restoration of the Salton Sea: Analysis of Technical and Market Potential," National Renewable Energy Laboratory, November 2015, nrel.gov/docs/fy16osti/64969.pdf.

[154] "Ten years left to redesign lithium-ion batteries," *Nature International Journal of Science*, July 25, 2018, nature.com/articles/d41586-018-05752-3.

availability of lithium-ion batteries in the future. In addition, cost-effective recycling of lithium and other minerals from spent lithium-ion batteries could be a source of lithium in the future.

5.1.2 | Technology Overview

A variety of energy storage systems, shown by maturity in Figure 5-6, can be used for one or multiple energy storage applications. Certain energy storage systems may be better suited for one application than another, based on the system's rated power, capacity, energy density, and discharge rate.

Rated power (expressed in megawatts) represents the maximum charge/discharge power, whereas energy storage capacity (expressed in megawatt-hours) represents the amount of energy that can be stored and discharged. Energy density represents the amount of energy stored in a given system or region of space per unit volume. Discharge rates represent how quickly the stored energy can be discharged at rated capacity. Short-duration batteries are designed to provide power for a very short time, usually on the order of minutes to an hour, whereas long-duration batteries can provide power for several hours. [155]

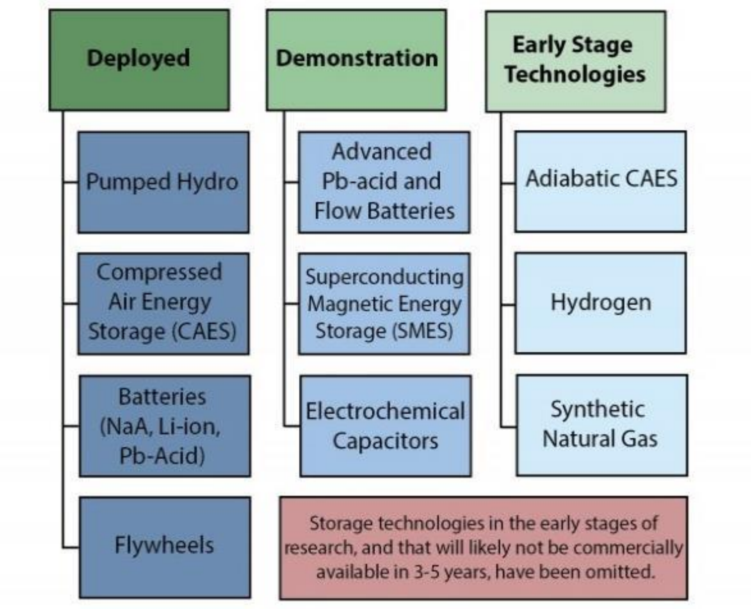

Figure 5-6. Maturity of Electricity Storage Technologies

Adapted from DOE 2013, Grid Energy Storage report.

This report organizes energy storage technologies into three broad categories: mechanical, electrochemical, and thermal. While many storage technologies are being installed behind customer meters, these sections focus primarily on utility-scale storage technologies.

5.1.2.1 | Mechanical Storage

Mechanical storage systems use mechanical components to store energy in the form of potential or kinetic energy. When desired, the potential or kinetic energy is released and used to generate electricity. Pumped hydro, flywheels, and compressed air are the most commercially advanced and common forms of mechanical energy storage.

Pumped Hydro

Pumped-storage hydropower (PSH) is the dominant utility-scale storage method in California and around the world. These facilities work by pumping water from a lower reservoir up to a higher reservoir during times of low demand and then releasing that water through traditional hydropower generators when

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[155] "U.S. Grid Energy Storage Factsheet," University of Michigan Center for Sustainable Systems, 2017, css.umich.edu/factsheets/us-grid-energy-storage-factsheet; adapted from "DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA," Sandia National Laboratories, July 2013, energy.gov/sites/prod/files/2013/08/f2/ElecStorageHndbk2013.pdf.

power is needed. Pumped hydro technology has existed commercially since the late 19th century. Despite few new installations in the past decade, PSH continues to account for 95.3% of total utility-scale storage capacity in California and 97% in the United States. [156,157]

Pumped hydro installations sites must have specific characteristics to accommodate large water volumes at two different heights. The round-trip efficiency for these plants varies between 60% and 80% because of the wide spread of installation ages. PSH plants vary in costs, but current estimates put a 1,000 MW fixed-speed plant between $1,750 and $2,500 per kW. A variable-speed plant costs between $1,800 and $3,200 per kW.[158]

As shown in Table 5-2, more than 91% of PSH capacity in California is over 30 years old, and some infrastructure has been operating for more than 50 years. Increased deployment of variable power generation has renewed interest in PSH projects. Several states and government agencies are actively evaluating and analyzing future PSH development in the United States. In California, one new pumped hydro facility is in development in Riverside County. However, this project missed a construction target in June 2018, which has put the plant's future in doubt.

Table 5-2. Pumped Hydropower Plants in California

Plant Name	Location (County)	Capacity (MW)	Gross Energy (GWh)	2017 *Capacity Factor (%)	Year Operational
Edward Hyatt Power Plant	Butte	644	2,387	42	1967
Thermalito Pumping-Generating Plant*	Butte	120	0	0	1968
W.R. Gianellis Pumped Storage Plant	Merced	424	201	5	1968
O'Neill Pumping-Generating Plant	Merced	28	0	0.04	1968
Castaic Pumped Storage Plant	Los Angeles	1,682	566	4	1978
Helms Pumped Storage Plant	Fresno	1,212	872	8	1984
Balsam Meadows/Big Creek (Eastwood) Pumped Storage	Fresno	200	425	24	1987
Olivenhain-Hodges Storage Project	San Diego	40	58	17	2012

*Thermalito Pumping-Generating Plant has shut-down

Flywheels

A form of kinetic energy storage, flywheels work by transferring electricity into mechanical energy by turning a spinning rotor. The rotor typically turns within a low-pressure enclosure to minimize resistance and energy losses. Flywheel systems can be manufactured from recyclable and non-hazardous materials and can last more than 25 years. Flywheel systems are useful to the grid because they provide ancillary

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[156] "DOE Global Energy Storage Database," Sandia National Laboratories, accessed November 19, 2018, energystorageexchange.org/.

[157] "Hydropower Vision Report: Full Report," U.S. Department of Energy, Water Power Technologies Office, energy.gov/eere/water/downloads/hydropower-vision-report-full-report.

[158] Koritarov et al., "Modeling and Analysis of Value of Advanced Pumped Hydropower in the United States," Argonne National Laboratory, June 2014, publications.anl.gov/anlpubs/2014/07/105786.pdf.

services such as voltage or frequency regulation. These systems are small-scale but can be stacked together to provide grid-scale energy storage.

California currently hosts several small (30–100 kW) capacity systems and one larger installation (2 MW).[159] The state also hosted the demonstration of one innovative flywheel technology developed by Amber Kinetics. That project was supported heavily by 2009 American Recovery and Reinvestment Act funding, with the Energy Commission and others also supporting the development. Those flywheels provided 25 kW of power for one hour.[160]

Flywheels are typically characterized by lower capital costs for total power of the systems (~$600 per kW)[161] but higher energy capacity costs ($1,500–$6,000 per kWh).[162]

Compressed Air Energy Storage

Compressed air energy storage (CAES) works by compressing and storing pressurized air in an underground cavern or in tanks above ground, though siting is typically easier for underground applications. The air is heated and expanded to drive a generator when producing power. These are typically bulk energy storage systems. Along the first plant began operation in Germany in 1978, there are currently only two utility-scale CAES facilities operating in the world. The plant in Germany has 290 MW of capacity, and the other plant, which opened in Alabama in 1991, has a capacity of 110 MW. Unlike flywheels, CAES systems typically have high capital costs (~$1000 per kW)[163] but lower energy capacity costs ($2–$84 per kWh).[164]

California is exploring development of a system in San Joaquin County with a 300 MW capacity that can operate for up to 10 hours. A feasibility study conducted in March 2018 found that, while technically feasible, the CAES plant has high estimated costs when compared to alternative energy storage facilities.[165] The future growth of CAES therefore relies on grants and R&D funding that can push system costs down. There are a number of planned CAES systems, including projects in Texas and Utah, that can provide valuable data and give a pathway for implementation in California.

5.1.2.2 | Electrochemical Storage (Batteries)

Electrochemical storage systems rely on chemical reactions to store energy. These reactions can be reversed later to release energy in the form of electricity. The most commonly deployed type of electrochemical storage is batteries. There are several different battery chemistries that have been deployed at scale that make this category diverse. Even within battery subsets, there are numerous chemistry and material combinations. For example, lithium-ion batteries have many different types of

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[159] “DOE Global Energy Storage Database,” Sandia National Laboratories, accessed November 19, 2018, energystorageexchange.org/.

[160] “California Energy Commission – Tracking Progress: Energy Storage,” CEC, August 2018, energy.ca.gov/renewables/tracking_progress/documents/energy_storage.pdf.

[161] Todd Aquino et al., “Energy Storage Technology Assessment,” Public Service Company of New Mexico, October 30, 2017, pnm.com/documents/396023/1506047/2017+-+HDR+10-30-17+PNM+Energy+Storage+Report.pdf/a2b7ca65-e1ba-92c8-308a-9a8391a87331.

[162] “Electricity Storage and Renewables: Costs and Markets to 2030,” International Renewable Energy Agency (IRENA), October 2017, http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf.

[163] BP McGrail et al., “Techno-economic Performance Evaluation of Compressed Air Energy Storage in the Pacific Northwest,” Pacific Northwest National Laboratory, February 2013, caes.pnnl.gov/pdf/PNNL-22235.pdf.

[164] “Electricity Storage and Renewables: Costs and Markets to 2030,” International Renewable Energy Agency (IRENA), October 2017, http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf.

[165] Michael Medeiros et al., “Technical Feasibility of Compressed Air Energy Storage (CAES) Utilizing a Porous Rock Reservoir,” Pacific Gas & Electric, March 2018, osti.gov/servlets/purl/1434264.

chemistries used in the cathode, such as cobalt, nickel, magnesium, iron, or aluminum. The materials used affect battery cost and performance and will result in batteries that are better suited for certain uses, such as deep cycling, fast response, or back-up power. Understanding a battery's abilities and limitations and operating accordingly will limit degradation to the battery and prolong battery life. However, all batteries are subject to degradation due to chemicals' aging and/or battery use.

The 2018 Lazard report provides estimates for the levelized cost of storage for various battery types, shown in Figure 5-7, and use cases, shown in Figure 5-5.[166] Costs for certain battery technologies can vary significantly based on storage duration. In general, long-duration storage has a higher upfront cost ($/kW) and a lower cost per energy capacity ($/kWh).

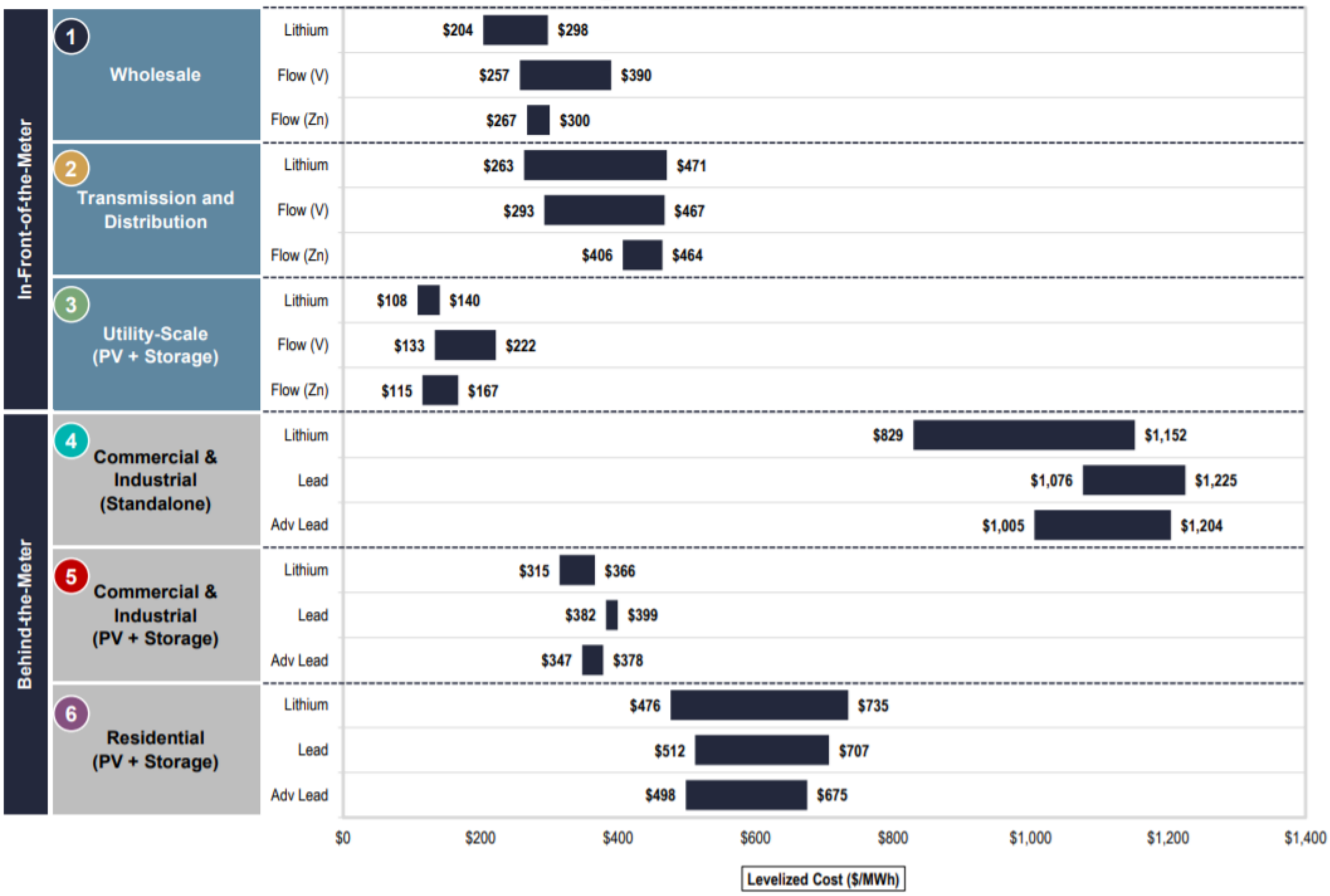

Figure 5-7. Unsubsidized Levelized Cost of Storage Comparison—$/MWh (Lazard 2018)

Flow battery vanadium and flow battery zinc bromide, denoted as Flow (V) and Flow (Zn).

Lithium-Ion

Lithium-ion batteries vary in chemistry type across manufacturers, thus differing slightly in performance and cost. Owing to different durations of storage, large-scale lithium-ion batteries vary in cost from $944–$2,430 per kW, with capacity weighted costs between $400 and $2,600 per kWh.

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[166] "Lazard's Levelized Cost of Storage Analysis – Version 4," Lazard, November 2018, lazard.com/media/450774/lazards-levelized-cost-of-storage-version-40-vfinal.pdf.

Lithium-ion batteries typically have a round-trip efficiency above 90%, higher than most other competing technologies. Recent advances in the technology have also enabled many different lithium-ion battery use cases, such as frequency regulation, energy shifting, customer demand reduction, and demand response. Most lithium-ion storage developers provide 10-year warranties for their systems, guaranteeing that the system will remain at or above 80% capacity until 10 years or the system will be replaced. Lithium-ion batteries are not typically designed for 100% depth of discharge; completely discharging them will cause degradation. Thus, systems usually have a "buffer" of energy that is not discharged to maintain system health.

Fire safety is a concern with lithium-ion batteries. The electrolyte of most lithium-ion batteries is flammable and, if overheated, can catch fire. This has raised serious fire concerns in some cities, such as New York City,[167] and will need to be addressed by code requirements and/or technological advances. Next-generation lithium-ion batteries are addressing fire safety and are either non-flammable or less flammable than commercial lithium-ion batteries today.

Lithium-ion batteries have emerged as the most popular battery chemistry in recent years, thanks to their high energy density and increasingly lower costs. Of the 177 MW of electrochemical energy storage capacity currently installed in California, 148 MW is provided by lithium-ion batteries. Of the 148 MW of lithium-ion storage, 145 MW was installed after 2009, and 127 MW was installed in 2015 or later.[168] Lithium-ion batteries comprise the majority of storage technologies procured by the IOUs for their AB 2514 targets and reliability needs.[169] Because of continuing cost declines, technology improvements, and familiarity with the technology among regulatory, utility, and permitting agencies, lithium-ion is likely to dominate both in-front and behind-the-meter energy storage procurement in the near future.

Flow Batteries

Flow batteries are typically used for daily deep cycling and long-duration energy storage. Unlike lithium-ion batteries, flow batteries can typically perform 100% depth of discharge daily with little to no degradation on the system; chemical aging typically degrades system performance more than cycling. Certain flow battery chemistries are designed to operate for several decades before degrading and do not need to be replaced as often as lithium-ion batteries. For example, Primus Power manufactures a battery that is meant to last 20 years.[170] Therefore, flow batteries are attractive to customers with frequent and long-duration energy storage needs.

Flow batteries are not as energy-dense as lithium-ion batteries and can take up a greater footprint. Consequently, they take more space and offer less capacity than lithium-ion batteries and are not well suited for appliances or electronics. Their round-trip efficiency is also less than lithium-ion batteries, typically around 65%–70%. Flow battery chemistries can be non-flammable and do not pose the same fire

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[167] "Fearful of fires, cities keep eye on lithium-ion batteries," *The Seattle Times*, May 20, 2018, seattletimes.com/business/technology/fearful-of-fires-cities-keep-eye-on-lithium-ion-batteries/.

[168] "DOE Global Energy Storage Database," Sandia National Laboratories, accessed November 19, 2018, energystorageexchange.org/.

[169] "Energy Storage Market Survey and Recommendations," CPUC Commissioner Briefing, October 24, 2018: 7; stated during the October 24, 2018 workshop, cpuc.ca.gov/uploadedFiles/CPUC_Public_Website/Test_Calendar/CPUC%20Energy%20Storage%20Market%20Survey%20and%20Recommendations%2010.22.18(1).pdf.

[170] EnergyPod2, *Primus Power* (website), accessed December 2018, primuspower.com/en/product/.

risks as lithium-ion batteries. However, many of the chemicals used are corrosive and can be dangerous if they leak. Figure 5-7 offers levelized costs of two flow battery chemistries, vanadium and zinc bromide.

While flow batteries have not gained the same traction as lithium-ion batteries in California, new commercialized products may offer a competitive alternative to stationary lithium-ion batteries for long-duration applications. This technology could see significant adoption in the coming years and diversify California's energy storage mix.

Lead Acid

Lead–acid batteries have had limited use for stationary applications in California. Southern California Edison's (SCE's) first grid-scale battery was a 10 MW/40 MWh lead–acid battery installed in 1988 at a substation in Chino. It was the largest lead–acid battery at its time and was used to research the impacts of battery storage on the electric grid from 1988 to 1996.[171] The battery proved successful in providing valuable data, but it did not lead to additional grid-scale battery installations.

Although their levelized costs are similar to those of lithium-ion batteries (Figure 5-7), lead–acid batteries have not achieved widespread utility-scale adoption, primarily owing to the use cases they provide; lead–acid batteries are ideal batteries for providing back-up power and uninterrupted power supply (UPS) for critical facilities. Lead–acid batteries have been used since the 1970s for similar off-grid applications that require daily cycling. However, these batteries require sufficient energy capacity to cycle at no more than 60% depth of discharge to maintain system health and longevity. This requirement results in high capital costs for both on- and off-grid application. Lead–acid batteries are not well suited to cycling consistently for grid support and/or to reduce customer bills. Therefore, they have been limited primarily to niche use cases for back-up and UPS.

5.1.2.3 | Thermal Energy Storage

Thermal energy storage uses energy to change the temperature of a medium away from its natural state. When the medium returns to its base temperature, the energy that is released during the temperature change can be recaptured. There are variety of mediums and methods for storing energy thermally, which allows these systems to operate at both large and small scales. Some mediums used for thermal energy storage are molten salt, water, rocks, and sand.

As of May 2018, California had 36 MW with 154 MWh of thermal storage installed across the state. This amount is up from 21 MW providing 142 MWh of thermal storage in 2014.[172] Nearly all projects and capacity are customer-sited chilled water or ice thermal storage systems. One of the most commonly installed thermal energy storage systems in California is Ice Energy's Ice Bear system, which provides 10 kW to 30 kW of storage for up to six hours. The "Ice Bear 20" costs around $14,000, or roughly $1,450 per kW.[173] Other thermal deployments in California include chilled water thermal systems. These deployments

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[171] "Moving Energy Storage from Concept to Reality: Southern California Edison's Approach to Evaluating Energy Storage," Southern California Edison whitepaper, https://www.edison.com/content/dam/eix/documents/innovation/smart-grids/Energy-Storage-Concept-to-Reality-Edison.pdf.

[172] "DOE Global Energy Storage Database," Sandia National Laboratories, accessed November 19, 2018, energystorageexchange.org/.

[173] Jeannine Anderson, "Public power authority to deploy up to 100 'Ice Bear 20' storage units," American Public Power Association (APPA), March 7, 2017, publicpower.org/periodical/article/public-power-authority-deploy-100-ice-bear-20-storage-units.

vary from around 1 MW to 6.5 MW in capacity and usually work by chilling water during off-peak hours, which can be used to offset loads during peak periods, as described below.

Offsetting refrigeration loads is one compelling application of these types of thermal energy systems, which can use the water chilled during off-peak hours in existing refrigeration systems to reduce electrical load during peak periods. Axiom Energy has demonstrated this type of thermal energy storage in several California locations.[174]

Another thermal energy storage application is offsetting heating, ventilation, and air conditioning (HVAC) load, which is one of the largest causes of system peak demand. Onsite HVAC thermal energy storage, especially when used in aggregate, can provide great system benefits and has been used cost-effectively by several utilities to defer system upgrades, relieve grid congestion, and avoid the build-out of new generation and distribution.[175] However, recent shifts in system peak demand (from 12 PM–6 PM to 4 PM–9 PM) are affecting the business case for thermal energy storage systems offsetting HVAC loads.

Many other technologies and materials—including phase change materials that offset the use of evaporators during peak periods—are being developed to provide thermal load shifting capabilities to customers. Given new technology offerings and customer thermal needs such as hot/cold water and air, thermal storage could see greater adoption at the customer level in the coming years, despite shifting peak time-of-use rates to the evening hours.

At the utility scale, thermal energy storage systems often accompany concentrating solar plants. These systems commonly use salts, rocks, and sand to capture solar power from a tower that has sunlight focused on it by mirrors. These installations can shift electricity from solar power away from the times that traditional PV solar operates. This can help alleviate some issues in California such as increasing the ramp-up and ramp-down in electricity required to respond to the “duck curve.” However, to date, utility-scale thermal energy storage deployment in California has not gained traction, with projects being postponed or cancelled.[176] Thermal storage projects in other states, such as Nevada (Crescent Dunes) and Arizona (Solana), could provide beneficial lessons learned for future projects in California.

5.1.3 | Research Initiatives

The following is a brief overview of some of the ongoing R&D initiatives related to energy storage. This summary is not intended to be comprehensive.

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[174] “Axiom Exergy Energy Storage Assists Whole Foods Market Store in Shifting up to 1040 kWh of Electricity to Lower Costs,” Axiom Energy, April 25, 2017, axiomexergy.com/news/axiom-exergy-energy-storage-assists-whole-foods-market-store-in-shifting-up-to-1040-kwh-of-electrici.

[175] “Ice Energy, NRG installing new energy storage solutions for SoCal Edison,” April 13, 2017, utilitydive.com/news/ice-energy-nrg-installing-new-energy-storage-solutions-for-socal-edison/440436/; “Genbright and Ice Energy Partner To Reduce Peak Electricity Demand On Nantucket,” *Market Wired*, June 15, 2017, marketwired.com/press-release/genbright-and-ice-energy-partner-to-reduce-peak-electricity-demand-on-nantucket-2222120.htm.

[176] “Systems Integration of Containerized Molten Salt Thermal Energy Storage in Novel Cascade Layout,” CEC-500-2016-006, October 2015, energy.ca.gov/2016publications/CEC-500-2016-006/CEC-500-2016-006.pdf.
“Rice large-scale solar project near Blythe all but dead,” *Desert Sun*, October 3, 2014, desertsun.com/story/tech/science/energy/2014/10/03/rice-solar-project-blythe/16671507/.

5.1.3.1 | EPIC Investment Initiatives

The EPIC 2018–2020 Triennial Investment Plan describes the short-term R&D priorities to increase energy storage deployment in California.[177] The latest plan focuses on understanding the deployment of optimal grid-scale storage systems through assessment and simulation. Past R&D priorities focused on development of specific technologies such as flywheels and small-scale pumped hydropower.

Table 5-3. Energy Storage – Summary of California Investment Initiatives

Initiative	Description/Goal	Potential Impact
2018–2020 EPIC Triennial Investment Plan		
Initiative 2.3.1: Development of Customer's Business Proposition to Accelerate Integrated Distributed Storage Market	Focus energy storage research on new technology development, new use cases, metering and telemetry, streamlined practices, improving cybersecurity, and financing structures.	Provide energy storage system developers with a roadmap of how they can fully maximize and be compensated for the value they provide.
Initiative 3.1.2: Assess Performance of Load Control System	Develop reliable estimates of performance under different conditions and times with the goal to reduce the need for telemetry on distributed resources and allow different loads to provide demand response.	Demand response technologies and strategies would be more widely adopted.
Initiative 3.2.1: Grid-Friendly PEV Mobility	Demonstrate advanced vehicle-to-grid (VGI) functions to better characterize the business cases for emerging applications.	Accelerate electric vehicle adoption, as there will be more opportunities to make revenue on electric vehicles.
Initiative 3.2.2: Battery Second Use	Develop battery monitoring technologies or test methods to better characterize and assess used EV cell condition to optimize configuration of second-life batteries.	Improve both primary and secondary use of batteries by providing health diagnostics for the batteries.
Initiative 3.4.1: Assessment and Simulation Study of the California Grid with Optimized Grid-Level Energy Storage	Determine future needs for grid-level energy storage connected to the distribution or transmission systems.	Provide information on which combinations and locations of grid-level energy storage will provide the best value. It will also inform energy storage policies and provide regulatory, technical, and institutional knowledge to stakeholders.
Initiative 4.3.1: Making Flexible-Peaking Concentrating Solar Power with Thermal Energy Storage Cost-Competitive	Conduct comprehensive research, technology development and demonstration, and studies that will advance CSP with thermal energy storage and make it more cost-competitive.	Assist in greater renewables integration and grid stabilization. This effort can attract additional investment into this technology.
Initiative 7.3.3: Improve Lifecycle Environmental Performance in the Entire Supply Chain for the Electricity System	Find substitute materials or processes that can reduce GHG emissions and other environmental impacts of energy technologies.	Assist the state in achieving its GHG and other environmental goals by making the manufacturing, decommissioning, and recycling of energy-related materials more environmentally friendly.

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[177] "Electric Program Investment Charge: 2018-2020 Triennial Investment Plan," California Energy Commission, CEC-500-2017-023-CMF, adopted on April 27, 2017, energy.ca.gov/research/epic/17-EPIC-01/.

Initiative	Description/Goal	Potential Impact
Previous EPIC Investment Plans		
1. Demonstrating the Commercial Business Case for Microgrids that Supports California's Aggressive Energy and GHG Reduction Policies and Integrates New and Emerging Technologies 2. Compressed Air Energy Storage a. High Temperature Hybrid Compressed Air Energy Storage (HTH-CAES) (EPC-14-027) 3. Flywheels a. A Transformative Flywheel R&D Project (EPC-15-016) 4. Batteries a. Utility Demonstration of Zynth Battery Technology to Characterize Performance and Grid Benefits (EPC-14-023) b. Pilot Testing of Eos' Znyth Battery Technology in Distributed Energy Storage Systems (EPC-15-018) 5. Storage Planning a. Energy Storage Valuation and Optimization Tool (EPC-14-019) 6. Alternative, Small-Scale Pumped Hydro Storage a. Electricity Pumped Storage Systems Using Underground Reservoirs: A Feasibility Study for the Antelope Valley Water Storage System (EPC-15-049) b. Advanced Renewable Energy Storage and Recycled Water Project (EPC-15-079)		

Select EPIC Projects

The Energy Commission has funded several innovative energy storage projects that are featured on the Energy Commission Innovation Showcase website.[178] While many of these projects contain elements of energy storage, the following table summarizes projects that demonstrate emerging storage technologies that could potentially be used for grid-scale energy storage.

Table 5-4. Energy Storage – Select EPIC Projects

Project Name	Technology Type	Description
Low-Cost Thermal Energy Storage for Dispatchable Concentrated Solar Power	Utility-Scale Thermal Energy Storage	CSP heats sulfur, which can be dispatched to generate electricity. The goal is to reduce the cost of thermal storage to $15/kWh.
High-Temperature Hybrid Compressed Air Energy Storage	Compressed Air Energy Storage	The storage system is designed to provide ancillary services and/or load following. The system is designed to cost $938/kW and $156/kWh.
Utility Demonstration of Znyth Battery Technology to Characterize Performance and Grid Benefits	Zinc-Based Battery	The system uses a non-toxic, non-combustible aqueous, zinc-based battery to perform various use cases. The system claims low cost ($160/kWh) and long life (10,000 cycles).
A Transformative Flywheel R&D Project	Flywheel	The project developed advanced manufacturing processes and improved the flywheel rotor geometries. Projected cost targets are below $150/kWh.
Electricity Pumped Storage Systems Using Underground Reservoirs: A Feasibility Study for the Antelope Valley Water Storage System	Pumped Hydro	This feasibility study determines the value of energy storage and associated grid support benefits provided by peak-hour pumped storage and aquifer pumped hydro applications at an existing water bank. The study identifies critical parameters for success for both technologies and identifies other water banking sites in the state where these technologies are likely to be successful.

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[178] California Energy Commission Innovation Showcase, accessed November 27, 2018, innovation.energy.ca.gov/SearchResults.aspx?cat=Topics&subj=Storage.

Project Name	Technology Type	Description
Advanced Renewable Energy Storage and Recycled Water Project	Flow Battery	This project uses a battery storage system combined with an advanced controller to enable the wastewater treatment plant to accommodate variable loads, increase onsite renewable power production, and substantially reduce its reliance on grid power.

5.1.3.2 | Research Initiatives from Other Funding Entities

DOE focuses on energy storage for a variety of uses. The vehicle application of batteries is a heavy focus of the Vehicles Technology Office (VTO), while grid- and residential-scale battery storage are investigated by offices such as the Buildings Technologies Office (BTO). Early-stage battery innovations are a priority of the Advanced Research Projects Agency–Energy (ARPA-E), and several past and current research programs have focused on energy storage. DOE is taking a holistic and comprehensive approach to dealing with energy storage from development to implementation.

New York State, Massachusetts, and Maryland identified energy storage as a major focus for renewable energy integration and future development. New York led a roadmap on energy storage, with next steps that include looking into funding opportunities for energy storage projects. Massachusetts developed its own Energy Storage Initiative that works to reach the state's goal of 200 MWh of energy storage by 2020. Maryland has taken a proactive approach to energy storage investment and offered a tax credit for FY 2018 that allows residents to fund their energy storage projects through the tax code.

Figure 5-8. State Energy Storage Procurement Targets

U.S. energy storage deployment is driven by:

- **California's target:** 1,325 MW by 2020
- **Massachusetts' target:** 200 MWh by 2020
- **Nevada's target:** Investigate biennial targets for electric utilities to procure energy storage systems
- **New Jersey's target:** 2,000 MW by 2030
- **New York's target:** 1,500 MW by 2025
- **Oregon's Target:** Both major utilities to have a minimum of 5 MWh by 2020
- **Vermont's Target:** Report on issue of deploying energy storage on the Vermont electric transmission and distribution system

Data obtained from State Policy Opportunity Tracker (SPOT): spotforcleanenergy.org/state/california/ energy-storage-standard/

Table 5-5. Energy Storage – Summary of DOE and Other Research Initiatives

Initiative	Description/Goal	Potential Impact
U.S. Department of Energy		
Grid Modernization Initiative (GMI)	GMI develops the concepts, tools, and technologies needed to measure, analyze, predict, protect, and control the grid of the future. The goals are to increase electrical system reliability and security.	Create a more robust, resilient, and reliable electrical grid. Reduce risks of cyber attacks, natural disasters, or physical attacks on the grid.
Beyond Batteries Initiative	As part of the Grid Modernization Initiative, Beyond Batteries focuses on advances in controllable loads, hybrid systems, and new approaches to energy storage to increase the reliability and resilience of our energy systems.	Create innovative types of energy storage that can be used for heating, cooling, electricity, and other energy needs.
Office of Electricity's Energy Storage Systems Program	This program collaborates with utilities and state energy organizations to design, procure, install, and commission pioneering types of energy storage. The program supports analytical, technical, and economic studies on	Foster the growth of energy storage technologies and markets at statewide and national levels. The program can also help in sharing lessons learned across different local, state, and national-level agencies.

Initiative	Description/Goal	Potential Impact
	energy storage technologies. It also conducts research into innovative and emerging energy storage technologies.	
ARPA-E	ARPA-E invests in early-stage high-potential, high-impact energy technologies that are at too early a stage for private-sector investment.	Potentiate radical improvement of our country's prosperity, national security, and environmental well-being. New technologies can greatly transform our energy systems.
NYSERDA		
New York Energy Storage Roadmap	This document was developed to give the state a plan to accomplish Governor Cuomo's 1,500 MW by 2025 energy storage target. The roadmap identifies the most promising near-term policies, regulations, and initiatives needed to realize the goal.	Help New York install 1,500 MW of energy storage to help the state meet its renewable energy and environmental goals.
Massachusetts Energy Storage Initiative	This initiative aims to make Massachusetts a national leader in energy storage deployments. The initiative requires the state to procure 200 MWh of energy storage by 2020.	Foster a new energy storage market in the Northeast that can help the state meet its energy and reliability goals.
Maryland Energy Storage Tax Credit Program	The purpose of this tax credit is to encourage energy storage deployment.	Create a customer-sited energy storage market in Maryland.

5.1.4 | R&D Opportunity Areas and Technologies

To identify and prioritize R&D opportunity areas and technologies for solar energy, technical assessment analysts relied on state and federal government reports, industry reports, and peer-reviewed research articles. Research also included phone interviews with energy storage experts from government and other research institutions across the United States.

The team visited the Center of Energy Research and Sustainable Power Energy Center laboratories at the University of California, San Diego (UCSD) and was able to see lithium-ion, hybrid zinc, and flow batteries being tested for grid and customer services. Mike Ferry and Shirley Meng of UCSD gave the project team a tour of the battery manufacturing and testing laboratories where numerous battery chemistries and types are fabricated and tested. Mr. Ferry and Dr. Meng also shared their insights on current and emerging energy storage technologies that can facilitate increased renewable adoption.

Figure 5-9. Energy Storage Experts Interviewed

- Sarah Busch, Membership Development, California Energy Storage Alliance (CESA)
- Mike Ferry, Director of Energy Storage, University of California, San Diego
- Cody Hill, Director, Energy Storage, LS Power
- Ben Kaun, Program Manager, Energy Storage, Electric Power Research Institute
- Shirley Meng, Director, Sustainable Power and Energy Center, University of California, San Diego
- Alex Morris, Senior Director of Policy, California Energy Storage Alliance (CESA)

5.1.4.1 | Key Considerations

Expert interviews and literature review identify a number of factors worth consideration when dealing with assessment, investment, or construction of energy storage systems in California. These areas are broadly categorized into the following topics:

Technical Considerations

- **Emerging technologies have difficulty entering the market because of technology lock-in**. Utilities and customers typically want to procure only technologies that have a proven track record of performance, making it difficult for emerging technologies to obtain customers. In recent energy storage procurements, utilities looked for technologies that have already installed utility-scale systems and that have a proven performance record. Emerging technologies with no utility-scale installations are not often considered.
- **Lack of standardized performance testing and certification prevents proper evaluation of storage technologies**. There has been limited adoption of universal standards or certifications for energy storage system performance, such as round-trip efficiency or number of cycles at a given depth of discharge. Pacific Northwest National Laboratory has developed one such standard, the Energy Storage Performance Protocol. However, without broader adoption, technology developers may not be measuring or testing technologies to the same requirements, and new technologies cannot gain third-party certification to verify performance claims. Greater adoption of universal performance standards tested and verified by third parties could help new technologies demonstrate system performance and help diversify the future energy storage mix.
- **Improving system performance can reduce losses and save energy but requires additional investment**. Increasing efficiency and system performance has been a challenge for many storage technologies. Current lithium-ion batteries are typically around 90% efficient, making it difficult for less efficient technologies to compete. Additionally, many lithium-ion technologies cannot routinely perform full depth of discharge without damaging the battery and shortening its useful life. Overcoming these challenges requires time, money, and expertise in the field, which can be difficult for companies, especially startups, to procure. Thus, more financial investment into laboratory research and testing of storage technologies could help improve system performance.
- **Communications devices and smart inverters can reduce issues with integrating storage systems onto the grid.** Advancements in control systems, smart inverters, and other power electronics will be crucial for the integration of energy storage systems.
- **Materials improvements can reduce the need for expensive system components.** Manufacturers are shifting toward more nickel-rich cathode materials in lithium-ion batteries to minimize the use of cobalt. Companies are also looking into polymeric electrolytes (non-liquid) such as silicon. These changes can improve system performance and lower costs. While heavy investment from industry is driving research in nickel-rich cathode materials, solid-state batteries or other emerging technologies could benefit from additional investments and demonstration projects.
- **Energy storage systems face integration barriers due to cybersecurity risks.** Meeting utility cybersecurity requirements can contribute to added soft costs and integration hurdles. If a vendor wants to be able to access data on its battery system performance, it creates a backdoor into the utility and grid operations that can increase vulnerability. Clearer expectations, agreements, and cooperation are needed between vendors, utilities, and regulators.

Financial Considerations

- **Finding utility-scale customers can increase the deployment of large-scale systems**. Although front-of-the-meter energy storage is growing quickly, utilities are still somewhat hesitant to procure large-scale energy storage systems unless required to do so or in response to an emergency. While some utilities have several decades of experience working with energy storage, it is still a new concept for many California utilities, especially smaller utilities and municipalities.
- **Additional investment is needed to lower costs of alternatives to lithium-ion battery systems**. The cost of lithium-ion batteries has dropped dramatically in the past decade. However, other storage technologies have not obtained similar cost reductions.
- **Front-of-the-meter storage integration costs to satisfy distribution protection requirements at the utility can be prohibitive for small-scale systems.** A recloser can cost $250,000 on a $1 million project, which can be prohibitive for a smaller-scale system. Additional testing and standards can help to avoid the need for reclosers to make the utility confident that a battery will operate as promised and will not backfeed to the grid. The soft costs for grid integration are too expensive for smaller organizations.

Regulatory Considerations

- **AB 2514 is mandating energy storage procurement in California.** California is one of the only states with a firm energy storage procurement requirement for the major IOUs. The bill requires 1,325 MW of energy storage be added to the grid by 2020.
- **Storage systems have multiple use applications that may conflict with each other.** Uncertainty remains surrounding energy storage's ability to provide multiple use applications. The CPUC is considering recommendations from a 2018 working group report that discuss different use cases storage systems can provide and rules on how to resolve potential conflict in signals or timing of services.[179] Until all multiple use application rules are officially adopted and clarified by the CPUC, it is unclear how and when storage systems can provide multiple use applications.
- **CAISO initiatives are showing how energy storage can be used in California's energy markets.** The CAISO has several initiatives that have direct and indirect impacts on energy storage systems. The Storage as a Transmission Asset and Energy Storage and Distributed Energy Resources (ESDER) initiatives are intended to clarify how energy storage can operate in the wholesale market. The CAISO is planning to refine energy storage rules every year through the ESDER initiative for at least the next three years. This initiative will likely incorporate changes from FERC Order 841.[180]
- **Updated communications protocols improve energy storage planning and operations.** Updated distribution communications protocols that consider input from regulators, utilities, and vendors can make sure that the systems can be operated and controlled to match grid demands. These protocols should include vocabulary for forward planning (scheduled charging and discharging), which has been lacking from previous protocols and systems.

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[179] "Multiple-Use Applications for Energy Storage: Final Working Group Report," August 9, 2018, docs.cpuc.ca.gov/PublishedDocs/Efile/G000/M233/K836/233836260.PDF.

[180] "2019 Three-Year Policy Initiatives Roadmap and Annual Plan," California ISO, November 27, 2018, caiso.com/Documents/Presentation-2019FinalPolicyInitiativesRoadmap.pdf.

- **Siting and permitting are barriers to deployment for some types of energy storage**. At the behind-the-meter level, some jurisdictions that are unfamiliar with energy storage have struggled to give permits to storage systems. At the utility scale, technologies with site-specific needs, such as CSP with thermal storage, pumped hydro, or a recent advanced rail energy storage project, have had challenges obtaining permits.[181]

5.1.4.2 | R&D Opportunity Areas

The R&D opportunity areas in Table 5-6 expand beyond those identified in the Energy Commission's 2018–2020 Triennial Investment Plan and are based on an extensive literature review and conversations with experts.

Table 5-6. Energy Storage – Technology Research & Development Opportunity Areas

ID	Opportunity Areas	Description
Mechanical		
O.ES.1	***Compressed Air Energy Storage**	Energy storage through pressurizing air and gases. Larger systems have extensive siting requirements.
O.ES.2	***Flywheels**	Form of kinetic energy storage that relies on a wheel spinning in a low-pressure container. Systems have existed for a while, but improvements are still forthcoming.
O.ES.3	***Small-Scale Pumped Hydro Storage**	Energy storage systems that store energy at the megawatt and tens-of-megawatts scales with pumped hydro technology.
Electrochemical		
O.ES.4	***Battery Improvements**	System chemistry improvements that can improve power or limit size of battery systems.
O.ES.5	***Battery Second Use[4]**	Batteries that are used after they are retired from their initial use.
O.ES.6	**Grid-Friendly PEVs[3]**	Plug-in electric vehicles (PEVs) that charge and discharge in ways that assist grid reliability.
O.ES.7	**Recycling of Li-ion Batteries**	Cost effective recycling of lithium and other materials in li-ion batteries.
O.ES.8	**Flow Batteries**	Increase in the round-trip efficiency and reduction in the lifecycle costs of flow batteries.
Thermal		
O.ES.9	**CSP Thermal Energy Storage[4,5]**	Solid and liquid storage mediums that are superheated by concentrated solar rays.
O.ES.10	**Refrigeration- and HVAC-Based Storage**	Assessment and simulation of refrigeration-based and HVAC-based thermal energy storage to evaluate optimal dispatch to provide GHG benefits and economic benefits by shifting peak periods.
Cross-Cutting		
O.ES.11	**Assessment and Simulation[2]**	Systems that optimize deployment and use of energy storage systems.
O.ES.12	**Distributed Storage[1]**	Storage that is located at residential and commercial properties and can be used to provide grid services even with kilowatt and small megawatt scales.
O.ES.13	**Innovative Energy Storage Systems**	New and emerging technologies, chemistries, and systems for storing energy.

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[181] "Can Newcomer Energy Vault Break the Curse of Mechanical Grid Storage?," *Greentech Media*, November 14, 2018, greentechmedia.com/articles/read/energy-vault-stacks-concrete-blocks-to-store-energy#gs.MUCl4x0.

O.ES.14	**Lifecycle Environmental Improvements**[6]	Technologies and systems that allow energy storage systems to reduce lifecycle GHGs from the grid.
O.ES.15	**Manufacturing**	Improvements in manufacturing that lower storage system costs.
O.ES.16	**Virtual Power Plants**	Aggregation and dispatch of small-scale energy storage systems to provide ancillary services in the wholesale markets, such as voltage and frequency regulation and spinning and non-spinning reserve.
O.ES.17	**Transactive Energy**	Assessment, simulation, and demonstration of transactive energy systems that optimize deployment and use of energy systems while providing grid reliability.

Several research areas overlap with EPIC investment interests. Those overlaps are given the following identifiers:
* Mentioned in EPIC Investment Plan: Previous and Planned EPIC Investments on Energy Storage Technologies
1 Relevant to Initiative 2.3.1 Development of Customer's Business Proposition to Accelerate Integrated Distributed Storage Market
2 Relevant to Initiative 3.1.2 Assess Performance of Load Control System
3 Relevant to Initiative 3.2.1 Grid-Friendly PEV Mobility
4 Relevant to Initiative 3.2.2 Battery Second Use
5 Relevant to Initiative 4.3.1 Making Flexible-Peaking Concentrating Solar Power with Thermal Energy Storage Cost Competitive
6 Relevant to Initiative 7.3.3 Improve Lifecycle Environmental Performance in the Entire Supply Chain for the Electricity System

5.1.4.3 | Emerging and Breakthrough Technologies

The emerging and breakthrough technologies in Table 5-7 represent more targeted opportunities for Energy Commission investment and fall within the aforementioned R&D opportunity areas.

Next-generation storage technologies seek to lower costs, increase cycle life, use more abundant and sustainable materials, increase ability to perform deep cycling, improve safety/reduce risk of fire, and increase energy density. Given lithium-ion's dominance in the market, manufacturing companies, venture capitalists, and research institutions are putting billions of dollars into system improvements and developing next-generation lithium batteries. New developments in cathode, anode, and electrolyte materials and chemistries are helping to achieve these goals, with technologies ranging from early-stage research to commercialized products. Other storage technologies, such as sodium, zinc, flow, lead–acid batteries, and fly wheels, have already deployed thousands of systems and are achieving breakthroughs in system performance and costs. Other technologies, such as the Energy Vault crane system, have moved past initial R&D and are looking for large-scale demonstration opportunities. As different technologies are developed further, they could offer competitive alternatives to lithium-ion batteries.

Table 5-7. Energy Storage – Emerging and Breakthrough Technology Matrix

ID	Name	Parallel Research Topic	R&D Opportunity Areas	Potential Impact
Mechanical				
ES.1	**Advanced Rail Energy Storage**	Innovative System Development	Innovative Energy Storage Systems	Electricity is used to move rail cars up a track. When electricity is needed, the cars are released to produce electricity.[182]
ES.2	**Long-Duration Fly Wheel**	Legacy System Improvement	Fly Wheel	New types of fly wheels offer longer duration, up to four hours. These technologies could be used to provide additional use cases, such as energy shifting. They can also be used for behind-the-meter applications.[183]
ES.3	**Mechanical Energy Storage – Cranes**	Innovative System Development	Innovative Energy Storage Systems	Cranes lift blocks to "store" energy and then release the blocks to generate electricity when needed. The technology does not require site-specific conditions (as pumped hydro or compressed air does), offers more than 8 hours of storage,

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[182] "Can Newcomer Energy Vault Break the Curse of Mechanical Grid Storage?," *Greentech Media*, November 14, 2018, greentechmedia.com/articles/read/energy-vault-stacks-concrete-blocks-to-store-energy#gs.MUCl4x0; "First Grid-Scale Rail Energy Storage Project Gets Environmental Approval From BLM," *Greentech Media*, April 18, 2016, greentechmedia.com/articles/read/first-grid-scale-rail-energy-storage-project-gets-environmental-approval-fr#gs.baxCMw4.

[183] Amber Kinetics, accessed December 2018, amberkinetics.com/.

ID	Name	Parallel Research Topic	R&D Opportunity Areas	Potential Impact
				is more efficient than pumped hydro, and does not require a manufacturing facility.[184]
Electrochemical				
ES.4	**Advanced Lithium Extraction**	Supply Chain	Manufacturing	Less time, money, and energy are required to extract lithium, helping to reduce lithium costs.[185]
ES.5	**Alternative Cathode Materials for Lithium-Ion batteries**	Legacy System Improvement	Battery Improvements	Alternative cathode chemistries can increase the energy density, increase cycle life, and decrease costs of battery cells.[186] Using earth-abundant materials will also increase supply chain reliability.
ES.6	**Alternatives to Rare Earth Metals**	Legacy System Improvement	Battery Improvements	Earth-abundant materials in all battery types have the potential to decrease system costs and increase reliability of supply chains.
ES.7	**Flow Battery**	Legacy System Improvement	Battery Improvements	Advanced flow batteries can increase battery life, increase energy density, and reduce costs.[187]
ES.8	**Gaseous Electrolyte**	Legacy System Improvement	Battery Improvements	Gaseous electrolyte is less flammable, can increase energy density, and can be used at lower temperatures than conventional electrolytes.
ES.9	**Lead–Acid Battery**	Legacy System Improvement	Battery Improvements	Advanced lead–acid batteries could increase charging time, efficiency, and cycle life and be used in more dynamic ways.[188]
ES.10	**Lithium Metal Anode**	Legacy System Improvement	Battery Improvements	Lithium metal anodes can dramatically increase the energy density of lithium-ion cells and have the potential to lower costs of cells.[189]
ES.11	**Silicon Anode**	Legacy System Improvement	Battery Improvements	Silicon anodes, as opposed to traditional graphite anodes used in lithium-ion batteries, can increase energy density, charging speed, and battery life while reducing cost and weight of battery cells.[190]

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[184] Can Newcomer Energy Vault Break the Curse of Mechanical Grid Storage?," *Greentech Media*, November 14, 2018, greentechmedia.com/articles/read/energy-vault-stacks-concrete-blocks-to-store-energy#gs.I4GWDg0.

[185] "Lilac Solutions Aims to Get Battery Costs Below $80 per Kilowatt-Hour," *Greentech Media*, July 9, 2018, greentechmedia.com/articles/read/lilac-solutions-aims-to-get-battery-costs-below-80-per-kilowatt-hour#gs.fI8ymBs.

[186] "11 Lithium-Ion Battery Makers That Don't Need Cobalt," *Greentech Media*, July 9, 2018, greentechmedia.com/articles/read/11-lithium-ion-battery-makers-that-dont-need-cobalt#gs.b5TukcA, oxisenergy.com/; endlisenergy.com/ ; scib.jp/en/.

[187] Advanced Flow Battery Electrodes," ARPA-E, arpa-e.energy.gov/?q=slick-sheet-project/advanced-flow-battery-electrodes.

[188] "Lead batteries for utility energy storage: A review," *Journal of Energy Storage*, Volume 15, February 2018, sciencedirect.com/science/article/pii/S2352152X17304437.

[189] "Status and challenges in enabling the lithium metal electrode for high-energy and low-cost rechargeable batteries, *Nature Energy*, January 2018, nature.com/articles/s41560-017-0047-2.epdf?shared_access_token=yKdwZbfIOa__Uq-dUD_PjtRgN0jAjWel9jnR3ZoTv0OtTMGP2Af99PNSCHwOOenxBDc-nPpvfP1ptnLgspRWkxVBVGYhO6QjtyBflML2J1pdkoFltnjT77nh-uPGMXq42fsmdskxkbhGvk8szkw21qajE5yeujdm-sJAA1yXlvYsoadYx4HFD_HH68R4sYWTRDdWMlZTjGAnF90oZLTfPzRr_2EYz5PT1KQk01bwhe8%3D; "The Promise and Challenge of Scaling Lithium Metal Batteries," *Greentech Media*, January 15, 2018, greentechmedia.com/articles/read/lithium-metal-battery-promise-challenge#gs.wSQZp8k; sionpower.com/.

[190] "Your Gadgets' Battery Life Could Be About to Get Much Better," *Popular Mechanics*, October 19, 2018, popularmechanics.com/technology/gadgets/a23890619/sila-silicon-anode-batteries-consumer-electronics/.

ID	Name	Parallel Research Topic	R&D Opportunity Areas	Potential Impact
ES.12	**Sodium Battery**	Legacy System Improvement	Innovative Energy Storage Systems	Emerging sodium batteries have many advantages over existing technology types: fast charging capabilities; low cost; long cycle life (tens of thousands of cycles at full depth of discharge); high power density; and abundant, non-toxic, non-flammable materials.[191]
ES.13	**Solid-State Electrolyte**	Legacy System Improvement	Battery Improvements	Solid electrolyte can significantly reduce fire risks and improve safety of lithium-ion batteries. It can also increase the battery cell's energy density.[192]
ES.14	**Zinc Battery**	Legacy System Improvement	Innovative Energy Storage Systems	Emerging zinc-based batteries have low system costs (target around $100/kWh), have a long cycle life at full depth of discharge, can provide multiple hours of storage, and use non-combustible, non-toxic materials.[193]
Thermal				
ES.15	**Concentrated Solar Power**	Legacy System Improvement	CSP Thermal Energy Storage	Next-generation CSP thermal storage is testing ways to eliminate the need for pressurized tanks, uses new phase change materials that are less corrosive, and is less expensive.
ES.16	**Liquid Air Energy Storage**	Innovative System Development	Innovative Energy Storage Systems	Electricity is used to cool air until it liquefies. The liquid is stored in tanks. When electricity is desired, the liquid air is heated back into a gas (by exposure to ambient air or with waste heat from an industrial process), and the gas turns a turbine to generate electricity.[194,195]
ES.17	**Pumped Heat Thermal Storage**	Innovative System Development	Innovative Energy Storage Systems	Electricity runs a heat pump to heat and/or cool a thermal energy storage medium. This stored thermal energy is later used to generate electricity back to the grid. This technology presents an opportunity for 6+ hour load shifting with minimal geographical constraint.[196]
ES.18	**Thermal Energy Storage Paired with Solar PV**	Innovative System Development	Innovative Energy Storage Systems	Heat exchangers are placed on the backs of solar PV panels to absorb heat from the panels. The captured heat is stored and used to generate electricity through an organic rankine cycle. This is a less expensive form of storage using standard industry components, and it boosts solar PV efficiency by reducing heat on panels.

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[191] "Monovalent manganese based anodes and co-solvent electrolyte for stable low-cost high-rate sodium-ion batteries," *Nature Communication*, February 28, 2018, nature.com/articles/s41467-018-03257-1 ; natron.energy/ ; aquionenergy.com/.

[192] "Industry Giants Samsung and Hyundai Invest in Solid-State Batteries," *Greentech Media*, September 11, 2018 greentechmedia.com/articles/read/industry-giants-samsung-and-hyundai-invest-in-solid-state-batteries#gs.hQs6KQU; https://ionicmaterials.com/.

[193] Examples of companies developing Zinc Batteries: nantenergy.com/; eosenergystorage.com/#products.

[194] "Liquid-air energy storage: The latest new 'battery' on the UK grid," *ARS Technica*, June 13, 2018, arstechnica.com/science/2018/06/liquid-air-energy-storage-the-latest-new-battery-on-the-uk-grid/.

[195] "Liquid Air Energy Storage (LAES)," Energy Storage Association, accessed January 9, 2019, energystorage.org/energy-storage/technologies/liquid-air-energy-storage-laes.

[196] "Pumped Heat Electrical Storage," Energy Storage Association, accessed January 2019, energystorage.org/energy-storage/technologies/pumped-heat-electrical-storage-phes.