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Energy Research and Development Division

DRAFT PROJECT REPORT

Utility-Scale Renewable Energy Generation Technology Roadmap

California Energy Commission

Gavin Newsom., Governor

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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 and research 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.

PREFACE

The California Energy Commission's Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Commission is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer. Additionally, the Energy Commission's Research and development programs assist the California electric ratepayer by:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility-scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

The Utility-Scale Renewable Energy Generation Technology Roadmap is the draft report for project 300-17-005. The information from this project contributes to the Energy Research and Development Division Program. For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

To reach the ambitious goals laid out in Senate Bill 100 (SB-100), California must triple its renewable energy production over the next decade. Utilizing a broad approach to research across all renewable energy resource areas will enable California to avoid technology lock-in and drive a diverse approach to meet SB-100 goals. This Utility-Scale Renewable Generation Technology Roadmap provides the Energy Commission with 17 recommended initiatives to guide research development, demonstration, and demonstration activities across nine technology areas: solar photovoltaic, concentrated solar power, land-based wind, offshore wind, bioenergy, geothermal power, small hydropower, grid integration technologies, and energy storage systems.

A comprehensive roadmapping process was conducted involving literature research, interviews, surveys, and webinars to gather input from experts and the public to identify barriers and research gaps and prioritize near, mid-, and long-term research, development, deployment, and demonstration activities for each topic area.

This roadmap report presents the methodology and results of the roadmapping process. Each technology area contains the prioritized recommended technology initiatives, supported by background information that includes generation trends, resource assessment, metrics, and technology area considerations that will impact future Energy Commission technology advancement efforts.

Keywords: Renewable Energy Generation; Utility-Scale; Roadmap

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EXECUTIVE SUMMARY

With the passing of Senate Bill 100 (SB-100) in the California Legislature, aggressive renewable goals of 60 percent of electricity provided by renewable sources by 2030 and 100 percent of electricity provided by carbon free sources by 2045. The California Energy Commission (Energy Commission) commissioned this Research Roadmap to identify research gaps in utility-scale renewable technologies and prioritize near, mid-, and long-term research, development, demonstration, and deployment activities that address those gaps and drive California toward SB-100 goals.

Introduction or Background

Utility-scale renewable generation in California has seen substantial growth since the beginning of the century, increasing from 12 percent of electricity generation in 2001 to 31 percent in 2018. SB-100's goals require another doubling of renewable energy generation over the next decade. Current renewable technologies producing electricity for California's grid can be grouped into the following categories: biomass, solar, geothermal, small hydro, and wind. A diverse approach that involves deployment of all of these and other renewable technologies is the best strategy for California to achieve a secure, reliable, and sustainable grid run primarily by renewable sources. This technology roadmap is a fundamental step in planning future Energy Commission efforts to achieve the greatest cost and utility-scale energy generation technology improvements.

Project Purpose

This Utility-Scale Renewable Energy Generation Technology Roadmap explores the following 9 technology areas: Solar Photovoltaics (PV), Concentrated Solar Power (CSP), Land-Based Wind, Offshore Wind, Bioenergy, Geothermal, Small Hydro, Grid Integration Technologies, and Energy Storage Systems. Through a thorough process of information gathering, expert input and review, seventeen technology area initiatives are recommended in this report. This roadmap report will benefit ratepayers in California by providing a description of the methodology and results stemming from the project roadmapping activities.

Project Approach

Energetics is the lead of this roadmap project, supported by a team of subcontractors (Center for Sustainable Energy, TSS Consultants, DAV Energy Solutions, Solar Power Consulting, and Renewable Energy Consulting Services). Energetics provides technology and management services in the fields of energy, manufacturing, sustainable transportation, climate, infrastructure and resilience; they have led multiple technology roadmaps for California Energy Commission over the past 15 years.

This roadmapping project is broken into two major deliverables: the Technical Assessment and this Research Roadmap. The Technical Assessment focuses on the current state of renewable energy and storage in California; significant considerations and barriers for future development; current research efforts in California, other states, and at the national level; and provides an extensive list of opportunity areas and specific breakthrough technologies for each renewable technology area. This Roadmap refines the findings from the Technical Assessment in to recommended initiatives with supporting metrics and considerations.

By design, the roadmapping project involved many contributors in addition the project team. Starting with the formation of a technical advisory committee at the outset of the project, outside participation was a priority of the project throughout. This included engaging technology area experts through interviews, surveys and webinars, and finally inviting the public to contribute to the refinement process through public webinars.

Project Results

The roadmapping approach laid out by the Energy Commission was adhered to by the Energetics team. The methodology allowed for identification of technology development barriers and opportunities, and subsequent refinement of priority recommendations and considerations. A total of seventeen initiatives are recommended in the roadmap report, with supporting background information including generation trends, resource assessment, metrics, and technology area considerations.

Technology/Knowledge Transfer/Market Adoption (Advancing the Research to Market)

Knowledge transfer and supporting market adoption is the rationale for involving outside project contributors. Engaging experts in California and beyond in the Technical Assessment research phase of the project expanded the scope of analysis and experience. Webinars and surveys were conducted to verifying and solidify opportunities identified through research and individual interviews. And finally, the greater public was invited to contribute to the refinement of recommended initiatives through the release of a preliminary draft roadmap and public comment webinar. A second public webinar was conducted to share the results with the public.

Benefits to California

This Utility-Scale Renewable Energy Generation Technology Roadmap provides a public record of the methodology, results and supporting background information. The roadmapping project provides benefit to ratepayers in California by providing an unbiased and thorough process for considering the challenges and opportunities for expanding utility-scale renewable generation technology needs in California. This roadmap report will serve as a foundational reference for future activities by the Energy Commission.

CHAPTER 1: Introduction

General Objective

California has established one of the most ambitious targets of any local or national government with the passing of Senate Bill 100 (SB-100) (California Renewables Portfolio Standard Program: emissions of greenhouse gases). SB-100 sets goals of 60 percent renewable electricity production by 2030 and 100 percent zero-carbon electricity production by 2045. A diverse investment approach that provides broad, consistent support across all the technology areas is necessary for California to achieve its energy goals. This Research Roadmap project serves as a basis for future Energy Commission's research and development (R&D) efforts, pushing for greater penetration of utility-scale renewable energy generation by identifying and prioritizing research, development, demonstration, and deployment (RDD&D) in a variety of renewable topic areas.

These topic areas include solar photovoltaics (PV), concentrated solar power (CSP), land-based wind, offshore wind (including a supplement on wave power), bioenergy, geothermal power, small hydropower, grid integration technologies, and energy storage. The selections of solar PV, CSP, land-based wind, bioenergy, geothermal, and small hydropower were made because they currently provide a percentage of utility-scale energy generation to California's electric grid. The inclusion of offshore wind is due to its significant technical potential in California which can contribute to grid and renewable energy goals. A brief supplement on wave energy is also included based on expert and public opinion that it too can contribute significantly to California's renewable energy targets. Wave energy is included in the offshore wind topic area as an adjacent technology that can benefit from the same offshore grid infrastructure development. The electricity sector considers energy storage and grid integration technologies essential enabling technologies that will increase the penetration of renewable energy while providing consistent and reliable utility power.

This roadmapping project is broken into two major reports: A Technical Assessment (TA) and this Research Roadmap. The TA summarizes research on the current state of renewable energy generation and storage in California; significant considerations for future development of various renewable technologies; and current research efforts in California, other states, and at the national level. A list of opportunity areas and specific breakthrough technologies for each renewable technology area is also provided in the TA.

The research and interviews used to develop the TA served as inputs into the second phase of the roadmapping process (described in Chapter 2: Project Approach), The Research Roadmap. The final result of the roadmapping process is this Research Roadmap that identifies research gaps and provides a series of recommended initiatives that address those gaps. These prioritized recommendations provide near (1-3 years), mid-term (3-5 years), and long-term (>5 years) RDD&D that can help California advance the commercial status of advanced technologies in a variety of renewable energy technology areas.

Relevant cost and performance targets are provided for each technology area to show both the current baseline for the technology area and to serve as a future indicator of success for the recommended initiatives. The metrics demonstrate possible improvements in the technology area that ultimately either reduce cost and/or increase renewable energy production in a way that provides more renewable and zero-carbon energy to investor owned utility (IOU) electric ratepayers in California and advances California toward SB-100 goals.

Current California Energy Mix and Future Expectations for SB-100

SB-100 sets goals of achieving 60 percent production from renewable energy by 2030 and 100 percent carbon-free energy by 2045. Based on the 2018 California energy mix (presented in Table 1), renewables will need to account for 29 percent more of the energy mix by 2030. Assuming large hydro production remains constant and nuclear production ceases when the last nuclear generator in California is shuttered in 2025, renewable production will need to account for at least 89 percent of the total CA energy mix by 2045 to reach SB-100 goals.

These future expectations rely on the unlikely assumption that demand will stay constant from 2018 to 2045. In their document, "California Energy Demand 2018-2030 Revised Forecast", the Energy Commission provides estimated 2030 utility-scale electricity demand. See Appendix A for supporting calculations for predicting renewable energy production for 2030 and 2045.

Table 1: 2018 Current CA Utility-Scale Energy Mix

Type	In-State Generation (GWh)	Percent of Instate Generation	In-State Capacity (MW)	In-State Capacity Factor	Imports (GWh)	CA Energy Mix (GWh)	CA Power Mix
Fossil Fuels	**91,450**	**46.9%**	**41,986**	**24.9%**	**18,101**	**109,551**	**38.4%**
Coal	294	0.2%	55	61.0%	9,139	9,433	3.3%
Natural Gas	90,691*	46.5%	41,491	25.0%	8,953	99,644	34.9%
Oil	35	0.0%	352	1.1%	0	35	0.0%
Other Fossil	430	0.2%	88	55.8%	9	439	0.2%
Renewables	**63,028**	**32.4%**	**23,671**	**30.4%**	**26,474**	**89,502**	**31.4%**
Biomass	5,909	3.0%	1,274	52.9%	798	6,707	2.4%
Geothermal	11,528	5.9%	2,730	48.2%	1,440	12,968	4.5%
Small Hydro	4,248	2.2%	1,756	27.6%	335	4,583	1.6%
Solar	27,265*	14.0%	11,907	26.1%	5,268	32,533	11.4%

Solar PV	*24,698**	*12.7%*	*10,658*	*26.5%*	-	-	-
Solar Thermal	*2,567**	*1.3%*	*1,249*	*23.5%*	-	-	-
Wind	14,078*	7.2%	6,004	26.8%	18,633	32,711	11.5%
Offshore Wind	*0*		*0*		*0*	*0*	
Wave	0		0		0	0	
Other Zero-Carbon Sources	**40,364**	**20.7%**	**14,647**	**31.5%**	**15,976**	**56,340**	**19.7%**
Large Hydro	22,096	11.3%	12,254	20.6%	8,403	30,499	10.7%
Nuclear	18,268	9.4%	2,393	87.1%	7,573	25,841	9.0%
Unspecified Sources of Power	**N/A**	**N/A**	**0**		**30,095**	**30,095**	**10.5%**
Total	**194,842***	**100.0%**	**80,304**	**27.7%**	**90,647**	**285,488**	**100.0%**

*Total In-state Generation does not match between the two California Energy Commission Sources. The 2019 source was used as the primary source except for Solar PV and Solar Thermal totals which were extrapolated based on the 2020 source.

Sources: California Energy Commission (2020) and California Energy Commission (2019a)

General Methodology

The roadmapping process began with general research and targeted stakeholder outreach in the nine selected topic areas. The targeted outreach resulted in 37 interviews with experts across all topic areas. Information gathered during this first step served as the basis for the TA.

The Energetics team distributed a series of surveys to a larger list of industry experts and conducted seven webinars to seek input on the topic areas. The focus of these two activities was to prioritize key barriers and considerations for each topic area and to identify the research opportunity areas and technologies that could best address those barriers and drive the commercial deployment of renewable technologies. The output from the surveys and webinars led to development of a diverse set of initial recommended initiatives that were spread equally across the topic areas (two recommended initiatives for all topic areas expect Offshore Wind which featured four). In a Preliminary Draft Roadmap, Energetics summarized these recommended initiatives for the public. Next, the Energy Commission hosted a Public Comment Workshop which gathered feedback on the recommendations.

Energetics' team closely reviewed the feedback received from the Public Comment Workshop and prepared a quantitative decision process to analyze the comments suggesting clarification, additions, or removal of recommended initiatives to finalize the recommendations that are featured in this Research Roadmap.

Opportunities for Energy Commission Involvement

Through the Electric Program Investment Charge (EPIC) program, the Energy Commission supports emerging technologies and strategies with the potential to grow clean energy in California (California Energy Commission 2019b). The EPIC program funds projects that support California's energy policy goals and fit into one of three program areas shown below.

EPIC Program Areas:

> **Applied research and development** projects center on activities supporting pre-commercial technologies and approaches that are designed to solve specific problems in the electricity sector.
>
> **Technology demonstration and deployment** projects aim to evaluate the performance and cost-effectiveness of pre-commercial technologies at or near commercial scale to bring these technologies closer to market.
>
> **Market facilitation** projects focus on overcoming non-technical barriers and challenges to help new technologies find early market footholds in investor-owned utility service territories. This category can include procurement and permitting approaches and development of advanced analytical tools.

The recommended technology initiatives presented in this document address the first two areas, applied R&D and technology demonstration and deployment. The team also received comments during the roadmapping process out of the scope of Energy Research and Development Division projects, related to the third program area (market facilitation and educational outreach). This introduction includes a summary of the most applicable non-technical challenges identified in this study and additional out of scope comments are included in Appendix B.

One additional idea for Energy Commission involvement brought up over the course of the roadmapping process was to leverage resources (e.g., knowledge, funding, facilities, personnel, and intellectual property) from national entities such as ARPA-E, DOE applied research programs, and national laboratories in support of California's renewable generation goals. While only one recommended initiative included in this document specifically encourages partnership with outside organizations, many additional opportunities exist for the Energy Commission to partner with national entities to advance the RDD&D of renewable energy technologies. Energetics researched and considered related national efforts in the roadmapping process, which are included in the TA and in this roadmap in Appendix C, and recognizes the benefit of future national collaborations.

Non-Technical Challenges Requiring Broad Stakeholder Involvement

Many of the barriers and considerations brought to light during the roadmapping process require engagement from other California entities or are outside of the Energy Commission's RDD&D program scope. These are systemic problems that need to be addressed to allow California's electric system and energy markets to accommodate a high penetration of renewables. The systemic or non-technical challenges facing the increased penetration of utility-scale renewables on California's electric grid require changes to market structures, policy and regulations, or active education and outreach to stakeholders. Three of the most significant barriers are permitting restrictions, resource valuation, and technology lock-in.

Utility-Scale System Permitting

Permitting restrictions represent a significant barrier to low-cost utility-scale renewable energy deployments. These restrictions affect all of the aforementioned technology areas, albeit in different capacities. Permitting barriers span local, state, and federal restrictions and therefore may require different tactics across all three levels. Additionally, there may be more than one regulatory body at each level with restrictions that can inhibit system deployment.

In the case of bioenergy, California's air quality standards limit the location and development of bioenergy facilities (Energetics 2019). Bioenergy systems produce air emissions due to the combustion of biomass or through production of syngas or biogas followed by their combustion. However, bioenergy systems can provide innovative, energy-positive solutions for waste management and forest fire mitigation. Although the available alternatives could pose a greater threat to air quality and public health, they provide benefits—waste disposal and reduced fire risk—that permitting decisions do not currently consider.

Wind and solar development also face land use challenges throughout California and on in-state federal lands that have reduced utility-scale investments. Locally, San Bernardino County's Board of Supervisors voted to ban utility-scale solar and wind farms across over a million acres of private land in the county. While the county does have smaller areas designated for renewable energy, this decision greatly restricts the opportunity to develop renewable energy in the Los Angeles metro area (Roth 2019). San Bernardino County is not alone, as Los Angeles, San Diego, Inyo, and Solano counties have voted to approve restrictions on large-scale wind installations (The Times Editorial Board 2019).

The Desert Renewable Energy Conservation Plan (DRECP) also added constraints on land for renewable energy development. The DRECP set aside 828,000 acres (7.7 percent) out of 10.8 million acres of federal land in Southeastern California for potential renewable energy development with streamlined permitting processes to access 388,000 of those acres. The remaining 440,000 acres available for renewable energy development are defined as general public land or have another designation (DRECP 2016). Ideal wind resources are available on 78,779 acres of land covered by DRECP and available for renewable energy development. There is some concern that this availability of wind resource area is too limiting as there is over 2 million acres of land with ideal wind energy resources covered by DRECP. The federal lands are largely in the jurisdictions of the counties that enacted renewable energy development restrictions as well. While the development of DRECP was a collaborative effort, when DRECP was announced, all wind projects being pursued in the region were cancelled, and there has been little to no development in wind power since in southeastern California (Perez 2018).

Resource Valuation

Resource valuation emerged as a common theme across all technology areas. Challenges arise because (1) current market structures value the lowest-cost resource at any given time, (2) power availability and other grid services are not part of the valuation, and (3) California's renewable portfolio standard (RPS) tallies credits annually, which does not encourage continuous use of renewables.

Solar PV and land-based wind power currently dominate the renewable energy landscape in California because of their low costs. However, these resources are inherently variable and necessitate the deployment of energy storage systems to allow for a full transition to a decarbonized electric grid. There are alternative renewable power systems that can provide power predictably, reliably, and when required to match grid demand; examples are concentrated solar power with thermal storage, geothermal power, bioenergy, and small hydro. However, the market does not value these benefits when selecting energy sources.

California's current RPS accounting methodology also favors solar PV and land-based wind by allowing renewable portfolio credits to be counted on an annual basis. This methodology creates an incentive to over-deploy these low-cost renewable resources, since they can generate enough portfolio credits during the day to account for a transition back to fossil-based electricity generation at night (CPUC 2019a). In the near term, this keeps energy costs low for consumers. However, in the long term, a different approach must support the grid's transition to be carbon-free at all hours of the day. According to experts and stakeholders, the RPS procedure must also incentivize deployment of non-solar PV and land-based wind renewable energy systems. The electricity sector requires consistent investment across all forms of renewables to maintain institutional knowledge, preserve and grow industry supply chains, and enable cost declines as experience and deployments increase.

The California Public Utilities Commission, California ISO (CAISO), U.S. Department of Energy (DOE), and U.S. Energy Information Administration (EIA) recognize these issues and are evaluating new options and market structures. Future market updates could account for the avoided costs of storage or other grid investments, the value of resource availability and dispatchability, and other societal benefits such as energy-positive waste utilization and wildfire mitigation.

Technology Lock-in (Stymied Innovation)

Technology lock-in can pose a significant barrier to innovation because of the scale and nature of investments in the electric grid. Grid infrastructure and generating assets can cost billions of dollars and have useful lives that span decades. Additionally, new technology deployments come with cost and reliability concerns, making utilities, regulators, and customers highly risk-averse. Extensive functional existing infrastructures, combined with concerns associated with new systems, make it difficult for new technologies to transition from pilot studies to full-scale deployment and market commercialization (Energetics 2019).

CHAPTER 2: Project Approach

The goal of this project is to develop a research roadmap that identifies, describes, and prioritizes technology RDD&D opportunities that have potential to achieve high-penetration of utility-scale renewable energy into California's electricity grid. Renewable energy includes transmission line connected renewable energy generation technologies and strategies, including energy storage.

Methodology of the Roadmap Project

To accomplish the project goals outlined by the Energy Commission, the Energetics team produced two reports: The TA and this Research Roadmap. The TA informs the Research Roadmap and can be accessed at the Research Idea Exchange docket (California Energy Commission 2019c). Figure 1 shows the timeline and steps that were followed for completion of this project.

Figure 1. Timeline for the Utility-Scale Renewable Energy Generation Technology Roadmap

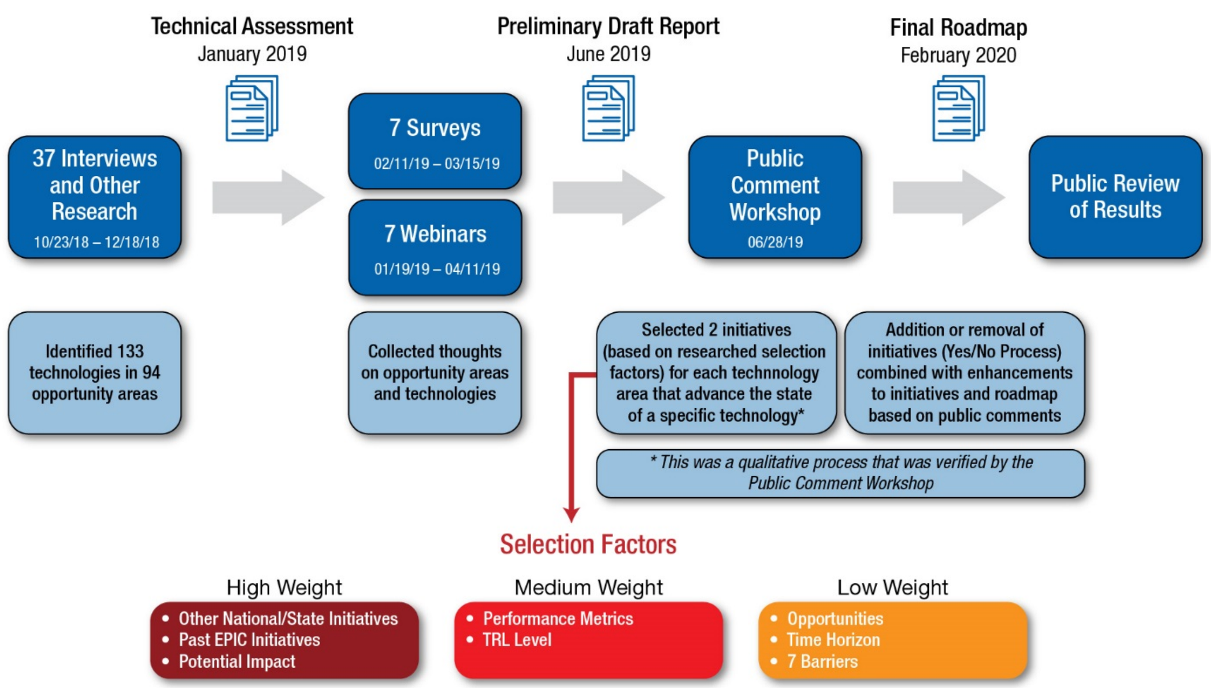


Table 2 shows the number of contributing participants in the roadmapping steps such as the interviews, surveys, and webinars for each topic area.

Table 2: Summary of Participation in Roadmap Project Methodology

	Solar	Wind	Bioenergy	Geothermal	Small Hydro	Grid Integration	Energy Storage	Total
Interviews	6	10	6	5	4	5	3	39
Survey Respondents	10	8	12	10	5	11	6	62
Webinar Participants	13	13	8	9	8	10	14	75
Total Roadmapping Participants	19	21	21	17	13	22	18	114 unique invited participants
Public Comment Workshop Participants								81 external public participants

The following section provides a detailed description of the individual activities comprising the roadmapping process.

Interviews – Energetics developed the TA based on a series of expert interviews and related research. The team conducted 37 total interviews between October 23rd, 2018 and December 18th, 2018.

Technical Assessment – This document set the stage for specific identification of research gaps in the Research Roadmap. Targeted research for the TA focused on resource assessments, cost and performance metrics, current capacity in California, current status of technology, RDD&D opportunity areas, and specific emerging and breakthrough RDD&D technologies and strategies for each technology area. In total, the TA identified 94 candidate opportunity areas and 133 emerging and breakthrough technologies. These opportunity areas and technologies served as the basis for the recommended initiatives presented in this roadmap.

Surveys – Energetics used the findings presented in the TA to the develop surveys sent out to experts in each technology area. The surveys asked experts how they would prioritize both RDD&D opportunity areas and emerging and breakthrough technologies. Additionally, experts provided opinions on priority investments in RDD&D opportunity areas or specific technologies in the near-, mid-, and long-term. The team distributed surveys the week of February 11th, 2019 and collected 62 responses by March 15th, 2019. The survey results allowed Energetics to focus discussion during the next roadmapping activity, the webinars.

Webinars – Energetics facilitated seven webinars between the dates of March 19th, 2019 and April 11th, 2019 with 75 total webinar participants. The team invited targeted topic area experts to participate in the webinars. To guide discussion during the webinars toward RDD&D advances that could most impact California's grid, moderators asked experts to rank seven different barriers by their level of inhibition on achieving greater renewable energy penetration from respective technology areas. Experts then suggested and discussed R&D projects that the Energy Commission could pursue to address highly ranked barriers. Additionally, the moderators collected key considerations and research gaps identified within the confines of these barriers. The barriers are as follows:

- **Cost:** Are there high-cost technology development and operations components that drive costs above what the market, financers, and producers will bear?
- **Dispatchability:** Are technology improvements or strategies needed to ensure that electricity can be used on demand and dispatched at the request of power grid operators, according to market needs?
- **Grid Integration and Interconnection:** Are there barriers to grid integration or interconnection?
- **Performance:** Are there barriers pertaining to power output, capacity, energy density, material durability, system degradation/corrosion, efficiency, curtailment, or other performance-related factors?
- **Production:** Are there issues related to manufacturability, supply chain and logistics, or other factors that limit system production?
- **Resource Availability:** Is there a clear understanding of geographical locations appropriate for deployment? What regulatory or permitting barriers that may inhibit the development of utility-scale systems? Are forecasting improvements necessary to enhance operations and certainty in power scheduling?
- **Resource Valuation** Are energy markets appropriately valuing all the benefits that this technology area may bring to the grid or society?

Findings from the surveys and webinars allowed Energetics to prioritize the list of 94 opportunity areas identified in the TA. The selection criterion used to select the most important opportunity areas was their ability to address highly ranked barriers and challenges. Energetics then sorted the emerging and breakthrough technologies identified through expert interviews and research, presented in the TA, and brought up in the webinars into prioritized opportunity areas.

Preliminary Draft Roadmap – The Preliminary Draft Roadmap outlined 20 recommended initiatives resulting from a qualitative down-selection process. The Energetics team wrote the initial list of preliminary initiatives to contain all relevant emerging and breakthrough technologies that were sorted into prioritized opportunity areas as described above. The criteria considered for down-selecting from the preliminary initiative list included: level of investment in the technology by other organizations, ability to address identified barriers and research gaps, past interest by the Energy Commission, current technology readiness, and potential impact on cost and performance metrics. This qualitative process resulted in two recommended initiatives for each of the nine Roadmap technology areas, with the exception of offshore wind which had four recommended initiatives (identified as an area with immense potential in California). In addition to these 20 recommended initiatives, the Preliminary Roadmap Draft contains key barriers and challenges as well as related EPIC and DOE initiatives for each technology area.

Public Comment Workshop – Soon after publishing of the Preliminary Roadmap Draft, the Energy Commission facilitated a public comment workshop on June 28, 2019 to gather feedback on the list of 20 initiatives. The Energetics team conducted the workshop virtually through a webinar; 108 people attended the workshop and comments were collected both during the webinar and through an Energy Commission public comment portal. Following the workshop, the Energy Commission held a public comment period to solicit written feedback on the preliminary roadmap draft and its given initiatives that lasted until July 12, 2019.

Energetics sorted comments both recorded during the webinar and submitted electronically into four categories: new ideas, initiative disagreements, gaps and/or clarifications, and other. Figure 2 presents the number of comments received, and the resulting actions taken by Energetics. The number of submissions during the Public Comment period is not exact because some comments contained multiple ideas. Additionally, the submission total includes verbal feedback recorded during the Public Comment Workshop. Gaps and clarifications and "other" comments were addressed on an individual basis with relevant suggestions being incorporated into this roadmap. Comments that presented new idea for investment or disagreed with initiatives were put through a quantitative initiative decision process to determine if they should result in changes to the 20 initiatives presented in the Preliminary Draft Roadmap.

Initiative Decision Process – This process involved nine different questions (shown Figure 2 below) used to evaluate a proposed addition or removal of an initiative. The Energetics team wrote each question so that "yes" was the desired answer to each question. However, a "no" answer to any of the nine variables did not disqualify a proposed action immediately. Four of these questions factored heavily into a pass or fail decision (are there few similar initiatives offered nationally or by other states?; is there limited overlap with past EPIC initiatives?; does this initiative have a medium or high potential impact on renewable penetration in California?; is this initiative within the Energy Commission's purview?).

Overlapping EPIC, DOE, state, and past Energy Commission initiatives were recorded to justify the yes or no decision for the two corresponding questions on past initiatives. Additionally, calculations were made to quantify the impact of an initiative on SB-100 goals to answer the question on medium or high potential impact when this question was the deciding factor for the decision process described below.

For new ideas for initiatives, a “no” to one of the heavily factored questions and another question or three “no” answers to any questions resulted in a failure of the process. The quantitative interpretation of that process is as follows: a score of two points or lower resulted in a passing score. The four heavily weighted questions received a score of two points for each “no” answer while the other five questions resulted in a score of one point for any “no”. All “yes” answers resulted in zero points.

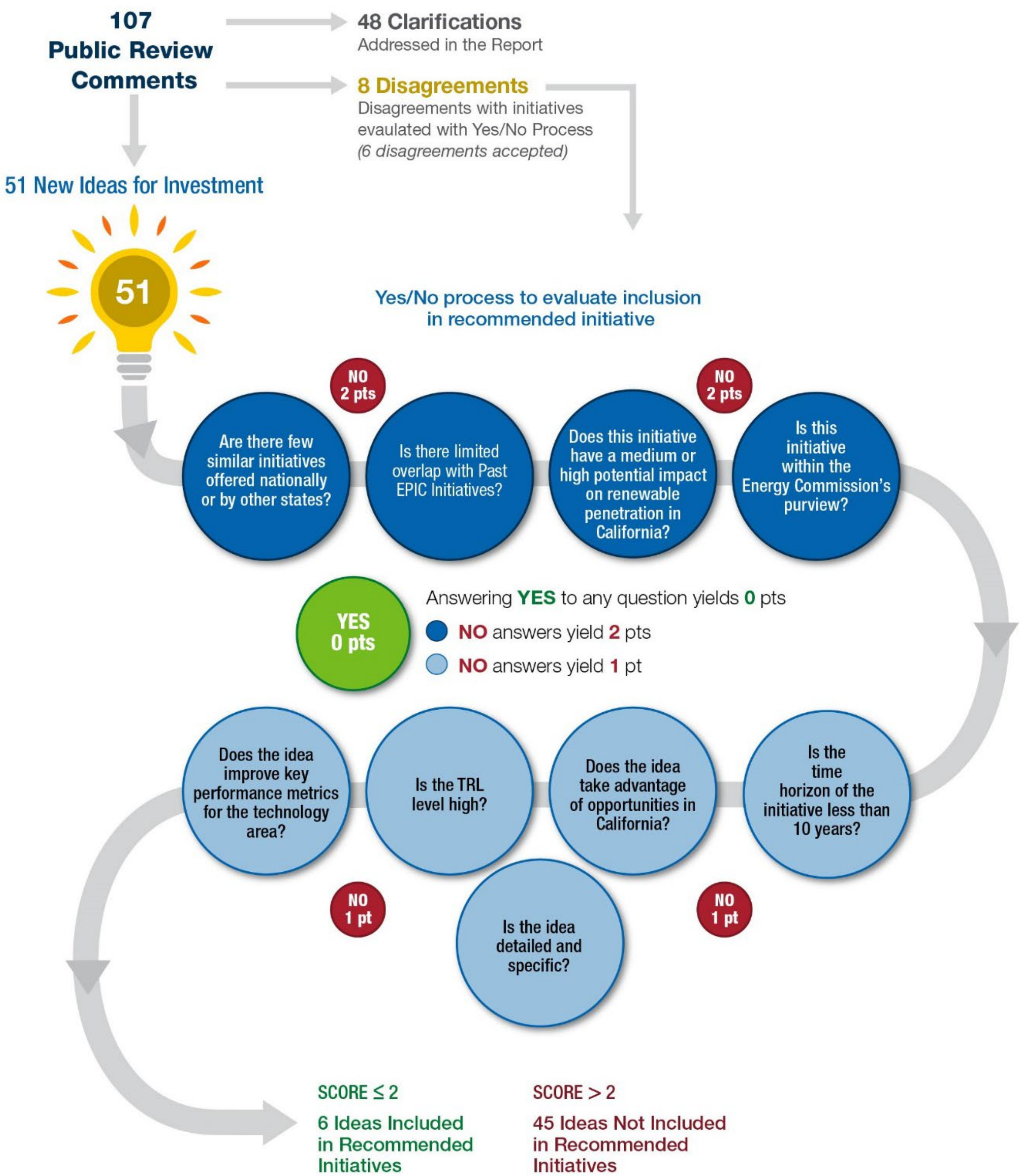
Alternatively, if an original recommended initiative was questioned, new information received through the comment resulted in re-evaluation of the original initiative through the decision process. If that initiative failed the process outlined above for new ideas, then the Energetics team removed the original recommendation from the roadmap and the comment passed the process. Researchers and technology experts further evaluated all proposed additions and removals of initiatives that passed the decision process on an individual basis. After expert review, the Energetics team evaluated each suggestion again with the decision process to determine its final pass/fail status.

New ideas for initiatives that passed both rounds of the decision process resulted in either a new initiative or a change to an existing initiative. Those changes involved one or more of the following actions: editing the content of an initiative, changing the technology area of an initiative, and/or combining initiatives. Figure 2 shows a flow diagram outlining the quantitative initiative decision process.

Research Roadmap – This document presents 17 recommended initiatives that address research gaps in the near-, mid-, and long-term. These initiatives have the opportunity to improve the quality (e.g. better environmental performance) or increase the quantity of utility-scale renewable energy available to California customers. The roadmap also includes the following information for each technology area to give context to the recommended initiatives: a summary of key information from the TA, cost and performance metrics, other key metrics, potential for reaching SB-100 goals, and the most important considerations and barriers identified throughout the roadmapping process.

Public Review of Results – The team presented the results of the roadmap in a final public webinar conducted in the first quarter of 2020.

Figure 2. Public Roadmapping Webinar Initiative Decision Process



CHAPTER 3: Project Results

This roadmap offers a diversity of recommendations that span nine topic areas to provide a comprehensive look at RDD&D initiatives that address pressing research gaps in the state of California. In addition to these initiatives, this chapter includes detailed information about each renewable topic area including generation trends, a resource assessment, potential for reaching SB-100 goals, cost and performance metrics, and additional relevant research findings including key technology area considerations.

The generation trends, resource assessment, and key considerations provide context for the recommended initiatives and demonstrate findings from the roadmapping process. Appendix B includes considerations that were brought up, but were out of scope for this research roadmap.

The resource assessment also serves as a basis for an estimate of the theoretical potential for each renewable technology area to reach the 2045 SB-100 goals. Appendix A contains the calculations used for all of these estimates.

The cost metrics presented throughout this chapter serve as a universal way to judge performance and competitiveness of renewable technologies. Improvements in levelized cost of energy (LCOE) and installed costs are a sign of ongoing progress for each technology area. Therefore, initiatives that lower LCOE contribute to the cost competitiveness of their respective topic area.

Other key metrics presented in each topic area provide additional benchmarks to judge the progress of specific recommended initiatives. These metrics include performance indicators and technology specific costs such as transportation costs.

At the core of this chapter are the recommended initiatives that were fleshed out through this intensive roadmapping process. These initiatives provide specific RDD&D funding opportunities for the research programs of the Energy Commission that will allow California to move toward Senate Bill 100 (SB-100) and climate change goals in the short, mid, and long term, and provide unique benefits to California ratepayers. The SB-100 aims to power this grid with 60 percent of eligible renewable resources by 2030 and 100 percent of zero-carbon resources by 2045.

Recommended Initiatives

Based on results obtained using the methodology described in Chapter 2, Table 3 lists the recommended initiatives for the nine renewable technology area included in the roadmap. Small hydropower has no recommended initiatives.

Table 3: List of Recommended Initiatives

Technology Area	Initiative	Success Timeframe
Solar Photovoltaics (SPV)	Initiative SPV.1: Field Test Tandem Material PV Cells	Mid-term/Long-term
	Initiative SPV.2: Increase PV Material Recovery from Recycling Processes	Near-term/Mid-term
Concentrated Solar Power (CSP)	Initiative CSP.1: Improve Cleaning Systems for CSP Mirrors	Near-term
	Initiative CSP.2: Advance Materials and Working Fluids for High Temperature TES	Mid-term
Land-Based Wind (LBW)	Initiative LBW.1: Advance Construction Technologies for Land-based Wind Turbines	Near-term/Long-term
	Initiative LBW.2: Demonstrate New Blades that Improve Conversion Efficiency	Mid-term/Long-term
Offshore Wind (OSW)	Initiative OSW.1: Pilot Demonstration of Floating Offshore Platform Manufacturing	Long-term
	Initiative OSW.2: Design Port Infrastructure to Deploy Floating Offshore Wind Technologies	Long-term
	Initiative OSW.3: Integrate Wave Energy Systems with Floating Offshore Platforms	Long-term
Bioenergy (BIO)	Initiative BIO.1: Improve Cleaning Methods to Produce High Quality Biomass-Derived Syngas	Mid-term
	Initiative BIO.2: Deploy Thermal Hydrolysis Pretreatment to Increase Biogas Production	Mid-term
Geothermal Power (GEO)	Initiative GEO.1: Improve Materials to Combat Corrosion from Geothermal Brines	Mid-term
	Initiative GEO.2: Advance Techniques to Assess Potential EGS Development Sites	Near-term
Grid Integration Technologies (GIT)	Initiative GIT.1: Deploy Smart Inverters to Improve Communication and Cybersecurity	Near-term
	Initiative GIT.2: Advance Underwater High-Voltage Infrastructure for Offshore Energy Interconnection	Long-term
Energy Storage Systems (ESS)	Initiative ESS.1: Lengthen Storage Duration of Energy Storage Systems (8-hour or greater)	Mid-term
	Initiative ESS.2: Optimize Recycling Processes for Lithium-Ion Batteries	Mid-term

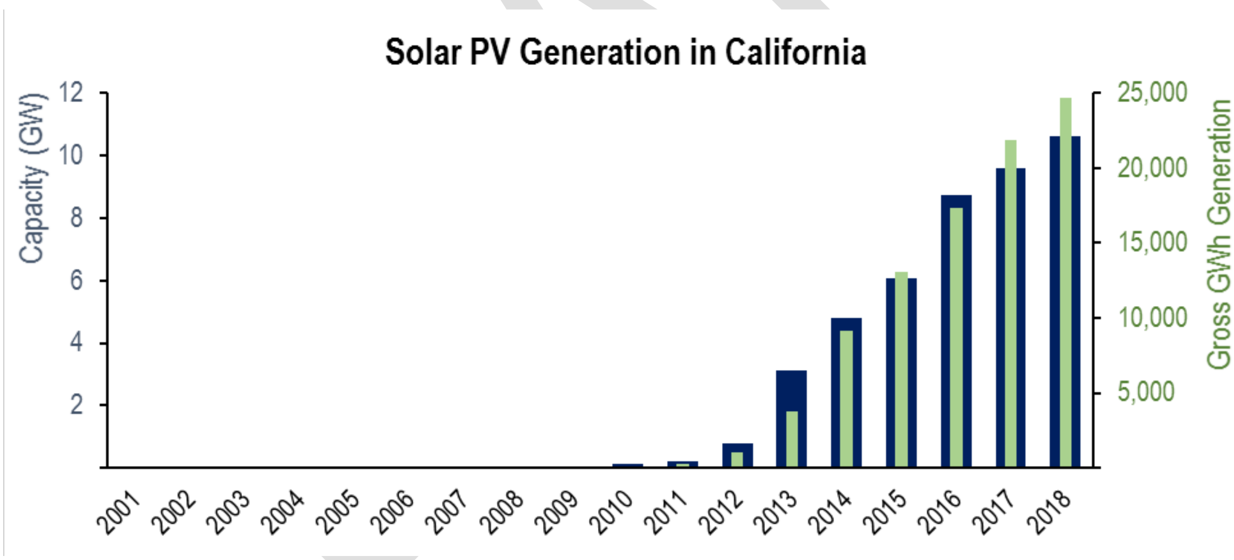
Solar PV

Solar PV has largest technical potential of any renewable energy type in California and can be installed feasibly across the entire state. The primary limitations to solar PV installations are rough geography and permitting laws. Currently, Solar PV systems generate more electricity than any other renewable energy sources within the state and will remain an integral part of California's energy mix. California has furthered its commitment to solar energy with its updated Title 24 building standards which requires rooftop solar generation for all new buildings constructed after January 1, 2020. Continued development in solar cell technology will enable further increases in solar energy efficiency and generation while decreasing costs.

Generation Trends

Solar energy is the largest source of renewable energy in the state. Beneficial policies have supported the growth of PV power systems across California. PV has gone from being a small percentage of California's total renewable generation to the largest source of renewable energy generation in the state over the past decade. Figure 3 shows the quantity of utility-scale solar PV generation in California from 2001 to 2018.

Figure 3: Solar PV Energy Generation in California from 2001 to 2018



Source: California Energy Commission (2019c)

Resource Assessment

California contains some of highest solar irradiance levels of any state, making the state ideal for large scale solar energy development. While southern deserts have been an area of focus, northern regions of the state are also suitable for solar development. The technical potential capacity of rural and urban utility-scale solar PV in the state is estimated at 4,010 gigawatts (GW) and 111 GW respectively (Lopez et al. 2012).

Potential for Reaching SB-100 Goals

If all 4,100 GW of solar PV resource potential were captured at the current statewide capacity factor (26.2 percent), solar PV systems would provide roughly 93,700,000 GWh of additional renewable power or 29 times as much renewable production as required to reach 2045 SB-100 goals (supporting calculations in Appendix A). This represents by far the largest potential for any renewable resource in the state.

Solar PV however is a variable renewable resource and needs to be paired with other forms of renewable energy or energy storage to provide power at night when the sun is not shining. The future growth of Solar PV is tied to increases in energy storage capacity more than any other renewable technology presented in this roadmap.

Cost Metrics

The LCOE for utility-scale PV solar systems ranges from $0.036/kilowatt-hour (kWh) to 0.044/kWh, unsubsidized. Installed costs for photovoltaic systems range from $950/kilowatt (kW) to $1,250/kW (Lazard 2018). The LCOE and installed costs have large ranges because they represent the cost of systems installed at a variety of locations globally. Additional current and future estimates of LCOE are provided below from a variety of sources to capture a diversity of cost projections for utility-scale PV. Solar PV power is still poised to lead the field in new renewable development based on these estimates, as it will remain the cheapest form of renewable energy.

Table 4: Solar PV Cost Performance Targets

U.S. Department of Energy 2018 Budget Request				
	FY 2017	FY 2018	FY 2019	Endpoint Target
Photovoltaic (PV)	7 cents/kWh (exceeded, 6)	6 cents/kWh	5.5 cents/kWh	3 cents/kWh by 2030
Solar + Storage	$1.96/Wdc	n/a	$1.65/Wdc	$1.45/Wdc by 2030
California Energy Commission 2018 Update				
	2017	2018	2019	2030
Photovoltaic (PV)	N/A	4.7 cents/kWh	4.5 cents/kWh	3.5 cents/kWh
IRENA Renewable Power Generation Costs				
	FY 2017	2018	2019	2020
Photovoltaic (PV)	9.7 cents/kWh	8.5 cents/kWh	5.1 cents/kWh	4.7 cents/kWh

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

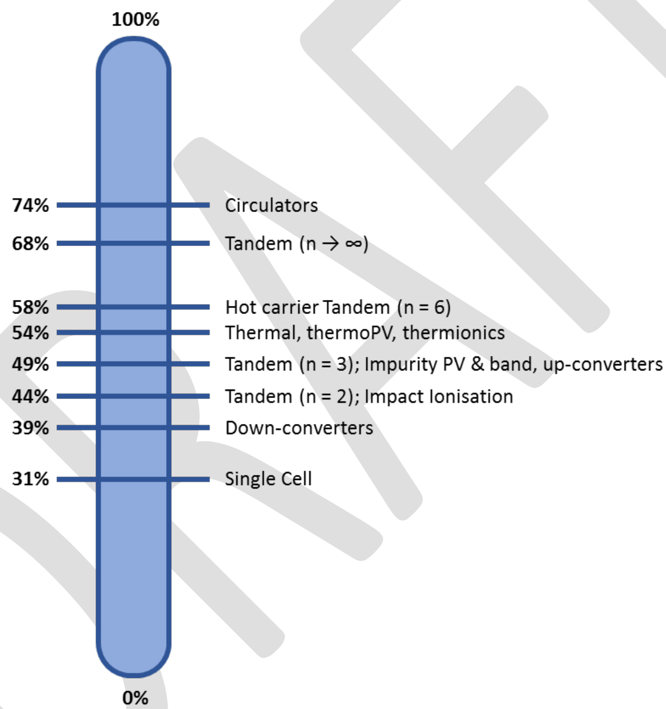
Solar + Storage: The solar + energy storage cost target is an unsubsidized cost of energy at utility-scale array with 4 hours of battery storage, actual installed costs in Watts direct current (Wdc). Model assumptions based on NREL analysis: 2017 NREL PV Benchmark Report, the Annual Technology Baseline,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

Source: DOE (2018a), Neff (2019), IRENA (2019)

Other Key Metrics

Conversion Efficiency – As Figure 4 shows, there is significant room for increased conversion efficiency beyond silicon single-junction cell technology, which sits just below the maximum of 31 percent for the optimum material. In particular, multijunction ("tandem") technologies range upward of 50 percent in theory and they have achieved nearly 50 percent in the laboratory to date (Green et al. 2018).

Figure 4: Comparison of Theoretical Solar Energy Conversion Efficiencies



Source: (Green 2012) adapted by Energetics.

Recycling Costs – Estimates show that recycling costs for PV modules fall between $10 and $30 per module, net of the recovered materials' market value (Libby and Shaw 2019). This cost currently represents 15 percent of the cost of a solar module, but without significant future reductions this fraction will increase with continued decreases in solar module costs.

Module Mass Recovery – Current recycling processes are able to recover over 90 percent of a PV module's glass and metal mass into essentially two useful streams. The principal issues for improving upon this relate to the still-small quantities of intimately mingled materials of different types, including metal framing, glass and plastic covers, solar cells, and wiring components. All of these can be recycled, but only after complex separations, which are not generally employed to date because of the small quantities involved (Marsh 2018). The European market is ahead of the U.S. because of recycling and antipollution regulations, but some U.S. manufactures (e.g., First Solar and Sunpower) have initiated recycling programs for their products. (Komoto and Lee 2018)

Recommended Initiatives

The following charts describe the two recommended initiatives selected for solar PV technologies. Regardless of investment, Solar PV will continue to grow and maintain its status as the largest provider of utility-scale renewable electricity. The below initiatives can improve that growth by lowering LCOE and decreasing the amount of land required for solar installations.

Initiative SPV.1: Field Test Tandem Material PV Cells

Description and Characteristics	Present-day commercial crystalline silicon PV modules have narrowed the gap between their practical and theoretical performance limits, such that future gains in their LCOE will come only from further economies of larger-scale manufacturing and deployment. Tandem-Junction PV technologies, which have 2 or more active p-n junctions in optical series, offer significantly higher efficiency potential than crystalline silicon single-junction PV. Such tandem-junction devices can be realized via deposition of single-junction thin-film devices on top of conventional silicon cells or in all-thin-film form using many layers of semiconductors deposited sequentially. However, transitioning today's promising tandem cell laboratory results to commercial module practice will require substantial field experience as well as manufacturing scale-up in addition to further laboratory development. This initiative would establish field-testing programs to accelerate acquisition of real-world experience by promising novel technologies, such as recent laboratory demonstrations of perovskite thin-film cells on top of crystalline silicon cells. This experience is vital for transferring laboratory advances toward commercial products. A 1970s government program provided much of the core knowledge that made crystalline silicon modules a durable success. Lack of similar experience has been a major barrier to market entry of tandem PV technologies in recent decades.

Impacts

Tandem-junction PV technologies, utilizing materials such as perovskite and cadmium telluride, have substantially higher theoretical efficiency limits than crystalline silicon's, which results in more energy production in a smaller area and can translate into significantly lower energy costs. Field testing will proof the designs in real-world environment and provide information on degradation and failure mechanisms that lead to commercially viable module lifetimes of more than 20 years.

Estimated Potential Impact on SB-100

An increase in the conversion efficiency of solar PV panels would increase the electrical output per installation. While a noticeable increase in conversion efficiency of Solar PV panels is not expected from until 2030, this initiative has the potential to result in 125 fewer installations between 2030 and 2045 (25 megawatts (MW) average per installation). Assuming current solar PV capacity factors, one hundred and twenty-five 25 MW installations would provide 2.2 percent of California's 2045 SB-100 goals (2045 SB-100 goals discussed in Current California Energy Mix and Future Expectations for SB-100 in Chapter 1).

Areas for Advancement

Tandem-cell modules must show higher sustained efficiencies in field tests to demonstrate the ability to compete in the long-term with crystalline silicon devices on cost.

While all semiconductor material types are encouraged for development, perovskite tandem cells are increasingly popular because they can be made using abundant raw materials and have shown a great increase in conversion efficiency in the laboratory over the past decade.

Real-world durability has been an issue in all nascent thin-film technologies, but recent progress in perovskite cell lifetimes shows good promise of stability. However, degradation rates must continue to improve. A number of companies are also trying to commercialize perovskite technology.

Technology Baseline, Best in Class

Silicon single-junction PV has a maximum theoretical solar conversion efficiency of about 28 percent in unconcentrated sunlight with the best commercial silicon PV modules today sitting at about 23 percent efficiency. Tandem-junction PV cells theoretically can exceed 50 percent and laboratory thin-film tandem devices in very early development have exceeded 22 percent to date.

Metrics and/or Performance Indicators	Field tested Tandem cells with a conversion efficiency greater than the 31 percent limit of single-junction PV cells. LCOE will have to be competitive with single-junction PV cells in the future at around 3 cents per kWh in utility-scale application.
Success Timeframe	Mid-term for field testing of prototypes (3-5 years) Long-term for commercial deployment (>5 years)
Key Published References	Green et al. (2018), Wikipedia (2019)
Correlation with Ongoing CEC Efforts	EPIC 2018-2020 Investment Plan – Initiative 4.1.1: Advance the Material Science, Manufacturing Process, and In-Situ Maintenance of Thin-film PV Technologies GFO-18-303: Cost Reductions, Advanced Technology for Solar Modules (CREATE Solar)

Initiative SPV.2: Increase PV Material Recovery from Recycling Processes

Description and Characteristics	Current commercial PV modules have expected service lives longer than first-generation PV products deployed in California. As such, end-of-life issues have not been given major emphasis and there is currently little incentive to focus on those issues. However, challenges facing disposal of PV modules will inevitably arise as the larger-scale systems now in use reach retirement. Commercial crystalline silicon PV modules typically contain some amounts of potentially hazardous materials such as copper, lead, silver, and heavy metals, as well as significant quantities of plastic and glass contaminated with metals and organic compounds. Cost-effectively separating these materials into viable recycling streams is an unmet challenge. This initiative proposes to address that challenge by helping develop innovative designs, processes, and techniques for economically reclaiming much of the materials in end-of-life PV modules. Designs should focus on recovering maximum amounts of high value materials from solar modules (silver, silicon, aluminum) and high percentages of remaining materials. The initiative may include not only laboratory R&D and prototype processing equipment

demonstrations, but also materials research on more durable, less toxic components to aid in end-of-life reclamation economics.

Impacts

Successful application of the results of this initiative will substantially reduce PV decommissioning costs that adversely impact PV lifetime electricity costs while also safeguarding the environment from hazardous material disposal. Likely additional benefits include possible uses of newly developed recycling techniques for non-PV waste streams.

Estimated Potential Impact on SB-100

Solar PV module lifespans can reach 25 years. The cost of retirement and recycling of a module is therefore outside the window where associated costs would factor into initial financing. As such, this initiative will have a limited impact in lowering PV costs and increasing the number of new PV installations.

However, SB-100 and other California Solar PV initiatives will continue to drive the number of installations in the state. By 2030 and 2045, retirements of Solar PV modules will increase at the same rate as installations seen 25 years earlier. Recycling programs will improve environmental performance and decrease future waste associated with Solar PV installations.

This initiative will impact the 4.8 GW of Solar PV installations that were brought online between 2001 and 2018 in California. Those installation will be decommissioned between 2030 and 2045. The 4.8 GW of California Solar PV is comprised of 16 million solar modules. A high-end estimate of recycling cost savings enabled by this initiative is $240 million.

Areas for Advancement

On-site module recycling can reduce transportation costs and potentially lead to on-site reuse of materials. Setting up a recycling network can improve supply chain and lower recycling costs.

Technology Baseline, Best in Class

EPRI has determined that current recycling cost is approximately $10 to $30 per module, which represents about 15 percent of the module's price, a fraction that will grow as PV costs continue to decline if recycling practices are not also improved significantly.

For silicon modules, the current practice, designed to meet E.U. legal requirements, is to separate the metal framing parts from the glass/plastic cell package and send the metal into existing metal-

	recycling operations while the cell package is generally crushed and fed into existing low-quality glass feed streams. This achieves “high recovery” of module material mass, but loses potentially valuable minor amounts of copper and silver as well as admixing some lead into the glass melt. A minority of cases so far attempt to recover copper and silver from the cells by chemical solution. (Komoto and Lee 2018) First Solar’s process for handling the company’s cadmium telluride thin-film modules at end-of-life is said to recover 90 percent of the glass and 95 percent of the semiconductor, which can then be reused in new modules. (Komoto and Lee 2018) Other useful metrics for this initiative include quantitative assessments of cost reductions versus current practices in recycling PV modules and estimates of reduced impacts on landfills due to improved recovery of spent materials.
Metrics and/or Performance Indicators	Net recycling costs lower than 10 percent of initial capital cost. Module mass recovery rates of 98-99 percent (to minimize net cost and landfill impacts). Recovery rates for high value materials (silver, aluminum, silicon) over 95 percent.
Success Timeframe	Near-term for Recycling Processes (1-3 years) Mid-term for improvements to Recyclability of Materials (3-5 years)
Key Published References	EPRI et al. (2017), Veolia (2018), EPRI (2018), Deng et al. (2019) SEIA (2019), Butler (2019), Libby and Shaw (2019), Komoto and Lee (2018)
Correlation with Ongoing CEC Efforts	Related Idea: EPIC 2018-2020 Investment Plan – Initiative 7.3.3: Improve Lifecycle Environmental Performance in the Entire Supply Chain for the Electricity System

Solar Photovoltaic Considerations

Provided here (in no particular order) are some of the notable considerations aligned with the solar PV technology area. These considerations include opportunities, barriers, and potential related technologies for future advancement.

Peak generation from PV solar systems does not match peak load. Dispatchability is a key challenge for PV systems. Solar power relies on the sun, creating a roughly 6-hour window when solar energy can be maximally produced. While it is possible to forecast solar energy production throughout the day, energy storage is required to offset solar PV generation to match grid demand. Developing technologies that can capture sunlight for more hours of the day or pairing solar PV systems with energy storage can make solar energy more reliable, consistent, and dispatchable.

The drop off of solar energy in the evening requires additional installations to provide ramping power. Due to the disparity between peak load and peak solar generation in California, the daily net load in the state forms what is known as the "duck curve". Solar power generation reduces the need for power from other resources during the day, but then solar production decreases as evening demand peaks. This decrease in production necessitates a large ramp up of power that strains the electric grid. This problem will be exacerbated with additional solar installations.

Pairing solar PV with energy storage systems will increase the grid-value of future installations. When combined with energy storage, solar PV systems are fast ramping and able to meet demand throughout the day. Deployment of storage systems also allows all produced energy to be stored instead of curtailed when overgeneration occurs, which prevents waste of renewable energy production.

PV solar technologies have lower efficiencies and capacity factors than other forms of renewable power. There are several solar PV technologies that can improve these metrics, but most demonstrations of high efficiency materials have only been done in labs. Field testing of these panels is required to bring them closer to commercialization. For existing technologies, weather, dust, soiling, and maintenance contribute to lower capacity factors.

Many locations in California are ideal for PV but are restricted from development due to local and national ordinances. Some counties have banned solar energy development outright. Existing national land use plans limit the amount of land available for renewable energy development in southwestern California. In these areas, steps can be taken to work with both local and national entities to open ideal land for solar development while balancing environmental and land-use concerns.

Solar PV is currently the least expensive option for renewable development in California. To maintain their status as the lowest cost renewable energy, solar PV systems must navigate upcoming cost challenges such as upgrading T&D infrastructure and incorporating energy storage. Both of these challenges will become more prevalent as solar PV development moves to more rural locations.

Most current PV modules are built in China where manufacturing costs are much lower. However, newer PV technologies, which require less materials and labor to produce, are developed in the United States. Many solar cell technologies also require rare earth metals, which are primarily mined overseas.

Variable renewable resources are favored by developers due to how the market values power generation. The electric grid currently pays the lowest cost producers first regardless of their ability to provide power consistently and reliably, which benefits PV operators. However, this structure has to be adapted to continue to increase the amount of renewable power on the grid while still meeting fluctuating demand. Non-variable renewable sources or variable sources paired with energy storage are a necessary part of a fully carbon-free grid.

Hardware resiliency is important for solar PV arrays in preparation for fire storms, seismic events, and other severe weather events which are occurring with increasing frequency. Environmental hazards can cause both physical damage to PV arrays and the transmission systems connected to PV facilities. Hardware that is resistant to environmental hazards and grid events caused by environmental disturbances minimizes maintenance costs and limits power outages due to damage.

Light-induced degradation needs to be characterized both to predict electricity production and to enable business transactions. Light-induced degradation reduces the energy production of solar panels overtime, but the amount of degradation is difficult to quantify due to varying rates of solar panel decay. Better understanding of the lifetime performance of solar systems will help accurately predict future production and ensure fair pricing.

Module cleaning of PV systems differs from cleaning CSP mirrors. Both PV modules and CSP reflectors require regular cleaning in order to remove dust and soil accumulation. Deionized water is a popular method for cleaning both systems. However, better systems with lower water use exist but are specifically designed for either PV or CSP systems. Mechanical methods such as brushing are more useful for cleaning PV systems, while ultrasonic and vibrational methods are better suited for CSP mirror cleaning.

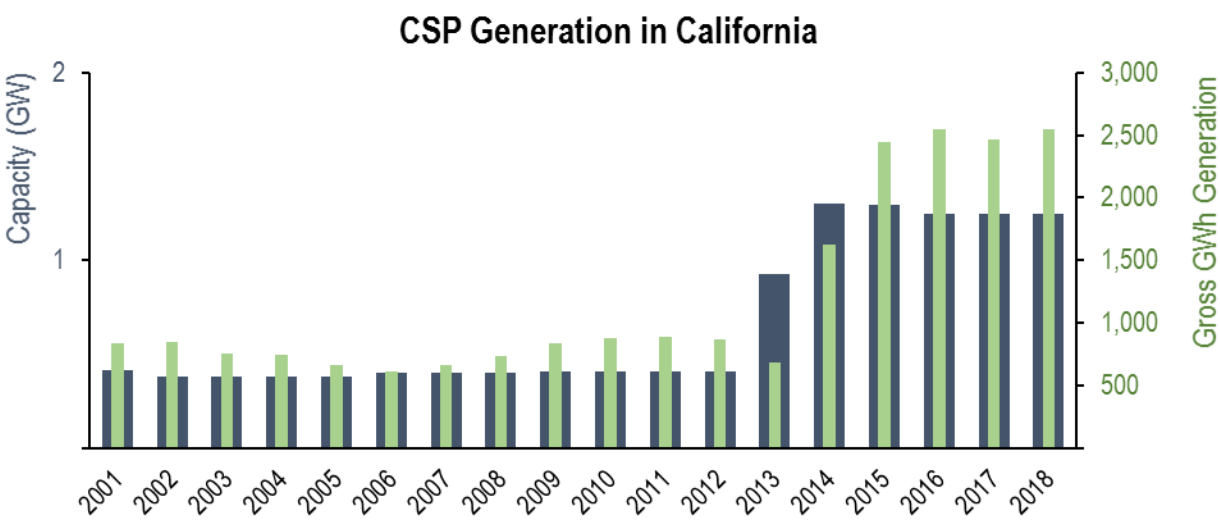
Concentrated Solar Power (CSP)

CSP represented a small but growing share of California's renewable generation since the 1980s. Parabolic troughs and solar power towers are the two most common forms of CSP with the former being the most mature technology. Solar towers have the potential to provide a significant upgrade in system efficiency. Continued efforts to increase CSP efficiency and integrate thermal energy storage (TES) can lead towards the development of CSP as a reliable, dispatchable source of renewable energy necessary to meeting SB-100 goals.

Generation Trends

After capacity from CSP systems remained relatively constant for over a decade, CSP capacity saw a recent expansion with the introduction of three new California facilities from 2012 to 2014 (Ivanpah, Mohave Solar, and Genesis Solar). Although solar central-receiver "power tower" designs are gaining worldwide acceptance, the Ivanpah Solar Power Facility is the only one currently operating in California. The remaining CSP facilities use parabolic trough designs. The trends in electricity generation from CSP can be seen in Figure 5.

Figure 5: Solar – CSP Energy Generation in California from 2001 to 2018



Source: California Energy Commission (2019d)

Resource Assessment

The high solar irradiance levels in California that make PV so desirable, also make the state ideal for utility-scale CSP development. California, Arizona, Nevada, and Florida are the only four states that currently have operational CSP deployments and look most attractive for future development. The southeastern part of California remains the best target for CSP development because that is where irradiance levels are the highest. The technical potential capacity of CSP in the state is around 2,700 GW (Lopez et al. 2012).

Potential for Reaching SB-100 Goals

If all 2,700 GW of potential Solar CSP was captured at the current CSP capacity factor of 23.3 percent, Solar CSP systems would provide an additional 5,500,000 GWh of electricity. This total would be enough to provide around 17 times as much renewable production as required to reach 2045 SB-100 goals (supporting calculations in Appendix A).

The availability of resources for Solar CSP and its non-variable nature when paired with TES make it an attractive renewable source for California. New CSP systems have included up to 10 hours of TES which would provide a significant boost to energy storage capacity throughout the state. However, heavy land use, environmental concerns, and high costs are barriers to increasing the number of CSP installations.

Cost Metrics

The LCOE for CSP systems with thermal storage, assuming a 35-year plant life, ranges from $0.098/kWh to $0.181/kWh while installed costs range from $3,850/kW to $10,000/kW (Lazard 2018). These capital costs are higher than those of CSP installations that lack thermal storage, but the LCOE can actually be lower because thermal storage increases the capacity factor of the plants which increases revenue that offsets additional plant capital investment.

Table 5: Solar CSP Cost Performance Targets

U.S. Department of Energy 2018 Budget Request				
	FY 2017	FY 2018	FY 2019	Endpoint Target
Concentrating Solar Power	10 cents/kWh	n/a	8 cents/kWh	5 cents/kWh by 2030
California Energy Commission 2018 Update				
	2017	2018	2019	2030
Concentrating Solar Power	N/A	15 cents/kWh	14 cents/kWh	13 cents/kWh
IRENA Renewable Power Generation Costs				
	2017	2018	2019	2020
Concentrating Solar Power	25 cents/kWh	19 cents/kWh	16 cents/kWh	8.3 cents/kWh

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.

Sources: DOE (2018a), NEFF (2019), IRENA (2019)

Other Key Metrics

Mirror Reflectivity

The solar mirrors, which reflect light toward the receiver to heat the working fluid, are prone to soiling from environmental exposure. Reflectors can lose around 0.5 percent of their reflectivity per day due to natural dust accumulation eventually resulting in more than 50 percent loss in production. Improvements to cleaning methods to maintain reflectivity can increase system energy production by 10 to 15 percent (Griffith et al. 2014).

Cycle Efficiency

Improvements in system efficiency will be necessary to make CSP a cost competitive renewable resource. Current system thermal-to-electric efficiencies are around 30 percent. Reaching efficiencies of over 50 percent will require solar tower systems to increase their operating temperature to above 700˚C, much higher than is able to be withstood by current system components.

Operating Temperature

Current tower CSP systems with thermal storage run at an operating temperature of 565˚C. Achieving higher temperatures will require improvements in materials and systems processes throughout the CSP cycle. Higher operating temperature solar towers are capable of improved system efficiency and greater storage energy density. CSP systems do have an optimal operating temperature however; as higher operating temperatures do lead to larger thermal loses (Glatzmaier 2011). This temperature is just above 700˚C.

Recommended Initiatives

The following charts describe the two recommended initiatives selected for solar CSP technologies. Recent large-scale Solar CSP installations have encountered significant obstacles with several failing to meet cost targets. The following initiatives provide a pathway to increasing production from CSP systems while lowering their LCOE.

Initiative CSP.1: Improve Cleaning Systems for CSP Mirrors

Description and Characteristics	CSP systems have large areas of mirrors used to concentrate sunlight onto their receivers. In contrast to flat-plate PV systems, which can tolerate soiling with relatively little impact, CSP mirrors lose effectiveness quickly with dust accumulation. The mirrors need high reflectivity for good performance, but they are easily soiled with wind-blown sand and dust. Mirror soiling can reduce plant energy production substantially (more than 50 percent loss) so frequent cleaning is necessary. Today's CSP systems use combinations of mechanized and manual cleaning techniques but even the best systems have difficulty maintaining peak mirror performance. Additionally, the costs of

currently practiced cleaning methods limit their economical application to approximately once a month on each mirror. Current cleaning methods are time consuming, expensive, prone to causing mirror breakage, and they can be water intensive accounting for the majority of plant water use.

Impacts

Reducing the cost per unit area cleaned would enable plant operators to increase cost-effectively CSP power production and reliability. Improvement in mirror reflectivity maintenance would raise plant production by at least 10 to 15 percent over current practice and improved mechanized cleaning would lower costs and reduce water consumption.

Estimated Potential Impact on SB-100

An increase in plant production by 15 percent would provide an additional 381 GWh annually (Current Solar CSP production discussed in Current California Energy Mix and Future Expectations for SB-100 in Chapter 1). This would contribute 0.5 percent of the electricity required to reach 2030 SB-100 goals. Additionally, lower costs and higher outputs of future CSP systems would make them more attractive for future installations.

Areas for Advancement

Improved electronic control systems used for better mechanization could have broad applications; e.g., for reduced-cost building window cleaning.

There is an opportunity to build upon international experience in CSP mirror cleaning.

Technology Baseline, Best in Class

Reflectors can lose around 0.5 percent of their reflectivity per day due to natural dust accumulation.

Experience shows that wind-born soiling degrades reflectivity to below 80 percent within a few months or less of normal California desert weather without aggressive cleaning campaigns.

Furthermore, occasional high-dust storm events can reduce reflectivity to below 50 percent overnight, causing complete plant shutdown for days or weeks without a means of rapidly cleaning the mirrors.

Metrics and/or Performance Indicators

Average mirror reflectivity should be maintained above 90 percent.

Success Timeframe	Near-term (1-3 years)
Key Published References	Griffith et al. (2014)
Correlation with Ongoing CEC efforts	2018-2020 EPIC Investment Plan – Initiative 4.3.1: Making Flexible-Peaking Concentrating Solar Power with Thermal Energy Storage Cost Competitive

Initiative CSP.2: Advance Materials and Working Fluids for High Temperature TES

Description and Characteristics	Achieving the DOE CSP endpoint cost target of 5 cents/kWh will require an increase in system efficiency. Current ideas for improved systems involve central-receiver (tower) systems with power-block cycle conversion efficiencies of over 50 percent. Such efficiencies will require the high-temperature side of the cycle to exceed 700˚C (1300˚F), which is higher than current system plumbing components and heat-transfer and heat-storage materials can handle. Today's CSP system power cycles have high-temperature reservoirs at up to about 565˚C (1050˚F). This temperature is limited by both fluid stability and containment plumbing durability. Known materials durable at such high temperatures are very costly and using them would largely negate efficiency gains. DOE is working to achieve their endpoint cost target of 5 cents per kWh by 2030; however, its CSP program is perennially constrained by budget limitations and its progress is hampered by political forces that make multiyear budgets uncertain. Therefore, having California investment will help not only to increase progress via greater overall resources, but also by providing greater financial stability for the program.
Impacts	Raising the upper temperature in the power cycle from 565˚C to 700˚C would increase CSP conversion efficiency from about 30 to 50 percent with LCOE reduction in nearly inverse proportion if the materials involved are not prohibitively expensive. A further benefit of the higher temperature is that the energy density of the storage system would be proportionately higher, meaning that each cubic meter of storage medium can contain significantly more megawatt-hours (MWh) of

usable heat. Other thermal power systems would also benefit from development of high-temperature lower-cost materials to increase their efficiency and lower costs. Material research can be time consuming, so increased funding toward development in this area can provide a needed boost to RDD&D. Similarly, advancement to working fluids may be able to be accomplished sooner and can done in conjunction with advancement to materials.

Estimated Potential Impact on SB-100

If DOE 2030 targets of 5 cents per kWh are met, Solar CSP will be cost competitive with current fossil sources. Future installations can therefore be expected between 2030 and 2045.

One additional power tower type CSP plant similar to the Ivanpah plant would provide additional in-state capacity of 400 MW. This plant would supply 0.6 percent of electricity toward 2030 SB-100 goals and 0.3 percent of SB-100 2045 goals (2030 and 2045 SB-100 goals discussed in Current California Energy Mix and Future Expectations for SB-100 in Chapter 1). Additionally, a 400 MW installation could be paired with as much as 400 MW of 10 hour storage (4,000 MWh) which would provide a significant boast to storage capacity throughout the state (400 MW is around 10 percent of current storage capacity).

Areas for Advancement

The key challenges addressed are to find low-cost containment materials that have sufficient high-temperature strength and corrosion resistance to contain molten salt at 700˚C and/or low-cost noncorrosive fluids stable at such high temperatures, together permitting CSP power cycles with over 50 percent efficiency.

Technology Baseline, Best in Class

CSP systems can currently operate at 565˚C

Metrics and/or Performance Indicators

Corrosion Resistant Materials that can stand 700˚C while achieving 5 cents/kWh goal for CSP systems.

Other useful metrics include material strength and corrosion rate versus temperature. These will determine the fluid service life and material amounts needed for fluid containment and, therefore, the cost of the containers and systems.

Success Timeframe	Mid-term (3-5 years)
Key Published References	Glatzmaier (2011), DOE (2019a)
Correlation with Ongoing CEC efforts	2018-2020 EPIC Investment Plan – Initiative 4.3.1: Making Flexible-Peaking Concentrating Solar Power with Thermal Energy Storage Cost Competitive GFO-18-902 – Cost Share for Federal Funding Opportunities for Energy Research, Development, and Demonstration

Concentrated Solar Power Considerations

Provided here (in no particular order) are some of the notable considerations aligned with the CSP technology area. These considerations include opportunities, barriers, and potential related technologies for future advancement.

CSP can match peak load and provide ramping power due to its ties to TES. Dispatchability is a major feature of CSP when paired with TES. Additionally, TES systems typically have a longer duration of storage (>8 hours) and higher capacity than lithium-ion batteries combined with utility-scale solar PV. CSP systems designed with TES have the ability to generate, store, and dispatch energy when it is needed making solar power more reliable and consistent.

CSP systems require energy storage to be competitive with other renewable sources. Current CSP deployments with TES already provide more dispatchability and better ramping performance than other renewable sources. These additional services increase the value of CSP systems to the grid giving CSP a better value proposition than other lower cost renewable technologies.

The high costs of CSP systems are often prohibitive when compared directly to PV. CSP and solar PV are easily linked because they have the same source of power, but PV systems can produce similar amounts of energy at lower costs. Even with the additional flexibility and dispatchability offered when paired with TES, CSP is typically not valuable enough to outcompete solar PV. Since CSP vies for the same resources as solar PV, CSP may lose valuable land to lower cost solar PV projects.

The current market structure values variable PV over dispatchable CSP. While CSP provides the type of reliable and dispatchable energy that will be necessary for a fully low-carbon grid, the energy marketplace currently pays the lowest cost producers first. Until CSP's ancillary capabilities are valued, it will struggle to compete against wind, PV, and other low cost renewables.

The Low Carbon Fuel Standard (LCFS) offers CSP systems a pathway to commercialization. Renewable power that is shown to directly power electric vehicles (EVs) may be eligible for LCFS credits. Creating these direct charging networks would provide a way for more expensive renewable sources such as CSP to reach profitability faster. However, creating a structure that feeds energy from CSP systems directly to EVs would divert power from the electric grid.

PV can help drive down the price of CSP with hybrid systems. The blended LCOE of hybrid plants would be lower than that of CSP alone. However, in most cases, no significant technological synergy is considered. Instead, the two portions of the plants operate entirely separately.

Hybrid systems may also provide co-benefits to both PV and CSP. This concept is being tested at the first commercial CSP-PV hybrid contract. This contract was signed by Morocco's MASEN in early 2019 for an "800 MW" plant (approximately half PV and half CSP) called Noor Midelt, which is scheduled to begin operation in 2022 (NS Energy 2019). This project hopes that unspecified synergies will lower the overall LCOE of both systems.

California siting restriction have an outsized impact on CSP installations. CSP systems are more economical when installed at a large-scale. These large systems can only be constructed at sites with a lot of land and the ability to handle CSP infrastructure. These sites are uncommon, and future CSP installations may be limited if too many ideal sites for CSP systems are restricted to development.

Environmental concerns tied to land-use and concentrated sunlight impact CSP installations. Since CSP systems take up a lot of land in remote locations, there is a high chance these systems impact wildlife. Most recently, the Ivanpah facility in California ultimately had to be scaled back to avoid disturbing the habitat of the desert tortoise (Woody 2010). Land-use and the effect of concentrated sunlight on avian life will always be considerations for new CSP systems.

California has an opportunity to work with the World Bank, CSP industry, and grid experts to expand CSP development. Convening a symposium and deciding on the potential value and importance of CSP in California and southwestern United States would be a useful activity. CSP systems require large capital investments but have a wide range of interested parties around the globe that can be leveraged for both capital and expertise.

Focus on developing incremental technologies that improve CSP performance. The best way to evaluate next generation CSP is to continue to test the components of these systems. While an entire CSP system may not be able to be built in the next few years, the internal components can be improved, and the system concepts tested to continue to advance CSP industry experience.

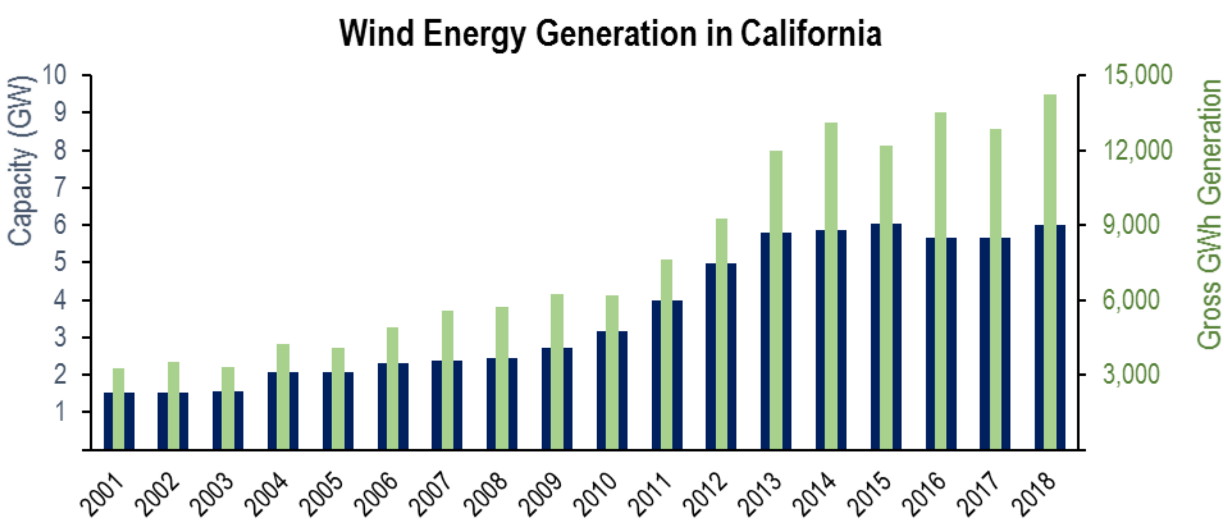
Land-Based Wind

Land-based wind represents one of the more established forms of renewable energy generation in the state. The majority of land-based Wind Resource Areas (WRAs) are currently saturated with older, smaller wind turbines. To restart growth of California's wind production, new resource areas located in regions with treacherous terrain and/or lower winds speeds must be accessed. Larger turbines that can reach higher elevations are a prominent technology that can achieve growth in undeveloped regions. Emerging manufacturing, transportation, and installation technologies offer a pathway to overcoming barriers preventing developers from building larger turbines in more remote areas.

Generation Trends

Starting in the 1980s, the first wind energy projects were installed in California. Like solar, wind has benefited from policies that have supported its continued development in the state. For instance, since California's RPS law was adopted in 2002, California's wind energy generation has more than tripled. Figure 6 shows the trends in wind energy prdouction since 2001. After a steady increase from the beginning of the century to 2013, the installed capacity of wind turbies has not significantly increased over the past several years despite changes in RPS goals.

Figure 6: Wind Energy Generation in California from 2001 to 2018



Source: California Energy Commission (2019e)

Resource Assessment

California's existing wind fleet primarily occupies six designated WRAs where both wind speed and grid access are ideal. However, these WRAs do not represent the only possible developments sites in the state. The California Wind Energy Association estimates that the state's near-term additional developable potential is approximately 2,000 MW (Rader 2016). Another opportunity exists at higher hub heights that can be accessed in the mid- to long-term with the taller towers and larger blades of advanced wind technologies. The National Renewable Energy Laboratory (NREL) estimates that at a 140-meter hub height, California's wind energy potential can be increased by almost 25,000 square miles to unlock an additional capacity of 128 GW (WINDExchange 2019).

Potential for Reaching SB-100 Goals

Using NREL's estimates at 140-meter hub heights, California has an estimated 301,000 GWh of electricity available from wind power if all potential capacity in the state was captured at 2018 capacity factors (supporting calculations in Appendix A). That amount of energy would fall just short of the total anticipated new renewable electricity requirement for 2045 based on SB-100 goals (326,000 GWh).

However, wind installations at 140-meter hub heights would provide electricity at much higher capacity factors (>40 percent) than current California installations and can be expected to raise the capacity factor seen throughout the state. Additionally, wind turbines ability to generate power at times when solar panels cannot make them an attractive addition to the California grid.

Cost Metrics

Wind is one of the cheapest forms of renewable energy, as it is a technologically mature form of renewable energy that has benefitted from incentivized development over the past decade. The LCOE for land-based wind from $0.029/kWh to $0.056/kWh unsubsidized, assuming a 20-year system life (Lazard 2018). Installed costs for onshore wind systems range from $1,150/kW to $1,550/kW (Lazard 2018).

Table 6: Land-Based Wind Power Cost Performance Targets

U.S. Department of Energy 2018 Budget Request				
	FY 2017	FY 2018	FY 2019	Endpoint Target
Land-Based Target	5.5 cents/kWh (exceeded at 5.2)	5.4 cents/kWh	5 cents/kWh	3.1 cents/kWh by 2030
Capacity Factor Target	TBD	TBD	TBD	TBD
California Energy Commission 2018 Update				
	2017	2018	2019	2030
Land-Based Wind	N/A	5.3 cents/kWh	6.3 cents/kWh	6.7 cents/kWh
IRENA Renewable Power Generation Costs				
	2017	2018	2019	2020
Land-Based Wind	6.3 cents/kWh	5.5 cents/kWh	4.6 cents/kWh	4.4 cents/kWh

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 of 5.6 percent; national capacity weighted average installed capital expenditures and operating expense values; 7.25 meter/second wind speed @50 meter hub height; and 25-year plant life.

Sources: DOE (2018a), Neff (2019), IRENA (2019)

Other Key Metrics

Onsite Installation Time and Cost

The costs of system installation often determine if a wind turbine is feasible for a developer to pursue. The installation of a wind turbine can take one to five days even after building the initial foundations and having all of the components on site. The total construction time varies based on a number of factors including vehicle availability and weather conditions. New technologies can consistently enable a shorter installation time by reducing the number of vehicles and labor hours required (Infinity Renewables 2016).

Capacity Factor

Based on 2018 generation data, the Capacity Factor for land-based wind turbines in California was 27 percent. In the U.S., new projects built between 2014 and 2016 achieved a capacity factor of 42 percent on average while projects build from 2004 to 2011 had an average capacity factor of 32 percent (IRENA 2019). These new projects have raised the total overall capacity factor in the United States to 34.6 percent in 2018 (EIA 2020). The lower capacity factors seen in California can be attributed to the use of older turbines and less productive wind resources than other regions of the United States.

Conversion Efficiency

Potential locations for new wind developments in California have lower wind speeds than the ideal sites for wind farms in the state which are already occupied by legacy wind power plants. Larger turbines with higher conversion efficiencies are able to make development in the new potential areas feasible and economical. The average efficiency of current utility-scale wind turbine is between 35 percent and 45 percent which is higher than legacy systems in California. Continued improvements to wind technologies can enable more turbines to achieve efficiencies of 50 percent.

Recommended Initiatives

The following charts describe the two recommended initiatives selected for land-based wind technologies. These initiatives focus on pathways to increasing deployment of larger turbines on rugged terrain by increasing conversion efficiency and lowering installation costs. Both initiatives drive down the LCOE of land-based wind energy and provide a way to increase the capacity factor which would also decrease variability.

Initiative LBW.1: Advance Construction Technologies for Land-based Wind Turbines

Description and Characteristics	Since California's preferred wind resource areas are already filled with wind turbines, new installations will have to occupy other, treacherous terrain at more remote locations. In addition, the current and projected future generations of wind turbines have larger, wider, longer, and heavier components that are difficult to transport to remote sites. Onsite assembly and manufacturing allow wind components to be broken up and transported in more manageable pieces. However, once transported to site, the assembly of wind components remains a challenge. A number of advanced construction technologies and techniques offer a way to facilitate onsite construction of tower structures and to lift and assemble turbine and blades in difficult settings. These technologies include advanced crane technologies, additive manufacturing (AM) techniques, and modified spiral welding. New crane technologies have the shortest time frame to commercial deployment. Two examples of potential new designs are cranes that can attach to the turbine towers and designs that can reach turbine locations and fit in small construction and installation areas. Other solutions that may be available in the long-term include telescopic towers and spiral welding. These technologies would reduce the need for large site equipment by enabling the incremental addition of new tower segments. AM is a technology that changes the process of producing concrete components by removing the need for larger preset equipment and materials.
Impacts	Advanced construction technologies and techniques can enable installation of wind turbines in areas not were not previously accessible or financially viable. This can unlock wind resources that are not currently accessible in California. Additionally, by lowering the amount of time it takes to assemble wind turbines, the cost of installation can be lowered. AM is advocated for its reduced tooling cost, quicker speed to market since there are less steps and reduction in waste and energy.
Estimated Potential Impact on SB-100	This initiative focuses on enabling technologies that decrease installation costs allowing for installations of larger wind turbines at more remote locations. To reach SB-100 goals with the same energy mix seen in California today, land-based wind will need to continue to play a large role in renewable energy production in the state (2030 and

	2045 SB-100 goals discussed in Current California Energy Mix and Future Expectations for SB-100 in Chapter 1). This initiative will enable access to areas with higher wind speeds which can allow turbines to produce at higher capacity factors than seen today in California. If wind continues to play a large role in renewable production in California, 2,600 new turbines would be expected by 2030 and 6,000 turbines would be expected by 2045. At maximum, this initiative can provide installation savings of $160,000 per turbine resulting in $416 million in savings by 2030 and $960 million in savings by 2045.
Areas for Advancement	Technologies and techniques that can improve onsite manufacturing and assembly include: Rough-Terrain Cranes; Turbine Tower Attached Cranes; Self-erecting tower/turbines (Telescopic towers); Additive Manufacturing (3D Printing) Techniques using Concrete; Automated Spiral Welding
Technology Baseline, Best in Class	$80,000 a day for Crane rental. Days to install can range 1-5 Days per Turbine for Onsite. Assembly depends heavily on location, number of pieces to lift, and size of turbine.
Metrics and/or Performance Indicators	Save 1 to 2 Days for Onsite Assembly ($80,000 to $160,000 on installation).
Success Timeframe	Near-term for Crane Technologies (1-3 years) Long-term for other Advanced Technologies (>5 years) (AM, Telescopic Towers, Onsite Welding)
Key Published References	Mammoet (2019a), Mammoet (2019b), ForConstructionPros.com (2019), Langnau (2019)
Correlation with Ongoing CEC efforts	EPIC 2018-2020 Investment Plan – Initiative 4.2.1 Advanced Manufacturing and Installation Approach for Utility-Scale Land-Based Wind Turbine Components GFO-19-302 – Advanced to Next-Generation Wind Energy Technology (Next Wind)

Initiative LBW.2: Demonstrate New Blades that Improve Conversion Efficiency

Description and Characteristics	On-land wind development in California is unlike any other state because of the age of the industry. As a result of decades of operation, most high wind, attractive wind development areas are already taken by less efficient machines that have lower capacity factors and operate more variably than modern wind turbines. For land-based wind development in California to continue to grow, greenfield project locations might be in low-wind speed areas. To access higher and more consistent wind speeds, larger turbines with taller towers provide one solution. These larger turbines will ideally generate electricity with less variability than current wind installations in the state. New blade materials can also decrease the variability of output from low-wind regions while increasing overall power output. These materials can reduce stress and extend the lifetime of blades, which are becoming physically longer and are being attached to larger rotors. Blades that are flexible and adaptable yet sturdy have the ability to increase economical production from wind in California, especially when combined with larger turbines. A subset of these blades that have a longer time frame for development are flexible blades that are able to handle variations in high wind speeds due to their ability to bend and twist passively to adapt to wind forces. The first testing of passively adapting blades is underway in Colorado by a German company. There is room for R&D from U.S. counterparts as well as these designs are developed further.
Impacts	Adaptable and flexible blade materials are able to operate in a wider range of wind conditions and dampen peak loads during times with highly variable wind speeds. The use of these blades will also increase the lifespan on blades and reduce maintenance costs. Since flexible blades increase power production, they may also enable smaller capacity turbines to be more economical.
Estimated Potential Impact on SB-100	An increase in converted energy for wind turbines can have two major impacts: higher capacity turbines or higher capacity factors. There is a negative correlation between these two metrics, so only one can be increased. In California, the variability of renewable energy production is expected to be a large problem so wind turbines with higher capacity factors will provide a greater benefit.

A 35 percent increase in capacity factor for wind turbines would raise the in-state capacity factor to 36.2 percent. Since this initiative has a long-term outlook, it will only impact 2045 SB-100 goals (2045 SB-100 goals discussed in Current California Energy Mix and Future Expectations for SB-100 in Chapter 1). If wind maintains its same percentage of California renewable energy production by 2045, over 17,500 MW of new wind energy capacity will be required between 2030 and 2045. An increase in capacity factor would lower this requirement to 13,000 MW. The difference in electricity production enabled by better blade materials in that scenario would be 10,700 GWh or 3.3 percent of SB-100 2045 goals.

Areas for Advancement	Development of improved blade materials that are more durable and can stand higher local stresses. Flexible blades that can bend and twist passively to adapt and produce more power.
Technology Baseline, Best in Class	Average capacity factor of California wind energy farms in 2018 was 27 percent. Converted energy of a utility-scale turbine is between 35-45 percent.
Metrics and/or Performance Indicators	Deployment of new blade materials should contribute to overall increases in the capacity factor of individual turbines to 35-50 percent and push the overall capacity factor in California above 30 percent on average. For flexible blades in the long-term, expect to see a converted energy rate near 50 percent. Preliminary modeling shows these blades can increase converted energy by 35 percent over current designs.
Success Timeframe	Mid-term for improved blade materials (3-5 years) Long-term for flexible blades with significant material and design changes (>5 years)
Key Published References	Cognet et al. (2017), Yirka (2017), Fraunhofer IWES (2019), Richard (2018), Hingtgen et al. (2019)
Correlation with Ongoing CEC efforts	EPIC 2018-2020 Investment Plan – Initiative 4.2.1 Advanced Manufacturing and Installation Approach for Utility-Scale Land-Based Wind Turbine Components

Land-Based Wind Considerations

Provided here (in no particular order) are some of the notable considerations aligned with the land-based wind technology area. These considerations include opportunities, barriers, and potential related technologies for future advancement.

Old turbines limit accessibility to land-based wind resources in California. As previously mentioned, California has installed wind energy systems for multiple decades. While this has been great for the maturation of the wind industry, it has resulted in a significant amount of space being occupied by less efficient, legacy wind turbines.

There are 2,600 Kenetech KCS 56-100 turbines in use in California making it the most common turbine in the state. The KCS-56 100 has a capacity of 100 kW, and some other turbines currently deployed in California have an even lower capacity (Hingtgen et al. 2017). The saturation of California's WRA with older models limits new developments with higher efficiency turbines which could increase renewable power generation in the state.

Permitting and land use restrictions are limiting further development. Multiple municipalities have banned the development of wind turbine projects due to environmental, community, and scenic aesthetic concerns. National plans such as the DCREP limited potential locations for wind resource development as well and added more permitting challenges. These additional barriers are both limiting locations for development as well as making development more time consuming in areas where wind development is allowed.

The environmental impact of wind turbines is heavily scrutinized. Average fatality rates for birds due to wind turbines range from three to six birds per MW per year nationwide. With California's wind capacity being around 5,500 MW, an estimated 17,000 to 34,000 birds are killed in the state by wind turbines per year. The amount of fatalities by turbine varies with turbine age, height, and blade length. However, the exact effects of both turbine design and fatality mitigation strategies on bird and bat fatality numbers are currently uncertain. (AWWI 2018).

There are social concerns such as sound and aesthetics that hamper wind development. The social impacts of wind turbines center around public health and community concerns. Locals living near both near and old model wind turbines have complained about sound and vibrations disrupting their living. Adding in complaints about aesthetics, backlash against wind turbines has led to several California counties banning their development within municipal borders (Roth 2019). Working with communities on limiting the potential health impacts of wind turbines with proper siting and continuing research on this impact is necessary to ensure communities have the best information accessible so they can work with developers.

Manufacturing of many wind components is not local to California. Limited local production of wind turbine components in California is causing the cost of system development to rise. While California is currently home to 12 utility-scale wind component manufacturing facilities, larger components such as blades and towers have to be transported into the state which increases the capital costs. A commitment to developing more utility-scale wind projects in and around the state could potentially attract new manufacturing growth, which is still seen domestically, to California.

New wind resource areas for development are not grid interconnection. Ideal wind resources in California can still be limited by the cost of grid integration, especially if the development site is far from currently existing transmission lines. Due to California's WRAs being saturated, new potential sites without wind development will require new infrastructure to connect to the grid.

Future advances in wind energy will require taller towers and larger blades. Component sizes will increase as wind turbines are designed with higher hub-heights to access faster wind speeds and unlock higher capacity factors. The transportation cost of these components will rise with turbine size increases as well. These cost increases will raise the LCOE of wind energy systems, which are currently among the lowest from all renewable sources.

Energy storage as well as advanced system design can increase the dispatchability of wind resources. New wind turbines are designed to operate at higher capacity factors with a lower rated capacity than technically possible to maximize energy output and reduce variability on the grid. Additional adaptations such as combination with energy storage and use of generators that can double as spinning reserves can increase the flexibility and dispatchability of wind energy systems to increase the overall value of wind energy to the grid.

Radar for wildlife mitigation has been funded in the past and should continue to be advanced. Wind energy farms negatively impact wildlife directly through fatal collisions and indirectly through the loss of a species' normal habitats or migration paths. However, the positive impact wind turbines play in addressing detrimental effects of climate change should be balanced with their other environmental impacts. Climate change poses a greater threat to birds and other wildlife in the long-term (Audubon 2019). Careful siting and specific location guidelines can help direct turbine installations into environmentally optimal areas. Additionally, radar systems exist that can detect birds and bats within several miles of wind turbines. Further advancement of this technology and coupling with wind turbine operations can protect wildlife.

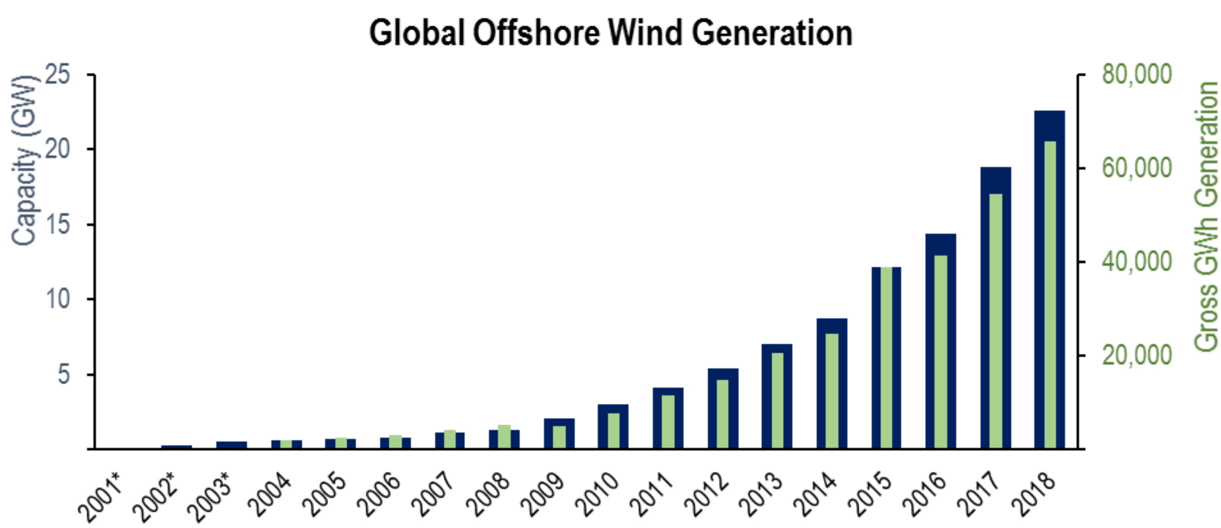
Offshore Wind

The development of offshore wind would provide a new resource for California to develop in order to meet SB-100 goals. Offshore wind is in the early stages of development along the eastern coast of the United States. Expanding the offshore wind industry in California requires investments in new port infrastructure, manufacturing hubs, vessels to install and maintain offshore wind systems. An added benefit of this investment would be numerous jobs that span the industry's supply chains and support services.

Generation Trends

Recently, offshore wind has seen its first deployments in the United States on the east coast. However, deploying wind energy on California's coast offers more challenges. On top of the cost and environmental factors, production challenges for California's coast are unique due to its deep-water coasts and need to adapt port infrastructure to deal with offshore turbine manufacturing and deployment. Potential deep-water locations will require the use of floating platforms, which have yet to be demonstrated in the United States and have limited deployments in the world. However, with global manufacturing and deployment infrastructure for offshore turbines in early stages, there is a unique opportunity for California to become a global leader in the emerging floating offshore wind industry.

Figure 7: Global Offshore Wind Energy Generation from 2001 to 2018



Sources: Musial et al. (2019), EWEA (2011), IEA (2019)

**** Unknown Value for Gross GWh Generation***

Resource Assessment

While land-based wind energy is well established in the state of California, offshore wind systems present a new opportunity for renewable energy development. Offshore wind energy has a high potential for development in California as the coast of California has many ideal wind resources. It is projected the technical capacity of wind resources off of the coast of California is 160 GW (Musial 2016). Only 9 GW of that total is located in areas with water depths that are suited for fixed bottom deployments (<60 meters). Both deep and shallow water potential can be unlocked if the right stakeholders are involved from the outset. These stakeholders include state and federal agencies, port managers, wind developers, grid operators, and the military.

Potential for Reaching SB-100 Goals

If the entire technical capacity of offshore wind was captured, California could produce an estimated 561,000 GWh of electricity which is 180 percent of 2045 SB-100 goals. The estimate assumes an overall capacity factor of 40 percent for all offshore wind production. If just areas where fixed bottom deployments could be utilized are considered, 32,000 GWh of electricity could be produced or roughly 10 percent of anticipated 2045 SB-100 renewable electricity goals (supporting calculations in Appendix A). Offshore wind installations would feature high capacity and high capacity factor wind turbines that are able to produce energy that complements solar installations.

Cost Metrics

For offshore wind, assuming a 20-year system life, current LCOE ranges from $0.062/kWh to $0.121/kWh while installed costs range from $2,250/kW to $3,800/kW (Lazard 2018). Similar to Solar PV, these cost estimates sit below the estimates from both IRENA and DOE. There is a large uncertainty in offshore wind pricing due to limited deployments globally and a low overall level of technical maturity. This puts offshore wind in the bracket of more expensive forms of renewable energy. However, offshore wind is a valuable resource due to higher wind speeds, leading to higher capacity factors.

Table 7: Offshore Wind Power Cost Performance Targets

U.S. Department of Energy 2018 Budget Request				
	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
IRENA Renewable Power Generation Costs				

	2017	2018	2019	2020
Offshore Wind	12.7 cents/kWh	12.6 cents/kWh	17.2 cents/kWh	15.1 cents/kWh

Sources: DOE (2018a), IRENA (2019)

Other Key Metrics

Offshore Vessel and Barge Costs:

Table 8. Offshore Wind Turbine Vessel Rental Cost

Vessel Type	Daily Rate ($)
Turbine Installation Vessel	150,000 – 250,000
Jack-up Barge	100,000 – 180,000
Crane Barge	80,000 – 100,000
Cargo Barge	30,000 – 50,000
Tugboat	1,000 – 5,000

The average time in vessel days for foundation construction for projects between 2014 and 2017 is 2.56 days, leading to an average total vessel cost of $362,560 – $592,800 per foundation (Lacal-Arántegui et al. 2018).

Floating technologies have different associated transportation and installation costs than fixed-bottom offshore deployments because they do not require construction of a foundation. A tugboat along with one other vessel to attach mooring lines may be all that is required to deploy a floating system (Douglas Westwood 2013).

Floating platform design also impacts the type of vessels required for installation. The spar-buoy design can be assembled offshore and requires heavy lift cranes and stabilization vessels for construction. Semi-submersible designs such as WindFloat (Portugal) can be assembled quayside and towed to project sites.

On-land Transportation:

The transportation of various wind turbine components are limited due to their size, which makes it more difficult to navigate through certain areas. Industry leaders have adopted limits in component size to attempt to facilitate easier travel, shown in Table 9. Port infrastructure would need to be able to receive components of this size or be able to manufacture components of this size or larger for offshore development.

Table 9. Wind Turbine Transportation Sizing Limits

Component	Conventional Size Limit	System Barriers due to Limit

Tower	Length: 52 to 63m	No Effect
	Width: 4.3 to 4.6m Diameter	80 – 160m Turbines Turbines larger than 1.9 MW
	Weight: 80,000 lbs (truck)	No Effect
Blade	Length: 52 to 63m	2.2 – 3.8 MW
	Width: 4.3 to 4.6m Diameter	4.3 – 7.3 MW
	Weight: 80,000 lbs (truck)	No Effect
Nacelle	Length: 11.7m	No Effect
	Width/Height: 4.3 to 4.6m	No Effect
	Weight: 80,000 lbs (truck) 225,000 (rail)	3 – 5 MW

Source: Mooney and Maclaurin (2016)

Supplement: Wave Energy

One additional source of renewable energy that could contribute at the utility-scale in California is hydrokinetic technologies capturing wave energy. There is some debate on the technical maturity of wave energy conversion technologies due to limited global demonstrations and no current utility-scale deployment. With a number of possible designs still being tested, the future of wave energy is promising but unclear.

There is an opportunity from wave energy systems to benefit from hybrid deployments with other offshore technologies because all offshore energy technologies require similar vessels for installation and infrastructure for interconnection to the grid on-land. Additionally, wave energy faces many of the same environmental and permitting concerns as floating wind power such as impact on shipping lanes and military activities. A hybrid floating offshore wind turbine and wave energy system provides a pathway to faster deployment and lower LCOE for wave energy systems.

Wave Energy Resource Assessment

Along California's 1200 kilometers of coastline, it is estimated that the theoretical deep-water wave power flux is 37 GW (EPRI 2007). The technical potential is estimated at 20 percent of the theoretical limit or 7.4 GW. Assuming wave energy achieves a 20 percent capacity factor, the total available energy from waves is 13,000 GWh in California or enough to supply 4 percent of SB-100 2045 goals (supporting calculations in Appendix A). This estimate is highly uncertain since few assessments are available for California's wave resource and capacity factor and technical feasibility percentages may be lower than actually attainable.

Wave Energy Cost Metrics

In 2014, IRENA offshore wave energy demonstration projects of 10 MW systems produced energy at a cost between 0.330 and 0.630 Euros/kWh (roughly 36.6 – 69.9 cents/kWh). The projected LCOE at that time for a 2030 system deployed at a 2 GW scale was between 0.113 and

0.226 Euros/kWh (12.5 – 25.1 cents/kWh). The cost of installation, operation, maintenance, and mooring is 41 percent of lifetime costs for wave energy systems (IRENA 2014).

Recommended Initiatives

The following charts describe the two recommended initiatives selected for offshore wind technologies. These initiatives focus on pathways to develop and deploy floating offshore wind technologies. All three initiatives take advantage of research and development occurring throughout the world on floating system designs and emphasize scale-up. The first two initiatives are necessary to enable California to have an in-state presence in manufacturing and deployment. The last initiative positions California to pursue early stage development of wave energy systems.

Initiative OSW.1: Pilot Demonstration of Floating Offshore Platform Manufacturing

Description and Characteristics	Floating offshore wind turbines place a wind turbine on a floating platform that is anchored to the seabed with cables. These systems are necessary to access wind resources in areas with water depths greater than 50 meters. Fixed bottom structures that are most commonly used for offshore wind development cannot be used in greater than 50-meter water depths due to the engineering complexity and cost. About 96 percent of California's offshore wind resources are located in deep waters (>60 meters) off the California coastline and are therefore best suited for floating platforms. Large-scale and long-term development of offshore wind resources in California will therefore require use of floating platforms. There are currently a few demonstrations of floating offshore turbines in progress globally including one in Scotland (Hywind) and another funded (WindFloat in Portugal). The early-stage development of floating offshore wind technology means there an opportunity to become a global leader in large-scale manufacturing and production of floating offshore turbines. This initiative recommends that California develops local manufacturing capabilities to enable large-scale deployment of a fully demonstrated floating offshore wind structure. The selection of a specific floating offshore design depends on the corresponding port location selected for assembly and deployment of these systems. The scale-up, siting, and logistics of such a manufacturing operation requires significant R&D.

Impacts

California has an opportunity to become one of the first global manufacturing centers for offshore floating wind infrastructure. The selection of demonstrated floating offshore designs eliminates risk associated with new testing and can attract established companies in the floating offshore market to move their operations to California or partner with California manufacturers.

Developing an offshore wind manufacturing industry in state will decrease the costs of transportation of wind turbine components and create jobs within the state. California is also positioned to become a leader across the Pacific Ocean as no floating structure manufacturing or deployment exists from the U.S. to Asia.

Estimated Potential Impact on SB-100

Recent reports declare it feasibile for California to install 18 GW of Offshore Wind power by 2045. This initiative will be necessary to enable this scale of installation in California. At estimated capacity factors for offshore wind turbines of 40 percent, this initiative can unlock 63,000 GWh of new renewable electricity. 18 GW of offshore wind energy would provide 19 percent of electricity needed to reach SB-100 2045 goals (2045 SB-100 goals discussed in Current California Energy Mix and Future Expectations for SB-100 in Chapter 1).

Areas for Advancement

This initiative can advance the California market readiness of demonstrated floating platform designs. However, selection and manufacturing of floating platforms will have to be done with heavy consideration given to the size of the port, the location of the manufacturing plant, and the transportation infrastructure. There is an opportunity to pair port development with manufacturing infrastructure as well.

Technology Baseline, Best in Class

Non-local manufacturing can add several more days of vessel transportation time resulting in hundreds of thousands of dollars of extra expenditure per floating turbine.

Metrics and/or Performance Indicators

Vessel transportation time less than 1 day for floating offshore California installations.

Success Timeframe

Long-term (>5 Years)

Key Published References	Gerdes (2018), IRENA (2016), James and Ros (2015), Musial et al. (2017), Collier et al. (2019)
Correlation with Ongoing CEC efforts	The Bureau of Ocean Management-California Intergovernmental Renewable Energy Task Force

Initiative OSW.2: Design Port Infrastructure to Deploy Floating Offshore Wind Technologies

Description and Characteristics	Due to the large size of offshore wind turbines, large cranes and ample space are required at ports to construct, pre-assemble, and eventually tow turbines into the ocean. Currently, no port in California has the ability to assemble offshore turbine components and few ports are able to accommodate the necessary equipment. There are currently six ports in the state suitable for conversion and improvements: Humboldt Bay, San Francisco Bay, Hueneme, Long Beach, and San Diego. Humboldt Bay is considered the most promising location. Locating and retrofitting a port so it is able to load an offshore wind turbine will be necessary to install any offshore wind turbines in California. Innovative port infrastructure design is required to enable the deployment of floating platform(s) in California. Design considerations include the location and type of floating platform used. Different assembly, staging, and processes are required to construct and assemble different types of floating platforms. Certain designs may not be possible to be deployed at certain ports as well due to water depths and other logistics. If possible, ports should not be designed to only handle a single offshore design to limit technology lock-in.
Impacts	Port development is necessary to unlock the potential of local manufacturing by providing an outlet to assemble and transport turbine components to offshore locations. Without a local port, offshore development will depend on the availability of parts from other states or countries which would introduce economic and logistic challenges to offshore projects. Additionally, upgrading a port would provide a bevy of jobs and a stimulus to the local economy.

Estimated Potential Impact on SB-100	This initiative is tied directly to initiative OSW.1. Without each other, these initiatives will not be able to enable the 18 GW of offshore wind energy declared feasible for California. The Estimated Potential on SB-100 is identical for this both this initiative and OSW.1 (see above for details).
Areas for Advancement	This initiative involves designing port infrastructure to be able to deploy floating offshore platforms that can be constructed locally. It is a critical enabling step to unlock production from offshore wind turbines. Improvements to these ports could include specially designed cranes and quayside space customization. Other improvements will be necessary based on the specific transportation and assembly requirements of the port.
Technology Baseline, Best in Class	Even with local manufacturing, a well-designed port is necessary to deploy floating offshore wind turbines. Without an acceptable in-state port, turbine installation requires several more days of vessel transportation time resulting in hundreds of thousands of dollars of extra expenditure per turbine.
Metrics and/or Performance Indicators	Vessel transportation time less than 1 day for floating offshore California installations.
Success Timeframe	Long-term (>5 Years)
Key Published References	Porter and Phillips (2016), Collier et al. (2019)
Correlation with Ongoing CEC efforts	The Bureau of Ocean Management-California Intergovernmental Renewable Energy Task Force

Initiative OSW.3: Integrate Wave Energy Systems with Floating Offshore Platforms

Description and Characteristics	Wave energy technologies (hydrokinetic) harness the potential energy from waves to generate power. The development of wave energy technologies has advanced to a point where devices are being commercially field tested around the world. While the cost of

electricity from wave power remains high, a specific synergy exists between floating offshore wind systems and wave energy devices.

Both technologies utilize similar infrastructure for deployment and eventual transmission of offshore power. The combination and integration of wave energy devices into the floating substructure offers a path to faster deployment and lower costs for wave power systems.

Impacts

Combined wave and wind systems will lower the overall cost of deployment of the hybrid system and will therefore drive down the combined cost of electricity. While wave systems may have to be adapted for integration, further testing and deployment will help advance the wave industry as a whole. Synergy between the devices can help address environmental concerns, offshore transmission and integration concerns, and offshore infrastructure concerns for both technology areas.

Estimated Potential Impact on SB-100

Wave energy could provide a limited amount of electricity along with deployment of offshore wind. Wave energy systems vary in their installed capacity (and anticipated capacity factors) due to a lack of consensus and development of commercial systems. Sizes from 500 kW to 7 MW have been proposed.

For this estimate, an average capacity of 1 MW and 20 percent capacity factor will be assumed for each wave energy system. Additionally, the same feasible potential of 18 GW of Offshore Wind Energy that is possible in California by 2045 will be used. The last assumption is the average Offshore Wind Turbine capacity is 8 MW. The resulting estimated impact of hybrid wave energy systems is an increase of 3,900 GWh or 1.2 percent of SB-100 2045 goals (2045 SB-100 goals discussed in Current California Energy Mix and Future Expectations for SB-100 in Chapter 1).

Areas for Advancement

Wave energy systems are not typically designed to be hybridized with other components. For this initiative, the wave systems will have to be flexible and adaptable to allow for integration into the floating wind substructure which will be the primary concern in the eventual deployment. This initiative will also involve offshore interconnection and integration of electrical energy from separate devices.

Technology Baseline, Best in Class	LCOE estimated at 30-40 cents/kWh for wave energy systems and 17.5 to 30 cents/kWh for floating offshore wind turbines. Installation, operation, maintenance, and mooring costs represent 41 percent of lifetime costs.
Metrics and/or Performance Indicators	LCOE less than 20 cents/kWh for wave energy systems that are synergistic with offshore floating wind structures. Floating offshore wind systems should achieve costs around 7.5 cents/kWh.
Success Timeframe	Long-term (>5 years)
Key Published References	IRENA (2014), OES (2018), Musial (2019)
Correlation with Ongoing CEC efforts	The Bureau of Ocean Management-California Intergovernmental Renewable Energy Task Force

Offshore Wind Considerations

Provided here (in no particular order) are some of the notable considerations aligned with the offshore wind technology area. These considerations include opportunities, barriers, and potential related technologies for future advancement.

Offshore wind turbine is one of the most expensive forms of renewable energy. These installations are so expensive due to the high capital costs of transportation and the lack of offshore systems in development. The operational and maintenance costs of these systems are also high due to their offshore location.

California needs to develop the infrastructure to manufacture an entire offshore turbine in state. Due to the size of the structures necessary for offshore wind turbines, it is typically prohibitively expensive or logistically impossible to transport turbine components from manufacturing locations that are not next to a deployment port. An in-state supply chain near a California port that can deploy offshore turbines would enable an offshore wind industry and eliminate the need to ship turbines from other states or countries.

Various different groups and entities will challenge the development of offshore wind systems when they are ready for demonstration. The effect of these systems on marine life as well as their aesthetic impact could pose limits on development locations. Cooperation with the military on developments will also be necessary to ensure that wind turbines do not interfere with their operations and goals in the region.

Offshore resources are closer in proximity to California's largest load generating areas than their land-based counterparts. This limits the amount of transmission infrastructure required to reach high load areas which improves the expected economics of offshore developments. However, some of the benefits of less infrastructure are offset by the high cost and safety concerns associated with water-based electrical systems.

The 2020 BOEM Auction is important for seeing future of Offshore Wind Energy. The Bureau of Ocean Energy Management (BOEM) is a government agency responsible for leasing areas within the U.S. Outer Continental Shelf for energy development. According to the BOEM's Budget Justifications for Fiscal Year 2020, there will be two leases sales conducted in FY 2020, one in the Atlantic offshore New York and one in the Pacific offshore California. Additionally, the BOEM has requested budgetary funding in order to hold one additional renewable energy lease auction per year (DOI 2019). In 2016, the BOEM published a report on the offshore wind potential in California (Musial et al. 2016). The agency found six locations in California that are best suited for an offshore wind farm, including Channel Islands, Morro Bay, and Humboldt Bay. The six sites have the potential to produce over 16 GW of wind power.

Fabrication and installation studies should be conducted in conjunction with develop of existing floating structures. Research into the unique challenges of fabricating, installing, and maintaining floating offshore wind turbines is necessary for taking advantage of the state's large offshore wind power potential. Unlike the shallow-water wind farms located on the East Coast, future wind farm sites in California will likely be located in depths of up to 500 meters. The DOE published the National Offshore Wind Research and Development Consortium in 2018, which detailed the areas of research necessary for developing offshore wind farms in the Pacific (NYSERDA 2018). The report also suggests that offshore wind technology presents an opportunity for previous employees of the offshore oil and gas sector to provide their unique knowledge to this growing sector. There is precedent for taking examples from the offshore oil and gas sector, as demonstrated by the vertical floating buoy turbines developed by the Norwegian company Equinor (Equinor 2019).

Fixed-bottom deployments should not be overlooked in California. Opportunities to develop fixed-bottom offshore wind farms in California should be considered due to its potential to increase the state's wind power production. While there is great potential for offshore wind farms in California, so far all prospective projects involve floating technologies due to the nature of California's coast, which exhibits a sharp plunge in the continental shelf relatively close to California's shore (NRDC et al. 2019). As an example, the sites under consideration by the BOEM to be leased to offshore wind farms are all located in deep water. The Humboldt Bay area ranges in depth from approximately 500 m to 1100 m and the Morro Bay ranges from 800 m to 1000 m (Trident Winds LLC 2016]

Artificial Intelligence systems can improve locating and siting deployments. Artificial intelligence systems can be effectively utilized during the planning process for offshore wind farm projects. A research project sponsored by the Engineering and Physical Sciences Research Council in the United Kingdom is currently testing the use of robotics and artificial intelligence technologies for mapping, surveying, and inspecting of offshore wind farms (ORCA Hub 2019). The goal of the project is to lower the operation and maintenance costs associated with offshore wind, the majority of which is due to the cost of transporting engineers and technicians to the wind farm site safely.

As Offshore wind systems are developed, deep water storage systems should be considered to further improve integration of offshore wind onto the grid. Integrating offshore wind farms with energy storage would help overcome the hurdle of intermittent energy supply, an issue that exists with many forms of renewable energy. According to the *Journal of Physics*, on-board energy storage would increase the monetary value of a wind turbine as a result of the increase in overall power quality and reliability (Buhagiar 2019). One possible method of energy storage includes a system designed by Buoyant Energy which consists of a floating reservoir that sinks and floats to charge & discharge, although the project is currently still in the theoretical phase (Klar et al. 2019). Other methods include a Compressed Air Energy Storage System, several of which are currently in operation (Manwell and McGowan 2018), and hydrogen storage. The traditional Pumped Hydro Storage System method, typically used on land and in mountainous regions, has been proposed by several countries for use in offshore wind farms. There is currently only one offshore example, a 30 MW capacity system located in Japan.

Monitoring of birds and other marine life needs to occur for offshore wind projects. A major concern of offshore wind farms is the risk of birds and bats colliding with the turbines or the indirect consequences of wind farm construction taking place within their migratory path. The BOEM is conducting research with the University of Rhode Island at the nation’s first offshore wind farm. The study involves tracking the movement of birds and bats fitted with nanotags. The tracking devices are installed on the foundations of the wind turbines (BOEM 2019). The goal of the project is to understand how the animals respond to the presence of the operating wind turbines. The data will be used for future offshore wind farm project planning and risk assessment conducted by the BOEM.

Offshore wind projects can maximize output by incorporating big data, artificial intelligence research, and hydrogen production. The Energy Commission can research ways to build upon DOE and NREL’s present programs in developing commercially efficient ways to electrolyze saltwater near floating offshore wind turbines powered by its generated electricity. Another potential action is to determine the cost-effective supply chain for offshore wind produced hydrogen to reach the State's existing hydrogen users.

Big Data and the Internet of things (IoT) can be used to record more data and affordably capture, process, store, manage and report useful findings from the data. Further, artificial intelligence is able to detect 'patterns' and to enhance the data in a manner that is far more sophisticated than humans. Big Data is being discussed in Europe in nearly all aspects of the offshore wind arena along with claims that it could enhance efficiency and offshore wind farm power output by an additional 20 percent. This is the time to understand how Big Data, IoT and artificial intelligence can be incorporated into California's offshore wind sector. This long-term project affects grid operators, offshore wind developers/owners, utilities, and California ISO operators.

Remote monitoring via drone inspection will save money and increase efficiency after installation of systems. Operations and maintenance account for 25-30 percent of the total lifecycle costs for offshore wind farms and represents a major hurdle for the offshore wind industry (Röckmann, Christine et al 2017). A study published in the Netherlands, where several offshore farms are currently operating, estimates that operations and maintenance technological advancements will reduce the number of required site visits from five per year to three per year (Röckmann, Christine et al 2017). Offshore turbine site visits are not only costly but can be hazardous for technicians working in rough weather conditions. Drones were successfully used to inspect the support structures and welds at the US's only wind farm in Block Island, Rhode Island in 2018 (Lillian 2018).

Projections for Offshore Wind Costs may be erroneous due to a lack of consideration for rapid advancement. There is a clear role for the Energy Commission to support the development and testing of new technologies and infrastructures. The Energy Commission could also play an important role in funding studies to evaluate potential sites, port infrastructure and manufacturing needs, and the environmental impacts of offshore wind deployment. Additionally, public outreach and stakeholder engagement are critical to ensure that local communities will encourage new development. With consistent support and investments, it is very likely that the necessary supporting infrastructures and supply chains will be developed and that the overall cost-competitiveness of offshore wind power will improve.

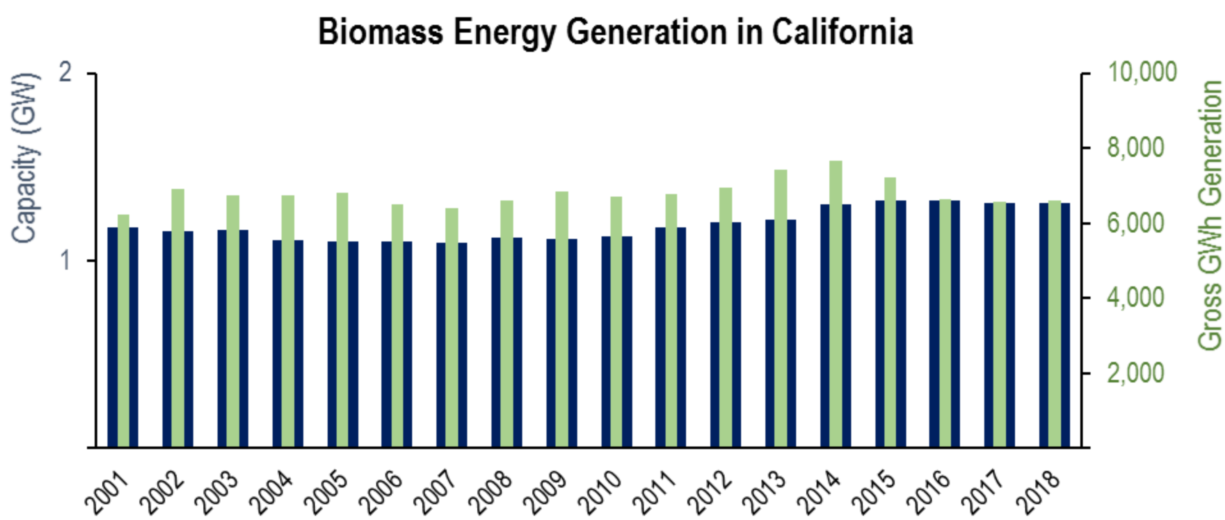
Bioenergy

Bioenergy generation utilizes existing waste as a form of electricity production. Common sources of biomass feedstock come from either municipal waste, agricultural waste and residue, and forest residue and thinnings, which produce energy by burning them directly or by utilizing them to produce biogas and syngas. By focusing initiatives on improving the yield and quality of biogas and syngas, these two fuels can achieve greater market acceptance and integration into the California energy mix.

Generation Trends

Bioenergy in California is one of the older operating renewable sources in the state and has a wide variety of associated technologies and feedstocks. The diversity of bioenergy is both a challenge to integrate into systems and an opportunity for expansion. Traditionally the most used feedstock for bioenergy plants is municipal solid waste (MSW) which is burned for power production. The decommissioning of several biomass plants with woody feedstocks has counteracted a number of new landfill gas and digester gas facilities to keep the production in the state relatively even over the last decade. Figure 8 shows the electricity production from bioenergy in California that produces less than three percent of the in-state generation and its share has decreased over the last years.

Figure 8: Biomass Energy Generation in California from 2001 to 2018



Source: California Energy Commission (2019f)

Resource Assessment

Feedstocks for bioenergy systems are very diverse and come primarily from agriculture, forestry, and municipal solid waste (MSW). The technical electricity potential of these products is 35,000 GWh or enough to support 4,650 MW of capacity (Williams et al. 2015).

Potential for Reaching SB-100 Goals

The above assessments anticipate a capacity factor of 85.9 percent. This estimate is much higher than the 52.9 percent capacity factor seen in California in 2018. A more conservative estimate can be calculated by multiplying the 2018 capacity factor by the technical electrical capacity (4,650 MW) provided above. The resulting electricity generation possible from bioenergy if the entire technical capacity is captured is then 21,500 GWh which would be enough electricity to provide 6.6 percent of 2045 SB100 goals (supporting calculations in Appendix A).

While bioenergy has one of the lower technical potentials of the renewable resources presented in this roadmap, it is uniquely positioned to offset fossil fuel usage with biogas and combustion products that can be dropped into fossil fuel setups. The 21,500 GWh of electrical potential would offset roughly 24 percent of 2018 natural gas usage and provide many of the same fast ramping capabilities as natural gas systems.

Cost Metrics

There are a variety of bioenergy technologies that fall into two major pathways for production: direct combustion of biomass and combustion of biomass derived gases. One of those gases, biogas, is generated from digesters and landfills among other sources. Producer gas can be generated through pathways such as gasification and pyrolysis. Biogas and other producer gases can be upgraded to renewable natural gas (RNG) which has a high methane content. The cost of some of the most common bioenergy technologies are given below.

Table 10: Cost Range and Estimated Range for Common Bioenergy Conversion Systems

NREL Annual Technology Baseline Projection				
	2017	2018	2019	2030
Bioenergy (unspecified technology)	11.3 cents/kWh	11.8 cents/kWh	12.1 cents/kWh	12.1 cents/kWh
California Energy Commission 2018 Update				
	2017	2018	2019	2030
Bioenergy (combustion)	N/A	15.9 cents/kwh	15.9 cents/kWh	16.6 cents/ kWh

* NREL Annual Technology Baseline does not factor in costs of building new lines for transmission and interconnection.

Sources: NREL (2019), Neff (2019)

Other Key Metrics

Cost of Syngas Production

While producer gas is readily producible using existing biomass processing methods, it is generated with varying degrees of quality due to contaminants in the conversion process. The cost of producing syngas (cleaning producer gas) to meet fuel purity standards for electricity generation is 23 cents/kWh. Lower costs syngas production should approach a price range between 6-20 cents/kWh.

Biogas Production from Feedstock

Biogas is primarily produced as biomass decomposes into a gaseous form. It is a natural process that is driven by technologies and processes to increase efficiency and the amount of biogas produced. Feedstocks used to produce biogas include food waste, waste water treatment plant (WWTP) sludges, dairy waste, and other organics. Food waste in particular has around three times the potential for methane production when compared to biosolids. Yields from anerobic digestion of raw food waste can be as high as 3,200 standard cubic feet of methane per ton (Kuo and Dow 2017). The figure will vary widely based on feedstock. New processes to pretreat feedstocks prior to biogas production can increase yield by 75-80 percent.

Sludge Disposal Costs

Waste sludges remain as a byproduct from biogas production which need to be disposed of. Tipping fees can vary widely based on time of year and the weather but can be estimated at between $20 and $50 a ton (Castellon 2015). New technologies to treat feedstocks before production can reduce sludge disposal costs by 25 percent.

Recommended Initiatives

The following charts describe the two recommended initiatives selected for bioenergy technologies. These initiatives focus on pathways to increase production of biogas and syngas which can be converted into electricity. As a plug-in replacement for natural gas, these biomass-derived gases serve a unique purpose in providing a bridge fuel as California transitions to a renewable economy. Additionally, using this gas in existing natural gas infrastructure allows for the same fast ramping capabilities which are so important to handle rapid load changes associated with mass variable renewable deployments.

Initiative BIO.1: Improve Cleaning Methods to Produce High Quality Biomass-Derived Syngas

Description and Characteristics	Synthesis gas (syngas) derived from biomass feedstocks is a potential source of clean, renewable fuel for electricity generation. Syngas can be produced from wet and/or dry biomass via thermochemical processes such as gasification (traditional, supercritical water gasification, steam hydrogasification, etc.); pyrolysis (fast/slow, catalytic, torrefaction at lower temperatures, etc.); and hydrothermal processing. The yields and purity of syngas produced by these methods varies considerably; some produce valuable oil or solid products in addition to gas. The raw gas contains varying amounts/types of contaminants (e.g., particulates, tar, alkali metals, and chlorine, nitrogen, sulfur compounds) depending on the biomass feedstock, process used, operating temperatures, and other parameters. Regardless of technology, raw biomass producer gas must be cleaned to meet fuel purity requirements for electricity generation. Producer gas cleaning has significant technical and economic challenges. While advances have been made, removing contaminants remains expensive and can require multiple techniques, depending on end use. Tar and ammonia removal are most problematic; catalytic removal has been promising but suffers from high cost, catalyst accessibility and fouling/deactivation. Catalyst application has scale-up issues related to temperature and pressure, impurities, fly ash, and catalyst destruction. Research areas could include lower-temperature catalysts, biomass ash catalysts, reduction of tar reformation, resolving scale-up issues, and exploring pretreatment processes such as thermal hydrolysis to reduce downstream product contaminants.
Impacts	Potential for higher yields and heating value of syngas; higher purity, lower-cost syngas with greater market acceptance for fuel gas production.
Estimated Potential Impact on SB-100	Syngas does not currently supply utility-scale energy to the California grid. This initiative is meant to spur development of syngas systems and enable conversion of new biomass. The assumption for this estimate is that syngas systems are positioned to increase electricity production specifically from forestry waste. Gasification and pyrolysis technologies are suited well for these dryer feedstocks. While agricultural residues also are available for gasification and pyrolysis, the inclusion of animal manure in this category makes it difficult to attribute increases in agricultural residue conversion to syngas

	technologies. Animal manure is typically processed through anaerobic digestion to produce biogas. The technical potential of forestry waste in California is estimated at 1.9 GW. Assuming a high capture percentage of 50 percent of all forestry residue, this initiative can enable syngas installations with the potential to provide 8,800 GWh of electricity to the grid. This much electricity would provide 1.4 percent of SB-100 2045 goals (2045 SB-100 goals discussed in Current California Energy Mix and Future Expectations for SB-100 in Chapter 1).
Areas for Advancement	Catalytic cracking (nickel-based); biomass ash or natural catalysts for tar and contaminant removal; physical or in situ upstream tar removal. Competitive small-scale syngas production; fouling/deactivation of catalysts; operating parameters and trade-offs for syngas purity versus yield; clean up in extreme environments.
Technology Baseline, Best in Class	Baseline processes: Tar removal during gasification (e.g., small particle feedstock) or downstream methods such as wet gas cleaning, dry gas cleaning, thermal cracking, catalytic cracking (e.g., nickel, non-nickel, alkali metal, acid catalysts, carbon-based). (2014) 23 cent/kWh for biomass gasification electricity production. Ammonia removal efficiencies for nickel catalysts 88-92 percent (high cost).
Metrics and/or Performance Indicators	Lower-cost syngas production: (2025) 6 cents/kWh – 20 cents/kWh. 20 percent or more syngas yield increase.
Success Timeframe	Mid-term (3-5 years). Gas cleanup requires cheaper, better catalysts and integrated processes for multiple producer gas contaminants.
Key Published References	Abdoulmoumine et al. (2015), Luo et al. (2018), Yang et al. (2017), Park et al. (2017), Woolcock and Brown (2013)
Correlation with Ongoing CEC efforts	EPIC 2018-2020 Investment Plan – Initiative 4.4.1: Tackling Tar and Other Impurities: Addressing the Achilles Heel of Gasification

Initiative BIO.2: Deploy Thermal Hydrolysis Pretreatment to Increase Biogas Production

Description and Characteristics	Thermal hydrolysis pretreatment (THP) can be used as a precursor to Anaerobic Digestion (AD) to increase biogas production and improve the breakdown of organic material. THP is used worldwide today in waste water treatment. It combines high-pressure boiling of waste/sludge followed by a rapid decompression to sterilize and make the waste more biodegradable, improving digestion performance. THP also alters rheology so that loading rates to the digester can be nearly doubled, with improved dewatering. The use of AD is growing for converting MSW, food processing and other agricultural wastes into biogas. Increasing the volume of waste that can be treated (degradation capacity) and output of biogas would enhance the viability of AD for gas production across feedstocks. Applying pre-treatments such as THP are one promising approach to increasing the yields of AD. Pretreatment of combined sludge/MSW streams is also a promising strategy. THP can also be applied to high pressure hydrothermal biomass conversion to improve biogas output. More research is needed to optimize the use of THP specifically for biogas production from mixed/diverse biomass streams.
Impacts	THP can potentially improve cake dewaterability, increase methane production, increase digester loading rates and produce bio-solids ready for land disposal. These improvements will lead to increases in energy output from feedstocks and potential cost reductions for waste treatment and conversion.
Estimated Potential Impact on SB-100	An increase in gas production at current California bioenergy plants would impact 295 MW of in-state capacity that relies on digester gas, landfill gas, and biogas. Assuming that this initiative causes a 75 percent increase in gas production at those facilities, 1,030 GWh of additional renewable electricity can be put on the grid. This much electricity would provide 0.7 percent of 2030 SB-100 goals (2030 SB-100 goals discussed in Current California Energy Mix and Future Expectations for SB-100 in Chapter 1).

Areas for Advancement	Thermo-pressure hydrolysis, high pressure thermal hydrolysis. Studied primarily for wastewater pretreatment to reduce sludge; some exploration for algae digestion and MSW/food processing wastes. Increased ammonia production and generation of soluble inert materials. Uncertain impacts of THP and operating conditions on feedstock microbial population (adverse or positive).
Technology Baseline, Best in Class	Sludge disposal rates estimated between $20 and $50 per ton. Yields from AD as high as 3,200 standard cubic feet of methane per ton of raw foot waste. Current systems in use include: wet AD systems (high-moisture-content feedstock types) such as covered lagoon and complete mix digester; dry AD systems for low-moisture-content feedstock (e.g., yard and green waste), plug flow digesters. THP used successfully for wastewater treatment to produce biogas and sanitized sludge.
Metrics and/or Performance Indicators	Implementation of full-scale thermo-pressure hydrolysis shown to provide higher anaerobic degradation efficiency, Increased biogas production (+75-80 percent) from waste activated sludge. Enhanced degradation of organic matter and improved cake's solids content from 25.2 to 32.7 percent. Total suspended solids reduce sludge disposal costs about 25 percent.
Success Timeframe	Mid-term (3-5 years); available for wastewater pretreatment, requires study and adaptation to biomass/dairy/diverted organic waste AD operations, MSW, and other waste streams.
Key Published References	Ahuja (2015), Meegoda et al. (2018), Oladejo et al. (2018), Keymer et al. (2013), Skinner et al. (2015), Westerholm et al. (2019)
Correlation with Ongoing CEC efforts	EPIC 2018-2020 Investment Plan – Initiative 4.4.3: Demonstrate Improved Performance and Reduced Air Pollution Emissions of Biogas or Low-Quality Biogas Power Generation Technologies

Bioenergy Considerations

Provided here (in no particular order) are some of the notable considerations aligned with the bioenergy technology area. These considerations include opportunities, barriers, and potential related technologies for future advancement.

RNG has a lower energy content than traditional natural gas. RNG can be upgraded or combined with traditional natural gas to increase its energy content so it can serve as a direct replacement for natural gas. While these practices are effective, waste must be available in large quantities and from consistent sources to be able to generate enough RNG for grid-scale electricity production.

The source and security of feedstock delivery is important to ensure consistent production from bioenergy sources. Ensuring this stability is critical especially for new sources of bioenergy. Load serving entities are reluctant to embrace new source of bioenergy due to the potential for inconsistent supply.

A lack of education on RNG and its potential integration into existing gas streams may be preventing its adoption. Coupled with a limited understanding of bioenergy is a breakdown in recycling programs which is limiting the availability of resources. Better public education and valuing of recycled material should allow bioenergy sources to operate more effectively.

The introduction of RNG and co-products into energy and other markets will have a disruptive affect. Both RNG and other bioenergy co-products will displace incumbents such as natural gas and traditional fertilizer. Longer term supply agreements are required to ensure that shorter term economic shifts tied to changing markets do not affect the revenue of a bioenergy plant detrimentally.

A need for markets for byproducts of bioenergy production is required. To provide value to bioenergy systems, coproducts need a revenue streams that can be predictable for producers. The idea of consistent supply and generation of resources is a worry throughout the bioenergy supply chain.

Without co-products, certain thermochemical processes are not economically feasible. A higher performance for these systems is required. Similarly, bioproducts often require further processing to be ready for sale. Increases in production or quality of bioproducts can increase the overall revenue of bioenergy systems.

Not all waste is currently accepted into the bioenergy supply chain. To enable more waste to energy systems, WWTPs and MSW systems must be willing to accept more wastes that can be converted into gaseous bioenergy sources. One major example of this is the rejection of food waste by WWTP operators. Food waste is not valued for despite its ability to increase biogas production through co-digestion due to the perception that it could introduce risks to wastewater treatment which is the main goal of WWTPs. A value tied to accepting food waste or a mandate for WWTPs to accept more waste streams would solve this problem.

Forest fire prevention through bioenergy systems is limited by cost. While wood residue and thinning collection is one of the most noticeable and currently relevant aspects of bioenergy conversion, the cost of collecting and delivering distributed wood resources remains prohibitively expensive. In general, woody biomass generation has a higher cost compared to other renewables even without accounting for collection of the types of wood resources that most often lead to wildfires.

The societal and environmental benefits of using excess wood for a beneficial purpose are not captured in the market today. While residual wood waste is difficult and expensive to collect, a price that encapsulates the benefit of avoiding forest fires would go a long way to making the production of bioenergy from these sources more appealing.

A market for carbon accounting would make RNG attractive. Monetizing GHG benefits would provide a path to greater profitability of RNG systems. To do this, a greater understanding of how waste diversion reduces GHG emissions is first required. A barrier to this analysis is that these GHG pathways are not currently well understood. There is a carbon negative potential for Bioenergy which does not exist for other products

Inconsistent power purchase prices and few agreements with utilities are a major barrier for bioenergy systems. When producers cannot expect revenue from their production, it makes it difficult to accurately value the systems which reduces the chance for financing projects. A long-term commitment to bioenergy by load serving entities would help reduce risks for financing bioenergy systems by increasing the value of their resource.

The costs of feedstocks are highly variable and dependent on the amount of waste created and used throughout the entire bioenergy systems. While bioenergy producers may currently receive money for taking waste that can be converted to energy, as more producers enter the market and convert waste, the value of that waste increases. The cost of feedstocks will vary due to availability, and with the volume of future wastes uncertain, there are long term risks tied to market growth.

Assessments of feedstock logistics from forestry and agriculture would help improve understanding of a key issue facing bioenergy systems. Collecting waste feedstock for power generation provides an alternative to landfill disposal or leaving it onsite after development. The cost and availability of feedstock collection and transportation limits the potential of using biomass for power generation. Assessments of this resource can clarify the potential and viability of waste feedstock as a reliable fuel for biomass.

Interconnection costs tied to plant siting must be considered for bioenergy facilities. This has to be balanced with a location that limits the costs associated with feedstock delivery and co-product dispatch. Typically, interconnection costs make small-scale bioenergy systems unideal in the marketplace.

Bioenergy plants provide a greater degree of flexibility and dispatchability when compared to other renewable resources. Any new bioenergy plants may benefit from siting themselves in an area that benefits most from a dispatchable resource both in grid value and revenue received at the plant. Studies and tools that identify the best locations could be useful in this matter.

Waste-to-energy systems have difficulty incorporating multiple waste streams. Within waste-to-energy facilities, it is difficult to separate small scale food and organic waste to the point the feedstock stream is usable for bioenergy production. While incorporating multiple waste streams diverts waste from landfills and increases sources for bioenergy production, separation challenges must be addressed before scale-up can occur.

Certain biopower plants are limited by air district regulations mandating the number of particulates and impurities that can emitted by a plant. It is important that bioenergy plants are not unjustly punished for their emissions to the point they cannot operate. Bioenergy plants provide a useful service by diverting waste from a worse environmental fate.

The organic component of waste to energy MSW systems must be as clean as possible as mandated by SB1383. This process needs to be done economically and efficiently to support profitable energy production.

There is a need to reduce unwanted byproducts at all waste and bioenergy facilities. WWTPs in particular need to avoid increasing the amount of sludge that may be introduced with additional feedstocks. Sludge can threaten the performance of bioenergy production systems and requires disposal which increases cost and complexity of systems.

Odors are an issue for any bioenergy plant using a waste or aggregate resource. This issue is particularly detrimental when bioenergy plants are sited close to residential areas.

Waste to energy systems such as microbial fuel cells offer a way to increase renewable energy generation. Microbial fuel cells (MFCs) can treat wastewater directly with microbial activity and use this waste to produce energy and pure water. Bacteria used for MFCs can thrive on sewage in wastewater and can filter it out, limiting the amount of waste that has to be sent to landfills. Another alternative to directly producing electricity is to use MFCs to produce biogas which can be used to produce heat and energy.

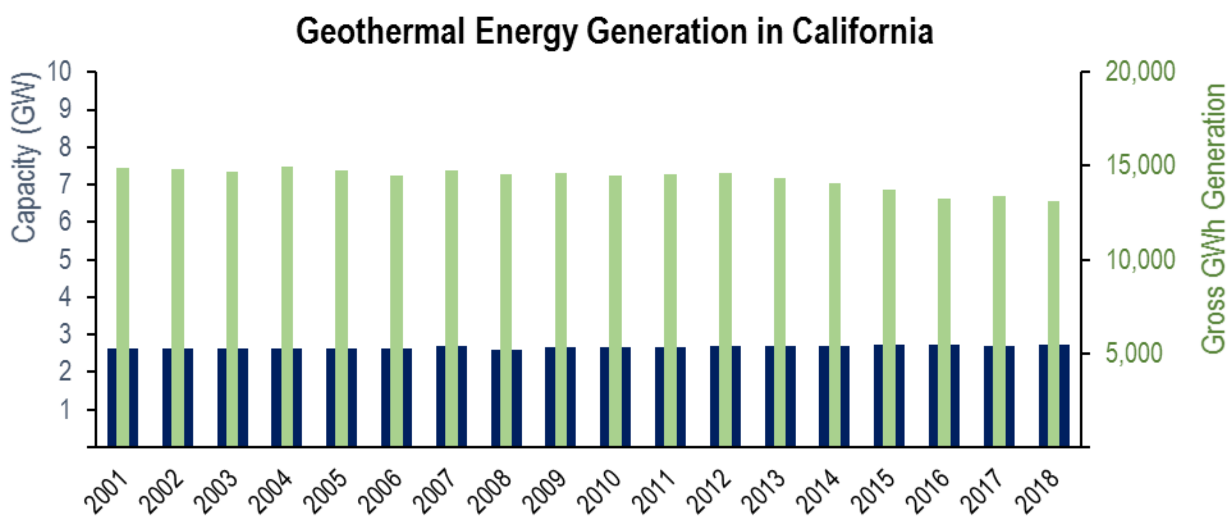
Geothermal

Geothermal systems have been a mainstay in the California energy mix since the 1960s. Geothermal plants utilize natural heat generated underground to produce steam and electricity. As the largest non-variable renewable resource in the state, increased geothermal development can increase California's renewable baseload energy. New technologies which can limit corrosion and access new areas for geothermal development will enable geothermal energy to provide increasing amounts of constant reliable energy while developing its capabilities as a flexible resource. Additionally, enhanced geothermal systems (EGS) provide a pathway to dramatically increase geothermal production in California.

Generation Trends

Geothermal power is the largest source of non-variable renewable power in the state of California and has been a major part of its energy mix for the past several decades. However, high costs of new systems combined with depleted production of existing resources has led to a stagnant geothermal capacity in the state, as shown in Figure 9.

Figure 9: Geothermal Energy Generation in California from 2001 to 2018



Source: California Energy Commission (2019g)

Resource Assessment

Estimates of additional capacity in California range from 5,000 MW–35,000 MW for conventional geothermal generation and estimates as high as 68,000 MW with the inclusion of EGS (Williams et al. 2008, USGS 2018). California has 25 known geothermal resource areas (KGRAs), of which 14 have temperatures above 300˚F. Currently, geothermal capacity in California is concentrated in five regions around the state, but future development is planned in the northeast of the state for the first time. EGS demonstration plants have been developed, and commercial facilities are targeted for deployment in 2030.

Potential for Reaching SB-100 Goals

Looking at technical capacities of 5.4 GW for conventional geothermal power and 48.1 GW potential for EGS (mean estimates of geothermal capacity in California according to 2008 USGS source), the total possible production from geothermal sources can be estimated at 226,000 GWh or 69 percent of 2045 SB100 goals. This estimate assumes the 2018 statewide capacity factor for geothermal power continues at 48.2 percent (supporting calculations in Appendix A).

Since geothermal systems typically operate in a baseload configuration, limited curtailment would be expected from geothermal production. New geothermal installations would be in a unique position to offset the decommissioning of remaining nuclear capacity in California at Diablo Canyon by providing a carbon-free replacement to this consistent source of baseload power. Flexible operating modes have also been considered for geothermal systems which would allow them to provide necessary ramping capabilities for the grid.

Cost Metrics

The LCOE for geothermal designs ranges from $0.04/kWh to $0.14/kWh, assuming a 25-year plant life (IRENA 2017). The estimated costs for EGSs range from $0.10/kWh to $0.30/kWh (IEA 2011]

Table 11: Geothermal Power Cost Performance Targets

U.S. Department of Energy 2018 Budget Request				
	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
California Energy Commission 2018 Update				
	2017	**2018**	**2019**	**2030**
Geothermal System (Flash)	N/A	13 cents/kWh	13 cents/kWh	14 cents/kWh
IRENA Renewable Power Generation Costs				
	2017	**2018**	**2019**	**2020**
Geothermal Systems	7.3 cents/kWh	7.2 cents/kWh	6.7 cents/kWh	7.6 cents/kWh

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.

Sources: DOE (2018a), Neff (2019), IRENA (2019)

Other Key Metrics

Maintenance Intervals

Geothermal plants produce power around 90 percent of the time from when they are commissioned and are capable of producing power on a near constant basis. Running the plant for longer periods of time can increase maintenance costs by stressing system components. Standard maintenance costs for geothermal plants are between $0.01 and $0.03 per kWh (DOE 2019b]

Discovery of EGS sites

EGS systems can be developed in any location where the subsurface rock is hot enough for a geothermal plant. California has not tapped half of its known potential geothermal resource, and potentially has only discovered 50 percent of the geothermal resource in the state (Matek and Gawell 2014).

Recommended Initiatives

The following charts describe the two recommended initiatives selected for geothermal technologies. These initiatives focus on the two major types of geothermal technologies: conventional and EGS. As a developed technology group, conventional geothermal systems need to reduce their cost and find ways to operate in difficult environments. On the other side, EGS are not at a stage of commercial development and must reduce risk while increasing understanding of the subsurface.

Initiative GEO.1: Improve Materials to Combat Corrosion from Geothermal Brines

Description and Characteristics	The high salinity of geothermal brines, especially in the Salton Sea region of California, degrades metal used throughout the power production process. As a result, expensive titanium-alloys are often used to prevent corrosion and reduce necessary maintenance. Maintenance trips increase down-time for the systems and increase operations and maintenance cost. Since titanium is one of the most expensive metals, finding an alternative offers a path to cost savings as long as the selected material is also corrosion resistant. New materials made from base metals such as nickel have been tested but still lack the durability of titanium-alloys. However, further advancement and testing of metal alloys may reveal lower cost and more corrosion-resistant materials.
Impacts	Corrosion resistant materials reduce maintenance and operating costs for geothermal systems and make high-salinity areas more attractive

	for deployment in California. The use of alternative materials other than titanium-alloys would provide cost savings and lower LCOE for geothermal production.
Estimated Potential Impact on SB-100	The most visible known geothermal resource area with high salinity brines is the Salton Sea. This region has an estimated development potential of 1.8 GW, but has seen limited additional capacity installed in recent years. This initiative can lower costs while keeping capacity factors high for traditional geothermal installations in the region. At maximum, this initiative will allow all 1.8 GW of Salton Sea capacity to be utilized providing an additional 7,600 GWh to the California grid. This much electricity would provide 2.3 percent of 2045 SB-100 goals (2045 SB-100 goals discussed in Current California Energy Mix and Future Expectations for SB-100 in Chapter 1).
Areas for Advancement	Titanium-alloys are currently the preferred material for high corrosion geothermal deployments. This material is unlikely to decrease in cost to improve system economics, so the development of other materials with cheaper base metals that are able to withstand corrosion are necessary.
Technology Baseline, Best in Class	Geothermal plants operate 90 percent of the time. Maintenance costs for geothermal plants ranges between 1 to 3 cents per kWh
Metrics and/or Performance Indicators	Achieve geothermal operation uptime in high salinity zones above 90 percent. Achieve maintenance costs at low end of normal range in high salinity zones (~1 cent per kWh) The corrosion rates of different metals are also an important factor for this initiative.
Success Timeframe	Mid-term (3-5 years)
Key Published References	Larsen (2019), Gagne et al. (2015)

Correlation with Ongoing CEC efforts	EPIC 2018-2020 Investment Plan – Initiative 4.3.2: Geothermal Energy Advancement for a Reliable Renewable Electricity System Geothermal Grant and Loan Program

Initiative GEO.2: Advance Techniques to Assess Potential EGS Development Sites

Description and Characteristics	EGS allows for the production of geothermal power without siting at a traditional geothermal resource with natural steam or hot water production. These systems involve artificially creating a subsurface pathway where a heat transfer medium (usually water) is pumped underground into an injection well and collected in a separate production well where it returns heated at the surface. There are a number of concerns with EGS that are prevalent in California. To achieve the required permeability underground for the heat transfer medium to go from the injection well to the production well, hydraulic fracturing (commonly known as "fracking") is required. Concerns over seismic activity and chemicals and substances utilized for hydraulic fracturing are particularly pronounced in California. While the technique is used with limited issues in Southern California oil production, any new use will be heavily scrutinized. Additionally, EGS involves drilling through hard rock which can drastically increase cost and threaten the potential financial viability of EGS systems. While all the techniques to create an EGS well exist, the two areas that could provide the most benefit to California are improved assessment and characterization of underground geothermal resources and adaptation of production methods for EGS systems. Improving and utilizing assessment techniques would provide more benefit to EGS systems at this point as potential operators will have to be as informed as possible about potential development sites to receive permission to proceed with EGS developments.
Impacts	Assessment of subsurface geothermal resources in specific areas of California will help pinpoint areas for geothermal production that have limited environmental concerns, reduce or eliminate the need for hydraulic fracturing, and reduce drilling costs.

Estimated Potential Impact on SB-100	EGS will be necessary to reach SB-100 2030 and 2045 goals if geothermal power maintains its same percentage of renewable energy production. Assuming that only 50 percent of available EGS sites are currently known, this initiative is estimated to lead to the discovery of 12 GW of additional EGS capacity. At current California geothermal power capacity factors, that resource could provide, at maximum, 16 percent of SB-100 2045 goals (2045 SB-100 goals discussed in Current California Energy Mix and Future Expectations for SB-100 in Chapter 1).
Areas for Advancement	Accuracy of sub-surface assessments can be improved with Artificial Intelligence techniques as well as improved data collection and analysis.
Technology Baseline, Best in Class	Estimated that only 50 percent of the geothermal resource in California has been identified.
Metrics and/or Performance Indicators	Assessment of new geothermal resources such that estimates of discovered geothermal resources in California can be increased to 75 percent.
Success Timeframe	Near-term (1-3 years)
Key Published References	DOE (2019c)
Correlation with Ongoing CEC efforts	Geothermal Grant and Loan Program

Geothermal Considerations

Provided here (in no particular order) are some of the notable considerations aligned with the geothermal technology area. These considerations include opportunities, barriers, and potential related technologies for future advancement.

The most substantial cost tied to geothermal production is for initial exploration and production. While borrowing heavily from practices employed in oil and gas exploration, the drilling practices for geothermal production focus on different rock formations. Hard rock increases the time it takes to drill and entails time-consuming maintenance. The high cost of exploration, which can account for over 50 percent of total project cost, remains one of the largest barriers to reducing the ultimate consumer-facing price of geothermal energy. Finding rigs that are available close to geothermal sites, developing drilling bits made for dealing with high temperature and pressure geothermal rock formations, and using techniques that can reduce the amount of time required to drill a well in general would all help lower exploration costs.

Associated with the drilling cost is the added risk of drilling unproductive wells. This risk is well known by financing institutions and limits the number of willing financiers. Better modeling and surveying technologies and techniques and knowledge gained through unsuccessful explorations can help lower drilling risks. However, assessing the accuracy of these techniques requires that wells be drilled. Another way to improve the outlook for financiers would be to value plants over longer time frames more consistent with their actual lifespan.

Lowering well field costs would increase deployments. Because the highest costs associated with geothermal resources are well exploration and drilling, cost decreases would likely result from improved geothermal reservoir discovery and accessibility. Further work in analysis and modeling of potential reservoirs can improve the likelihood of drilling successfully. By improving the certainty of reaching viable reservoirs, developers can decrease costs by minimizing the number of drilling attempts necessary. Improving methods to reach geothermal reservoirs would encourage more developers to drill and develop new power facilities by adding more certainty and reliability to the process.

While geothermal resources are located at KGRAs, the exact siting of wells can still be improved. New assessment methods have come about in recent years with the advent of new modeling and exploration techniques. Utilizing and improving these methods will help access the best resources.

Once a well is developed and productive in a KGRA, maintenance and material costs can continue to hamper geothermal profitability. Geothermal brines found in likely areas of new development, such as the Salton Sea, contain large concentrations of corrosive impurities that degrade equipment and require constant maintenance.

Extraction and sale of co-product impurities such as lithium present in the brines can help increase total revenue from geothermal systems. The development of lithium collection technologies can also support lithium-ion battery development in California. This additional revenue stream may attract financing to geothermal systems that would not be financed based on energy production alone.

Development of new geothermal wells is affected by limited availability of both skilled drilling crews (especially with geothermal experience) and oil and gas rigs. A number of rigs are currently being used for policy-mandated plugging and abandoning of old oil and gas wells, which ties up resources. Some policy relief would help free up rig resources.

One aspect of geothermal energy that is especially relevant to California is the water requirement for geothermal systems. New installations increasingly require water injection in hot formations to generate the steam required for power production. The constrained nature of California's water resource threatens geothermal plants' ability to operate consistently in future decades. Possible solutions involve bringing water to constrained locations, but these approaches are area-specific and add another ongoing cost to geothermal power production. For example, transporting treated wastewater by pipeline to the power plant was a solution for the Geysers. At other geothermal sites, using desalinated water or disposed or treated water is a potential solution.

Geothermal power is typically run in a baseload configuration. Geothermal power is one of the only reliable and consistent forms of renewable energy available in the energy market today. However, increases in variable solar power installations at a lower price point threaten to push out new geothermal generation and have led to curtailments of this renewable resource.

Geothermal resources also have the potential to provide black start capabilities and ramping flexibility services. However, to provide these services for the grid, flexible geothermal operations must be fully developed. These ancillary services will require a higher value in the market to incentivize geothermal producers to change their operating mode from baseload to flexible generation.

Methods of flexible generation, including controlling steam release and shutting in wells and equipment, put wear on equipment and introduce risks to normal system operation. New technologies and testbeds are required to address problems with flexible generation. In addition to system risks, there are cascading effects tied to flexible generation, including byproduct development. These risks may be viewed as an unnecessary by system operators.

The California Public Utilities Commission's current structure provides incentives for solar production while leaving little incentive for new geothermal installations. A proper valuing of geothermal's reliable baseload generation and potential flexibility will promote further installations. However, this valuation would require a holistic grid design that looks at the specific value that all types of renewable generation provide. **On the regulatory side, the California Environmental Quality Act (CEQA) has a number of environmental restrictions that prevent project permitting.** These restrictions put undue burdens on geothermal systems over 50 MW, which is changing the face of geothermal generation in the state. Addressing these concerns would help reduce the high risk already present at the outset of a geothermal project. Streamlining CEQA at the state level would help as well.

The degree of difficulty connecting new geothermal wells and KGRAs to the grid depends on existing infrastructure and load locations, which cannot be controlled. The lack of developed transmission in new geothermal resource areas is problematic, as is the cumbersome interconnection process to access utilities. The cost of connecting geothermal facilities to transmission networks should be accounted for as a part of system development as well. Even existing systems have integration problems. For example, the Geysers have had curtailment issues due to transmission congestion.

The Imperial Valley is a strategically important place for geothermal development. Expansion of geothermal energy in the Imperial Valley would help overall geothermal development as a strategically important element of a balanced renewable portfolio. Capital costs are higher in this area for geothermal energy. Would help reach goal of 500 MW of energy in Imperial by 2030.

California needs an updated resource assessment. Both high temperature systems as well as lower temperature resources that could be utilized for direct use applications should be studied. Improved models and techniques are needed to identify zones of subsurface permeability as well. This would improve well success for both exploration and development drilling. Improved reservoir models and field monitoring methods (such as microseismic monitoring systems and the use of geochemical tracers) will enable operators to better manage the utilization of geothermal resources as well.

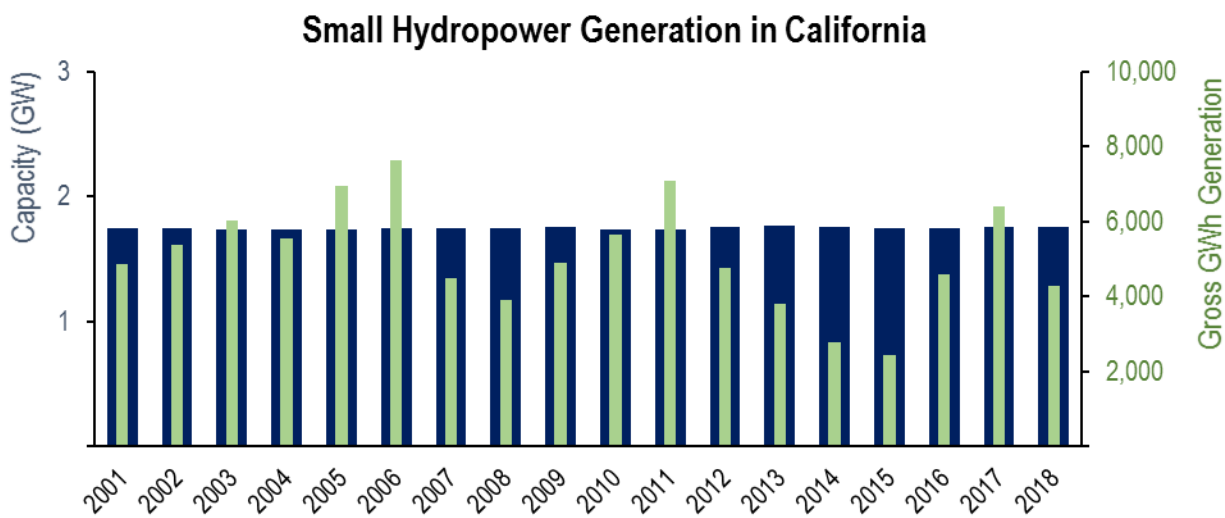
Small-Scale Hydroelectric (<30 MW)

Small Hydropower systems utilize existing water infrastructure by adding turbines in locations feasible for small amount of power generation. With California's large water infrastructure, there are multiple areas across the state where small hydropower systems can be installed. Developing technologies to make these systems feasible for developers can support continued development and provide benefits to both water purveyors and ratepayers.

Generation Trends

The primary types of small hydropower that exist are new stream development, powering non-powered damns, and in-conduit hydropower. The capacity and energy generation of small hydropower in California is shown in Figure 10. Of the total small hydro energy capacity in California, 320 MW is in-conduit hydropower (Samu et al. 2016).

Figure 10: Small Hydropower Energy Generation in California from 2001 to 2018



Source: California Energy Commission (2019h)

Resource Assessment

As shown in the graph, the capacity of small hydropower has not changed significantly since 2001. Rainier years tend to produce more hydroelectric energy, while dry years produce less energy (note that periods of decline shown in Figure 10 all occurred during droughts).

Potential for Reaching SB-100 Goals

Based on current understanding of small hydropower resources in California, the current maximum technical potential is 2.5 GW. At a 2018 California capacity factor for small hydropower of 27.6 percent, this technical potential can provide 6,040 GWh of total electricity or 1.8 percent of 2045 SB-100 goals (supporting calculations in Appendix A). The majority of the technical potential in California is estimated to be from existing waterways.

Cost Metrics

The LCOE of small hydropower projects in North America ranges from $0.05/kWh to around $0.18/kWh, assuming a system life span of 30 years (IRENA 2018). Installed costs can vary highly among systems, ranging from $2500/kW to $5000/kW (O'Conner 2015). Hydrology and civil construction required prior to turbine installation play a significant role in total costs. DOE has looked at streams as having promise, and cost targets for this form of hydropower are shown in Table 12.

Table 12: Small Hydro Cost Performance Targets

U.S. Department of Energy 2018 Budget Request				
	FY 2017	FY 2018	FY 2019	Endpoint Target
Small Hydro (streams)[1]	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
NREL Annual Technology Baseline Projection				
	2017	2018	2019	2030
Small Hydro (non powered dams)	5 cents/kWh	5.7 cents/kWh	6 cents/kWh	6.1 cents/kWh
Small Hydro (streams)	5.8 cents/kWh	6.6 cents/kWh	7 cents/kWh	7 cents/kWh

1. The new stream development energy cost target is an unsubsidized cost of energy at utility-scale. The target is for small, low-head developments.
2. NREL Annual Technology Baseline does not factor in costs of building new lines for transmission and interconnection.

Sources: DOE (2018a), NREL (2019)

Other Key Metrics

Permitting Time for Interconnection

FERC permitting approval for small hydro projects has been shortened following the passage of the Hydropower Regulatory Efficiency Act in 2013, which allows small hydro projects in conduits that are smaller than 5 MW in capacity to be exempt from FERC permitting if there are no objections to development during a 45-day public notice period (Johnson 2013). Permitting at the state level can still take many months however.

Recommended Initiatives

There are no recommended initiatives for small-scale hydroelectric in this roadmap. However, there were a number of ideas brought up throughout the roadmapping process that are worthy of mention here as future considerations. Presented in no particular order, they are:

Advanced assessment of velocity and head of small hydropower resources. The current resource assessment for small hydropower systems has it pegged as a small resource for California. One type of small hydropower that was brought up in the roadmapping process was hydrokinetic technologies. These technologies rely on the velocity of water to produce power instead of water height. While these technologies are attractive generally, there is no comprehensive assessment of hydrokinetic resource for California. To better understand the potential for hydrokinetic technologies, an assessment of velocity of head of canals, streams, and other water ways in California is recommended.

Modular systems for hydropower. Modular systems are adaptable to different waterways and limit the need for site specific design which limits installation and maintenance costs. Development of these standardized systems was originally included as an initiative. However, modular systems exist already and have shown little impact on small hydropower in the state.

Improved interconnection. Removing obstacles to interconnection of spatially isolated and small devices would lower risks for new small hydropower installations. However, it is difficult to identify a specific process or technology that would universally help small hydropower technologies. Smart inverters exist that can be adapted to each small hydropower device to ease with this process, but these are already developed and on the market.

Additive manufacturing for small hydropower systems. AM would enable manufacturing based on site specific needs and characteristics. However, as a fledgling technology, it is difficult to pinpoint a specific element or component of small hydropower systems that would benefit significantly from AM. The lack of clarity surrounding AM makes it difficult to recommend a specific initiative related to small hydropower.

Small-Scale Hydroelectric Considerations

Provided here (in no particular order) are some of the notable considerations aligned with the small-scale hydroelectric technology area. These considerations include opportunities, barriers, and potential related technologies for future advancement.

System development costs are high enough that they often prohibit small hydropower development. These costs stem from a variety of factors. Each site is custom engineered, as a site's hydrology and structure contributes to a unique (and therefore expensive) design. As with site development, hydropower components and additional civil structures required for deployment are also custom engineered which again increases upfront costs.

Smaller system designs face high soft costs for permitting and grid integration. Small hydropower systems deal with similar permitting and interconnection costs as larger projects but produce less energy. Regulatory changes at both the national and state levels have sought to mitigate permitting costs, but challenges remain at local levels. Soft costs associated with grid integration are harder to address, as many locations are far from existing transmission lines.

The total amount of energy that can be produced from small hydropower in California is uncertain. The last hydropower resource assessment for the state was conducted in 2006 and was limited in scope (Navigant 2006). California experienced many changes to water availability and flow since that time. The 2018 National Climate Assessment highlighted increasing temperatures and climate change as reasons for decreased winter snowpacks and amplified droughts in California (U.S. Global Change Research Program 2018). Additional assessments can increase current understanding of and future expectations for water flows.

The performance of in-conduit systems is tied to area hydrology and water flows. When water is available, hydropower systems have high capacity factors at their rated power outputs. However, climate change impacts are reducing the amount of water available in California. Limited water availability prevents maximum performance of in-conduit and other hydropower systems, decreasing the potential impact hydropower systems can have on state energy goals.

California places tight controls on water use to meet farming and municipal needs. Small hydro systems cannot control how much water flows through them at any given time because changes in water flow affect downstream water distribution. This lack of control prevents small hydropower from providing dispatchable and reliable energy and makes it a more variable resource.

Hydropower systems are not typically paired with energy storage. Traditional hydropower systems can control the flow of upstream water and utilize this water as a form of energy storage which makes pairing with other energy storage systems unnecessary. However, with unpredictable water flows in California, using storage would mitigate production risk and ensure small hydropower stays a non-variable resource. But, costs for small hydropower increase when energy storage is added which limits the feasibility of paired systems.

In-conduit hydropower provides several services which are known but not valued by the marketplace. Small hydro projects can help defer grid upgrades by providing ancillary services such as frequency and voltage control. Policy changes that value these grid services can allow small hydro to flourish and maintain necessary cash flows. Separately, in-conduit hydropower can be used as a revenue generating replacement for pressure reduction valves, which are used to control water pressure in the state.

Hydro projects are heavily governed by Rule 21. The need for generating units to install smart meters that communicate with the grid affects small hydropower more than other systems due to remote and undeveloped location of these resources. Finding ways to decrease the burden of Rule 21 on small hydropower systems can reduce financing and installation risks.

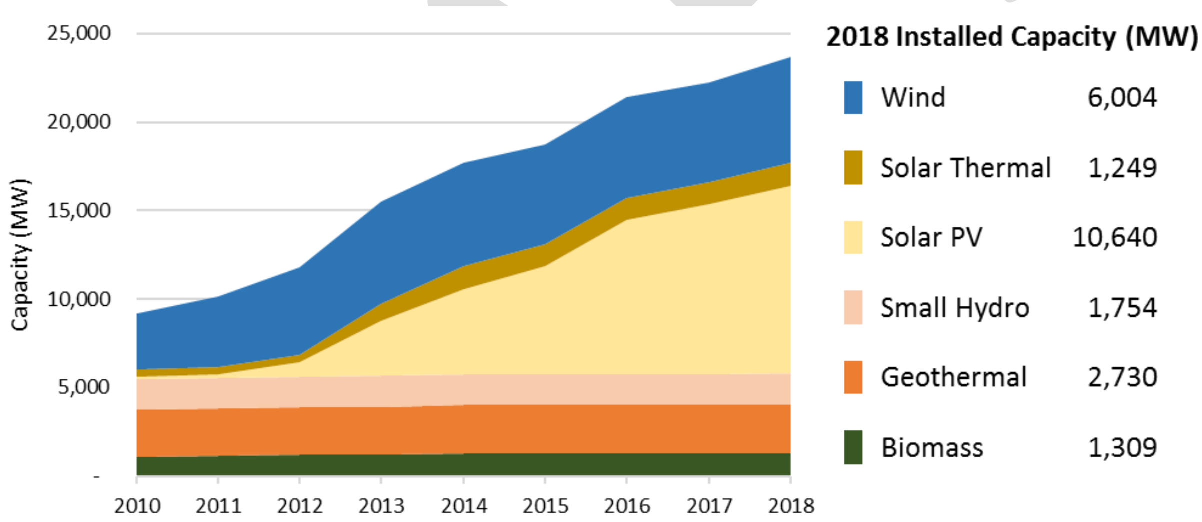
Grid Integration Technologies

A flexible grid which can incorporate multiple points of generation and consumption is necessary for California to meet SB-100 goals. Grid integration and infrastructure upgrades will support the continued implementation of variable renewable resources into the state grid through and create a more resilient, reliable electric grid.

Generation Trends

In 2017, California's electricity system generated over 292,000 gigawatt hours (GWh) of energy, with over half of that total being provided by low carbon (nuclear and large hydropower) and zero carbon sources. Zero carbon sources include the many large-scale renewable energy sources discussed in this roadmap. The profile of cumulative installed capacity of these renewable resources is shown below in Figure 11. The total installed large-scale renewable capacity does not include the 6,800 megawatts (MW) of renewable energy generated from homes and businesses across the state.

Figure 11: Cumulative Installed Large-Scale Renewable Energy Capacity from 2010 to 2018



California Energy Commission (2019a)

Resource Assessment

To handle all electric load in the state, 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 (DOE 2015). However, the energy grid of California requires a new type of grid infrastructure development to balance the growing number renewable energy resources with the decreasing number of conventional energy resources. Inefficiencies in the system lead to problems like curtailment. In 2015, CAISO was forced to curtail over 187,000 MWh of solar and wind generation. In 2016, that total rose to over 300,000 MWh (CAISO 2017]

Effective planning can help California achieve 100 percent zero carbon energy by 2045 by both optimizing the existing transmission system and installing new state-of-the-art transmission infrastructure. Both types of improvements will be necessary to handle new electric flows and increases in power generation from renewable sources.

Improvements are required in the four main technology areas within grid integration: transmission and distribution; devices, measurement, and system controls; design, modeling, and resource planning; and grid resilience. All four of these systems coexist to ensure electricity is reliably transferred from generation sources to load sources.

Reaching SB-100 Goals

Expansion of the electric grid either through line capacity upgrades or construction of new electric lines is essential to reaching SB-100 goals. For 2030, an increase in consumption of 54,500 GWh coupled with additional offsets of fossil fuel generation leads to a 2030 SB-100 goal of 141,000 GWh in new capacity on the grid (all renewable). Similarly, for 2045, SB-100 goals require 326,000 GWh in new electricity from renewable sources compared to 2018 generation (supporting calculations in Appendix A).

While renewable energy expansion is expected in some areas that are already grid connected, any development of new resource areas (most noticeably offshore resources) will necessitate new power lines. The high costs of power lines, substations, and other grid equipment must be accounted for in financial planning and serve as a barrier to entry for many new systems.

Cost Metrics

Table 13. Baseline Transmission Line Costs

Type of Transmission Line	New Line Cost ($/Mile)
230 kV Single Circuit	$959,700
230 kV Double Circuit	$1,536,400
345 kV Single Circuit	$1,343,800
345 kV Double Circuit	$2,150,300
500 kV Single Circuit	$1,919,450
500 kV Double Circuit	$3,071,750
500 kV HVDC Bi-pole	$1,536,400
600 kV HVDC Bi-pole	$1,613,200

Source: Black and Veatch (2014)

Table 14. Baseline Substation Costs

Substation	Baseline Cost
230 kV Substation	$1,706,250
345 kV Substation	$2,132,700
500 kV Substation	$2,559,250

Source: Black and Veatch (2014)

Table 15. Baseline HVDC Bipole Submarine Cable Cost

Voltage	Power (MW)	Cost (Million $/mile)
150 kV	352	2.52
300 kV	704	2.64
300 kV	1,306	5.02

Source: Liun (2015)

Other Key Metrics

Curtailed Energy

The curtailment of renewable energy is when renewable energy sources are ordered by grid operators to stop producing energy as a result of grid conditions, such as line congestion or overgeneration in the system. CAISO curtailed 401,492 MWhs of electricity in 2017 and 461,000 MWhs in 2018 (CAISO 2019). Decreasing the amount of energy curtailed will further enable California to meet is SB-100 goals.

Interconnection Energy Losses

As electricity travels from points of generation to points of consumption, up to 15 percent of it is lost through line resistance. In 2017, California lost an estimated 14 million MWh of electricity from losses. Utilizing HVDC lines instead of HVAC lines where appropriate can decreases losses by 30-50 percent where implemented (Siemens 2014]

Cyber Attacks

Between 2013 and 2015, the US energy sector experienced over 250 cyber incidents, more than any other sector, with cybercrime costing the sector $27.62 Million in 2015. Meanwhile, spending on security systems for the electric grid totaled between $150 to $800 million dollars in 2015 (DOE 2018b]

Recommended Initiatives

The following charts describe the two recommended initiatives selected for grid integration technologies. These initiatives focus on two separate but important aspects of the grid: security and offshore integration. Cybersecurity is a constant threat to the grid and diligence will be required to prevent any future attacks as massive amounts of new capacity comes into California's grid at both the utility and distributed levels. Additionally, as land-based resources become more stressed, expanding energy production to offshore sources (mainly wind and wave power) will provide a new pathway to growing utility-scale renewable production. These systems present unique challenges that must be addressed to transport energy efficiently to shore.

Initiative GIT.1: Deploy Smart Inverters to Improve Communication and Cybersecurity

Description and Characteristics	The electricity grid is transitioning to a system with multiple points of generation and consumption. The grid must integrate variable energy systems, large scale energy storage, and net metering along with enabling the development of thousands of distributed energy systems. In order to maintain grid stability, grid operators must be able to access data in real-time and communicate with multiple inverters on the grid. To integrate the power from many renewable sources onto the grid, the electricity produced by renewables must be passed through an inverter to match the voltage and frequency of power on the grid. Smart inverters can allow data to be transferred faster which allows the grid to monitor early warnings of grid events and behavior, identify failing equipment, and develop improved system models among other capabilities. California is already transitioning away from traditional (non-smart) inverters due to the implementation of Rule 21. However, not all smart inverters that fulfill Rule 21's requirements have the level of responsiveness and security required for optimal and secure grid operation. To increase the speed that data is available from smart inverters, the devices must be internet connected and able to access grid monitoring and control systems directly. However, the increased amount of data and frequency of data transfer requires careful management and standards of practice to ensure security. Cyberattacks in particular have become a point of focus for new smart inverter technologies.
Impacts	Inverters will be able to transfer data and be remotely controlled with limited risk of cyberattack. Contingencies will be required in case a cyberattack does occur. The advancement of smart inverters at the grid will require an accepted standard for data transfer as well. An increase in smart inverters on the grid will enable more efficient transmission

	and distribution of electricity and will improve integration of renewable energy sources. The quicker and safer data can be transferred, the more efficient the system can be.
Estimated Potential Impact on SB-100	This initiative will impact the safety and security of all existing electrical transmission. Additionally, smart inverters will protect 141,000 GWh of new renewable energy generation by 2030 and 326,000 GWh by 2045. This will require protection of 55,000 MW of capacity by 2030 and 129,000 MW by 2045 (2030 and 2045 SB-100 goals discussed in Current California Energy Mix and Future Expectations for SB-100 in Chapter 1). Due to low capacity factors associated with renewable energy technologies, the capacity put onto the grid will surpass the current capacity required for similar amount of electricity.
Areas for Advancement	Synchrophasor technology can collect 30 to 60 samples per second to provide grid performance data; Encryption of transferred data; Virtual Oscillator Control.
Technology Baseline, Best in Class	250 cyber incidents on the U.S. electricity sector between 2013 and 2015
Metrics and/or Performance Indicators	No successful cyber incidents in California.
Success Timeframe	Near-term (1-3 Years)
Key Published References	Brown (2019), Microgrid Knowledge (2018), CPUC (2019b), GTM (2018)
Correlation with Ongoing CEC efforts	EPIC 2018-2020 Investment Plan – Initiative 3.3.1: Optimize and Coordinate Smart Inverters Using Advanced Communication and Control Capabilities EPIC 2018-2020 Investment Plan – Initiative 3.3.2: Advance Distribution Planning Tools to Reduce the Cost and Time Needed for Interconnection to the Grid and Improve Interoperability

Initiative GIT.2: Advance Underwater High-Voltage Infrastructure for Offshore Energy Interconnection

Description and Characteristics	To connect offshore resources to the onshore grid, extensive cabling and interconnection systems are required. Additionally, underwater cabling represents a very high upfront cost for offshore systems, so optimal design and management of cables, interconnections, and substations is important. Also, the type, structure, and location of cables should minimize electrical losses for the system. Currently, high-voltage alternating current (HVAC) cables are used most commonly to transmit power for the grid. For specific on-land and offshore transmission where there is a long transmission distance, High-voltage direct current (HVDC) transmission lines have been implemented. The ideal offshore wind resource in California exist in areas with large enough transmission distances to warrant the use of HVDC infrastructure. There is a need to understand the design and location of HVDC systems to optimize costs and ensure proper connection to on-land grid infrastructure. In addition, there is room for improvement in HVDC infrastructure in terms of cost and efficiency. Infrastructure that can use improvement include the substations and converter stations that collect energy from multiple devices and switch between AC and DC power in addition to the HVDC lines themselves. As a starting point, Europe's sub-sea cable development provide a blueprint for optimal locations where HVDC should be deployed to bring offshore wind generated electricity to high load areas. Additionally, Massachusetts has undertaken HVDC transmission studies for their proposed wind farms that can serve as a template for California.
Impacts	HVDC cable infrastructure will decrease power losses and enable more efficient connections especially to resources located further from the shore. HVDC also require a smaller amount of material since they have smaller cross-section which limits cable cost and reduces the complexity of installation. Development of HVDC cables and interconnection infrastructure can also be applied to on-land transmission to lower line losses.

Estimated Potential Impact on SB-100	HVDC cable infrastructure will reduce line losses for offshore infrastructure. By 2045, it is feasible that 18 GW of offshore wind power will be put on the California grid. Typical line losses seen when integrating offshore systems are around 15 percent for high voltage AC systems. A reduction in line losses using HVDC infrastructure would save 4,750 GWh of electricity or 1.5 percent of total 2045 SB-100 goals (2045 SB-100 goals discussed in Current California Energy Mix and Future Expectations for SB-100 in Chapter 1).
Areas for Advancement	HVDC Cables are commercial but have limited demonstration for offshore use. Successful deployment of offshore infrastructure will also require offshore interconnection and substations to couple energy from separate turbines before transmission to shore. There is room for improvement in costs, availability, and transmission for HVDC infrastructure. The location and on-land interconnection of HVDC transmission into the grid also requires an understanding of load centers and interconnection processes.
Technology Baseline, Best in Class	Submarine HVDC cable cost: 150 kV and 352 MW: \$2.52 million per mile 300 kV and 704 MW: \$2.64 million per mile 300 kV and 1,306 MW: \$5.02 million per mile
Metrics and/or Performance Indicators	Future deployment of HVDC systems below current estimated costs. Estimated reduction in line losses of 30-50 percent over comparable HVAC system.
Success Timeframe	Long-term (>5 Years)
Key Published References	Baring-Gould (2014), Apostolaki-Iosifidou et al. (2019), Collier et al. (2019)
Correlation with Ongoing CEC efforts	No correlated Energy Commission efforts currently

Grid Integration Considerations

Provided here (in no particular order) are some of the notable considerations aligned with the grid integration technology area. These considerations include opportunities, barriers, and potential related technologies for future advancement.

Grid infrastructure does not produce revenue. Ratepayers are therefore left to pick up the costs of integrating new power lines and grid devices into the energy system. Therefore, the value of these upgrades must be justified in order to support the upfront capital costs of new transmission lines, smart devices, and other grid management components. The California Public Utilities Commission has oversight of the state's electric infrastructure and has a significant role to play in future activities related to grid infrastructure as well.

Renewable resources tend to be concentrated in centralized areas. This leads to large amounts of power coming from multiple facilities located all in the same place. This can create overloading on the grid as a result of overgeneration of renewables in these areas. Increases in line capacity of existing infrastructure or deployment of additional power lines are two ways to address centralization issues.

Distributed resources have increased the complexity of integrating renewables. The advent of distributed energy resources, net metering, and energy storage systems require advanced grid systems and control to deal with multiple directions of power flow. With new sources of electricity being introduced to the grid at an increasing rate, distributed systems will heavily shape future grid designs.

The benefits of new grid infrastructure are not all captured. Grid upgrades can mitigate wildfire hazards, improve system cyber security, and increase energy flow from generation sources to load sources. It is important to demonstrate all the ways a specific upgrade improves the grid so that each benefit can be properly valued.

Sensors and communications systems will be required to interpret measurements from across the grid. The transition from a conventional grid to a flexible grid with more dispatchable resources requires the development of smart grid devices. With constantly changing loads due to variable generation, distributed energy resources, and energy storage systems, all grid inputs and outputs must be connected to ensure that grid operators can maintain a balanced system.

Operators are hesitant to install new grid integration technologies due to technology lock in and high costs. One example of a technology that is unlikely to be upgraded is transformers. Because transformers are a critical component for grid reliability and have a high initial cost of replacement, IOUs are unwilling to stray from traditional designs. This technology lock in occurs despite the fact that upgrading grid components is an easy way to improve grid performance. Many other existing grid integration technologies have lower efficiencies than new replacement technologies.

Developing new infrastructure that increases accessibility to new resources is often more expensive than upgrading current infrastructure. Many projects go undeveloped because of their distance from existing grid infrastructure and the associated cost of interconnection. The preference for easier to connect resources with lower upfront costs limits the number of renewable projects that can be brought online. To reach SB-100 goals, new development sites and grid infrastructure will eventually be required.

Transactive energy systems have the potential to integrate more renewables and improve load factors on the grid. Transactive energy systems facilitate communication between grid operators, power producers, and consumers. With access to information about real-time electricity costs, consumers have the option to alter their consumption to lower their energy bills. Anticipated changes in behavior include increasing energy usage when renewable energy production is at its peak in the afternoon and decreasing usage in the evening as solar energy goes offline and fossil fuels ramp up generation.

The growing development of smart devices is allowing for the transformation of the electricity system. Smart devices allow consumers to automatically control their behavior by adjusting consumption to energy pricing signals (e.g. charging cars at night when prices are low or running appliances in the middle of the day when there is an excess in energy). Consumers are also able to participate in demand response programs with the use of smart devices. This automated behavior will gain importance as California increases its reliance on renewable energy resources. Grid operators can allow consumers to help change electric flow patterns and reduce consumption through their smart devices which can defer the need for grid upgrades.

Advanced power electronics and system controls can help increase penetration of renewables in the electric grid and improve reliability. Improved resource forecasting and modeling efforts can reduce renewable energy curtailment and optimize supply- and demand-side resources. Smart devices can also help increase understanding of how the system can operate most efficiently as the deployment of distributed energy resources, in addition to utility-scale systems, increases.

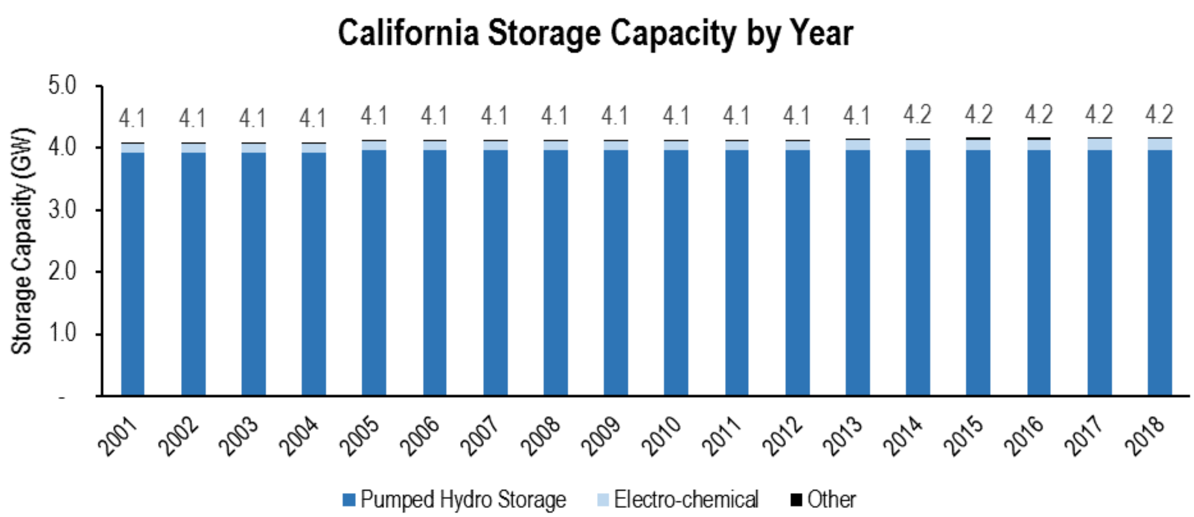
Energy Storage Systems

As the California grid incorporates increasing amounts of variable resources, continued incorporation of storage systems into the grid will be necessary to ensure reliability while minimizing curtailment of energy sources. Low-cost, high-performing energy storage systems are essential to enabling a greater penetration of renewable energy on California's electric grid. Incentive programs and the California legislature have made development and installation of energy storage systems a priority, and the Energy Commission can play a key role in the development, testing, demonstration, and deployment of new systems (Energetics 2019]

Generation Trends

The value of energy storage lies in its ability to increase the penetration of inexpensive variable renewable sources and to provide ancillary services that stabilize the grid. While traditionally, storage in California has been provided by pumped storage hydropower (PSH) systems, decreasing prices of lithium-ion batteries and the continued emergence of other forms of thermal, mechanical, and electrochemical storage are leading to an increase in energy storage capacity in the state for the first time in decades. These trends are visualized in Figure 12 below.

Figure 12: Energy Storage Capacity in California from 2001 to 2017



Source: DOE (2019d)

Resource Assessment

PSH plants require specific sites with a low- and a high-height water reservoir nearby. DOE's Hydropower Vision report conservatively estimates that 650–1,075 MW of additional pumped hydropower capacity is available in California (DOE 2016). Other types of storage systems have a bevy of capacity available since they can be flexibly located and have few locational and legislative limitations, although installing storage systems near transmission lines and junctions has the benefits of limiting losses and easing system integration.

Potential for Reaching SB-100 Goals

Energy storage is a necessary asset to achieve SB-100 electricity goals. Since the most plentiful resources in California, Solar and Wind, are variable, renewables will be unable to provide enough supply to meet demand without installing renewable systems at a capacity level massively over California's requirements. Energy Storage Systems allow renewables to smooth generation and to provide electricity to the grid even when renewable assets are not generating.

Renewables are currently able to provide 10-20 percent of generation throughout the day with maximums greater than 40 percent during peak daylight hours. A rough future 2045 estimate assumes that for 6 hours a day, renewables are able to provide 100 percent of electricity while for the remaining 18 hours, renewables average 20 percent of total grid production. Applying these values to 2045 SB-100 targets, yields a requirement of 247,000 GWh of storage available throughout the year. If storage systems on average operate at maximum for 8 hours, a high-end estimate for necessary storage installations is 85 GW of 8-hour storage by 2045 (supporting calculations in Appendix A).

Cost Metrics

The cost of storage systems other than PSH has decreased in the last several years. Looking forward, the DOE FY 2019 budget request establishes cost performance targets for grid-scale energy storage technologies, summarized in Table 16. Aqueous soluble organic electrolyte batteries (redox flow battery systems) currently represent DOE's choice for the chemistry of a utility-scale battery.

Table 16: Energy Storage Cost Performance Targets

	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	\$100/kWh for a prototype redox flow battery system by the end of FY 2025

Source: DOE (2018a)

Table 17. Current and Projected Energy Storage Capital Costs

Energy Storage System	2018	2025
Lithium Ion Battery	271 $/kWh	189 $/kWh
Flow Battery	555 $/kWh	393 $/kWh
Lead Acid Battery	260 $/kWh	220 $/kWh
Pumped Hydro	2,638 $/kW	2,638 $/kW
Compressed Air	1,669 $/kW	1,669 $/kW
Flywheel	2,880 $/kW	2,880 $/kW

Source: Mongird et al. (2019)

Other Key Metrics

Table 18: Energy Storage Metrics

System	Max Discharge Duration	Max Cycles /Lifetime	Energy Density(wH/L)	Conversion Efficiency
Lithium Ion Battery	8 hours	1,000 – 10,000 Cycles	200 – 400	85 – 95%
Flow Battery	8 Hours	12,000 – 14,000 Cycles	2 – 6	60 – 85%
Lead Acid Battery	8 Hours	6 – 40 Years	50 – 80	80 – 90%
Hydrogen	1 Week	5 – 30 Years	600 (at 200bar)	25 – 45%
Molten Salt	Hours	30 Years	70 – 210	80 – 90%
Pumped Hydro	16 Hours	30 – 60 Years	0.2 – 2	70 – 85%
Compressed Air	30 Hours	20 – 40 Years	2 – 6	40 – 70%
Flywheel	Minutes	20,000 – 100,000 Cycles	20 - 80	70 – 95%

Source: EESI (2019)

Recycled Batteries

Currently, less than 5 percent of Lithium-ion batteries in the United States are recycled. Since the majority of key Lithium ion battery are only accessible overseas, DOE has made it a priority to develop the battery recycling industry within the US and seeks to recycle 90 percent of domestic lithium battery technologies (DOE 2019e).

Recommended Initiatives

The following charts describe the two recommended initiatives selected for energy storage technologies. These initiatives recognize that lithium-ion batteries are the dominant technology type while seeking to diversify energy storage technology deployments. At the utility-scale, all energy storage technologies offer more value if they are able to provide longer durations of storage. However, in the short-term, lithium-ion batteries are expected to dominate deployments of energy storage systems and addressing their environmental and supply chain impacts can reduce LCOE for these battery systems.

Initiative ESS.1: Lengthen Storage Duration of Energy Storage Systems (8-hour or greater)

Description and Characteristics	Energy storage systems are limited by the amount of time they can store and discharge energy. Most storage systems have storage capabilities which last from minutes to a few hours. Longer duration storage systems are necessary to mitigate the future effects of increased penetration in variable renewable resources such as solar power. Utility-scale long duration storage systems can be both behind and in front of the meter. There is a great demand for systems that can be paired with solar power in particular to ease variability and provide a baseload power. Energy storage systems also serve a valuable function when not paired with a specific generating asset as they can provide a variety of services from voltage control to instantaneous black-start power. The increasing need for fast start energy due to massive solar PV installations will require large amounts of available power on stand-by which can be provided by long duration storage. Current solar PV installations are not likely to be retrofitted with behind the meter storage, so separate storage installations fill a specific utility need. The increase in storage time above 8 hours would ensure the constant availability of excess energy. A push toward days-long storage would ensure energy availability even during prolonged times of decreased renewable output. Problems with variability and potential low renewable production will be exacerbated as additional renewable power comes online to meet SB-100 goals.
Impacts	Longer duration storage could help reduce renewable generation curtailment, reduce natural gas ramping requirements to meet evening peak demand, and even shift excess renewable generation to days and/or seasons that have less generation. Additionally, long duration storage will alleviate concerns surrounding increased renewable integration on the grid.
Estimated Potential Impact on SB-100	Even being able to provide 8 hours of storage, an estimated 85 GW of energy storage capacity will be required by 2045 to support the electric grid. An increase from 8 hours to 10 hours of energy storage capability on average would reduce the necessary of energy storage capacity by

	17 GW for 2045 (2045 SB-100 goals discussed in Current California Energy Mix and Future Expectations for SB-100 in Chapter 1).
Areas for Advancement	The following energy storage technologies are capable of providing greater than 8-hours of economic energy storage: Lithium-ion Battery Improvements, Small-Scale Pumped Hydro Storage, TES, Hydrogen, Compressed Air Energy Storage, Flow Batteries. Any energy storage technology that can achieve long-term energy storage should be supported.
Technology Baseline, Best in Class	Maximum duration of many energy storage technologies shown in Table above.
Metrics and/or Performance Indicators	Utility-scale energy storage systems should be able to provide 10-12 hours of storage.
Success Timeframe	Mid-term (3-5 years)
Key Published References	Navigant (2018), Dyer (2018)
Correlation with Ongoing CEC efforts	EPIC 2018-2020 Investment Plan – Initiative 3.4.1: Assessment and Simulation Study of the California Grid with Optimized Grid-Level Energy Storage EPIC 2018-2020 Investment Plan – Initiative 4.3.1: Making Flexible-Peaking Concentrating Solar Power with Thermal Energy Storage Cost Competitive

Initiative ESS.2: Optimize Recycling Processes for Lithium-Ion Batteries

Description and Characteristics	In the coming decades there is expected to be terawatt hours of used electric vehicle (EV) batteries in addition to the gigawatt hours of stationary battery storage, nearly all of which are currently lithium-ion technologies. However, there is currently a dearth of lithium-ion battery recycling programs in California. Without recycling programs, these batteries will either be thrown away or sent out of state or out of country

for repurposing or recycling. There is a massive lost opportunity without recycling since many materials in lithium-ion batteries are expensive and primarily sourced outside of the United States.

Lithium-ion batteries also potentially pose a serious environmental hazard if recycling is not done properly. Sending used batteries out of California is a massive lost opportunity for the state as keeping the battery materials in-state could create new markets for recycled battery materials and components and spur California's battery manufacturing industry.

Impacts

Battery recycling in California represents a huge economic opportunity which could help create new markets for battery manufacturing and ultimately reduce the costs of batteries using materials recycled in California. Many materials in lithium-ion batteries, such as cobalt, are expensive and sourced almost entirely out of the US. Keeping these materials in California through battery recycling would open opportunities to reuse these materials in battery manufacturing, helping to lower the costs of battery manufacturing. California needs targeted market and business drivers to encourage in-state battery recycling in order to capture this economic opportunity. Additionally, this initiative would reduce environmental impacts of discarded or improperly dismantled batteries.

Estimated Potential Impact on SB-100

This initiative will improve environmental outcomes associated with lithium-ion energy storage. With lithium-ion batteries slated to be the primary type of energy storage system installed over the next 25 years, the proper disposal of these systems will be necessary.

Recycling of lithium-ion batteries will impact system installation costs due to shorter lifespans (10-15 years). Reduction in recycling costs can therefore help spur new installations and financing.

This initiative will impact 100 MW of lithium-ion batteries currently operating in California and an additional 600 MW of contracted and announced lithium-ion installations. Any future installations between now and 2030 would also be impacted by before the end of SB-100's timeframe in 2045.

Areas for Advancement	Streamlined recycling processes; metal and material extraction processes; battery manufacturing from recycled materials. Battery disposal; battery manufacturing; material recycling/repurposing.
Technology Baseline, Best in Class	Less than 5 percent of Lithium-ion batteries in the United States are recycled
Metrics and/or Performance Indicators	DOE target of 90 percent rate of recycling for lithium-ion batteries.
Success Timeframe	Mid-term (3-5 years)
Key Published References	Engel et al. (2019), Battery University (2019), Duesenfeld (2019), Walton (2019)
Correlation with Ongoing CEC efforts	EPIC 2018-2020 Investment Plan – Initiative 3.2.2: Battery Second Use EPIC 2018-2020 Investment Plan – Initiative 7.3.3: Improve Lifecycle Environmental Performance in the Entire Supply Chain for the Electricity System

Energy Storage Considerations

Provided here (in no particular order) are some of the notable considerations aligned with the energy storage technology area. These considerations include opportunities, barriers, and potential related technologies for future advancement.

The most important performance characteristics are site- and use-dependent for energy storage systems. Energy storage performance can be judged by a variety of factors including power output, energy density, and efficiency. The relative importance of these factors is determined by the specific use case of energy storage systems. Focusing on developing systems that are customizable and modularizable would make them more attractive to a variety of customers with diverse use cases. System performance across the board will improve as technologies continue to be demonstrated and funded.

A standardized way to judge energy storage system performance would be beneficial. In California, the grid requires technologies that can store and deliver power quickly to adequately handle the variability created by solar and wind installations. The performance characteristics that are most important to the California grid should be communicated and incentivized properly by California's energy markets.

Recommend a focus on application and performance attributes that are needed for a decarbonized electric grid. Improvements are needed in systems and performance across multiple areas in order to develop a decarbonized grid. Performance standards for a decarbonized grid need to be discussed and modeled in order to discover the best route towards decarbonization. Multi day and seasonal system modeling of renewable energy generation, storage capabilities, and grid technologies can provide insights on which performance improvements provide the greatest benefit towards decarbonization.

A focus on improving the round-trip efficiency of batteries would help improve economics. This is especially true for flow batteries. Batteries are incapable of releasing all their stored energy, as some is lost in the process of storing and discharging it. Improving round trip battery efficiency will decrease the amount of energy that is lost, maximizing energy storage system capabilities.

Storage duration needs to be longer. Storage duration is becoming an increasingly important feature of energy storage projects as more variable generation is introduced on the grid. While short-duration storage has shown viability to shave peak demand during high-stress hours on the grid and provide other ancillary services, to deal with long-term lulls of renewable production, longer-duration storage is required.

Energy storage must avoid technology lock-in to prevent new technologies with potentially better performance for certain applications from entering the market. The increased penetration and manufacturing of lithium-ion batteries is threatening the viability of other types of storage. Lithium-ion batteries suffer from poor performance in certain areas, such as a high degradation of cycle life over time. Other types of energy storage, such as flow batteries, thermal batteries, and mechanical storage, have characteristics that make them more attractive for applications such as voltage regulation, long-duration storage, and heating and cooling. New technologies cannot improve without moving from the laboratory scale to pilot projects and full-scale demonstrations. The true value and cost of a technology cannot be determined accurately until it is demonstrated.

The costs associated with energy storage can be broken into two categories: the cost of capacity ($/kW) and the cost of electricity ($/kWh). Based on the application, these two costs should be considered separately when evaluating a system's long-term viability and profitability. While the cost of capacity remains high for underdeveloped systems, these systems have the potential to operate for many years. Underdeveloped systems include compressed air energy storage (CAES), flywheels, and molten salt storage. As energy storage systems work to provide long-duration storage, the cost of electricity will be a more effective way to determine technologies' value to the grid than the cost of capacity.

Energy storage technologies can provide a bevy of valuable services, but it is difficult to decide which use is the most valuable for the operator and the grid at any given time. The value stacking of energy storage services will be better understood as energy storage systems continue to be deployed. However, the outlook for value stacking is currently focused on the short term. While one operation mode may best serve the grid today, an understanding of the changing nature of the electricity grid will prevent these systems from losing their value in the future.

Energy storage systems can also be used for both distributed generation and utility-scale generation. A contract and market structure that values energy storage services in a way that unlocks their full value for the grid is in California's best interest but must be researched further. It is possible that distributed energy storage systems provide a greater value to the grid, and resources and investment should be focused on those technology scales. Distributed advancements still have the potential to help increase the performance and cost characteristics of utility-scale systems, and the Energy Commission should pursue overlapping research opportunities.

The market structure in California has a harder time capturing the true value of ancillary services provided by energy storage. While some ancillary services such as grid regulation and system and local capacity are currently valued appropriately, flexibility and avoiding curtailment are not. Grid operators should determine which energy storage capabilities are most useful to the grid so storage providers can be incentivized to provide those services.

Challenges with grid integration and interconnection are driven primarily by the type of energy storage technology. Pumped hydropower and CAES systems have many more environmental and permitting challenges than smaller lithium-ion or other battery systems that can be sited flexibly to avoid these issues. These challenges must be considered when accounting for the time and cost of a larger energy storage project. Some standardized processes could help reduce the costs of interconnection and address some of the complexity presented by a specific site and technology. Avoiding a long wait time for interconnection will reduce risks and potential costs associated with grid interconnection.

The true amount of energy storage capacity needed on the grid is unknown. Energy storage smooths variability, but without adequate long-duration storage, long periods of sun or wind deprivation will limit the amount of renewable energy available to the grid and increase the need for fast-start energy and non-variable renewable production. A greater understanding of how often these deficit scenarios occur and predictions of population, electrical load, and renewable energy production are necessary to accurately estimate the need for energy storage. If more non-variable renewable sources are integrated into the grid, the amount of energy storage needed to ensure grid reliability will be less.

The expectation that smaller behind-the-meter systems will contribute grid services also creates several complicated integration considerations. The integration of behind-the-meter energy storage as a utility-scale asset requires advanced meters that can respond to price signals. It will is more difficult for grid operators to utilize behind-the-meter systems for ancillary services than energy storage systems connected directly to the grid.

California is currently reliant on imports of batteries, mainly from China. The materials and manufacturing of energy storage technologies are not significant barriers to deployment due to a current abundance of manufacturing capability in China. However, California can increase its control of the supply chain for energy storage devices by domestically procuring lithium through geothermal brines in the Salton Sea and recycling retired batteries. Additionally, California can learn from the example set in Nevada with the development of the Tesla Gigafactory to create its own in-state manufacturing capabilities.

Local manufacturing and lithium production would reduce transportation costs. In state manufacturing and recycling would also limit environmental impacts due to creation, transport, and recycling of lithium-ion batteries. California also has an opportunity to become a manufacturing and production leader in new thermal, electrochemical, and mechanical energy storage devices that will soon be demonstrated at scale.

Despite providing most grid storage capacity, Pumped Hydro Storage has limitations. Pumped hydro storage systems are limited by site selection. A feasible location must have the capability to maintain two large reservoirs of water with a significant elevation difference between them. The efficiency of pumped hydro power systems is limited due to it being a mechanical form of energy storage. There are battery systems which have higher efficiencies than pumped hydro systems. Pumped hydro systems also have environmental issues such as requiring large amounts of water which could lower plant efficiency when droughts occur.

TES will benefit California by providing flexible, dispatchable energy generation. TES provides a method to store larger amounts of energy for longer timescales than many other current storage technologies. TES systems integrated with concentrated solar power or geothermal can maintain high efficiency by storing the heat transfer fluid produced during the day and releasing it to produce energy when the grid requires it. TES can also be provided by concrete materials which are readily available and can withstand the high temperatures that are used for CSP. Concrete TES can also reheat compressed air required for efficient operation of CSP systems by reusing heat of compression avoiding the need to burn natural gas to generate heat.

Green Hydrogen has applications in bioenergy, CSP, and geothermal production and along with renewable natural gas can provide long-term storage options While current methods of hydrogen production often require the use of fossil fuels to split water, there are multiple alternatives which do not require processes that emit carbon dioxide. These processes include splitting water using the same solar concentrators used for CSP as well as producing biohydrogen using biomass and waste. Hydrogen is readily storable as a molecule and can be stored for long periods of time without having energy dissipate.

CHAPTER 4: Technology/Knowledge/Market Transfer Activities

Energetics' Team included experts in solar energy, wind energy, geothermal energy, bioenergy, energy storage, and grid integration. A diverse team of experts was engaged to conduct the initial research and outreach, identifying barriers and opportunity areas in the various technology areas of study. This foundational multi-disciplinary teamwork served as the baseline for establishing the recommended initiatives. The project team went on to impart their individual expertise by providing commentary, review and verification.

Knowledge transfer and supporting market adoption was the rationale for involving outside project contributors. Experts in California and beyond were engaged through interviews during the TA research phase of the project to expand the scope of analysis and experience. Roadmapping webinars and surveys were conducted to further engage selected subject matter experts to verify and solidify the barriers and opportunity areas identified.

The knowledge transfer was expanded to include the general public through two public webinars. These webinars shared information and collected feedback from the public on the recommended initiatives. The first public webinar took place on June 28, 2019, and provided an opportunity to share and gather feedback on the preliminary roadmap draft, including the initial 20 initiatives. 107 comments were collected during the public webinar and comment submittal process. A second public webinar presentation will take place in the beginning of 2020 to present the final results of the roadmap and the final recommended initiatives developed for the Energy Commission.

CHAPTER 5: Conclusions/Recommendations

Utilizing a broad approach of research across multiple renewable energy technology areas will enable California to avoid technology lock-in and advance a diverse approach to meet SB-100 goals. This Utility-Scale Renewable Generation Technology Roadmap provides the Energy Commission a selection of initiatives to guide RDD&D activities across nine technology areas: solar photovoltaic, concentrated solar power, land-based wind, offshore wind, bioenergy, geothermal power, small hydropower, grid integration technologies, and energy storage systems.

Through a literature review, expert interviews and surveys, and multiple expert and public webinars, the roadmapping project has produced both a TA and this Research Roadmap. While the TA focused on the current state of renewable energy resources and research efforts in both California and nationally, the Research Roadmap pinpoints recommended initiatives which fill current technology gaps. Accompanying the initiatives are performance baselines and targets to show both the current state of each technology area as well as the anticipated impact on the technology type. These recommended initiatives can all also reduce the cost of renewable energy systems and/or increase renewable energy produced for electric ratepayers in California. Below is a high-level summary of recommendations for each technology area.

Solar PV

Solar photovoltaics remain in an ideal position to continue being deployed as a renewable energy resource in the state. Already the largest source of renewable energy, low costs and a large technical capacity continue to make it an attractive option. Testing new solar cells in the field will enable the acceleration of real-world experience for new solar technologies, providing valuable information and increasing future reliability. As PV modules continue to be deployed in increasing quantities, methods of cell recycling can decrease PV decommissioning costs and lower system capital costs by creating a revenue stream for modules at the end of their lifespan.

Concentrated Solar Power

CSP systems are proven to be effective in California and the state remains attractive for future deployments. Methods to improve dust cleaning will enable CSP power outputs to be reliably maintained over time, increasing energy generation. The development of corrosion resistant materials and heat transfer mediums will enable CSP systems to operate at higher temperatures, increasing system efficiency while decreasing system costs.

Land-Based Wind

California's ideal wind resources are saturated with older wind turbines, limiting the potential for future system development across the state. New construction technologies and methods are required in order to increase the accessibility of the remaining wind resources that are available to harvest. New technologies and onsite manufacturing methods can decrease build time and enable taller wind turbines that can benefit from a higher wind resource. New blade technology can also enable access to lower wind resources by improving turbine efficiency. New blades deployed in low wind areas can produce electricity with less variability than older counterparts in higher wind resource, improving power output and system reliability.

Offshore Wind

Offshore wind represents one of the greatest opportunities for California due to its position as an undeveloped resource. Areas ideal for offshore wind are closer to California's largest load generating areas than other forms of power generation, which will decrease the amount of transmission infrastructure required and the losses due to transmission as a result. Due to California's deepwater coasts, the state is ideally positioned to utilize floating turbines. California can lead on this front, since there are limited demonstrations of other floating wind turbine systems globally. California port infrastructure must also be able to handle wind turbine components so turbines do not have to be shipped from out of state. Another technology type that is undeveloped in California is wave energy. Co-deployment with offshore wind systems will allow this technology to benefit from synergies in transmission and platform use.

Bioenergy

Biomass provides the opportunity to convert waste into energy. The amount of waste available for energy production in California represents a high technical capacity, with most of the feedstock coming from agricultural, forestry, and municipal solid waste. Opportunities exist to expand bioenergy production by improving pre-treatment of waste used to produce biogas and the post production cleaning of syngas. By improving pretreatment and cleaning respectively, production yields can increase, producing more gas for energy while reducing costs.

Geothermal

While geothermal has been a key part of California's energy mix since the 1960s, just under 3,000 MW out of the known 20,000 MW available has been tapped for energy production, making it a widely available resource that is waiting for new developments to take place. Despite its wide availability, geothermal systems are costly due to the process of siting and drilling for geothermal resources. Improvements in site assessment and drilling for potential enhanced geothermal sites can reduce these upfront costs. New materials for geothermal systems which reduce the amount of corrosion caused by brines can reduce both maintenance time and cost, enabling plants to produce more energy and minimize their time offline.

Small Hydro

Small Hydropower utilizes California's existing water supply and infrastructure to generate smaller amounts of power than a typical hydropower deployment. Multiple opportunities exist for small hydropower in new stream developments, powering non powered dams, and installing in conduit systems in existing aqueducts and pipes. The cost of small hydropower is variable due to every development site having a unique hydrology, leading to projects that can either be competitively priced or too expensive for their power output. Methods to standardize interconnection of small hydro systems can reduce system costs and complexity.

Grid Infrastructure

Grid infrastructure improvements will be necessary to handle the shifting loads that result from an overreliance on variable renewable energy and ever expanding renewable installations. Implementing more smart inverters across the grid can enable more communication between grid systems and system operators, mitigating potential hazardous grid events. Separately, the development of offshore high voltage cables will enable offshore wind resources to be incorporated into the state grid more efficiently.

Energy Storage

Energy storage enables a shift in renewable energy from peak generation to peak load, which is necessary to meet SB-100 goals while ensuring grid reliability. Future energy storage systems must be able to store and discharge energy on time scales longer than currently available from most energy storage technologies. Long duration storage will support renewable energy growth by reducing energy curtailment and decreasing the amount of natural gas ramping required in the evenings. However, continued deployment of battery storage systems will also necessitate the development of disposal methods. Developing a recycling industry provides a new opportunity for California to limit costs of importing materials necessary for lithium-ion battery production, often from foreign nations.

GLOSSARY

Term/Acronym	Definition
AD	Anaerobic Digestion
AM	Additive Manufacturing
BIO	Bioenergy
BOEM	The Bureau of Ocean Energy Management
CAES	Compressed Air Energy Storage
CAISO	California ISO
CEQA	California Environmental Quality Act
CSP	Concentrated Solar Power
DOE	U.S. Department of Energy
DRECP	Desert Renewable Energy Conservation Plan
EGS	Enhanced Geothermal System
EIA	Energy Information Administration
EPIC	Electric Program Investment Charge
ESS	Energy Storage Systems
EV	Electric Vehicles
GEO	Geothermal Power
GIT	Grid Integration Technologies
GW	Gigawatt
GWh	Gigawatt-hour
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IoT	Internet of Things
IOU	Investor Owned Utility
KGRA	Known Geothermal Resource Areas

KW	Kilowatt
KWh	Kilowatt-hour
LBW	Land-Based Wind
LCFS	Low Carbon Fuel Standard
LCOE	Levelized Cost of Energy
MFC	Microbial Fuel Cell
MSW	Municipal Solid Waste
MW	Megawatt
MWh	Megawatt-hour
NREL	National Renewable Energy Laboratory
OSW	Offshore Wind
PSH	Pumped Storage Hydropower
PV	Photovoltaics
R&D	Research and Development
RDD&D	Research, Development, Demonstration, and Deployment
RNG	Renewable Natural Gas
RPS	Renewable Portfolio Standard
SB-100	Senate Bill 100
SHP	Small Hydropower
SPV	Solar PV
TES	Thermal Energy Storage
THP	Thermal Hydrolysis Pretreatment
Wdc	Watts direct current
WRA	Wind Resource Area
WWTP	Waste Water Treatment Plants

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APPENDIX A: Calculations related to SB-100

Included here are the calculations that support estimates provided throughout this roadmap. These estimates center around predictions for 2030 and 2045 renewable production and the relationship to SB-100 goals.

Current California Energy Mix and Future Expectations for SB-100

2030 Consumption Estimate: 340,000 GWh (Rounded from 339,160)

This mid-range estimate from the model predicts an increase of 1.27% annually from 2016 onward. Applying this to the 2030 estimate yields:

$$340{,}000\ GWh\ (1\ +\ 0.0127)^{15} =\ 411{,}000\ GWh$$

Goal for 2045 estimated at 411,000 GWh

Renewable Targets

Both calculations for SB-100 Goals assume constant electricity generation from Large Hydro in the future.

Nuclear production is expected to decrease to zero by 2045 due to the last remaining nuclear generators in the state (both at Diablo Canyon) scheduled to be retired in 2024 and 2025 (Walton 2018).

SB-100 2030 Renewable Targets: 60%.

$$340{,}000\ GWh * 60\%\ Renewable\ Target\ =\ 204{,}000\ GWh$$

$$\begin{aligned}204{,}000\ GWh\ 2030\ Target - 63{,}028\ GWh\ 2018\ Instate\ Renewable\ Generation \\ = 141{,}000\ GWh\ new\ renewable\ generation\ required\ for\ 2030\end{aligned}$$

SB-100 2045 Low Carbon Sources Target: 100%.

$$411{,}000\ GWh * 100\%\ Clean\ Energy\ Target\ =\ 411{,}000\ GWh$$

$$\begin{aligned}411{,}000\ GWh\ 2045\ Target - 63{,}028\ GWh\ Instate\ Renewable\ Generation - 22{,}096\ Large\ Hydropower \\ = 326{,}000\ GWh\ new\ renewable\ generation\ required\ for\ 2045\end{aligned}$$

For the purpose of this roadmap, the anticipated 2030 and 2045 Renewable Energy Mix is as follows. Capacity factors held constant.

$$\frac{204{,}000\ GWh\ 2030\ Renewable\ Target}{63{,}028\ GWh\ 2018\ Renewable\ Generation} = 324\%\ Higher\ for\ 2030$$

$$\frac{388{,}904\ GWh\ 2045\ Renewable\ Target}{63{,}028\ GWh\ 2018\ Renewable\ Generation} = 617\%\ Higher\ for\ 2045$$

Table C19: Projection of Renewable Capacity and Generation in 2030 and 2045

Renewables	2018 Total (GWh)	2030 Projection (GWh)	2045 Projection (GWh)	2018 Total (MW)	2030 Projection (MW)	2045 Projection (MW)
Biomass	5,909	10,784*	10,784*	1,274	2,325*	2,325*
Geothermal	11,528	37,312	71,132	2,730	8,836	16,845
Small Hydro	4,248	7,272**	7,272**	1,756	3,006**	3,006**
Solar PV	24,488	94,829	197,147	10,658	41,273	85,805
Solar Thermal	2,545	8,237	15,704	1,249	4,043	7,707
Wind	14,078	45,566	86,866	6,004	19,433	37,047
Total	63,028	204,000	388,904	23,671	78,915	152,735

*Biomass maximum theoretical potential given below is 4.65 GW. 2030 and 2045 totals have been set to a maximum of 50% of the recoverable potential (2.33 GW). Solar PV given balance of generation to reach SB-100 goals.

**Small hydropower undeveloped theoretical potential given below is 2.5 GW. 2030 and 2045 totals have been set to reflect an increase that is 50% of that theoretical potential (1.25 GW). Solar PV given balance of generation to reach SB-100 goals.

Renewable Technology Area Maximum Technical Potential in Relation to SB-100 Goals

All Maximum Potential Estimates use the estimated resource availability of the technology area. This GW total is multiplied by the number of hours in the year to give the maximum theoretical energy production from the technology area in GWh. This GWh total is then multiplied by the 2018 Statewide Capacity Factor to provide an estimate of total available electricity from each technology area.

The GWh estimate for total available electricity is divided by the 2030 and 2045 renewable targets provided above to demonstrate how much each resource can theoretically contribute to SB-100 goals at full statewide installation.

While these totals are not expected to every reach 100 percent installation, higher totals indicate that it will be easier to access resources in the short-term.

Solar PV: Potential for Reaching SB-100 Goals

Capacity Factor: 26.2 percent

Estimated Maximum In-state Resource: 4,100 GW

$$4{,}100\ GW * \frac{8760\ Hours}{1\ Year} * 26.2\%\ Capacity\ Factor = 9{,}410{,}000\ GWh$$

$$\frac{9{,}410{,}000\ GWh}{326{,}000\ GWh\ 2045\ SB100\ Goal} = 29{,}000\%$$

Solar CSP: Potential for Reaching SB-100 Goals

Capacity Factor: 23.3 percent

Estimated Maximum In-state Resource: 2,700 GW

$$2{,}700\ GW * \frac{8760\ Hours}{1\ Year} * 23.3\%\ Capacity\ Factor = 5{,}510{,}000\ GWh$$

$$\frac{5{,}510{,}000\ GWh}{326{,}000\ GWh\ 2045\ SB100\ Goal} = 17{,}000\%$$

Land-Based Wind: Potential for Reaching SB-100 Goals

Capacity Factor: 26.8 percent

Estimated Maximum In-state Resource: 128 GW

$$128\ GW * \frac{8760\ Hours}{1\ Year} * 26.8\%\ Capacity\ Factor = 301{,}000\ GWh$$

$$\frac{301{,}000\ GWh}{326{,}000\ GWh\ 2045\ SB100\ Goal} = 92\%$$

Offshore Wind Potential: Potential for Reaching SB-100 Goals

Anticipated Capacity Factor: 40 percent

Estimated Maximum In-state Resource: 160 GW

$$160\ GW * \frac{8760\ Hours}{1\ Year} * 40\%\ Capacity\ Factor = 561{,}000\ GWh$$

$$\frac{561{,}000\ GWh}{326{,}000\ GWh\ 2045\ SB100\ Goal} = 180\%$$

Offshore fixed bottom potential

Anticipated Capacity Factor: 40 percent

Estimated Maximum In-state Resource: 9 GW

$$9\ GW * \frac{8760\ Hours}{1\ Year} * 40\%\ Capacity\ Factor = 31{,}500\ GWh$$

$$\frac{31{,}500\ GWh}{326{,}000\ GWh\ 2045\ SB100\ Goal} = 10\%$$

Wave Energy Resource Assessment

Anticipated Capacity Factor: 20 percent

Estimated Maximum Theoretical In-state Resource: 37 GW

Only 20% of the theoretical resource is estimated to be technically feasible to collect.

$$37\ GW * 20\%\ technically\ feasible * \frac{8760\ Hours}{1\ Year} * 20\%\ Capacity\ Factor = 13{,}000\ GWh$$

$$\frac{13{,}000\ GWh}{326{,}000\ GWh\ 2045\ SB100\ Goal} = 4.0\%$$

Bioenergy: Potential for Reaching SB-100 Goals

Capacity Factor: 52.9 percent

Estimated Maximum In-state Resource: 4.65 GW

$$4.65\ GW * \frac{8760\ Hours}{1\ Year} * 52.9\%\ Capacity\ Factor = 21{,}500\ GWh$$

$$\frac{21{,}500\ GWh}{326{,}000\ GWh\ 2045\ SB100\ Goal} = 6.6\%$$

Bioenergy (specifically biogas or renewable natural gas) can be a direct replacement for Natural Gas making it an ideal renewable energy source to use in existing infrastructure. Below is an estimate of the amount of Natural Gas that can theoretically be replaced with bioenergy.

$$\frac{21{,}500\ GWh}{90{,}691\ GWh\ 2018\ Natural\ Gas\ Electricity\ Generation} = 23.7\%$$

Geothermal: Potential for Reaching SB-100 Goals

Capacity Factor: 48.2 percent

Estimated Maximum In-state Resource: 5.4 GW Conventional + 48.1 GW EGS = 53.5 GW

$$(5.4\ GW\ Conventional\ Geothermal + 48.1\ GW\ EGS) * \frac{8760\ Hours}{1\ Year} * 48.2\%\ Capacity\ Factor$$
$$= 226{,}000\ GWh$$

$$\frac{226{,}000\ GWh}{326{,}000\ GWh\ 2045\ SB100\ Goal} = 69\%$$

Small Hydro: Potential for Reaching SB-100 Goals

Capacity Factor: 27.6 percent

Estimated Maximum In-state Resource: 2.5 GW

$$2.5\ GW * \frac{8760\ Hours}{1\ Year} * 27.6\%\ Capacity\ Factor = 6{,}040\ GWh$$

$$\frac{6{,}040\ GWh}{326{,}000\ GWh\ 2045\ SB100\ Goal} = 1.8\%$$

Energy Storage: Potential for Reaching SB-100 Goals

Rough assumption of 20 percent of power provided by renewables for 18 hours a day and 100% of power provided by renewables for 6 hours a day (estimated time with direct sunlight) would yield:

$$\begin{aligned} 411{,}000\ GWh\ 2045\ Target * \frac{18\ hours}{24\ hours} * 20\%\ of\ Power\ from\ Renewable + \ 411{,}000\ GWh\ 2045\ Target \\ * \frac{6\ hours}{24\ hours} * 100\%\ of\ Power\ from\ Renewable \\ = 164{,}400\ GWh\ from\ Renewables\ direct\ to\ Grid \end{aligned}$$

$$\begin{aligned} 411{,}000\ GWh\ 2045\ Target - 154{,}000\ GWh\ from\ Renewable\ direct\ to\ Grid \\ = 246{,}600\ GWh\ in\ Storage\ Required \end{aligned}$$

Assumption is average grid storage length will be 8 hours by 2045. This would provide an overall capacity factor of 33 percent.

$$\frac{246{,}600\ GWh}{8760\ hours} * \frac{1}{33\%\ Capacity\ Factor} = 85\ GW\ of\ 8\ Hour\ Storage$$

Calculations of Initiatives' Potential for Reaching SB-100 Goals

Initiative SPV.1: Field Test Tandem Material PV Cells

Estimates for increases in Solar PV capacity for this roadmap between 2030 and 2045 are 44,532 MW.

Last Five Years average MW of new installation was 25 MW.

Increase of conversion efficiency from current levels 23 percent to 30 percent would yield a 7 percent increase in capacity for the same surface area.

$$\frac{44{,}532\ MW\ by\ 2030}{25\ MW\ Average\ MW\ per\ Installation} = 1{,}780\ new\ installations\ between\ 2030\ and\ 2045$$

This initiative is expected to have a long-term horizon. Its impact can be estimates by increase in capacity by 7 percent per year for installations between 2030 and 2045:

$$1{,}780\ Installations * 7\% = 125\ Fewer\ Installations$$

At 25 MW per installation, this contribution of this initiative to SB-100 goals assuming 2018 capacity factors is:

$$125\ Fewer\ Installations * 25\ MW\ per\ Installation * 26.2\%\ Capacity\ Factor * 8760\ hrs = 7{,}200\ GWh$$

$$For\ 2045\text{:}\ \frac{7{,}200\ Additional\ GWh}{326{,}000\ GWh\ 2045\ Goal} = 2.2\%\ of\ SB100\ 2045\ Goals$$

Initiative SPV.2: Increase PV Material Recovery from Recycling Processes

4.8 GW of Capacity installed between 2001 and 2018 in California.

Assuming 300 Watts per module and an average panel lifespan of 25 years.

$$\frac{4{,}800{,}000{,}000\ Watts}{300\ Watts\ per\ module} = 16\ Million\ modules\ due\ for\ recycling\ between\ 2025\ and\ 2045$$

It is estimated that the recycling cost of a module is 15 percent per module.

The following is a high-end estimate for cost savings enabled by this initiative:

At a rough cost of $1 per Watt for installed Solar PV (within range of source used for roadmap), recycling costs are:

$$300\ Watts\ per\ Module * \$1\ per\ Watt * 15\% = \$45\ per\ module$$

This is higher than EPRI's estimates of ($10-$30) given in the roadmap but is unknown how many Watts are in the modules used for EPRI's estimates.

The goal of this initiative is to reduce recycling costs from 15 percent of capital costs for each module to 10 percent. A reduction of 5 percent would save:

$$300\ Watts\ per\ Module * \$1\ per\ Watt * 5\% = \$15\ per\ module$$

$$\begin{gathered}\$15\ per\ module * 16{,}000{,}000\ modules\ due\ for\ recycling\ between\ 2025\ and\ 2045\\ = \$240\ million\ in\ recycling\ savings\ by\ 2045\end{gathered}$$

Initiative CSP.1: Improve Cleaning Systems for CSP Mirrors

This initiative is expected to increase plant production 15 percent more than current totals.

Increase in Capacity Factor:

$$\begin{gathered}23.3\%\ 2018\ CSP\ Capacity\ Factor * 15\%\ Increase\ in\ output\ due\ to\ Mirror\ Cleaning\\ = 26.8\%\ Capacity\ Factor\ after\ Improved\ Mirror\ Cleaning\end{gathered}$$

2018 Production from CSP: 2,544 GWh

$$2{,}544\ GWh * 15\%\ Increase\ in\ output\ due\ to\ Mirror\ Cleaning = 382\ GWh\ Increase\ in\ CSP\ Electricity$$

Potential of SB-100 Goals for 2030:

$$For\ 2030\text{:}\ \frac{382\ Additional\ GWh}{141{,}000\ GWh\ 2030\ Goal} = 0.3\%\ of\ SB100\ 2030\ Goals$$

Initiative CSP.2: Advance Materials and Working Fluids for High Temperature TES

A reduction in CSP cost could drive new installation. Even a single new power tower design CSP plant identical to the Ivanpah facility would increase capacity by roughly 400 MW. At current CSP capacity factors, this would equate to an increase in production of:

$$400\ MW * 23.3\%\ 2018\ Solar\ PV\ Capacity\ Factor * 8760\ hours = 816\ Additional\ GWh$$

Percentage of SB-100 Goals for 2030 and 2045

$$For\ 2030\text{: } \frac{816\ Additional\ GWh}{141{,}000\ GWh\ 2030\ Goal} = 0.6\%\ of\ SB100\ 2030\ Goals$$

$$For\ 2045\text{: } \frac{816\ Additional\ GWh}{326{,}000\ GWh\ 2045\ Goal} = 0.3\%\ of\ SB100\ 2045\ Goals$$

Initiative LBW.1: Advance Construction Technologies for Land-based Wind Turbines

Expected increases in wind energy based on above projections are:

$$For\ 2030\text{: } 19{,}433\ MW - 6{,}004\ MW = 13{,}429\ MW\ Increased\ Wind\ Capacity$$

$$For\ 2045\text{: } 37{,}047\ MW - 6{,}004\ MW = 31{,}043\ MW\ Increased\ Wind\ Capacity$$

Advanced cranes are an enabling technology unlocking higher capacity factors. This can reduce the amount of required capacity from wind to reach SB-100 electricity goals.

If California achieves closer to national capacity factors for wind of 34.6 percent, that will reduce expected requirements of wind capacity by:

$$13{,}429\ MW\ Increased\ Wind\ Capacity * \left(\frac{26.8\%\ 2018\ CA\ Wind\ Capacity\ Factor}{34.6\%\ Anticapted\ Capacity\ Factor}\right) = 10{,}400\ MW\ Adjusted\ Wind\ Capacity\ Requirement\ for\ 2030$$

$$31{,}043\ MW\ Increased\ Wind\ Capacity * \left(\frac{26.8\%\ 2018\ CA\ Wind\ Capacity\ Factor}{34.6\%\ Anticapted\ Capacity\ Factor}\right) = 24{,}000\ MW\ Adjusted\ Wind\ Capacity\ Requirement\ for\ 2045$$

This initiative could save between $80,000 and $160,000 in crane rental costs per turbine.

Financially, assuming an average of 4 MW per turbine for these new, larger turbines, this initiative has the following estimated impacts:

$$\frac{10{,}400\ MW\ of\ New\ Capacity\ Expected\ Instate\ by\ 2030}{4\ MW\ Assumed\ Capacity\ per\ Turbine} = 2{,}600\ New\ Turbines\ by\ 2030$$

$$\frac{24{,}000\ MW\ of\ New\ Capacity\ Expected\ Instate\ by\ 2045}{4\ MW\ Assumed\ Capacity\ per\ Turbine} = 6{,}000\ New\ Turbines\ by\ 2045$$

$$For\ 2030\text{: } 2{,}600\ New\ Turbines * \$160{,}000 = \$416\ Million$$

$$For\ 2045\text{: } 6{,}000\ New\ Turbines * \$160{,}000 = \$960\ Million$$

Initiative LBW.2: Demonstrate New Blades that Improve Conversion Efficiency

Increasing converted energy of Wind Turbines can either result in an increase in their rated capacity on average or an increase in their capacity factor if rated capacity is kept the same.

The assumption in this case is that rated capacity is unchanged. An increase in capacity factor of 35 percent would result in a state-wide capacity factor increase from:

$$26.8\%\ 2018\ CA\ Wind\ Capacity\ Factor * 135\% =\ 36.2\%\ Estimated\ Capacity\ Factor$$

Since this initiative has a long-term outlook, the change in capacity factor is anticipated for 2030. Between 2030 and 2045, based on above projections:

$$For\ 2045\text{: } 37{,}047\ MW - 19{,}433\ MW = 17{,}614\ MW\ Increased\ Wind\ Capacity\ between\ 2030\ and\ 2045$$

The 35 percent increase in converted energy would reduce the required MW to:

$$17{,}614\ MW * \frac{26.8\%}{36.2\%} = 13{,}000\ MW$$

This would account for an increase of GWh toward SB-100 goals of:

$$13{,}000\ MW * (36.2\% - 26.8\%) * 8760\ Hours = 10{,}700\ GWh$$

$$For\ 2045\text{: } \frac{10{,}700\ Additional\ GWh}{326{,}000\ GWh\ 2045\ Goal} = 3.3\%\ of\ SB100\ 2045\ Goals$$

Initiative OSW.1: Pilot Demonstration of Floating Offshore Platform Manufacturing

This initiative is viewed as an enabling technology necessary to open deployment of Offshore Wind systems in California.

No Utility Scale Offshore Wind currently exists. Manufacturing would enable the state to set up Port Infrastructure (OSW.2) and move forward with specific offshore wind platform designs.

As an enabling technology, this initiative would open up development of offshore wind power in California. It is feasible that California could support 18 GW of Offshore Wind energy by 2045. The indirect impact of this initiative could therefore be as high as:

$$18{,}000\ MW * 40\%\ Estimated\ Offshore\ Wind\ Capacity\ Factor * 8760\ Hours = 63{,}000\ GWh$$

$$For\ 2045\text{: } \frac{63{,}000\ GWh}{326{,}000\ GWh\ 2045\ Goal} = 19\%\ of\ SB100\ 2045\ Goals$$

Initiative OSW.2: Design Port Infrastructure to Deploy Floating Offshore Wind Technologies

This initiative is viewed as an enabling technology necessary to open deployment of Offshore Wind systems in California.

No Utility Scale Offshore Wind currently exists. Port Infrastructure is required to scale-up deployment of offshore wind in-state. This initiative is linked to manufacturing of Floating Offshore Wind structures in state (OSW.1) as well.

Port infrastructure would unlock potential floating offshore wind and eliminate potential barriers to deployment. A necessary step in creating a feasible offshore wind industry in the long-term.

As an enabling technology, this initiative would open up development of offshore wind power in California. It is feasible that California could support 18 GW of Offshore Wind energy by 2045. The indirect impact of this initiative could therefore be as high as:

$$18{,}000\ MW * 40\%\ Estimated\ Offshore\ Wind\ Capacity\ Factor * 8760\ Hours = 63{,}000\ GWh$$

$$For\ 2045\text{:}\ \frac{63{,}000\ GWh}{326{,}000\ GWh\ 2045\ Goal} = 19\%\ of\ SB100\ 2045\ Goals$$

Initiative OSW.3: Integrate Wave Energy Systems with Floating Offshore Platforms

Wave energy could provide a limited amount of electricity along with deployment of offshore wind. Wave energy systems vary in their installed capacity (and anticipated capacity factors) due to a lack of consensus and development of commercial systems. Sizes from 500 kW to 7 MW have been proposed.

For this assumption, an average capacity of 1 MW operating at 20 percent capacity factor will be used. Additionally, the same potential of 18 GW of Offshore Wind Energy that is possible in California by 2045 will be used. The last assumption is the average Offshore Wind Turbine capacity is 8 MW.

$$\frac{18{,}000\ MW\ of\ Potential\ Offshore\ Wind\ Power}{8\ MW\ per\ Offshore\ Wind\ Turbine} * 1\ MW\ Coupled\ Wave\ Energy\ System\ per\ Turbine$$
$$* 20\%\ Anticipated\ Capacity\ Factor * 8760\ Hours = 3{,}900\ GWh$$

$$For\ 2045\text{:}\ \frac{3{,}900\ GWh}{326{,}000\ GWh\ 2045\ Goal} = 1.2\%\ of\ SB100\ 2045\ Goals$$

Initiative BIO.1: Improve Cleaning Methods to Produce High Quality Biomass-Derived Syngas

No Utility Scale Syngas production. Would be an enabling.

Assumption that syngas development is positioned to increase electricity production specifically from forestry waste. Gasification and pyrolysis technologies are suited for dryer feedstocks which fits well with forestry wastes. Agricultural residues also are available for gasification and pyrolysis. However, the inclusion of animal manure in this category makes it difficult to attribute syngas advances to increases in agricultural residue conversion. Animal manure is typically processed through anaerobic digestion to produce biogas.

The technical potential of forestry waste is estimated at 1.9 GW. At the capacity factor of 52.9 percent seen for bioenergy throughout California, this translates to enabling:

$$1{,}900\ MW * 52.9\%\ Bioenergy\ Capacity\ Factor * 8760\ Hours = 8{,}800\ GWh$$

High-end assumption that improved syngas production helps capture 50 percent of the technical forestry resource:

$$For\ 2045\text{: } \frac{8{,}800\ GWh * 50\%\ Capture}{326{,}000\ GWh\ 2045\ Goal} = 1.4\%\ of\ SB100\ 2045\ Goals$$

Initiative BIO.2: Deploy Thermal Hydrolysis Pretreatment to Increase Biogas Production

This initiative is both an enabling technology and a performance enhancer. For this assumption, the focus is on how this initiative would increase production from current gas facilities.

Landfill and Digester Gas accounts for 295 MW of capacity in state currently. Assumption is that biogas production can be increased 75 percent. A similar 75 percent increase in electricity production is assumed here:

$$295\ MW * 52.9\%\ Bioenergy\ Capacity\ Factor * 8760\ Hours = 1{,}370\ GWh$$

$$1{,}370\ GWh * \ 75\%\ Increase\ in\ Production = 1{,}030\ GWh\ new\ Production$$

$$\frac{1{,}030\ GWh}{141{,}000\ GWh\ 2030\ SB100\ Goal} = 0.7\%\ of\ 2030\ SB100\ 2030\ Goal$$

Initiative GEO.1: Improve Materials to Combat Corrosion from Geothermal Brines

This initiative seeks to increase installations in the Salton Sea region and other known geothermal areas with high salinity contents of underground water. Taking just the Salton Sea, there is an estimated additional development potential of 1.8 GW.

While a lack of development in the region cannot be only attributed to high costs, an alternative to titanium would encourage and enable new development in the region.

Assumption here is a new alloy allows for full development of the Salton Sea region at current geothermal capacity factors:

$$1{,}800\ MW * 48.2\%\ Geothermal\ Capacity\ Factor * 8760\ Hours = 7{,}600\ GWh$$

$$\frac{7{,}600\ GWh}{326{,}000\ GWh\ 2045\ SB100\ Goal} = 2.3\%\ of\ 2045\ SB100\ Goal$$

Initiative GEO.2: Advance Techniques to Assess Potential EGS Development Sites

Enabling technology for EGS. With only 5,400 MW of projected conventional geothermal potential in California, to maintain geothermal's share of the California grid, EGS development is required.

$$For\ 2030\text{: } 8{,}836\ MW - 2{,}730\ MW = 6{,}106\ MW\ Increased\ Geothermal\ Capacity$$

$$For\ 2045\text{: } 15{,}719\ MW - 2{,}730\ MW = 12{,}989\ MW\ Increased\ Geothermal\ Capacity$$

Only 50 percent of geothermal resource in California estimated to be discovered. Initiative expected to increase that percentage to 75 percent:

$$48.1\ GW * 25\%\ Increase\ in\ EGS\ Site\ Discovery * 48.2\%\ Capacity\ Factor\ for\ Geothermal\ Power * 8760\ Hours = \ 51{,}000\ GWh$$

$$\frac{51{,}000\ GWh}{326{,}000\ GWh\ 2045\ SB100\ Goal} = 16\%\ of\ 2045\ SB100\ Goal$$

Initiative GIT.1: Deploy Smart Inverters to Improve Communication and Cybersecurity

Improve system security and safety of existing and new infrastructure. California will have to handle the following approximate new renewable energy capacity:

$$For\ 2030\text{: } 78{,}915\ MW - 23{,}671\ MW = 55{,}000\ MW\ increase\ from\ 2018\ to\ 2030$$

$$For\ 2045\text{: } 152{,}735\ MW - 23{,}671\ MW = 129{,}000\ MW\ increase\ from\ 2018\ to\ 2045$$

In addition to the following new electrical load from renewables:

$$For\ 2030\text{: } 204{,}000\ GWh - 63{,}028\ GWh = 141{,}000\ GWh\ increase\ from\ 2018\ to\ 2030$$

$$For\ 2045\text{: } 388{,}904\ GWh - 63{,}028\ GWh = 326{,}000\ GWh\ increase\ from\ 2018\ to\ 2045$$

Initiative GIT.2: Advance Underwater High-Voltage Infrastructure for Offshore Energy Interconnection

Reduction in line losses by 30-50 percent. Based on anticipated offshore installations, it is possible to achieve 18 GW Offshore Wind Installation by 2045. Line losses can reach 15% for large-scale offshore HVAC systems. A reduction in line losses would yield an increase in power of:

$$18\ GW * 40\%\ Expected\ Capacity\ Factor for\ Offshore\ Wind * 8760\ Hours * 15\%\ Line\ Losses = 9{,}500\ GWh\ Lost$$

$$9{,}500\ GWh * 50\%\ Line\ Loss\ Reduction = 4{,}750\ GWh\ Saved$$

$$\frac{4{,}750\ GWh}{326{,}000\ GWh\ 2045\ SB100\ Goal} = 1.5\%\ of\ 2045\ SB100\ Goal$$

Initiative ESS.1: Lengthen Storage Duration of Energy Storage Systems (8-hour or greater)

Less required Energy Storage capacity lowering overall system costs. An increase in capacity to 10 hours from 8 hours would reduce highest end storage requirements by:

$$85\ GW\ of\ 8\ Hour\ Storage * \frac{8\ Hour\ Storage}{10\ Hour\ Storage} = 68\ GW\ of\ 10\ Hour\ Storage$$

Reduction in storage requirement of:

$$85\ GW - 68\ GW = 17\ GW$$

Initiative ESS.2: Optimize Recycling Processes for Lithium-Ion Batteries

Improved environmental outcomes. Recycling of lithium-ion will impact costs due to shorter lifespan of batteries (10-15 years). Reduction in costs can help spur new installations and financing.

Will impact 100 MW of lithium ion batteries currently operating in California. The 600 MW of contracted and announced lithium-ion installations and any future installations between now and 2030.

APPENDIX B: Considerations for the Energy Commission Outside the Scope of this Roadmap

The following ideas were out of scope for inclusion in the rest of the roadmap but were brought up through the course of the roadmapping process:

1. Tours for Public Information and Education would help spread information on Renewables
2. One commenter expressed general concern over shifting away from Nuclear and Natural Gas generation
3. There is a potential to lower cost of energy through taking account of farmland synergies (cheaper land use)
4. One commenter advocated for a focus on technology readiness level advancement
5. Optimize the design and operation of carbon capture and storage systems

APPENDIX C: Related Initiatives from the Energy Commission and Other Agencies

Solar 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.
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.	
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.

Wind 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.
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.
Bioenergy 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 emissions controls are needed for these low-quality-biogas producing facilities.	Improved air quality would better meet permitting requirements and lead to wider use of biogas that is otherwise emitted or flared.
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.
Geothermal 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.
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.

Energy Storage 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.
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 energy storage technologies. It also conducts research into innovative and emerging energy storage technologies.	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.
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.