

MAY 2019



OPTIONALITY,



FLEXIBILITY



& INNOVATION



**PATHWAYS FOR DEEP
DECARBONIZATION IN CALIFORNIA**

SUMMARY FOR POLICYMAKERS

ABOUT EFI

The Energy Futures Initiative (EFI), established in 2017 by former Secretary of Energy Ernest J. Moniz, is dedicated to addressing the imperatives of climate change by driving innovation in energy technology, policy, and business models to accelerate the creation of clean energy jobs, grow local, regional, and national economies, and enhance energy security. We are fact-based analysts who provide our funders with unbiased, practical real-world energy solutions.

The study was produced with the support of a group of funders to define the existing California clean energy landscape and recommend steps for accelerating the move to meet the state's carbon reduction goals by midcentury.

The analysis and conclusions of this report are solely those of the Energy Futures Initiative. EFI is responsible for its contents.

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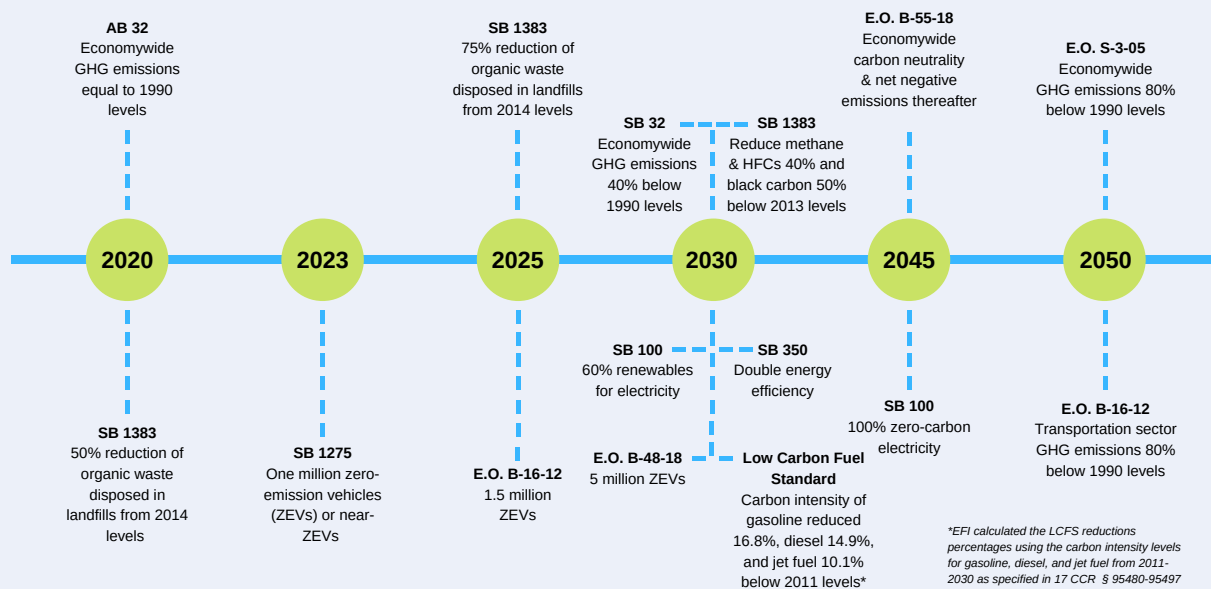
SUMMARY FOR POLICYMAKERS

California is a global leader in climate policy. It has adopted aggressive goals to reach a low-carbon future at a scale and pace needed to meet the underlying Paris commitment of keeping temperature increases to two degrees Celsius, or even significantly lower, by the end of the century. California’s commitment fundamentally translates to an 80 percent (or more) reduction in greenhouse gas emissions (GHG) relative to a 1990 baseline. If California meets its aggressive goals, it will enhance its leadership status, setting an example for the world where, unfortunately, carbon dioxide emissions continue to rise. As the world’s fifth largest economy, what happens in California is critical for shaping the global response to climate change, reinforcing the importance of California’s leadership.

This study analyzes the options—described as “pathways”—for meeting California’s near- and long-term carbon emissions reduction goals. This analysis is designed to work within the parameters of existing state policy; it does not offer explicit policy recommendations.

California’s decarbonization goals include both economywide and sector-specific policy targets (Figure S-1): Executive Order S-3-05 (2005) calls for an economywide emissions reduction of 80 percent by 2050 (from 1990 levels); Executive Order B-55-18 (2018) establishes a statewide goal of carbon neutrality by 2045; SB 100 (2018) requires 60 percent renewable electricity generation (excluding large hydro) by 2030, and net-zero-emissions electricity by 2045. Some policies are more prescriptive (e.g., five million zero emissions vehicles by 2030), while others are less so (e.g., 40 percent reduction of emissions economywide by 2030).

Figure S-1
California’s GHG Emissions Reductions Policy Timeline

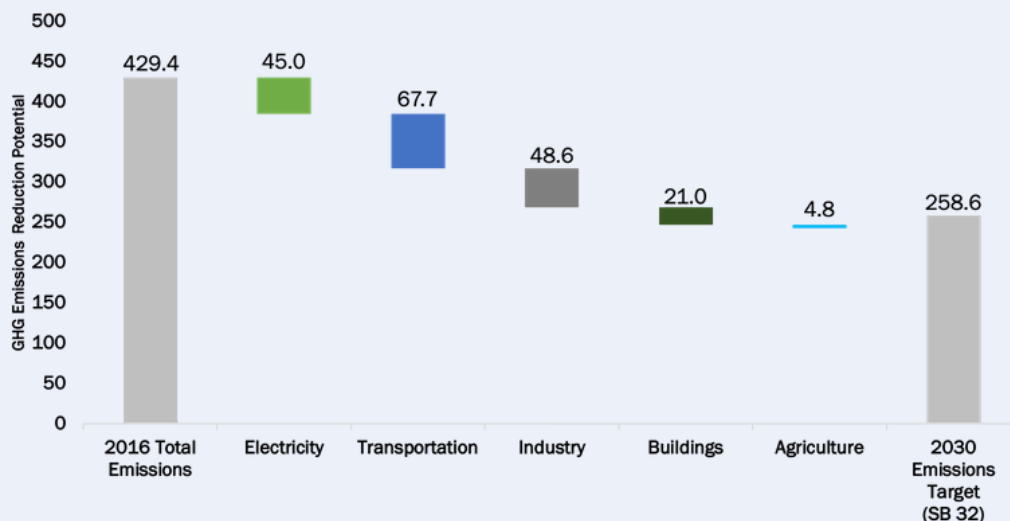


To meet its aggressive GHG emissions reduction goals, California has a number of policies aimed at reducing emissions from various sectors and end uses. Note that bill numbers were used as a shorthand. Source: EFI, 2019

To develop decarbonization pathways and technology options for California, this study focuses on two targets, identifying separate but overlapping tracks: aggressive decarbonization by 2030 and deep decarbonization by midcentury, both from a 2016 baseline. Each target presents its own unique challenges and opportunities. To support these different tracks, the analysis emphasizes the value of technology optionality and flexibility. Over the longer term, managing an economy that has the scale and sector diversity of California's, and is deeply decarbonized, presents dynamic challenges that have not been addressed previously. For both the near and long term, engaging a range of stakeholders is key; energy incumbents and legacy infrastructures may slow the deployment of existing clean technologies in the near term.

The top-level outcome of the analysis: California can indeed meet its 2030 and midcentury targets. Figure S-2 shows meeting the 2030 target will require success across economic sectors (Electricity, Transportation, Industry, Buildings, and Agriculture), with multiple technologies contributing in each.

Figure S-2
Identified Emissions Reduction Potential for Meeting the 2030 Targets by Sector (MMTCO₂e)



California can meet its 2030 target of a 40 percent emissions reduction with commercially available technologies, assuming some incremental improvements and supportive policy and regulatory environments. Emissions reduction strategies will have to accommodate and address policy interactions and business decisions. As such, technology pathways may not be additive.
Source: EFI, 2019

Achieving deep decarbonization in the midcentury timeframe will depend on innovation, including in clean energy technologies that cut across sectors. Meeting emissions reductions goals while managing their costs will require a strong focus on, and commitment to, technology optionality, flexibility, and innovation. This focus is essential for several critical reasons:

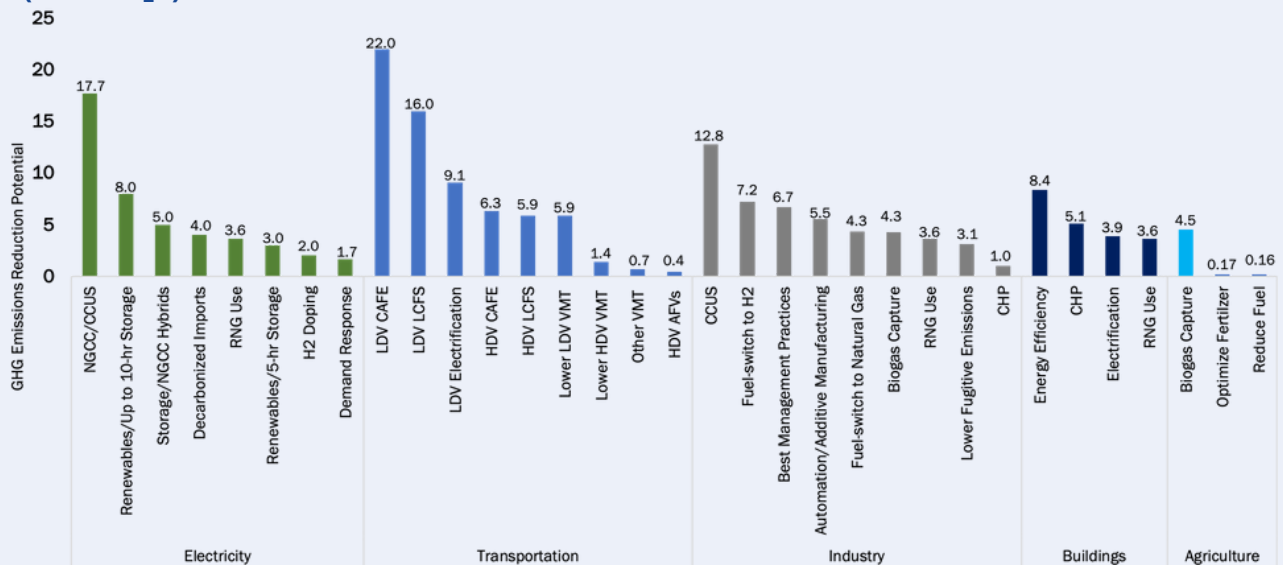
- The energy system must provide essential services (light, heat, mobility, electricity, etc.) reliably at all times;
- The current cost of many important low- and zero-carbon technologies is too high;

- Energy delivery infrastructure must be available, reliable, and secure as the system transforms;
- Affordable negative emissions technologies will ultimately be important at large-scale for deep decarbonization and acceptable stabilization of the earth’s temperature; and
- Success will require aligning the interests and commitment of a range of key stakeholders.

Looking to 2030, this analysis provides a comprehensive, sectoral study of policies and decarbonization options for California. The analysis identifies a portfolio of 33 clean energy pathways that cover all economic sectors in California—including the most difficult-to-decarbonize (e.g., Industry and Agriculture)—and assesses the emissions reduction potential of each (Figure S-3). The portfolio prioritizes technologies with strong technical performance and economics; pathways that augment existing energy infrastructure are emphasized as they can offer significant benefits in terms of cost savings and market readiness. Detailed descriptions of each pathway are found in Part 2 of the report.

Meeting California’s long-term decarbonization targets—including an 80 percent economywide reduction (or more) by 2050 and carbon-free electricity by 2045—will be extremely challenging. Managing and operating a deeply decarbonized energy system over a long duration and at the scale sufficient to meet these goals in an economy the size of California’s is technically very difficult. Technology development timescales are unpredictable; technology cost curves constantly evolve; energy markets can change; public acceptance issues have been problematic in other locations and can contribute to substantial deployment and technology diffusion delays; the supporting infrastructure must be available and funded; and state and national legislative and regulatory environments can shift, constrain, or promote technology choices.

Figure S-3
Identified Emissions Reduction Potential for Meeting the 2030 Targets by Pathways (MMTCO_{2e})



The estimated emissions reduction potential for each pathway is shown by sector. They are based on an attempt to meet California’s target to reduce emissions economywide by 40 percent. This approach attempts to meet the target with an equal share from each economic sector. Source: EFI, 2019

The growing impacts of climate change on energy systems and new and changing supply chains for sustainable energy technologies must be accommodated in policies and planning. Certain clean energy pathways are more susceptible to disruption, such as hydroelectric generation or power lines exposed to wildfires. Materials and metals needed for clean energy technologies may see price spikes or supply disruptions in the future.

These factors imply that detailed, bottom-up analysis of specific pathways, while instructive for meeting 2030 goals, have little value for informing the technologies needed to operate low- to zero-carbon energy systems by midcentury. The near-term focus should be on working as hard as possible to develop many viable options, making it clear that innovation must be at the heart of a decarbonization strategy.

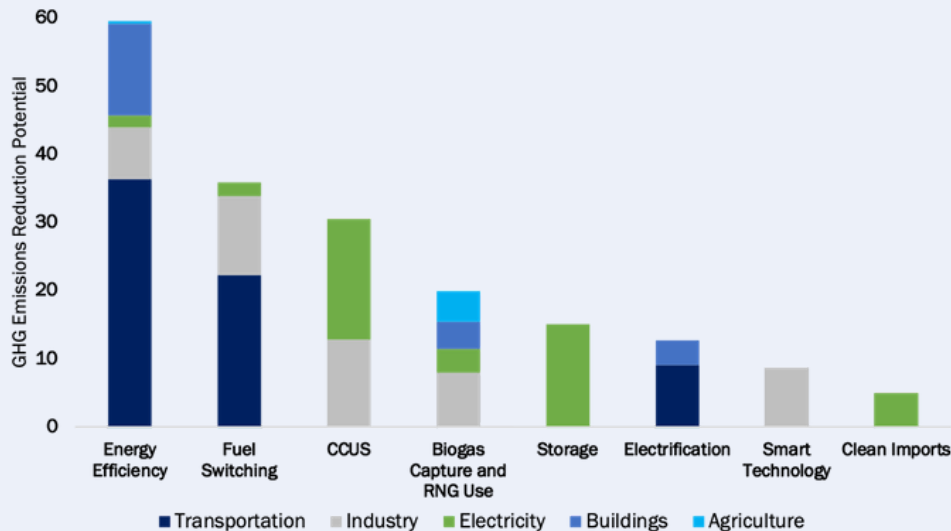
This report presents a “success model” for the longer term, strictly to illustrate both one of the many strategies that could meet long-term goals, as well as to demonstrate the overall difficulty of achieving midcentury goals without having a range of options for doing so. It identifies an analysis-based innovation portfolio for California, focused on technologies with long-term breakthrough potential. Technologies were screened based on California’s existing policies and programs, energy system and market needs, and other distinctive regional qualities that position California to be a technological first mover and global leader (e.g., a strong resource base, relevant workforce expertise, and robust scientific and technological capacity). Eleven breakthrough technologies were identified as major potential contributors to California’s deep decarbonization over the long term, including hydrogen produced by electrolysis, smart systems, floating offshore wind, seasonal energy storage, and clean cement, among others. The pace of research and development work on technologies with breakthrough potential must be accelerated and sustained to meet deep decarbonization goals.

MAJOR FINDINGS FOR AGGRESSIVE DECARBONIZATION BY 2030

- Meeting California’s carbon reduction goals by 2030 will require a range of clean energy pathways across all economic sectors—Electricity, Transportation, Industry, Buildings, and Agriculture (Figure S-4). This is due to the uncertainty of each pathway and the fact that there are no “silver bullet” solutions. There are sufficient commercially available pathways to meet 2030 targets, though some technologies are less expensive and more advanced than others. To meet the 2030 target, however, it is expected that there will be incremental improvements and cost reductions in key technologies, including, for example, carbon capture, utilization, and storage (CCUS) at industrial facilities and natural gas power plants. Notably, the Industry, Transportation, and Agriculture sectors have not seen measurable emissions improvements in recent years.
- California’s ambitious policy to double economywide energy efficiency is an important step for meeting 2030 decarbonization targets. Energy efficiency, defined broadly, is likely to be the most cost-effective approach to decarbonization in the energy end-use sectors in California. This includes technologies and processes that increase fuel efficiency of vehicles (on-road and off-road, including farming equipment in Agriculture); demand-response mechanisms in the Electricity, Transportation, and Buildings sectors; highly efficient end-use technologies in all sectors,

especially Buildings and Industry; and measures, such as smart systems, that reduce energy consumption in sectors with high non-combustion emissions, such as Industry and Agriculture.

Figure S-4
Identified Emissions Reduction Potential for Meeting the 2030 Targets by Cross-Cutting Technologies (MMTCO₂e)



Some decarbonization strategies are applicable to multiple sectors of the economy. Of these, energy efficiency/demand reduction is most significant, representing the largest emissions reduction potential and cutting across all five sectors. Source: EFI, 2019

- California’s decarbonization policy focus on the Electricity sector is important. The latest policy, SB 100, signed into law in September 2018, has a requirement for 60 percent renewable electricity by 2030 and carbon-neutral electricity by 2045. Electricity plays a critical role in California’s decarbonization as it is both a source of emissions (16 percent of statewide emissions in 2016), and is crucial in supporting the decarbonization of all end-use sectors. Because Electricity accounts for only 16 percent of emissions, decarbonization policy in California must extend well beyond the Electricity sector. Electrification of other subsectors, where feasible and desirable, can reduce emissions elsewhere if the Electricity sector is sufficiently decarbonized. Electricity is also relatively easier to decarbonize than other sectors: its emissions are highly concentrated, the sector is highly regulated, and there are multiple clean energy technology options, including CCUS.
- Transportation is the single largest emitting sector in California and requires transformational change to achieve aggressive decarbonization by 2030. Existing policies will have a major impact on the sector’s emissions reduction by 2030. California’s plans for addressing emissions from this sector rely on deploying alternative fuel vehicles, including electric vehicles; increasing vehicle fuel efficiency; decreasing the carbon intensity of fuels; and reducing vehicle-miles traveled. As there are multiple Transportation subsectors that are difficult to decarbonize—heavy-duty vehicles, aviation, marine, and rail—options for achieving deep decarbonization over the long term will go have to extend beyond energy/fuel-based technologies, and will, increasingly, depend on an ecosystem of solutions that includes new infrastructure systems, platform technologies, behavioral incentives, urban design, and advancements in materials science.

- Clean fuels (e.g., renewable natural gas [RNG], hydrogen, biofuels) are critical clean energy pathways due to the enormous value of fuels in providing flexibility and reliability for energy systems. Fuels that are durable, storable, and easily transportable play a fundamental role in ensuring that all sectors can operate at the scale, timing, frequency, and levels of reliability that are required to meet social, economic, and stakeholder needs.
 - ▶ The development of RNG in California has multiple tangible benefits: RNG is a carbon-neutral fuel; RNG diverts methane from being released into the atmosphere, enabling major emissions reductions from the difficult-to-decarbonize Industry and Agriculture sectors; and it leverages existing carbon infrastructure, potentially avoiding the costly stranding of these established systems and their associated workforces, as well as their time-consuming and costly replacement.
- California can meet its 60 percent RPS target by 2030 with continued expansion of wind (both onshore and offshore) and solar resources; some geothermal and increased imports of clean electricity will play a role as well. California will, however, have to manage the significant operational issues that arise from high penetration of intermittent renewables to ensure reliability, manage costs, and minimize system emissions. The Western Energy Imbalance Market, demand response, and increased deployment of energy storage technology including battery storage, pumped hydro, and other technologies will be critical to balancing electricity from intermittent renewables. These options are, however, currently limited in size, and by duration or geography.
- Natural gas generation will continue to play a key role in providing California's electric grid with operational flexibility and system reliability, while enabling the growth and integration of intermittent renewables. Natural gas-fired generation provides key load-following services. It has short- and long-duration applications, including the management of seasonal shifts in demand. As renewable generation has increased, natural gas units, in their balancing role, are being operated for shorter intervals and higher heat rates; this suboptimal operation is increasing their emissions intensity. Battery storage systems can be leveraged with natural gas combined cycle (NGCC) units to smooth their ramping operation, measurably reducing their emissions profile.
- Policies that affect natural gas in some sectors (e.g., building electrification) may have unintended impacts on other sectors that consume and rely on natural gas. These impacts include price volatility, reduced resource availability, and relatively higher infrastructure costs for those sectors that have limited near-term options for decarbonization.

MAJOR FINDINGS FOR DEEP DECARBONIZATION BY MIDCENTURY

- Meeting California's deep decarbonization goals by midcentury will be extremely difficult (if not impossible) without energy innovation. This is due to many challenges inherent in economywide deep decarbonization, including:
 - ▶ Predicting the mix of clean energy technologies needed by 2050. This is extremely challenging. While many studies explore technology pathways over the long term, they cannot be used to prescribe technologies or predict the future and therefore the optimal energy mix by midcentury.
 - ▶ Rising marginal costs of abatement. It is highly likely that these costs will increase over time as the lowest cost opportunities to reduce emissions are widely deployed. This study modeled the cost of reaching deep decarbonization without technology innovation (i.e. a major improvement in performance and/or cost) at \$1,027 per ton of carbon dioxide in 2050, an extremely high cost. This is at or above the cost estimates for several advanced technologies, such as direct air capture.
 - ▶ Performance issues of deeply decarbonized energy systems. Managing a large, carbon-free electric grid offers challenges in terms of operation, design, size, and the growing concerns about the availability of wind and hydro due to climate change, for example. Also, scalable clean technologies are not readily available for meeting deep decarbonization goals in several key applications, including: high-temperature process heat for industry; time-flexible load-following generation; large-scale, long-duration electricity storage; and low-carbon fuels including fuels for heavy-duty vehicles, air transport, and shipping that can be stored for daily, weekly, and seasonal uses.
 - ▶ Deployment of cost-effective and efficient negative emissions technologies are needed by 2045. Technologies that could help achieve carbon neutrality are in relatively early stages of development and include carbon dioxide capture from dilute sources; massive utilization of captured carbon dioxide in commodity products; and both geological and biological sequestration at very large scale.
- There are several cross-cutting technologies or classes of technologies that can help meet the large-scale decarbonization needs for several economic sectors. These include technologies for large-scale carbon management (LSCM), hydrogen applications, leveraging carbon infrastructure and expertise, and smart systems and platforms.
 - ▶ LSCM involves CCUS from both concentrated (stationary point sources) and dilute (atmosphere and oceans) sources. Developing these technologies is a necessity because of the need to mitigate emissions from difficult-to-decarbonize sectors that may lack other suitable decarbonization options (e.g., heavy industry), as well as the need for carbon dioxide removal from the environment at the scale of 100 to 1,000 gigatons by 2100.

- ▶ Hydrogen is an energy carrier that can be produced through multiple production pathways for end uses across the Electricity, Industry, and Transportation sectors. Hydrogen that is produced in a low-carbon manner (e.g., electrolysis with a clean grid; steam methane reforming of natural gas with CCUS) has a considerable potential to assist with decarbonization. For example, it could be used for making high-temperature process heat for industry or as a seasonal storage medium for electricity.
- ▶ Decarbonization pathways are as much about infrastructure as they are about technology. The transition to a low-carbon future could potentially be improved and accelerated by seeking opportunities to leverage existing infrastructure, technological expertise, and a skilled and readied workforce. Repurposing the existing carbon infrastructure—a highly-engineered system-of-systems that spans thousands of miles across California and employs more than 100,000 people, many of whom have skillsets that could be utilized—could enable, accelerate, and improve the performance of the energy sector’s transition to a deeply decarbonized economy. Repurposing existing infrastructures will also help diminish political opposition to the transition to a clean energy future.
- ▶ The rapid development of digital, data-driven, and smart systems—largely from outside the energy sector—has unlocked the potential of other “platform technologies,” such as smart sensors and controls and additive manufacturing. These technologies could be scalable across the entire energy value chain. These platforms can be used to support decarbonization by optimizing performance based on emissions; advancing levels of reliability and resilience; and creating new business models that enable new services.
- As a U.S. and global leader in clean energy, California is well suited to promote the development of an advanced clean energy technology portfolio. California has robust energy innovation infrastructure including an active private sector, strong workforce, world-class research universities, four national laboratories, and major philanthropies that are aligned with the goals of decarbonization. It has multiple supportive state entities, including the California Energy Commission, the California Air Resources Board, and the California Public Utilities Commission. A clear portfolio with specific priorities can help ensure that programs pursued by multiple stakeholders in California (and beyond) are timely, durable, and mutually supportive. This approach can give innovators a framework for assessing the prospects of a particular initiative and the steps needed to sustain critical innovations over long time periods. It can also give corporate adopters, financial investors, and policymakers visibility into the evolving future of clean energy. This work must begin today.

There are technology priorities with long-term innovation breakthrough potential that California should develop (Figure S-5). These include hydrogen production with electrolysis, advanced nuclear, green cement, and seasonal storage, among others. These technology priorities were screened based on California’s policies and programs, energy system and market needs, and other distinctive regional qualities that position California to be a technological first mover: a strong resource base, relevant workforce expertise, and robust scientific and technological capacity. A broader list of candidate

technologies was also developed and organized by energy supply (electricity and fuels), energy application (Industry, Transportation, and Buildings), and cross-cutting technology areas (LSCM).

A REPEATABLE FRAMEWORK FOR DECARBONIZATION

This report is designed to advise California’s near- and long-term decarbonization strategy. It offers insights on decarbonization pathways, timescales, technology utilization, energy system operational needs, costs, and energy innovation. It provides a comprehensive review of on-the-ground issues in California that may aid or slow the state’s progress toward deep decarbonization. In addition to benefitting California, there are high-level findings that may also provide a framework for decarbonization strategies that can, and should, be repeated in other economies around the world, including:

- Energy system “boundary conditions,” including considerable system inertia that works against rapid change, complex supply chains, long-duration of technology development, and commodity business models must be taken into consideration when developing decarbonization strategies.
- There is no “silver bullet” technology for deep decarbonization. Technology optionality and flexibility are critical to any decarbonization strategy, especially for the difficult-to-decarbonize sectors.
- Existing carbon infrastructure and expertise must be aligned with deep decarbonization goals to prevent the creation of strong and dilatory political and business opposition to decarbonization pathways when acceleration is called for.
- Decarbonization pathways should address multiple timescales, emphasizing commercially-available technologies in the near-term and developing (and/or supporting the development of) new technologies with long-term innovation potential.
- Decarbonization pathways should support local and regional energy capacity that includes the existing workforce, the structure of economic sectors, clean technology firms, natural and scientific resources, and many other factors that shape the opportunities and challenges on the ground.

Figure S-5
Technology Priorities with Long-term Breakthrough Potential



Technologies were identified as having longterm breakthrough potential for California based on EFI-developed screening criteria. Source: EFI, 2019

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