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Innovative Technologies for a Low Carbon Electricity System

Opportunities for California and Beyond

Stephen Meyers, Rongxin Yin, Kristina Hamachi LaCommare, Jennifer Stokes-Draut, Cynthia Regnier, Purabi Thakre

February 2022

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ABSTRACT

The electricity sector represents the centerpiece of decarbonization pathways for the state. Decrease in the cost of renewable electricity generation, combined with ample solar energy, wind and other renewable resources, presents a realistic way to achieve electricity generation that is nearly free of CO_2 emissions by mid-century. Expansion of renewable electricity supply could allow replacement of many CO_2-emitting technologies with ones that use electricity—in transportation, buildings, and possibly industry. Key elements of the path for California's electricity sector are: restrain electricity demand through higher efficiency, rapidly expand renewable electricity generation, develop electricity storage to complement renewable electricity, manage flexible electricity loads for a low-carbon electricity system, electrify where appropriate to reduce CO_2 emissions, and maintain reliable and resilient electricity supply.

This report provides an overview of a multitude of innovative technologies in each of the above areas that have the potential to help the state meet its decarbonization goals, while lowering costs and promoting greater reliability. The information presented provides a portrait of the landscape of technology innovation that can help policymakers, state agencies, and interested parties develop strategies to meet the state's goals and to target efforts to support and nurture technology innovation.

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EXECUTIVE SUMMARY

California has led the nation in ambitious climate policies, and a recent Executive Order calls for economy-wide carbon neutrality by 2045. Meeting these goals will require a dramatic change to the current trajectory of carbon dioxide (CO_2) emissions.

The electricity sector represents the centerpiece of decarbonization pathways for the state. Decrease in the cost of renewable electricity generation, combined with ample solar energy, wind and other renewable resources, presents a realistic way to achieve electricity generation that is nearly free of CO_2 emissions by mid-century. Expansion of renewable electricity supply could allow replacement of many CO_2-emitting technologies with ones that use electricity—in transportation, buildings, and possibly industry.

The path forward for California's electricity sector has several key elements.

Manage Electricity Demand Through Higher Efficiency. Energy efficiency is important to ensure that growth in electricity demand does not outpace expansion of renewable electricity supply.

Rapidly Expand Renewable Electricity Generation. A large and rapid expansion of renewable electricity generation is needed to sharply reduce CO_2 emissions from electricity supply and to support electrification of vehicles and other uses. Development of "clean firm power" (carbon-free power sources that can be relied on whenever needed, for as long as they are needed) may also help to enhance reliability and reduce overall costs.

Develop Electricity Storage to Complement Renewable Electricity. Because the main renewable electricity sources (solar and wind) have intermittent production, electricity storage of various duration will help maximize the use of generated renewable electricity and provide electricity when sufficient renewable generation is not available.

Manage Flexible Electricity Loads to Support the Electricity Grid. Management of flexible electric loads can better match demand with the availability of renewable electricity or stored electricity. Electric vehicle batteries could be used as electricity storage to alleviate onsite peak demand and provide grid services.

Electrify Where Appropriate to Reduce CO_2 Emissions. Large shares of California's CO_2 emissions come from transportation and industry, and to a lesser extent, from buildings. For buildings and light vehicles, and possibly for some industry and heavy vehicles, electrification may be the most viable way to reduce emissions.

Maintain Reliable and Resilient Electricity Supply. As the electricity system continues to evolve, strategies will be necessary to ensure that electricity is available when needed and that the system is able to withstand and recover from threats related to climate change and other forces.

Many of the technologies needed already exist, but new and improved technologies could make it easier—and potentially less costly—for the state to meet its decarbonization goals. Moreover, technological innovation can be an engine of economic growth and provide employment opportunities.

This report provides an overview of a multitude of innovative technologies in development that have the potential to help the state meet its goals, while lowering costs and promoting greater reliability. The technology descriptions are based on literature reviews of relevant work and input from subject matter experts. The information presented provides a portrait of the landscape of technology innovation that can help policymakers, state agencies, and interested parties develop strategies to meet the state's goals and to target efforts to support and nurture technology innovation.

Efficient Use of Electricity

Without improved efficiency, electricity demand would grow substantially due to population and economic growth, and electrification of motor vehicles and other end uses. It would be difficult to add enough renewable electricity sources and electricity transmission to offset this increase.

Buildings account for over two-thirds of total electricity use. Improving the energy performance of the opaque envelope−the barrier that helps maintain comfortable indoor conditions irrespective of prevailing outdoor conditions− in buildings is important to reducing energy use for heating, cooling and ventilation. Innovative technologies are in development for high-performance insulation materials, envelope remediation (retrofit) technologies, tunable envelope materials, and envelope diagnostic technologies and modeling tools.

Windows have a strong relationship to the performance and energy use of building climate control and lighting systems. Opportunities exist in improving window glazing, gas filling, vacuum insulation, insulating frames, and air infiltration/exfiltration. Furthermore, improvements to dynamic facades and glazing, fixed and operable attachments, and daylight redirection can significantly increase the performance of window systems and their ability to reduce building energy use.

As the climate grows warmer, energy use for air conditioning will rise, and as building heating becomes electrified, use of heat pumps will increase. Energy-efficient equipment using refrigerants with very low global warming potential is being tested, but there are trade-offs between global warming potential, performance, efficiency, flammability, and cost relative to current refrigerants. Non-vapor compression systems have the potential to provide cooling for buildings without the use of any refrigerants. In addition, evaporative cooling systems and evaporative pre-coolers are commercial but R&D continues to investigate improved designs.

Light emitting diode (LED) based solid-state lighting is on course to become the dominant technology across all lighting applications. In just 10 years, LED luminous efficacies have increased over three-fold from less than 50 lumens/Watt to approximately 165 lm/W. With greater breakthroughs in the green-amber-red spectral regions, there is the potential to reach the ultimate theoretical limit of 325 lumens/Watt for direct-emitting architectures that combine color LEDs to make white light. In addition, innovation in low-cost sensors, wireless communication, computation, and data storage can facilitate the development of automated and intelligent lighting control systems.

Electronics and other small appliances (sometimes called "plug loads") account for a large share of California residential electricity use. Increasing the energy efficiency of plug loads is challenging. Zero or near-zero standby power is feasible in several families of products, but the solutions require further technical improvements and cost reductions before they can be introduced into new devices. Another approach is to utilize direct current (DC) input. DC-connected loads can connect directly to higher-efficiency DC distribution at lower cost. Successful market deployment of DC systems in buildings requires the availability of reliable, cost-competitive end-use appliances and equipment that can directly use and enable DC power.

In the area of building construction and retrofit, work is underway on innovative building technologies that can be deployed quickly with minimal onsite construction time, are affordable and appealing to the market, and leverage related efforts to increase the productivity of the construction industry.

In the industrial sector, over two-thirds of the electricity is used by motor-driven systems. While electric motors have high efficiencies, end-use motor-driven systems have much lower system efficiencies. Variable-speed or variable-frequency drives dynamically adjust motor speed or frequency to match power requirements and can save a considerable amount of electricity for applicable systems. A key focus of technology development is expanding the range of potential applications for these drives through use of wide-bandgap semiconductors.

Wide-bandgap semiconductors are able to operate at higher voltages and power densities than silicon-based semiconductors, allowing the same amount of power to be delivered with fewer chips and smaller components. Their greater thermal tolerance reduces the need for bulky insulation and additional cooling equipment, allowing for more compact system designs. More efficient and compact variable-frequency drives using wide-bandgap semiconductors are expected to expand the existing variable-frequency drive market into a wider range of motor system sizes and applications.

Medium-voltage integrated motor drive systems that leverage the benefits of wide-bandgap devices with energy-efficient, high-speed, direct-drive, megawatt class electric motors are in development. Applications areas include the chemical and petroleum refining industries, natural gas infrastructure, and general industry compressor applications like refrigeration and wastewater pumps.

In the water sector, ~75% of the electricity is used for pumping. Electricity used for pumping can be managed by minimizing water demand and with better sized and controlled pumps and motors. Two areas show particular promise: autonomous control systems, and more efficient decentralized water treatment to serve rural and disadvantaged communities.

Renewable Electricity Generation

Reaching the state's goal of having renewable and zero-carbon account for 100% of retail sales by 2045 will require an enormous increase in renewable electricity generation. The substantial growth in electricity demand that will come from electrification of passenger vehicles and end uses in buildings adds to the challenge. Technology innovation can play a key role by improving resource utilization through higher efficiency of generation, reducing the cost of generation, and expanding the renewable resources that can be utilized for electricity generation.

Most of the new electricity generation is expected to come from solar photovoltaics (PV), whose cost has declined substantially in the past decade. Solar PV innovation has led to improved cell efficiency that reduces the number of modules needed to produce a given output necessary. While improvements are expected for existing PV technology, other technologies have the potential to push efficiency further and to lower costs.

Multijunction solar cells (referred to as tandem cells when two different cells are used) are stacks of individual cells that each selectively convert a specific band of light into electrical energy, leaving the remaining light to be absorbed and converted to electricity in the cell below. Three-junction devices have reached efficiencies of greater than 45% using concentrated sunlight. This architecture can also be transferred to other solar cell technologies, and multi-junction cells made from various materials are being investigated.

Perovskite solar cells convert ultraviolet and visible light into electricity very efficiently, meaning they could be excellent tandem partners with absorber materials such as crystalline silicon that efficiently convert lower-energy light. Innovative tandem architectures using perovskites hold the potential to achieve efficiencies above 30% at reasonable cost and are garnering extensive interest. R&D is underway to advance perovskite efficiency and stability at the cell or mini-module scale, and to address challenges with manufacturing perovskite modules at relevant scale and throughput.

Concentrating solar power (CSP) systems capture energy during the day to charge a thermal energy storage medium, and can then run a generator after sundown, providing value to the grid. The decreasing cost of PV+battery storage has brought the viability of CSP into question, however. Technical challenges, including increasing the temperatures at which CSP plants operate, need to be addressed in order to significantly reduce costs. R&D is exploring new system designs and innovative concepts in the collector, receiver, thermal storage, heat transfer fluids, and power cycle subsystems.

Wind power has seen technological advances—in the wind turbines themselves and in the manufacturing process—that have made wind turbines more efficient at lower cost. Technology innovation centers on developing enhanced micro-siting strategies, improved resource forecasting, and complex control systems for arrays of wind turbines. These enhanced technologies broaden the range of viable wind sites by facilitating greater energy capture at high wind speeds as well as economical energy capture at lower wind speeds.

Offshore wind energy is in the early stages of growth in the United States. It has a large potential for development in California, but current fixed-bottom technology would not be possible for most of the available resource. Designs for floating offshore wind platforms are fundamentally similar to oil and gas platforms, but technological advances seek to optimize floating offshore platforms for wind capture. The profile of generation from offshore wind would complement generation from solar PV.

Considerable geothermal potential exists in enhanced geothermal systems, which are man-made geothermal reservoirs. R&D targets breakthroughs in non-invasive, lower-cost geophysical and remote-sensing technologies. Major advances in reservoir and subsurface engineering will be required to enable the cost-effective creation of enhanced geothermal system reservoirs and sustain their productivity once they are created.

While bioenergy for electricity generation has less technical potential than other renewable resources, it is uniquely positioned to offset fossil fuel usage with products that can be dropped into fossil fuel setups. Areas of innovation include improved cleaning methods to produce high quality biomass-derived syngas and techniques to increase biogas production.

Electricity Storage

The ability to store significant amounts of electricity from variable sources such as solar PV and wind power will be an important part of a low- or zero-carbon electricity system. Getting between 50% and 80% of annual energy from solar and/or wind may be feasible with storage durations of up to 10 hours. However, achieving renewables penetration over 90% would require storage durations of tens to hundreds of hours.

Lithium-ion batteries are expected to maintain a cost advantage over other storage technologies for short and medium-duration storage. While much of the R&D on next-generation lithium-ion technology is focused on the needs of electric vehicles, innovations could also enhance batteries suited for grid storage. Early stage research is looking at replacing the traditional materials in lithium-ion technologies with more abundant sodium technologies while retaining the lithium-ion manufacturing process.

A flow battery is attractive for grid applications because the power and energy capacity can be designed separately, and they offer long operational lifetimes with deep discharge capabilities. It is likely that the next generation of systems will be composed of significantly different materials than those being used today. Pathways that could enable lower costs include the use of inherently lower-cost materials, as well as materials that can enable significantly higher energy and/or power densities.

Chemical energy storage with hydrogen or other chemicals offers high energy density and seasonal storage. For hydrogen production, storage, and utilization, cost reductions through technology improvements and economies of scale will be needed to support market adoption.

Electrolyzers could use surplus renewable electricity to split water into hydrogen and oxygen. Proton exchange membrane electrolyzer technologies offer high current density, reduced footprint, higher efficiency than traditional alkaline electrolyzers. Proton exchange membrane electrolyzers are available today at the multi-megawatt scale, but R&D is needed to reduce their cost and improve efficiency and durability. The leading high-temperature electrolysis technology under development utilizes solid oxide electrolysis cells, which offer the advantage of more efficient hydrogen production. Increasing lifetime is a key goal of current research efforts for this technology.

Conversion of hydrogen to electricity can be achieved using modified turbines or fuel cell technologies. Polymer electrolyte membrane fuel cells can respond quickly to changing loads, making them suitable for distributed generation, backup, or portable power applications that require fast start-up times or must react to variable loads. Solid oxide fuel cells, which operate at much higher temperatures, are more suitable for use in modular and utility-scale stationary power systems. An advanced approach that combines electrolysis and fuel cell functions into a single unit, referred to as a reversible fuel cell, could lower cost, decrease the footprint, and simplify the system.

Mechanical storage systems include pumped water, compressed air, and gravity storage systems. The advantages of mechanical solutions are their long lifetime, long duration, and low technology risk. Pumped storage hydro systems provide the long lasting, reliable, predictable energy storage that utility asset planners seek. New designs could reduce capital investment requirements, expand siting possibilities, and shorten the development timeframe for new facilities. Similarly, novel approaches for compressed air energy storage include use of thermal storage technology to capture and reuse the heat that is generated during air compression, storing liquefied air in above-ground tanks, and purpose-built caverns. A new breed of gravity storage solutions, using the gravitational potential energy of a suspended mass, seeks to replicate the cost and reliability benefits of pumped hydro, without the siting limitations.

High-temperature reservoir thermal energy storage systems can use excess electricity to heat a storage medium to high temperature. The heat can then be used to generate electricity. Storage of energy as heat can be far cheaper than storing electricity in batteries, and using heat at very high temperatures can maximize the efficiency of electricity generation. New technologies under development use electricity to resistively heat a storage medium, which allows for a much higher storage temperature. Different high-temperature storage media have been proposed, as have innovative methods to produce electricity.

Managing Flexible Loads for a Low-Carbon Electricity System

A major challenge for California's electricity system is the growing mismatch between the daily and seasonal availability of renewable electricity generation and the expected peak demands on the system. Electric vehicle (EV) charging and electrification of other end uses could exacerbate the problem.

Increasing electricity storage capacity on the grid is one way to address these problems. Another way is to increase the flexibility of electricity demand such that demand can be reduced during periods of peak demand or shifted from peak to off-peak periods in real-time response to grid needs.

In buildings, many of the electrical loads have potential to be flexible. With advanced communications and controls, loads can be managed to draw electricity at specific times and levels, while still meeting occupant productivity, service levels and comfort requirements. Dispatchable demand response resources can directly respond to signals from utilities, grid operators, or third-party demand response providers.

Buildings can adjust solar heat gain to actively reduce heating/cooling needs using windows with electrochromic glass or automatic shading. Dynamic windows can be integrated with shading, lights, and HVAC systems through advanced control algorithms to manage heating, cooling and lighting energy. Connected lighting technologies can be used to adjust lighting levels and modulate lighting power demand with minimal impact on occupant visual comfort. Innovations for next generation lighting include communications for interoperability between lighting, daylighting, and HVAC systems.

Envelope-based energy storage systems charge and discharge in response to ambient temperatures and can shift heating or cooling load to off-peak hours. Related innovations include an HVAC system coupled with phase-change material storage. Grid-interactive water heaters can provide real-time monitoring, load forecasting, and algorithm-based controlling to maximize the amount of capacity available for grid services. At the whole-building level, innovations in advanced sensors, controls, and communication for grid participation will enhance the ability of buildings to meet the needs of building occupants and the grid.

The operational demands of process loads are of paramount importance for industry and agriculture, but opportunities exist to shift electric load without compromising production. These include innovative applications of phase change materials in refrigerated warehouses and smart irrigation systems that can reduce operational cost and enable demand flexibility.

With proper management, EVs can serve as a flexible load that stores electricity when renewable generation is abundant and limits charging at peak times. To meet the potential of this resource, the communication interoperability between the EV charging infrastructure and the grid needs to be improved to provide maximum demand flexibility while meeting charging needs. EVs with bi-directional operation can be used as electricity storage to power critical loads during power outages or provide valuable grid services. To achieve the optimal charging control of large numbers of EVs, a hierarchical control framework can be used to manage EVs through aggregators while meeting grid needs and customer requirements. Additional areas of technology innovation include wireless EV charging, connective mobility among EVs and charging stations, and integration of EVs with distributed renewable resources.

Electrification to Reduce CO_2 Emissions

In addition to its critical role in transportation, electrification represents one means to reduce CO_2 emissions in the industrial and buildings sectors.

In industry, promising cross-cutting electrification opportunities include low- to mid-temperature process heat, machine drives, and intermittent fuel switching (e.g., hybrid boilers). Opportunities also exist in specialized materials production, heating/drying, surface curing, and melting processes.

In process heating, the low-temperature range (<150 °C) offers the best opportunity for electrification. This range accounts for nearly all of the process heat energy used in the food industry and for over half of the total process heat used in the chemicals industry. Although the cost of electricity can be a barrier to adoption of electro-technologies, they provide benefits over fuel-based process heating for applications such as curing and drying through infrared, microwave, and radio frequency technologies, and for heating and melting though induction systems. Industrial heat pumps are of interest due to their high efficiency. Heat pumps with a heat sink temperature of 160°C are expected to reach market maturity in the near future, and higher temperatures may be feasible in some applications.

Energy-intensive industries such as steel, petroleum refining, chemicals and cement generally require high temperatures and are more difficult to electrify. With the exception of steel production, these industries are important for California. For production of commodity chemicals such as ammonia and ethylene, there are many options for electricity to drive a chemical reaction, and electrochemical methods have some advantages over traditional thermochemical methods. The development of new catalysts is essential to electrification of the chemical industry. Decarbonization strategies for cement production that involve electricity are also being investigated.

In buildings, new types of heat pumps could help facilitate electrification of space heating if they increase heating-side efficiency or reduce overall cost. The technical and economic barriers to electrification in the buildings sectors are much lower than in industry, but electrification in homes could pose problems for the electricity grid. Electric space heating, water heating, and cooking could all add to the system peak demand in the 5 p.m. to 9 p.m. period, when renewable electricity is less available. Strategies for load shifting and expanding electricity storage will be important companions to electrification.

Maintain Reliable and Resilient Electricity Supply

As the power system evolves to include more variable and dispersed renewable energy resources, maintaining reliability and enhancing resilience will require new approaches. One promising technology area not yet widely utilized in the utility sector is machine learning and artificial intelligence. Increased application in this sector could help optimize generation, improve demand response programs, operations and maintenance of energy assets, better understand energy usage patterns, and provide better stability and efficiency of the power system. Digital enhancements of service territory landscape using virtual reality can improve situational awareness and more efficiently assess and diagnose problems in the system. As well, the use of deep learning can help handle big data from smart metering by filtering out bad input data, which can improve forecast planning models.

Additional areas of promise include advanced energy management systems, autonomous energy grids, and advanced power quality monitoring technologies that will help secure the electric grid of the future.

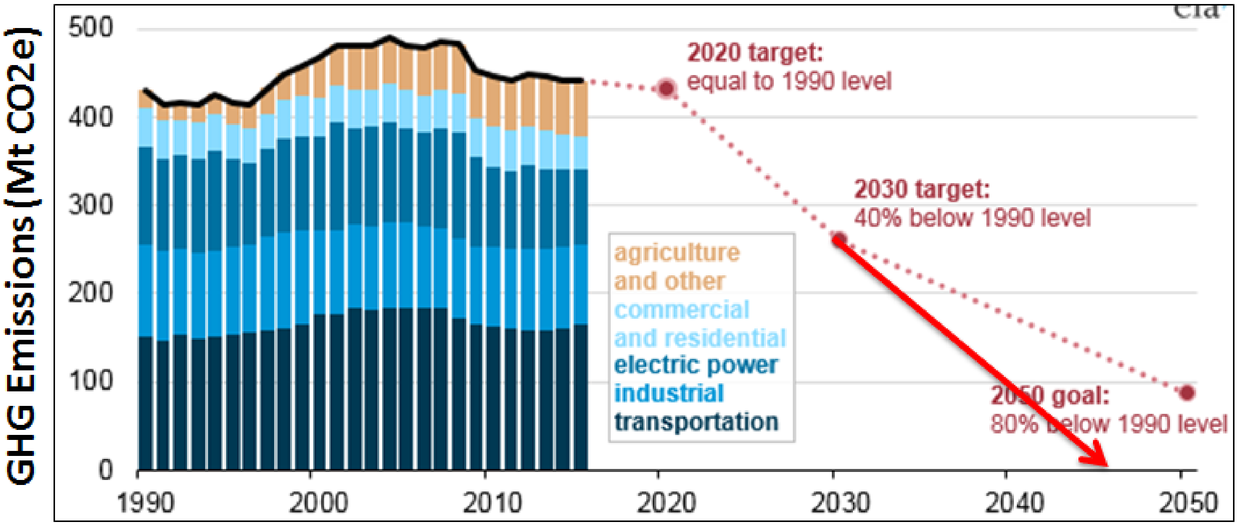
Cross-Cutting Areas of Technology Innovation

There are a number of areas of technology innovation that could have benefits across multiple sectors of the energy economy. They include smart manufacturing techniques, advanced materials that could improve performance and lower the cost of energy-producing and energy-using technologies, novel manufacturing techniques that could reduce energy use, recycling of various materials that could dramatically reduce the embodied energy and carbon emissions associated with materials production, and advances in computing that will have impacts in a multitude of areas.

CHAPTER 1: Introduction

California has led the nation in ambitious climate policies, and a recent Executive Order (B-55-18) calls for economy-wide carbon neutrality by 2045. This order builds upon the 2030 target of having greenhouse gas (GHG) emissions 40% below the 1990 level (in SB32) and the Executive Order S-3-05 directive to reduce GHG emissions to 80% below 1990 level by 2050. Figure 1.1 shows the dramatic change in the trajectory of emissions that will be needed to meet these goals. The challenge is all the more daunting considering that the state's population and economy are projected to grow considerably between now and mid-century.

Figure 1.1: California GHG Emissions and Emissions Targets



Source: Wei et al. (2020)

Achieving California's climate goals will require phasing out the combustion of fossil fuels, or decarbonization. The potential elements of pathways to meet California's GHG reduction goals have been described in scenario studies prepared for the California Energy Commission (CEC)[1] and the Air Resources Board.[2] The electricity sector is the centerpiece of these pathways. Decrease in the cost of renewable electricity generation, combined with ample solar energy, wind and other renewable resources, presents a realistic way to achieve electricity generation that is nearly free of carbon dioxide (CO_2)

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[1] Mahone, Amber, Zachary Subin, Jenya Kahn-Lang, Douglas Allen, Vivian Li, Gerrit De Moor, Nancy Ryan, et al. 2018. *Deep Decarbonization in a High Renewables Future: Updated Results from the California PATHWAYS Model.* California Energy Commission. Publication Number: CEC-500-2018-012

[2] Mahone, Amber, Zachary Subin, Gabe Mantegna, Rawley Loken, Clea Kolster. 2020. *Achieving Carbon Neutrality in California: PATHWAYS Scenarios Developed for the California Air Resources Board*. Energy and Environmental Economics. https://ww2.arb.ca.gov/sites/default/files/2020-10/e3_cn_final_report_oct2020_0.pdf

emissions by mid-century. Expansion of renewable electricity supply, if achieved at a reasonable cost, would allow replacement of many GHG-emitting technologies with ones that use electricity—in transportation, buildings, and possibly industry.

The path forward for California's electricity sector has several key elements.

Restrain Electricity Demand Through Higher Efficiency. Energy efficiency is important to ensure that growth in electricity demand from population and economic growth, and from electrification, does not outpace expansion of renewable electricity supply.

Rapidly Expand Renewable Electricity Generation. A large and rapid expansion of renewable electricity generation is needed to sharply reduce GHG emissions from electricity supply and to support electrification of vehicles and other uses. Development of "clean firm power" (carbon-free power sources that can be relied on whenever needed, for as long as they are needed) may also help to enhance reliability and reduce overall costs.

Develop Electricity Storage to Complement Renewable Electricity. Because the main renewable electricity sources (solar and wind) have intermittent production, electricity storage of various durations will be important to maximize use of renewable electricity and provide electricity when renewable generation is less available.

Manage Flexible Electricity Loads for a Low-Carbon Electricity System. Management of flexible electric loads can help to better match demand with the availability of renewable electricity, and electric vehicles could be used to store electricity for onsite use, provide valuable grid services, or power emergency loads during power outages.

Electrify Where Appropriate to Reduce CO_2 Emissions. Large shares of California's CO_2 emissions come from transportation and industry, and to a lesser extent, from buildings. For buildings and light vehicles, and possibly for some industry and heavy vehicles, electrification may be the most viable way to reduce a major share of their emissions.

Maintain Reliable and Resilient Electricity Supply. As the electricity system evolves, strategies will be necessary to ensure that electricity is available when needed and that the system is able to withstand threats related to climate change and other forces.

In addition, decarbonization must be done in an equitable manner to ensure benefits also accrue to under-resourced communities.

Many of the technologies to support the above goals are already available but require efforts to increase their market penetration. In most areas, however, new technologies or improvements and cost reduction in existing technologies could make it easier—and potentially less costly—for the state to meet its GHG reduction goals. Moreover, technological innovation can be an engine of economic growth and employment opportunities.

Report Goals

This report provides an overview of a multitude of technologies in development that have the potential to help the state meet its emissions goals, while lowering costs and promoting greater reliability. It is organized around the key elements described above. The technology descriptions are based on literature reviews of relevant work, and input from subject matter experts. Estimates of potential costs and performance goals are presented where possible, as is information on current R&D sponsored by the U.S. Department of Energy.

The report endeavors to characterize the technical maturity of the technologies described. Because one goal of this report is to inform stakeholders involved in support of technology innovation, it focuses on technologies in the middle of the maturity range. Very early-stage technologies are more speculative and can be hard to identify because published information may not exist or may only be found in specialist literature. Later-stage technologies are more likely to already be supported by public and/or private actors and investors.

The report does not attempt to prioritize technologies, as such an exercise requires in-depth information on specific technologies and their development prospects, a nuanced understanding of their potential application in California’s electricity system, and input from actors with relevant expertise. Instead, the end of each chapter presents strategic considerations that shed light on which technologies may be most important for meeting the state’s goals.

Benefits of Innovative Electric Sector Technologies

Reduced Emissions of CO_2 and Other Air Pollutants

All of the technologies discussed in this report have the potential to reduce CO_2 emissions by displacing combustion of fossil fuels in electricity generation, buildings, industry, and transportation.[3] The magnitude of that reduction will depend on a variety of factors.

For technologies that improve electricity efficiency or enable load management, the timing of demand reduction is important. Currently, the CO_2 intensity of electricity generation varies over the course of a day and between seasons. In the past it was most important to reduce peak electricity demand, which was typically in the afternoon throughout the year and in the summer. With CO_2 reduction becoming the primary motivating factor for lowering or shifting electricity demand, such reduction is most important when CO_2 intensity is highest (i.e., when gas-fired power plants are in heavy

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[3] Although the focus of this report is electricity, many efficiency-enhancing technologies can reduce direct use of natural gas in applications where it remains in use.

use). As solar electricity becomes the largest source of electricity supply, the CO_2 intensity of generation will be lowest in the afternoon, and could be relatively high in the winter when solar output is low. These changes mean that efficiency improvement will be more impactful for some end uses than for others. Accurate assessment requires understanding of future diurnal and seasonal patterns of specific electric loads and electricity generation by sources.

In the case of electrification technologies, substituting electricity for natural gas or motor fuels will reduce CO_2 emissions associated with fuel combustion. In some cases, such as with electric heat pumps or electric vehicles, electrification results in much higher energy efficiency than use of fossil fuels. Still, the net effect on emissions depends on the diurnal and seasonal patterns of the increase in demand and of electricity generation from various sources. If not well managed, electrification might not have the full intended effect on emissions.

For renewable electricity generation as well, displacement of natural gas combustion depends on both the diurnal and seasonal patterns of generation and the types of natural gas plants in the system and how they are used. For periods when renewable generation is not sufficient to meet demand, electricity storage will be critical to avoiding use of natural gas power plants or overbuilding of renewable capacity.[4]

Because California's electricity system is changing rapidly, precise estimates of CO_2 reduction from demand-side and supply-side technologies based on the current system are not likely to be good predictors of long-run outcomes. More robust estimates require detailed modeling of the electricity system over time.

CO_2 emissions are not the only air pollutants that are relevant. Gas-fired power plants produce negligible amounts of sulfur, mercury, and particulates, but burning natural gas does produce precursors to smog. These emissions disproportionately affect disadvantaged communities, and reducing them can have public health benefits. In addition, the drilling and extraction of natural gas from wells and its transportation in pipelines results in the leakage of methane, the primary component of natural gas that is 34 times stronger than CO_2 at trapping heat over a 100-year period and 86 times stronger over 20 years. Electric vehicles that displace gasoline and diesel vehicles also reduce tailpipe emissions that contribute to smog, as well as emissions associated with petroleum production and refining.

Lower Electricity Sector Costs

An important goal of technology innovation in the electricity sector is to reduce the cost of technologies that generate, store, use or manage electricity, or to provide improved performance at a comparable cost. Not all of the many technologies discussed in this

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[4] Other potential options include use of green hydrogen or other renewable fuels in gas-fired power plants, or using natural gas with carbon capture and storage.

report will prove successful at achieving cost goals, of course, but the existence of many different types of innovation bodes well for positive outcomes overall.

Efficiency technologies that are successful in the market typically have a cost of conserved electricity that is less than the marginal cost of electricity supply. This is reflected in one of the complementary guiding principles of the CEC's Electric Program Investment Charge (EPIC) program, which is to support California's loading order to meet energy needs first with energy efficiency and demand response. Put differently, successful efficiency technologies provide the services that consumers and businesses want at a lower resource cost.

The main way that efficiency technologies can lower system costs is by avoiding or delaying the need for electricity providers to procure additional electricity. The combination of growth in electricity demand from traditional sources and from new sources such as electric vehicles and electrification in buildings will require a very large expansion of electricity supply. While it seems likely that innovations in renewable electricity generation technologies will lower the cost of new supply in the future, the extent of that is uncertain. Furthermore, expansion of supply in areas that are distant from demand centers may require significant investment in new transmission infrastructure. End-use efficiency can help to reduce the need for such investment. Similarly, efficiency can also decrease investment in electricity distribution infrastructure. This effect is especially important in light of the likely growth in demand from electric vehicles and building electrification. Indeed, growth in demand from electrification, if not balanced with reduced demand from energy efficiency, could increase electricity sector costs for resource procurement and investment in distribution infrastructure. Industrial electrification in particular could require distribution upgrades.

On the supply side, most of the renewable electricity technologies described in this report have the potential to reduce system costs relative to a future without technology innovation. When the share of variable renewable electricity begins to exceed 70 to 80 percent, however, long-duration electricity storage and/or dispatchable generation using renewable fuels is critical to prevent system costs from rising substantially. Technology innovation is key in these areas.

Other Benefits

A number of the technologies described here could help improve the reliability of an electricity system with a heavy dependence on variable generation that cannot be readily dispatched. End-use energy efficiency can reduce the amount of necessary generating capacity needed and therefore help address reliability in the form of improved resource adequacy. Load management technologies can enhance the capacity of grid operators to balance electricity demand with available supply, which also helps reliability. Electricity storage along with renewable electricity technologies that are dispatchable are critical to maintaining reliability of a low-CO_2 power system.

Many of the technologies could enhance economic development in the state. Examples of potential job creation include construction and maintenance of solar and wind power installations, delivery of building energy efficiency measures, and also manufacturing of some of the technologies.

For energy efficiency, non-energy benefits include reduced operations and maintenance costs, increased comfort, and increased worker and student productivity. Electrification that displaces gas appliances may bring an increase in safety as well as improved indoor air quality. Innovative building ventilation technologies can also deliver indoor air quality benefits.

Evaluating Technical Maturity

One way of characterizing the technical maturity of a technology involves a scale developed by the U.S. government that describes nine levels of technology readiness, referred to as TRLs. A brief description of the nine levels is given in Table 1.1. Longer descriptions are presented in the U.S. Department of Energy (U.S. DOE) Technology Readiness Assessment Guide.[5]

Assigning a level of technical maturity is not an exact science. How narrowly one defines a "technology" is one factor. A broadly-defined technology may be comprised of component technologies that are at varying degrees of readiness. A technology may have a high TRL in certain applications or sizes, and a lower TRL for a more broad (and relevant) range of applications. A technology may be relatively mature, but improvements that could reduce its cost or otherwise make a difference in its viability may be at lower maturity. Moreover, the TRL scale doesn't fully address issues of manufacturing a technology at scale.

Technical maturity is not always described in the literature. To supplement published information, we asked experts in specific areas to assign TRLs where possible.

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[5] U.S. Department of Energy. *Technology Readiness Assessment Guide*. (See Table 1.) https://www2.lbl.gov/dir/assets/docs/TRL%20guide.pdf

Table 1.1: Technology Readiness Levels

Level	Title	Description
TRL 1	Basic Research	Initial scientific research has been conducted. Principles are qualitatively postulated and observed. Focus is on new discovery rather than applications.
TRL 2	Applied Research	Initial practical applications are identified. Potential of material or process to solve a problem, satisfy a need, or find application is addressed.
TRL 3	Critical Function or Proof of Concept Established	Applied research advances and early-stage development begins. Studies and laboratory measurements validate analytical predictions of separate elements of the technology.
TRL 4	Laboratory Testing/Validation of Prototype Component/Process	Design, development and lab testing of components/processes. Results provide evidence that performance targets may be attainable based on projected or modeled systems.
TRL 5	Laboratory Testing of Integrated/Semi-Integrated System	System component and/or process validation is achieved in a relevant environment.
TRL 6	Prototype System Verified	System/process prototype demonstration in an operational environment (beta prototype system level).
TRL 7	Integrated Pilot System Demonstrated	System/process prototype demonstration in an operational environment.
TRL 8	System Incorporated in Commercial Design	Actual system/process completed and qualified through test and pre-commercial demonstration.
TRL 9	System Proven and Ready for Commercial Deployment	Actual system proven through successful operations in operating environment, and ready for full commercial deployment.

CHAPTER 2: Efficient Use of Electricity

As the share of renewable sources in California's electricity supply grows, the CO_2 intensity of electricity generation (CO_2 emissions per kilowatt-hour generated) will decline, and there is less reduction in CO_2 emissions from improving the efficiency of electricity use. Improving efficiency is nonetheless an important element in a CO_2 reduction strategy because it makes the goal of a zero or near-zero CO_2 electricity supply easier to achieve.[6] Without higher efficiency, electricity demand would grow substantially due to population and economic growth, and the electrification of motor vehicles and other end uses. In that event, it would be difficult to add renewable electricity sources−and the necessary electricity transmission infrastructure− fast enough to achieve a zero or near-zero CO_2 electricity supply by mid-century.

Fortunately, California has a strong track record in improving electricity efficiency and a robust framework of state agencies, electric utilities and private sector actors to continue that improvement. In 2015, California set an ambitious goal to achieve a statewide cumulative doubling of energy efficiency savings and demand reductions in electricity and natural gas end uses, relative to 2015 estimates, by January 1, 2030. Senate Bill 350 codified this goal and directed the CEC to set annual targets to accomplish it. In its 2019 California Energy Efficiency Action Plan, the CEC noted that the state will need to harness emerging technologies, develop progressive program designs, and promote innovative market solutions as part of this effort.[7]

Figure 2.1 shows how electricity is used in California. Buildings account for over two-thirds of the total, followed by industry. The share of buildings will increase if electrification of heating and water heating is successful. Thus, buildings will be the primary source of electricity savings.

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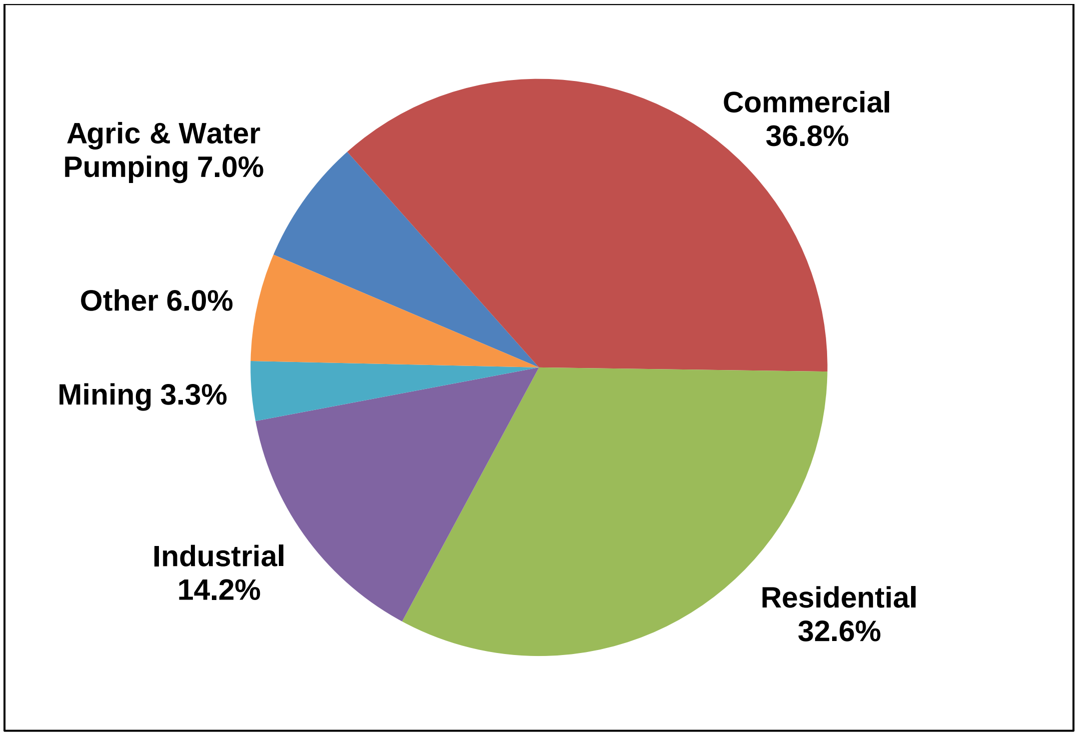
[6] Technologies that affect end-use efficiency are the focus of this chapter. Technologies that improve the efficiency of electricity transmission and distribution are also important.

[7] California Energy Commission staff. 2019. *2019 California Energy Efficiency Action Plan*. California Energy Commission.

Figure 2.1: California Electricity Consumption by Sector, 2019



Source: California Energy Commission

Buildings

Residential and commercial buildings account for 33 and 37 percent of California's 2019 electricity consumption, respectively, and buildings end uses also account for a portion of electricity use in industry.

Figure 2.2 show estimates of how electricity is used in the residential and commercial sectors.[8] Space heating and water heating account for small shares of California building electricity use currently, but they would increase significantly if electrification efforts are successful. The share of air conditioning is higher – 23 percent in the commercial sector and 8 percent in the residential sector – and very likely will grow as a warming climate increases demand for air conditioning from existing equipment and induce more Californians to install systems.[9]

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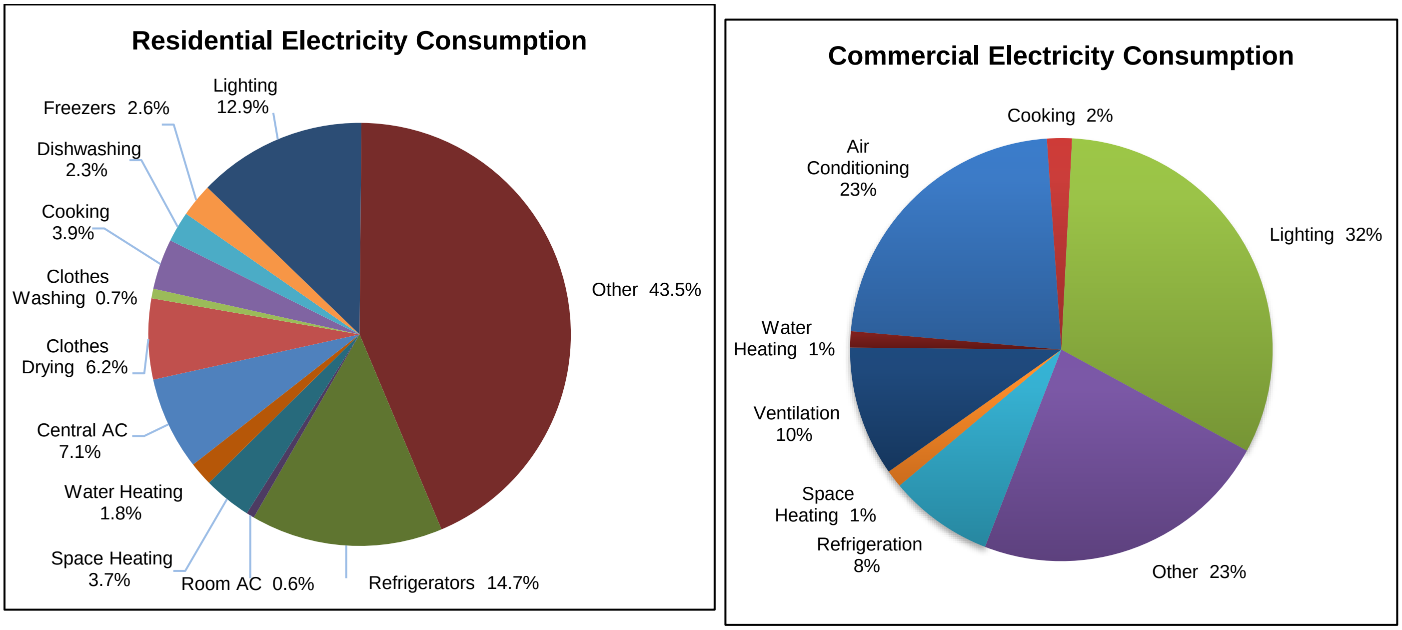
[8] The estimates are from the PATHWAYS model spreadsheet prepared for the CEC report: Deep Decarbonization in a High Renewables Future, June 2018.

[9] California's Fourth Climate Change Assessment: Statewide Summary Report. https://www.energy.ca.gov/sites/default/files/2019-11/Statewide_Reports-SUM-CCCA4-2018-013_Statewide_Summary_Report_ADA.pdf

Figure 2.2: Estimated End Use Shares of California Buildings Electricity Consumption



Residential Electricity Consumption

Commercial Electricity Consumption

Much of the electricity use in buildings is from appliances and equipment that can be replaced with more efficient equipment when they end their useful life (or sooner). Sometimes that replacement is as simple as screwing in a new light bulb, while in other cases replacement is more disruptive and complicated. Modifying the building envelope (opaque elements and windows) in a significant way is often costly, and is usually only done when a building is being renovated. That makes it harder to apply efficiency-enhancing technologies for the opaque building envelope and, to a lesser extent, for windows. New buildings present the easiest opportunity to design for energy efficiency and use high-efficiency components, and there is momentum in California to increase the share of new buildings that use zero net energy.[10]

It is worth noting that many building efficiency technologies can improve the resilience of buildings to interruptions in utility service. High-performance building envelopes generally reduce heating and cooling energy use, and thus increase the time from when an interruption occurs to when the building becomes uncomfortable because of temperature conditions.

Opaque Building Envelope

The insulating properties of the building envelope and construction quality together control the way heat, air and moisture flows into or out of the building. Improving the

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[10] Zero-net-energy buildings consume only as much energy as they produce on-site from renewable resources. https://newbuildings.org/resource/2019-california-getting-to-zero-watchlist/

energy performance of the opaque envelope−the barrier that helps maintain comfortable indoor conditions irrespective of prevailing outdoor conditions− in buildings is important to reducing energy use for heating, cooling and ventilation.

New buildings provide an opportunity to incorporate new technologies, especially if designers take a holistic perspective of building design, construction, and operation. This approach might lead to the development of novel envelope configurations that integrate multiple control layers for air, moisture, and heat, as well as structural functions, into fewer layers and components.

For existing buildings, a major barrier to the adoption of high-efficiency envelope retrofits is that currently available envelope retrofit products and processes can be disruptive in occupied buildings. Furthermore, unlike other building equipment that is replaced periodically, building envelopes are much less frequently altered. More common changes, such as reroofing or residing, rarely result in improved energy performance. To tap into the potential for substantial energy savings from opaque envelope retrofits while improving durability and occupant health and comfort, building owners need affordable, less-disruptive alternatives for improving building envelope performance.

For new and existing buildings, technology improvement is needed to:

- Reduce Air Leakage
- Improve Moisture Management
- Increase R-Value
- Improve Constructability
- Increase Longevity
- Improve Affordability

The U.S. DOE has identified technology focus areas that address the above needs.[11] Specific technology innovations in each of the topic areas are presented in Table 2.2.

Ultra-High R/in Insulation Materials: Materials with a high R-value per inch of thickness can enable higher insulation levels in new construction and reduce the cost and complexity of retrofits of existing buildings. Examples include aerogels and vacuum insulated panels in which the casing is evacuated of gas, extremely reducing heat transfer.

Envelope Remediation (Retrofit) Technologies: Once a building envelope is complete, it is difficult to improve performance without substantial teardown and reconstruction. Novel remediation (retrofit) technologies and techniques are needed to resolve this challenge.

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[11] U.S. Department of Energy. May 2020a. DRAFT *Research and Development Opportunities Report for Opaque Building Envelopes*. https://www.energy.gov/eere/buildings/downloads/research-and-development-opportunities-report-opaque-building-envelopes

Table 2.1: U.S. DOE Targets for Wall Insulation

	Current	2040 Target
Insulation Level	<18 R/in	20 R/in
Cost	\$14-17 ft^2 area	\$0.64-1.91 ft^2 area

Tunable Transport Materials: Tunable transport materials promise new envelope functionality, adjusting envelope properties in response to electric grid needs and interior and exterior conditions to minimize energy use while maximizing occupant benefits. These materials have the potential to deliver significant energy savings, as well as grid-related benefits such as load shifting or peak shaving, improved thermal comfort, and increased durability.

Envelope Diagnostic Technologies and Modeling Tools: Technologies that can characterize the key energy performance-related properties of existing opaque envelopes could facilitate retrofit adoption by quantifying the benefit of retrofits and verify post-retrofit performance.

Table 2.2: Technology Innovations for Opaque Building Envelopes

Technology	Description of Innovations	Technical Maturity
Ultra-High R/in Insulation Materials for Walls/Ceilings • Aerogels • Vacuum insulated panels • Nano-insulation materials	Materials and encapsulation methods that are durable and ensure long life with stable R-value	TRL 5-7
	Materials and fabrication methods that yield convenient form factors for installation	TRL 2
	Materials that allow for on-site modification of the dimensions of the as-delivered product while maintaining R-value and durability	TRL 2-4
	Material formulations that achieve expected R-values at the macroscale	TRL 4-7
	New metrology that offers accurate measurement at low thermal conductivities	TRL 5
Envelope Remediation (Retrofit) Technologies	Novel materials and methods for overcladding with reduced labor effort and complexity	TRL 3-6
	Materials and installation methods that can yield air sealing in the climate-appropriate plane without significant teardown	TRL 3-6
	Autonomic self-healing air barrier films	TRL 2-3
	One-step spray- or liquid-applied air and vapor control materials.	TRL 6-9
Tunable Transport Materials	Evaluate cycling durability and develop materials with minimal performance degradation over thousands of cycles	TRL 2-3
	Establish viable heat sinks and sources for anisotropic systems (which can change or assume different properties in different directions) and demonstrate operation	TRL 4-5
Envelope Diagnostic Technologies	Novel diagnostic metrology suitable for year-round buildings testing conditions	TRL 2-4
	Virtual sensing to evaluate envelope performance	TRL 3
	Diagnostic metrology for envelope moisture performance	TRL 2-4

Source: U.S. Department of Energy. (May 2020a). Technical maturity estimated by subject experts at Oak Ridge National Laboratory.

Windows and Facades[12]

Windows have a strong relationship to the performance and energy use of building climate control and lighting systems. An ideal window would provide attractive lighting

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[12] This section draws on: U.S. Department of Energy. May 2020b. *DRAFT Research and Development Opportunities Report for Windows*. https://www.energy.gov/eere/buildings/downloads/research-and-development-opportunities-report-windows

levels without glare, high levels of thermal insulation, and allow infrared light to enter when it is useful for heating but block it when it would add to cooling loads.

Significant progress has been made in window technology over the past three decades. Innovations include glass coatings that reduce absorption and re-emission of infrared light, thermal conductivity improvements, electrochromic windows that can be controlled to reduce light and solar energy transmission, and the use of low-iron glass to improve visible clarity. Modern windows provide improved thermal performance, including reduced air leakage, but also offer enhanced amenities such as daylight, views to the outdoors, and natural ventilation. In many newer commercial buildings, windows comprise a major part of the vertical building envelope.

Optimizing the energy performance of windows requires taking into account heat conduction, convection, and radiation while also ensuring that aesthetic considerations are satisfied. Opportunities exist in improving window glazing, gas filling, vacuum insulation, insulating frames, and air infiltration/exfiltration. Furthermore, improvements to dynamic facades and glazing, fixed and operable attachments, and daylight redirection can significantly increase the performance of window systems and their ability to reduce building energy use. Next-generation windows could approach the thermal performance of most existing buildings' insulated walls, while also harvesting passive heating contributions in winter and rejecting unwanted solar heat gain in summer.

New material discovery, novel technological approaches, as well as applied engineering, is key to addressing many of the performance and cost challenges of producing highly efficient affordable windows that can achieve mainstream market acceptance. These technologies are generally expected to offer significant energy savings compared to the current technology, but they also have other energy and non-energy benefits—reduced peak load, the ability to shift windows-related thermal loads to match distributed renewable generation availability, reduced glare, increased thermal comfort, and improved occupant satisfaction and productivity.

There are a range of opportunities to improve upon the current state-of-the-art with respect to total installed price, energy performance, and non-energy characteristics that can influence technology adoption. These opportunities include:

- Reducing infiltration through window frames
- Reducing the thermal conductivity of the window frame and insulated glass unit
- Enabling improvements in the design, configuration, installation, commissioning, and operation of the sensors and control systems for dynamic facade components and systems
- Developing self-powered systems for dynamic and automated facade elements
- Developing dynamic glazing that can independently control visible and near-infrared transmission at much lower prices through improvements in materials and the compatibility of those materials with high-volume throughput manufacturing methods.

High-Performance Windows

Modifications to the frame, advanced glazing packages, and subcomponents are essential to achieving high levels of window performance. These include advanced glazing (e.g., thin triple or vacuum-insulated glazing), higher-performing inert gas fills (e.g., krypton), or replacing the gas fill with a transparent low-conductivity solid material and developing highly insulated window spacers and frames.

Critical Characteristics for High-Performance Windows are:

- Insulated glass unit (IGU) thickness should be comparable to double-pane IGUs to enable use in existing frames manufactured for double-pane IGUs
- IGU weight should be similar to double-pane IGUs
- Durability should be equivalent or superior to existing windows
- Novel IGU and frame components should have a pathway to compatibility with current typical manufacturing methods.

Table 2.3 summarizes technology innovations for windows.

Upgrading the inefficient single-pane windows that are common in existing homes and businesses in California and elsewhere has been slow due to the cost of replacement and size and weight incompatibilities of double-pane windows with single-pane units. The Advanced Research Projects Agency-Energy (ARPA-E) has a program (SHIELD, short for "Single-Pane Highly Insulating Efficient Lucid Designs") that aims to develop innovative materials that will improve the energy efficiency of existing single-pane windows in commercial and residential buildings.[13] The program focuses on three technical categories: products that can be applied onto existing windowpanes; manufactured windowpanes that can be installed into the existing window sash that holds the windowpane in place; and other early-stage, highly innovative technologies that can enable products in the first two technical categories.

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[13] Single-Pane Highly Insulating Efficient Lucid Designs. https://arpa-e.energy.gov/technologies/programs/shield

Table 2.3: Technology Innovations for High-Performance Windows

Technology	Description	Technical Maturity
High-Performance Glazing	Approaches focus on minimizing heat transfer between the panes, particularly by controlling convection by removing the air between the panes or replacing the air between the panes with another material	
Multi-pane thin glass glazing system	Utilizes inexpensive thin glass (1.1 mm or less) as inner pane(s) and single spacer system filled with krypton gas	TRL 5
Aerogels	Replacing the air or fill gas between the panes in an IGU with a solid material	TRL 3
Vacuum insulated glazing	Reduces heat transfer by eliminating the air (and need for fill gas) in the space between the two panes of glass in an IGU. In comparison with standard triple-insulated IGUs, vacuum IGUs with low-E films are thinner and lighter and have better thermal insulating performance and lower reflection.	TRL 4[a]
Highly Insulating Window Frames	Modifications to improve thermal performance generally involve inserting material with very low thermal conductivity between the exterior and interior portions of the frame to inhibit heat transfer. There might be further opportunities to improve frame thermal performance through the development of novel materials.	TRL 3

[a] This technology has been on the market, but there are challenges to manufacture products at a competitive cost. R&D in this area is primarily focused on manufacturing methods.

Source: U.S. Department of Energy (May 2020b). Technical maturity estimated by LBNL subject expert.

Table 2.4: U.S. DOE Whole-Window Performance and Price Targets

	Performance	Installed Price Premium
Residential	R-6 to R-13	\$1.8-5.6/ft^2 window area
Commercial	R-6 to R-10	\$3.9-11.9/ft^2 window

A Novel Thin Highly Insulating Window. State-of-the-art, dual-pane windows have an insulation level of about R-3. A recent project at Lawrence Berkeley National Laboratory (LBNL) developed a lightweight, triple-pane window, resulting in an R-5 insulation level.[14] The 1-inch-thick IGU was designed with a nonstructural 1/36-inch glass center layer placed between two conventional 1/4-inch glass layers and assembled with a warm edge spacer and krypton gas fill. The project team combined this "thin" insulating glass unit with a novel thermally broken frame. The frame utilizes a non-continuous design that minimizes conductive heat transfer between the outdoors and indoors. Overall, the window shows potential to reduce HVAC energy use roughly 5 to 7 percent across all California climate zones, with a payback of 10 years, given a mature market incremental cost of $1 per square foot of window.

Dynamic Glazing and Facades

Dynamic glazing and façade systems, which have variable solar heat gain control characteristics, can substantially lower energy use compared to static glazings. Thermochromic windows change their performance metrics as sunlight hits the glass. When the sun warms the window, the thermochromic elements darken and create a tinting effect over the window. Electrochromic windows have an electrochromic coating that consists of micro-thin layers applied onto insulating glass units. The tint of the glass is controlled directly by the amount of voltage applied to the glass.

The high cost of dynamic glazing systems is a significant barrier. Novel approaches that rely on low-cost, high-throughput production methods could reduce product costs and expand availability of dynamic glazing. For automated attachments and electrochromic glazing systems, systems that have an integrated power system would reduce installation and construction complexity while also avoiding additional ongoing maintenance costs. These systems can use small photovoltaic (PV) cells surface-mounted to the frame or on protruding structures anchored to the frame or attachment system (if externally mounted) to provide electricity for state-change operations, and could include energy storage for nighttime operation.

Dynamic glazings and shading systems enable real-time management of window configuration in response to diurnal and seasonal changes in heating and cooling demand, occupancy, and available daylight. With proper control, dynamic glazing and facades can be used to provide grid benefits by enabling changes in the timing of heating, cooling, and lighting loads (see Chapter 5).

Table 2.5 presents technology innovations for dynamic glazing and facades.

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[14] Lee, E.S., D.C. Curcija, T. Wang, C. Gehbauer, L. Fernandes, R. Hart, D. Blum, et al. 2020. *High-Performance Integrated Window and Façade Solutions for California*. California Energy Commission. Publication Number: CEC-500-2020-001. https://www.energy.ca.gov/publications/2020/high-performance-integrated-window-and-facade-solutions-california

Table 2.5: Technology Innovations for Dynamic Glazing and Facades

Technology	Description	Technical Maturity
Active and passive switching	Novel materials for active and passive switching compatible with fabrication methods suited to existing float glass production processes	TRL 5
Increased selectivity of wavelength attenuation	Novel materials than can independently attenuate visible or near-infrared wavelengths	TRL 2-4
Self-powered systems	Automated attachment and electrochromic glazing systems use small PV cells surface-mounted to the frame, or on protruding structures anchored to the frame or attachment system (if externally mounted), to provide electricity for state-change operations.	TRL 2
Glazing with integrated PV	Static PV glazing can be transparent (converting only nonvisible solar energy) or semi-transparent (converting a fraction of the incident visible light). Switchable PV windows switch from a visibly transparent state to a darkened state in a manner similar to thermochromic glazing.	TRL 3-5
Improved component sensors, controls, and system integration	Automatic control of dynamic facade components requires a complex balance between solar control and daylighting to maximize energy savings and occupant comfort. Model predictive controls can use thermal and daylighting models of dynamic glazing and models of room thermal response; HVAC, lighting, and thermal energy storage parameters; and occupant preferences to produce optimal control over a specified time horizon.	TRL 2-3

Source: U.S. Department of Energy (May 2020b). Technical maturity estimated by LBNL subject expert.

Dynamic (Switchable) Photovoltaic Glazing. Most designs where PV is integrated into the glazing are semi-transparent (or translucent), only absorbing a fraction of the incident visible light. The amount of light absorbed and converted to electricity is limited by the need to maintain adequate visible light transmittance. Switchable PV windows circumvent this fundamental trade-off by switching from a visibly transparent state to a darkened state, which allows for increased power conversion efficiency in the darkened state without sacrificing visible light transmittance during off hours. The technology uniquely combines higher power conversion efficiency PV with the energy-saving benefits of dynamic glazing in a single system. The electricity from PV glazing could be used to operate other dynamic facade components. If significant additional generation is feasible, the additional cost required to integrate the glazing PV into the building electrical system could be more than offset by the value of the electricity generated.

Dynamic PV glazing is still in its early stages, and durability and switching temperature must be optimized before commercialization of switchable designs will be realized.

An alternative to dynamic PV glazing is PV blinds (shades), which integrate light-weight thin-film PV with existing window treatments. An opaque PV shade will deliver higher power output than its semi-transparent counterparts, but requires a complicated control system to avoid unwanted shading effects.

Daylight Redirection (Daylighting) Systems

Daylight provided by windows can make a major contribution not only to the ambiance of indoor environments but to reducing a building's demand for artificial lighting. Daylight redirection (daylighting) systems increase the usability of available natural light by illuminating interior spaces that were not otherwise daylit. Commercialized daylighting systems include interior and exterior light shelves, louvers, and films adhered to the glass itself. These systems typically apply to clerestory windows or the upper part of the main windows. Systems include technologies that capture light at the roof or facade and redirect it to interior spaces that do not have windows. Daylight redirection devices intended to reduce lighting energy use in buildings have found limited commercial adoption because of challenges related to both the technologies themselves and the supporting infrastructure required to realize consistent lighting energy savings. Table 2.6 presents some technology innovations that could advance daylight redirection systems.

When these technologies are combined with lighting sensors and controls and, ideally, with dimmable lamps or luminaires, they can significantly reduce the lighting energy use in some types of commercial buildings by substantially increasing the floor area with adequate illumination from available daylight alone. A project at LBNL developed a daylight redirecting system to provide daylight in areas of commercial buildings that are 15 to 40 feet from windows.[15] The team designed the system to redirect beam sunlight from the upper area of an east-, south-, or west-facing window to the ceiling plane using a set of automated, variable-width, mirrored louvers. Field measurements of early prototypes confirmed that the system redirected light deep into the space without discomforting glare. Simulations indicated that annual lighting energy use was reduced by 35–54 percent for east- and south-facing orientations and 9 percent for west-facing orientations compared to a manually operated, matte white venetian blind.

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[15] Ibid.

Table 2.6: Technology Innovations for Daylight Redirection Systems

Technology	Description	Technical Maturity
Technologies that redirect light to interior spaces or otherwise do not require sidelighting	Technologies that do not depend on sidelighting for visible light redirection have the potential to be effective for spaces with low or otherwise incompatible ceilings and for windowless interior spaces. These capabilities are critical to maximizing the lighting energy savings potential from utilizing available ambient light, particularly for retrofit applications where these building characteristics are not easily changed.	TRL 3
Novel materials with greater control over directional distribution of light	The patterns of redirected sunlight can be non-uniform and produce high contrasts of bright sunlight and shadowed areas on the ceiling and walls. Novel light redirection materials could allow better control of the distribution of light.	TRL 1-2
Daylighting software	Opportunities include software for sensor configuration to ensure adequate glare control and software to simplify design for lighting savings and occupant comfort while simplifying commissioning.	TRL 3-5

Source: U.S. Department of Energy (May 2020b). Technical maturity estimated by LBNL subject expert.

Heating and Air Conditioning Equipment

As global warming increases, energy use for air conditioning will grow, and as electrification of space heating advances, the efficiency of electric heating equipment becomes more important. Electric heat pumps that provide both heating and cooling are already quite efficient, though some further improvements in current vapor-compression technology are possible.

At present, the predominant vapor-compression technology utilizes hydrofluorocarbon refrigerants (HFCs) with very high global warming potential (GWP), but products using lower-GWP refrigerants (such as R466A, R32 and CO_2-R744) and having comparable or improved efficiency relative to today's typical equipment are already commercially available in several HVAC equipment categories.[16] Energy-efficient equipment using very low-GWP refrigerants are being tested, but there are trade-offs between GWP, performance, efficiency, flammability, and cost relative to current refrigerants. For that

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[16] California has a goal of reducing HFC emissions by 40% below 2013 levels by 2030, as mandated by SB 1383. California has already prohibited certain HFCs in retail refrigeration equipment, and the Air Resources Board is conducting a rulemaking to prohibit refrigerants with a GWP of 750 or greater in new stationary air conditioning systems starting January 1, 2023.

reason, there is interest in moving beyond vapor-compression technology altogether, while maintaining or improving efficiency.

Further work is needed to bring down the cost of low-GWP vapor-compression systems, and to develop low-GWP equipment offering efficiencies in line with today's best-in-class equipment. DOE focus areas include compressors that will be able to handle low-GWP refrigerants and low-GWP heat pumps using natural refrigerants such as CO_2 (R744).

Non-vapor compression (NVC) systems can provide sensible and/or latent cooling for buildings without the use of any refrigerants. Many NVC technologies are available today for certain applications, but most require additional R&D to meet the cost, efficiency, and performance of vapor-compression systems. Solid-state technologies, which include magnetocaloric and electrocaloric systems, produce useful temperature differences based on the intrinsic material properties of their core solid-state substance when activated through electrical input. Electro-mechanical technologies are electrically driven technologies that alter the phase or other properties of a working fluid to pump heat.

In a recent study for DOE of RD&D opportunities for commercial building HVAC systems, the technologies given the highest rank with respect to their potential were membrane cooling system, metastable critical-flow cycle, and thermoelastic.[17] (The membrane cooling system is most applicable in hot humid climates.) **Table 2.7** presents technology innovations for heating and air conditioning equipment.

Evaporative cooling technologies that are appropriate for hot dry climates have been used for many years, but new approaches could help overcome the barriers that have impeded more widespread use. Evaporative cooling systems have a high coefficient of performance (COP) in hot dry climates. The savings in power demand relative to vapor-compression systems increases along with the outdoor air temperature. Indirect evaporative cooling works based on heat transfer and mass transfer between two air flows separated by a heat transfer surface. Two-stage evaporative cooling (combined indirect/direct) aims to reduce the wet bulb temperature from the outdoor air before entering the evaporative pad by installing a heat exchanger. Evaporative cooling systems and evaporative pre-coolers, which combine an evaporative cooling system with a vapor-compression system, are commercially available but R&D continues to investigate improved designs.

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[17] U.S. Department of Energy. 2017a. *RD&D Opportunities for Commercial Buildings HVAC Systems*. https://www.energy.gov/sites/prod/files/2017/12/f46/bto-DOE-Comm-HVAC-Report-12-21-17.pdf

Table 2.7: Technology Innovations for Heating and Air Conditioning Equipment*

Technology	Description	Technical Maturity
Turbo-Compressor-Condenser-Expander Heat Pump	A system that combines multiple vapor compression components into a joint assembly operating on a common shaft for improved work recovery and energy efficiency.	TRL 3-4
Magnetocaloric	Provides space cooling by exposing specialized magnetocaloric materials to a strong magnetic field.	TRL 3-4
Electrocaloric	Specialized electrocaloric materials are oscillated in an electric field, which causes them to experience reversible temperature change and transfer heat.	TRL 1-2
Membrane Cooling System	System use specialized polymer membranes to transfer water across several assemblies that enable efficient dehumidification and evaporative cooling.	TRL 5-6
Thermoelastic	Systems that transfer heat by cyclically applying physical stress to a specialized elastocaloric (shape memory alloy) material that changes temperature when compressed and released.	TRL 3-4
Metastable Critical-Flow Cycle	A novel cooling cycle that uses a specialized converging-diverging nozzle to expand a high-pressure refrigerant, which decreases temperature as it evaporates supersonically.	TRL 3-4
Electrochemical Heat Pump	An electrochemical cell using a proton exchange membrane compresses a hydrogen working fluid to drive a vapor-compression or metal-hydride heat pump cycle.	TRL 3-4

* Not all of the technologies provide space heating as well as cooling.

Source: U.S. Department of Energy (2017a)

Table 2.8: Potential Energy Savings and Markets for Novel Heating and Air Conditioning Equipment

Technology	Energy Savings	Potential Market
Turbo-Compressor-Condenser-Expander Heat Pump	Estimated 20 SEER performance for residential-type split-system configuration would yield 30% savings relative to 14 SEER baseline.	Could be used in any type of air-cooled packaged A/C system.
Magnetocaloric	Estimated 20% energy savings for A/C applications.	Could be used in all vapor-compression type air cooling systems.
Thermoelastic	40% space cooling savings over conventional packaged commercial A/C systems	In the long term, could technically replace most vapor-compression type HVAC systems. Current developments focus on packaged space cooling applications.
Metastable Critical-Flow Cycle	Estimated 30% savings for chillers. Researchers believe that cooling cycle coefficient of performance (COP) could approach 10 or more.	The technology is potentially applicable for a wide range of space cooling applications. Large commercial chillers represent one of the clearest applications of the technology.
Electrochemical Heat Pump	20% -- R&D efforts underway target COP of >4 for space cooling.	Could technically have the potential to replace most vapor-compression type HVAC systems.
Electrocaloric	The research team projects energy savings of 20% or greater.	Could be applied in all vapor-compression type air cooling systems.

Source: U.S. Department of Energy (2017a).

Micro-distributed HVAC and Personal Comfort Devices

One of the primary challenges in indoor thermal comfort is that occupants' thermal sensation and thermal preferences within a given environment vary widely. Alternative HVAC system architectures could provide localized comfort to building occupants to reduce the operating requirements of traditional HVAC systems.

Micro-distributed HVAC on-demand concepts might include individual bed, seat, desk, floor, and surface heating and cooling.[18] Technologies that could enable this distributed

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[18] Snyder, G. Jeffrey, et al., 2021. Distributed and localized cooling with thermoelectrics. *Joule,* Vol. 5, Issue 4. DOI: https://doi.org/10.1016/j.joule.2021.02.011

architecture include a new generation of associated sensors and controls and solid-state heat pumps, such as thermoelectric Peltier coolers, that can provide heating or cooling with no moving parts or noise.

Making personal comfort systems both wearable and thermally effective poses challenges in terms of the device's size, location, weight, and daily operating life. A few wearable comfort devices have been manufactured and evaluated, and a number of prototypes of such devices have been reported in the research, development, and demonstration phases (Table 2.9).[19]

Table 2.9: Technology Innovations for Personal Comfort Devices

Technology	Description	Technical Maturity
Robotic Personal Comfort Device	A miniaturized heat pump on a motorized base that provides localized space heating and cooling for building occupants as they travel around the building.	TRL 5-6
Dynamic Clothing Technologies for Personal Comfort	Advanced materials and fabrics that reject or trap heat more efficiently than other materials, so that building occupants require less thermal comfort from the HVAC system.	TRL 3-4
Wearable Devices for Personal Comfort	Wearable devices, furniture, and other innovations that provide personalized comfort to building occupants, using small-scale heating and cooling elements.	TRL 5-6

Source: U.S. Department of Energy (2017a)

Ventilation

Ventilation directly accounts for 10 percent of electricity use in California's commercial sector. The share in the residential sector is small but may rise as concerns over air quality grow (especially during fire season) and air cleaning becomes of greater importance. In both sectors, the energy associated with outside air exchange in dwellings (i.e., "ventilation") is substantial, ranging anywhere from 20% to 50% of HVAC loads.

The quality of indoor air has a significant impact on health and comfort. Moisture buildup can also lead to structural damage to the building. There are a number of

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[19] Wang, Zhe, et al. 2020. Evaluating the comfort of thermally dynamic wearable devices. *Building and Environment*, Vol. 167, Jan. 2020. https://www.sciencedirect.com/science/article/abs/pii/S0360132319306535?via%3Dihub

strategies used to ensure adequate indoor environmental conditions in buildings.[20] Using the full range of options is important, since higher ventilation rates increase energy consumption when unconditioned outside air must be heated or cooled to replace conditioned indoor air that is being exhausted.

Strategies to reduce leaks in building shells and ducts can substantially reduce outside air exchange and the associated thermal HVAC loads. If sealing is very aggressive, however, mechanical ventilation may be required to ensure adequate indoor air quality.

Demand-controlled ventilation is common in commercial spaces using CO_2 sensors, which vary the outside air ventilation rate with the occupancy rate in the space. An issue with relying on CO_2 for demand controlled ventilation is that it only accounts for emissions from occupants or their activities, while ignoring emissions from building materials and other sources. Ventilation controls based on temperature or humidity are available in the market. These controls avoid ventilation during particularly hot or cold periods, which saves energy.

Other currently-available technologies include variable air volume systems with variable-speed fans, as well as heat recovery devices that allow incoming cool air to be heated by warm building air being exhausted (or the reverse if the building is cooled). Automated kitchen exhaust fans and smart ventilation controls are close to commercial readiness. Table 2.10 describes some emerging technology opportunities for ventilation systems.

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[20] First is the elimination of pollutant sources by using low-emitting materials, furnishing and products. Second is the removal of localized emissions through local exhaust fans, including kitchen, bathrooms and laundry areas. Third is dilution of other contaminants by providing consistent outside air to the space (i.e., traditional whole dwelling/building ventilation). Finally, remaining issues can often be resolved using air cleaning technologies, such as media or carbon filters.

Table 2.10: Technology Innovations for Ventilation Systems

Technology	Description	Technical Maturity
Advanced demand-controlled ventilation systems	Sensors can detect concentrations of CO_2 and other contaminants, and this information can be used to make appropriate adjustments to ventilation rates.	TRL 7
Recirculating kitchen range hoods with air cleaning	Some of the benefits of kitchen exhaust hoods may be achieved using recirculating units with adequate filtration for particles and carbon buffering for odors. Moisture emitted during cooking remains an issues, and must be removed by whole building dilution.	TRL 5
Automatic commissioning and fault detection	To deliver their intended outcomes, ventilation equipment must be commissioned to ensure adequate airflow. This commissioning can be automatically incorporated into the packaged equipment, and a technician can simply read-out and record the results. Some equipment might be able to proactively inform users if a fault has been detected, such as a clogged supply air inlet or an excessively dirty filter.	TRL 5

Source: Brennan Less, Building Technology & Urban Systems Division, Lawrence Berkeley National Laboratory

Lighting

Solid-state lighting (SSL), particularly with light emitting diode (LED) technology, is on course to become the dominant technology across all lighting applications. In just 10 years, LED luminous efficacies have increased over three-fold from less than 50 lumens/Watt (lm/W) to approximately 165 lm/W. LEDs are the rare energy efficiency technology that offers high efficiency, low cost, and improved performance. Improvements to efficiency reduce costs and size while enabling new form factors, improved optical performance, and new lighting applications.

Solid-State Lighting

The principal reason for gains in LED efficiency to date has been improvement in blue LED efficiency, although progress has also been made in phosphors (efficiency and wavelength match to the human eye response) and package (optical scattering and absorption) efficiency. Progress towards improving the efficiency of LED architectures requires improving efficiency in the green-amber-red spectral regions, where there has been limited development. With greater breakthroughs, there is the potential to reach the ultimate theoretical limit of 325 lm/W for direct-emitting architectures that combine direct-emitting color LEDs to make white light.

Advanced material discovery is necessary to accelerate the rate at which new potentially viable materials are detected. LED efficiency is still limited at high current density due to a phenomenon known as efficiency droop or current density droop. Operation at higher current densities is desirable to maximize the light emitted from the chip, thereby lowering the cost per lumen of LED lighting products. Remaining research challenges include efficiency improvements, cost reduction, reliability, color consistency, and compatibility with dimmers and other controls.

Organic LED (OLED) technology is a form of solid-state lighting that has lower efficiency than LEDs but produces diffuse light over a broader spectrum, and is manufactured in flat, flexible sheets. The result is better quality ambient light with less glare and greater application flexibility than standard LEDs. However, significant technology barriers remain for OLED lighting, with progress lagging behind LED performance and cost. OLED lighting technology needs ongoing R&D to translate lab scale efficiency and performance advancements to commercially practical approaches.

Table 2.11 presents the key R&D opportunities for solid-state lighting identified by DOE in a recent report.[21] Because the categories comprise a range of technologies, it was not feasible to characterize technical maturity.

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[21] U.S. Department of Energy. January 2020. *2019 Lighting R&D Opportunities*. https://www.energy.gov/sites/prod/files/2020/01/f70/ssl-rd-opportunities2-jan2020.pdf

Table 2.11: Technology Innovations for Solid-State Lighting

Technology Area	Description
Light Emitting Diode Devices and Materials	New or improved emitter materials with an advanced fundamental understanding of materials device-synthesis relationships and resulting performance for light-emitting diodes.
High Luminance Emitter Device Architectures	Advanced emitter device architectures with state-of-art-emitter materials to improve existing trade-offs between (a) the extraction of white photons from a device package, as measured by overall package power conversion efficiency (lm/W), and (b) the ability to deliver white photons to a target.
Diffuse Light Source Emitter Materials	Materials and structures that can improve the performance of low profile, diffuse lighting concepts that leverage the OLED technology platform. Advancements to the state of the art of OLED platform could be in the emitter materials, the device architecture, or system reliability.
Diffuse Light Source Optical Efficiency	Optical efficiency and optical control approaches to improve the performance of low profile, diffuse lighting concepts.
Quantum Dot Technology	On-chip quantum dot down converters to match or exceed performance of conventional on-chip phosphor materials at a range of emission wavelengths relevant to high efficiency solid-state lighting.
Advanced LED Lighting Concepts	Component or full lighting product concepts that demonstrate new or advanced lighting features, including very high efficacy, color tunability with high efficiency, or improvements to other aspects of lighting application efficiency. Improvements can be to the LED chip, package, module, or integrated lighting product.
Power and Functional Electronics	Advanced prototype LED or OLED power delivery concepts for luminaires with high efficiency, high reliability, and minimal size and weight. Use of new components, devices, materials, circuits, and system designs to provide improved performance.
Additive Fabrication Technologies for Lighting	High volume additive manufacturing technologies for any portion of the LED lighting manufacturing value chain that reduce part count and are cost effective. Printable materials with properties specific to lighting applications are of interest for additive manufacturing approaches.

Source: U.S. Department of Energy (January 2020)[22]

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[22] In February 2022, DOE issued a new report: *2022 Solid-State Lighting R&D Opportunities.* https://www.energy.gov/sites/default/files/2022-02/2022-ssl-rd-opportunities.pdf.

Table 2.12: LED Package Historical Efficacy and U.S. DOE Targets (lumens/W)

Type	2020	2025	2035	2050
Phosphor-Converted Cool White	185	228	249	250
Phosphor-Converted Warm White	165	210	241	250
Color Mixed	138	204	281	336

Source: U.S. Department of Energy (February 2022)

Outlook for Advanced Solid-State Lighting

U.S. DOE conducted an analysis that compares the current path for LED lamps and luminaires given continuation of current levels of solid-state lighting investment and effort from DOE and industry stakeholders, with a path that assumes the goals in DOE's SSL R&D Plan are met.[23] From 2017 to 2035, the DOE SSL Program Goals scenario shows additional cumulative energy savings of 16 quads (primary energy).

The next generation of energy savings from SSL will come from improving lighting application efficiency, which characterizes the efficient delivery of light from the light source to the lighted task.[24] Lighting application efficiency can account for the effectiveness of the light spectrum for the lighting application and the ability to actively control the source to minimize energy consumption when the light is not being used. Improved optical design can allow more efficient delivery of light with the optimum optical distribution. Precise spectral control enables delivery of more suitable light for the application needs and building occupants. Instantaneous control over a wide range of intensity provides the ability to deliver the right amount of light on demand.

Non-Energy Benefits of LEDs[25]

LED technologies can enable new lighting functionality beyond basic illumination for vision and visibility. The inherent spectral tunability in SSL provides the potential to improve building occupant well-being and productivity by supporting healthy circadian rhythms. LED lighting can also improve roadway safety by providing more suitable lighting that can enhance visual acuity and discernment for different roadway situations. The LED lighting platform is also capable of providing outdoor lighting that reduces environmental and ecological impacts, while also increasing security. In addition, it can

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[23] U.S. Department of Energy. December 2019. *Energy Savings Forecast of Solid State Lighting in General Illumination Applications*. https://www.energy.gov/sites/prod/files/2020/02/f72/2019_ssl-energy-savings-forecast.pdf

[24] The paragraph is drawn from: Advanced Lighting R&D Challenges. https://www.energy.gov/eere/ssl/advanced-lighting-rd-challenges

[25] https://www.energy.gov/eere/ssl/advanced-lighting-rd-challenges

also improve the sustainability and resiliency of food production by providing light sources that enable indoor, optimized growing conditions.

Lighting Control Systems

Innovation in low-cost sensors, wireless communication, computation, and data storage can facilitate the development of advanced, automated, and intelligent lighting control systems. A recent project at LBNL developed a suite of networked lighting solutions that could significantly reduce lighting energy use in commercial buildings.[26] The technologies include a platform for low-cost sensing, distributed intelligence and communications: the "PermaMote," which is a self-powered sensor and controller for lighting applications. The PermaMote includes multiple sensor types (e.g., light level, light color, motion, temperature) as well as energy harvesting capability, contained in a small and light form factor, and using industry-standard networking protocols. The simple, low-cost, wireless multi-sensor platform allows dense distribution of sensors in the controlled space, providing rich spatial coverage for the measured attributes.

The project team also developed a task ambient daylighting system that integrates sensors with data-driven daylighting control using an open Application Programming Interface. This technology, the "Readings-At-Desk" (RAD) system, uses illuminance measured at the desktop, with user-desired illuminance inputs, to control overhead lights. The sensors located at the desktop easily integrate with commercially available controllable lamps and luminaires for a low-cost networked lighting control retrofit.

For the PermaMote, testing showed that with the occupancy control and daylight dimming features, the experimental offices saved around 73% energy on average during the week-long test. For the RAD controller, testing showed significant energy saving through daylight harvesting, and more precise desktop illuminance. Overall, the project team estimates that these advanced technologies can reduce California office lighting energy use by 20% (above and beyond normal advanced lighting controls mandated by Title 24), resulting in about 1,600 gigawatt-hours (GWh)/year in savings.

Major Energy Consuming Appliances

Refrigerators and Freezers

Refrigerators and freezers in homes account for ~10 percent of residential electricity use in California, and larger refrigeration and freezing equipment account for ~8 percent of commercial electricity use. While there are common basic features among all types of refrigeration and freezing equipment, the wide range of sizes and types means that some technologies will work better than others for specific types of equipment.

The most common type of refrigerator[27] is based on a vapor compression cycle (VCC). For improving energy efficiency, advanced cycle options include dual evaporator cycles,

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[26] Brown, Rich, Peter Schwartz, Bruce Nordman, Jordan Shackelford, Aditya Khandekar, Erik Page, Neal Jackson, et al. 2019. *Developing Flexible, Networked Lighting Control Systems That Reliably Save Energy in California Buildings*. California Energy Commission. https://escholarship.org/uc/item/4ck0216d

[27] For simplicity, this section uses "refrigerator" as a stand-in for refrigeration and freezing equipment.

expansion loss recovery cycles (ejector and expander) and multi-stage cycles (two-stage and dual loop).[28]

The concerns about high-GWP refrigerants discussed for air conditioning also apply to refrigerators and freezers with VCC. Most of the low-GWP refrigerants under consideration for refrigerators and freezers are based on hydrocarbon refrigerants and composed of binary or trinary mixture to improve cooling capacity and COP.

As for air conditioners, non-VCC technologies are being investigated for refrigerators and freezers.[29] The absorption refrigeration cycle is the most developed and widely used non-VCC technology for refrigeration applications, but primarily for small sizes. Magnetic refrigeration, which uses the magneto-caloric effect in solid-state refrigerants and the temperature changes as the magnetic field changes, is the subject of active research. With respect to cooling capacity and COP, the magnetic refrigerator is closest to the current VCC-based household refrigerator.

Vacuum-insulated panels (VIPs), which are based on the reduction in conductivity that occurs in a low vacuum, have the potential to reduce refrigerator energy use by 20-30 percent.[30] Development of cheaper and more durable core materials is one of the major areas of research in VIPs. Computer modelling of the complex heat transfer phenomenon is necessary to develop newer core composites and envelopes leading to the most cost-effective and longest useful life VIPs.

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[28] Choi, S. et al. 2018. Review: Recent advances in household refrigerator cycle technologies. *Applied Thermal Engineering* 132 pp. 560–574.

[29] Ibid.

[30] Verma, S., H. Singh. 2020. Vacuum insulation panels for refrigerators. *International Journal of Refrigeration* 112 pp. 215–228.

Table 2.13: Technology Innovations for Refrigerators and Freezers

Technology	Description	Technical Maturity
Vapor Compression Technologies		
Ejector Cycle	Recovers expansion losses	Development stage
Two-Stage Compression Cycle	Reduces compression and expansion losses	Development stage
Dual Loop Cycle	Reduces compression ratio by smaller compressor and increases fresh food compartment evaporator temperature.	Commercially available for large-capacity refrigerators
Non-Vapor Compression Technologies		
Diffusion-Absorption Refrigeration Cycle	The cycle consists of a generator including a bubble pump, a rectifier, a condenser, an evaporator, an absorber and a reservoir.	Commercialized (small capacity)
Thermoelectric	Thermoelectric refrigeration is operated by a direct current passing through a circuit formed by two dissimilar conductors or semiconductors that produce a temperature difference at the junction of two conductors (Peltier effect).	Commercialized (small capacity)
Magnetic	Magnetic refrigeration is based on the magneto-caloric effect, a magneto-thermodynamic phenomenon in which a reversible change in temperature of a paramagnetic material is caused by exposing it to a changing magnetic field.	Development Stage
Thermoelastic	Thermoelastic refrigeration uses elastocaloric effect, which uses latent heat associated with transformation in shape memory alloys.	Development Stage
Other		
Vacuum Insulated Panels	Typical VIPs consist of a core material and an airtight envelope. VIPs have a thermal resistance about 10 times higher than that of equally thick conventional polystyrene boards used in refrigerators.	Commercial but development needed to reduce cost

Source: Choi et al. (2018); Verma and Singh (2020)

Other Appliances

Other major electric appliances used in homes and some commercial facilities are shown in Table 2.14.

Table 2.14: Other Major Electric Appliances

Appliance	Estimated Share of California Residential Electricity Use (%)
Clothes Dryer	6.2
Clothes Washer	0.7
Stove/Oven	3.9
Dishwasher	2.3
Water Heater	1.8

The share of water heaters is low because most residential water heaters in California use gas. To the extent that electrification of water heating is successful, this share will rise considerably. The same is true, though to a smaller degree, for clothes dryers and stoves/ovens, which currently use a mix of electricity and gas.

For water heating and clothes drying, high-efficiency electric alternatives to gas and electric resistance heating are available in the form of heat pump devices. Issues regarding integration of lower-GWP refrigerants also apply to these heat pumps.

As part of its long-term strategy, DOE is investigating thermoelectric systems for heat pump water heaters and clothes dryers, as well as electrochemical compression for heat pump water heaters. Oak Ridge National Laboratory (ORNL) has worked with GE Appliances to design, develop, and test a prototype clothes dryer that uses ultrasonic transducers to mechanically extract water from fabric.[31] The ultrasonic dryer works by using piezoelectric transducers, which are devices that convert electricity to vibration. When voltage is added, the transducers vibrate at a high frequency and turn the water into a mist as it is removed from the fabric. This project aims to develop a clothes dryer that can increase the energy factor from 3.7 to 5.43 lb. per kilowatt-hour (kWh) without increasing the drying time by more than 20% over baseline units.

Electronics and Other Plug Loads

Recent decades have seen a proliferation of electronics and other small appliances, especially in homes. The "Other" category (sometimes called "plug loads") accounts for ~44 percent of California residential electricity use, and ~23 percent of commercial electricity use.[32]

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[31] https://www.energy.gov/eere/buildings/downloads/ultrasonic-clothes-dryer

[32] Some of the electricity used by plug loads provides space heating (portable heaters), cooling (ceiling fans and other fans), or cooking (microwave ovens and various kitchen devices). In the commercial sector, servers and related equipment in data centers fall into the "electronics and other" category.

Increasing the energy efficiency of plug loads is challenging. One approach is to reduce standby-power use to zero or nearly zero. A recent project demonstrated zero or near-zero standby power to be technically feasible in several families of products.[33] These solutions have both advantages and drawbacks and will require further technical improvements and cost reductions before they can be commercialized and introduced into new devices. In addition, the portfolio of solutions needs to be broadened.

Another approach is to utilize DC input. DC-connected loads can connect directly to higher-efficiency DC distribution at lower cost. DC input also allows for a great reduction in the size of capacitors and improves power quality.[34] There is increased interest in using DC power distribution within zero-net energy buildings to connect very efficient end-use equipment, such as solid-state lighting and variable speed motors, with on-site solar generation and energy storage. Successful market deployment of DC systems in buildings requires the availability of reliable, cost-competitive end-use appliances and equipment that can directly use and enable DC power, as well as mature standards that address DC power distribution voltages, connectors, and protection schemes.[35]

Table 2.15 describes several technology innovations for plug loads.

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[33] Meier, Alan, Richard Brown, Daniel L. Gerber, Aditya Khandekar, Margarita Kloss, Hidemitsu Koyanagi, Richard Liou, et al. September 2020. *Efficient and Zero Net Energy-Ready Plug Loads*. California Energy Commission. https://ww2.energy.ca.gov/2020publications/CEC-500-2020-068/CEC-500-2020-068.pdf

[34] Ibid.

[35] Vossos, V., et al. 2019. *Direct Current as an Integrating and Enabling Platform for Zero-Net Energy Buildings*. California Energy Commission. https://ww2.energy.ca.gov/2019publications/CEC-500-2019-038/CEC-500-2019-038.pdf

Table 2.15: Technology Innovations for Plug Loads

Technology	Description	Technical Maturity
Zero or Near-Zero Standby Power		
Burst Mode	Burst mode allows a lightly loaded power converter to operate at a higher-efficiency point.	TRL 3
Optical Energy Harvesting	Optical energy harvesting to turn on line-of-sight remote-controlled devices like televisions, set-top boxes, lights, and fans.	TRL 4
RF Wake-up	Uses an ultra-low-power "wake-up radio" to activate the device.	TRL 3
Direct Current Devices		
A network of "direct DC" devices powered by USB or ethernet[a]	Many electronic devices, such as Wi-Fi routers, are already "native" DC and require a transformer to operate with AC power. The direct DC arrangement obviates the need for power supplies, reducing materials and conversion losses. It also enables management of devices through signals on the DC connections so that the devices can, for example, respond to changes in electricity prices.	TRL 5
Controller capable of managing the ecosystem of DC devices	An open-source controller capable of managing the ecosystem of DC devices would optimize operation based on real-time electricity price and can incorporate PV and storage.	TRL 5

[a] Direct DC refers to the concept of powering devices with low voltage DC through ethernet and USB PD wires. Many electronic devices, such as Wi-Fi routers, are already "native" DC and require a transformer to operate with AC power. The direct DC arrangement obviates the need for power supplies, reducing materials and conversion losses. It also enables management of devices through signals on the DC connections so that the devices can, for example, respond to changes in electricity prices.

Sensors and Controls

Lighting, windows, HVAC equipment, water heaters, and other building equipment are starting to be equipped with smart controllers and wireless communications capabilities. These systems open many opportunities for improving building efficiency, managing peak loads, and providing services valuable to controlling the cost of large utility systems. They also offer many non-energy benefits that may be of greater interest to building owners and occupants, such as improved security, access control, fire and other emergency detection and management, and identification of maintenance issues before they lead to serious problems.

While individual subsystems such as lighting require their own control, the building as a whole will perform most efficiently if all the building systems are controlled as a part of an integrated system. A challenge in developing building sensor and control systems is getting complex control systems to work correctly.

An emerging area of interest involves predictive controls. These are "smart" controls of HVAC, automated facades, plug load, lighting, etc. that utilize data on occupant behavior, technology operation and climate conditions to save energy by anticipating the occupants' needs and reducing waste.

In addition to managing and optimizing building operations, control systems in buildings can also play a major role in optimizing the performance of the next-generation electric grid. Advanced building controls and control strategies can provide a portfolio of services ranging from short-term load shedding by controlling water heaters and other appliances, to longer-term load shifting using the thermal mass of the building, HVAC controls, water heater controls, or storage systems. Emerging control technologies that can facilitate interaction with the grid are discussed in Chapter 5.

Data Centers

Data centers process, store, and communicate the data behind the myriad information services that are central to modern life. Servers, networking, and data storage equipment used in data centers, and the air conditioning equipment required to keep them cool, consume a large amount of electricity. Whereas large data centers are operated by companies with the resources and incentives to maintain high levels of energy efficiency, smaller data centers typically pay less attention to energy efficiency and have inadequate cooling equipment. California is home to a large number of small and medium-size data centers. One study estimated that 20 percent of all small and midsize data centers are located in the Pacific region.[36]

Given the relative lack of management resources in small and midsize data centers, finding simple ways to improve operations would yield significant benefits. Reducing the energy used by the servers and other equipment decreases the cooling load that the air conditioning system needs to meet.

One potentially helpful technology builds on the fact that ENERGY STAR certification for computer servers requires direct access to power, utilization, and intake temperature.[37] The data must be in a user accessible format that is readable by third-party, non-proprietary software over a standard network. Hundreds of servers can now individually be monitored without any external measurement equipment. For example, since all intake temperatures are accessible, thermal management in the data center can be greatly improved. Thermal management, in turn, improves both server reliability and infrastructure energy efficiency. Since the direct-access features are neither well known

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[36] Ganeshalingam, M., Arman Shehabi, Louis-Benoit Desroches. 2017. *Shining a Light on Small Data Centers in the U.S*. Lawrence Berkeley National Laboratory. https://eta-publications.lbl.gov/sites/default/files/lbnl-2001025.pdf

[37] This paragraph and the following one were prepared by Magnus Herrlin, Building & Industrial Applications Department, Energy Technologies Area, LBNL.

nor well understood, the potential for automation is hampered. Developing a universal data access technology (working for all server brands and models) for this purpose could pay off handsomely in a relatively short time.

Another approach that could reduce energy use in data centers (and in computers elsewhere) involves promotion of computer coding techniques and algorithms that are mindful of the impact to computational efficiency and system energy usage. Such measures can substantially affect the compute load, and end users rarely have the ability to make changes. If better techniques and algorithms became more widespread, it would result in immense energy savings for data centers. Not only would it help reduce the energy use of the computer systems (since the code now runs faster), but also the energy going to support systems in the data center since less cooling is required.

Advanced Building Construction

Lagging construction sector labor productivity increases the cost of new buildings and retrofit upgrades while limiting the use of energy-efficient technologies in these projects. To address these challenges, there is growing interest in new practices that combine advanced off-site manufacturing of building components with streamlined delivery and installation methods.

DOE's Advanced Building Construction Initiative is developing building technologies that can be deployed quickly with minimal onsite construction time, are affordable and appealing to the market, and leverage related efforts to increase the productivity of the construction industry.[38] The initiative focuses on building design, construction, and installation to improve affordability, scalability, and performance of energy efficient building systems and methods. It includes a special emphasis to make mobile homes significantly more efficient while maintaining the same initial cost. Some of the technologies can be deployed with minimal onsite construction in the existing building stock as well as new construction.

The initiative targets innovations in several key areas. Table 2.16 presents some of the technologies under development.

NEW BUILDING MATERIALS. Building with newly developed materials, such as recycled materials or existing materials not traditionally used in construction, can decrease the overall energy used to construct buildings while simultaneously decreasing operational energy usage.

3D PRINTING AND NEW METHODS OF FABRICATION. Additive and subtractive manufacturing tools, such as 3D printers and computer numerical control machines, have improved dramatically over the past few decades, opening doors for building structures and components that were previously impossible or very time-consuming to

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[38] Advanced Building Construction Initiative. https://www.energy.gov/eere/buildings/advanced-building-construction-initiative

create. With recent breakthroughs, these fabrication techniques may hold promise in accelerating production time and quality of building components.

OFFSITE MANUFACTURING. Factory and off-site construction methods have the potential to produce higher quality and faster construction timelines, improve productivity, increase the integration of various energy-efficiency technologies, and provide workers with controlled working conditions at lower costs. The increased precision and scalability that controlled factory settings provide can help ensure greater energy performance with the integration of tighter envelopes, better installed windows, smarter controls, and improved HVAC system designs.

ROBOTICS. Advancements in robotics capabilities and controls allow for human workers to reach places or perform activities that were previously impossible. For example, robots can safely enter small spaces and cavities, such as ductwork, to perform air-sealing or other efficiency activities. Robots can be used to improve productivity and ensure consistency when installing energy-efficiency measures.[39]

DIGITIZATION. Complex software and faster computing power, combined with artificial intelligence and machine learning, allow for the rapid intake and processing of information. For energy-efficient construction, machines can intake visual images, energy analysis and modeling information, and other inputs to directly translate data into the fabrication of building components, including walls, roofs, or interior design features. This process can help in the design of high-performance buildings with smarter, energy-efficient components.

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[39] U.S. Department of Energy is sponsoring the American-Made Buildings Prize: Envelope Retrofit Opportunities for Building Optimization Technologies (E-ROBOT), which is designed to catalyze the development of minimally invasive, low-cost, and holistic building envelope retrofit solutions that make retrofits easier, faster, safer, and more accessible for workers. https://americanmadechallenges.org/EROBOT/

Table 2.16: Technology Innovations for Building Construction[a]

Technology	Description	Technical Maturity
Insulated precast concrete wall panels that will reduce the contribution to heating and cooling loads from walls by ~ 40% compared to current practice	Technologies include: High-performance concrete mix for 1.5 inch-thick wythes that allow doubling the amount of insulation without affecting the overall thickness of the wall panel; Non-corroding inserts and connections for 1.5 inch-thick wythes; Primer-less, self-healing sealant that will increase the longevity of the airtight and watertight panel joints; 3D printed molds that can be assembled ~50% faster than traditional wood molds.	TRL 8
Additive manufacturing of concrete walls	The proposed technology aims to achieve 50% improvement in thermal resistance) without compromising structural performance at no additional first cost.	TRL 6
Advanced manufacturing techniques to mass-customize and produce energy-efficient and moisture-durable overclad panels for envelope retrofits	Develop new printable materials, design methods to use multi-material printing to co-optimize structural and thermal performance, and integrate existing building materials with customized 3D printing parts that expedite the assembly of the overclad panel.	TRL 3
Integrated building system for the design, manufacturing, and delivery of zero-energy-ready cottage-style single-family homes	The integrated building systems will include: An automated off-site production platform, consisting of a virtual prototype production line and pilot robotic cell that utilizes off-the-shelf industrial robotics to reduce the labor cost associated with closed wall panel fabrication and construction; An efficient design platform consisting of predefined assemblies and modules that can be combined to create a variety of homes.	TRL 2
A streamlined, automated software workflow for the specification, manufacturing, and installation of panelized overclad retrofits for existing low/mid-rise wood-framed buildings	The novel software workflow will support the automated specification of the panels and the finishing components to be fabricated off-site.	TRL 3
Integrated mechanical system pods for small and large multifamily buildings	The pods will provide heating, cooling, ventilation, domestic hot water, dehumidification and grid-interactive controls in one simple, highly efficient, and easy to deploy package. They will be designed to be deployed in low-load applications driven by corresponding envelope improvements or mild climates.	TRL 3

[a] These technologies and techniques are among the projects being funded by DOE's Advanced Building Construction Initiative. Technical maturity was estimated by experts at Oak Ridge National Laboratory.

Industry

The industrial sector (not including mining) accounted for 14 percent of California's 2019 electricity consumption. An end-use breakdown of California industrial electricity consumption is not available. Estimates for the United States show that half of the consumption goes to machine and motor-drive, including operating fans, pumps, compressors, forming and machining tools, and materials processing and handling equipment (Table 2.17).[40] Though listed separately, HVAC and cooling/refrigeration systems are also motor-driven. A more recent study estimated that motor systems (including all motor-driven systems) account for 69% of total industrial electricity consumption in 2018.[41]

Table 2.17: U.S. Manufacturing Electricity Consumption by End Use, 2014

End Use	Percent of Total
Machine/Motor Drive	50
Process Heating	11
Electrochemical Processes[a]	9
Facility HVAC	8
Process Cooling and Refrigeration	7
Facility Lighting	6
Other Process Use	2
Other	7

[a] Electrochemical processes include aluminum processing, which is not done in California, so the share of electrochemical processes is lower than for the U.S.

Machine/Motor Drive

While electric motors have high efficiencies, end-use motor-driven systems have much lower system efficiencies, particularly for pumps, fans, compressed air and materials processing equipment. Hence, the largest opportunity for increasing efficiency in motor-driven systems is improving overall system designs. Systems are often designed for greater throughput than normally operated, with excess throughput throttled by process controls that result in efficiency losses. Variable-speed drives (VSDs) or variable-frequency drives (VFDs) dynamically adjust motor speed or frequency to match

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[40] Schwartz, Lisa, Max Wei, William Morrow, III, Jeff Deason, Steven Schiller, Greg Leventis, Sarah Smith, et al. 2017. *Electricity End Uses, Energy Efficiency, and Distributed Energy Resources Baseline*. Lawrence Berkeley National Laboratory. https://emp.lbl.gov/publications/electricity-end-uses-energy

[41] Rao, Prakash, et al. 2021. *U.S. Industrial and Commercial Motor System Market Assessment Report, Volume 1: Characteristics of the Installed Base*. Lawrence Berkeley National Laboratory. https://eta-publications.lbl.gov/sites/default/files/u.s._industrial_and_commerical_motor_system_market_assessment_report_vol_1_.pdf

power requirements and can save a considerable amount of electricity for applicable systems.[42] Opportunities also exist to better harmonize alternating current (AC) and DC power to reduce conversion losses and improve power quality for industrial applications.

Because of the energy savings possible with VSDs and VFDs, a key focus of technology development is expanding the range of potential applications through use of wide-bandgap (WBG) semiconductors. In addition, improvements to electric motors can be realized through the application of technologies such as advanced magnetic materials, improved insulation materials, aggressive cooling techniques, high speed bearing designs, and improved conductors or superconducting materials.

Wide-Bandgap Semiconductors

WBG semiconductors have bandgaps significantly greater than those of silicon semiconductors, enabling superior current control and reducing energy losses. WBG semiconductors are able to operate at higher voltages and power densities than silicon-based semiconductors, allowing the same amount of power to be delivered with fewer chips and smaller components.[43] In addition, these more powerful WBG semiconductors can operate at higher frequencies, which helps to simplify system circuitry and reduce system costs. The materials in WBG semiconductors tolerate heat better than silicon. As a result, WBG-based power electronic chips can operate in harsher conditions without degrading the semiconductor material. Their greater thermal tolerance (300°C vs. 150°C) reduces the need for bulky insulation and additional cooling equipment, allowing for more compact system designs.

Silicon carbide (SiC) and gallium nitride (GaN) are the two most prominent WBG materials for power devices. Lateral GaN devices are available for voltages up to 650 V. Vertical GaN devices, which are currently under development, will be able to operate at higher voltages. SiC devices can operate at even higher voltages, but the design and manufacturing challenges for very high voltage modules are limiting SiC devices from achieving their maximum potential.[44]

The higher voltage capabilities, switching frequencies, and junction temperatures of WBG devices will enable the integration of medium-voltage motors[45] with WBG-based VFDs. More efficient and compact VFDs using WBG semiconductors are expected to expand the existing VFD market into a wider range of motor system sizes and applications (Table 2.18). New applications could include very high power systems or applications where silicon-based VFDs would degrade too quickly.

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[42] A variable speed drive refers to either AC drives or DC drives, while a variable frequency drive refers to AC drives only. VFDs vary the speed of an AC motor by varying the frequency to the motor. VSDs referring to DC motors vary the speed by varying the voltage to the motor.

[43] The discussion of WBG semiconductors is based on https://www.energy.gov/eere/amo/power-america

[44] Morya, A.K., et al. March 2019. "Wide Bandgap Devices in AC Electric Drives: Opportunities and Challenges," *IEEE Transactions on Transportation Electrification*, vol. 5, no. 1, pp. 3-20. https://doi.org/10.1109/TTE.2019.2892807

[45] In the IEC 60038 standard, medium voltage is from 1000 V to 35 kV.

Table 2.18: Applications for Wide-Bandgap Devices in AC Motor Drives

Low Inductance Motors	High Speed Motors	Motor Drives Operating in High Ambient Temperature
Motors with large effective airgap	High power density motors – vehicle electrification	Integrated motor drives
Slotless motors	High pole count high speed motors wit high torque density	Hybrid electric vehicle
Low leakage induction machines for high speed traction	MW level high speed motors	Sub-sea and downhole applications

Source: Morya, et al. (2019)

Other Motor Technologies

The Next Generation Electric Machines program in DOE's Advanced Manufacturing Office (AMO) is supporting development of medium-voltage integrated motor drive systems that leverage the benefits of WBG devices with energy-efficient, high-speed, direct-drive, megawatt class electric motors for the chemical and petroleum refining industries, natural gas infrastructure, and general industry compressor applications like HVAC systems, refrigeration, and wastewater pumps.[46] These application areas represent a large amount of electrical energy consumption. The aim of the projects is to reduce the size of megawatt-scale motors and drive systems by up to 50 percent and cut energy losses by as much as 30 percent. Table 2.19 shows some of the technologies under development.

The AMO is also advancing technologies that will drive cost-effective efficiency enhancements and weight reductions in electric machines while addressing the limitations of traditionally used conductive metals and electrical steels. The goal of the initiative is to develop and demonstrate scalable, high throughput processes for manufacturing enabling technologies, including high performance thermal and electrical conductors, low-loss silicon steel manufacturing, high-temperature superconducting wire manufacturing, and other technologies to increase performance.

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[46] https://www.energy.gov/eere/amo/electric-machines

Table 2.19: Technology Opportunities for Medium-Voltage Motor Drives

Technology	Description	Technical Maturity
High Power Density Drive with Silicon Carbide Based Converter	High-performance, high-speed drive incorporating a silicon carbide based five-level modular multilevel converter. Capable of integrating into 13.8 kV electric grids while avoiding energy losses associated with power transformers. Suitable for industry sectors such as oil and gas, chemical, and mining.	Mid-TRL
Integrated Variable Speed Drive and High Speed Motor for Gas Compression	Integrating a VSD (using high current silicon carbide devices, high-frequency inductors, and other advanced reactive components) with state-of-the-art switching frequency power electronics into a permanent magnet motor to increase power density and energy efficiency.	Mid-TRL
Silicon Carbide Drive for High-Speed Motor Applications	The major R&D focus is on silicon carbide-based high frequency switching devices that can work directly with high voltages, switch at high frequencies, and do so very efficiently. Suited for high-speed direct drive equipment in many industry sectors.	Mid-TRL

Source: DOE Advanced Manufacturing Office. https://www.energy.gov/eere/amo/electric-machines

Process Heating[47]

Electricity-based process heating systems (sometimes called electro-technologies) are used for heating, drying, curing, melting, and forming. Across U.S. manufacturing, electricity accounts for only 5% of process heating energy consumption. Examples of electricity-based process heating technologies include infrared radiation, induction heating, radio frequency drying, laser heating, and microwave processing.

In addition to offering greater efficiency, high-frequency electro-technologies such as microwave, radio frequency, and induction can enable the manufacture of improved or novel products due to attributes such as selective and volumetric heating. However, successful deployment of microwave and radio frequency processes requires a comprehensive understanding of the process and system physics. Computational modeling and optimization can improve the design process and facilitate technology development by enabling improved simulations of the electromagnetic, thermal, and materials interactions. There is also a need for conformable/adaptable applicators for microwave, radio frequency, and induction systems that can adjust to changes in product size and shape.

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[47] Based on: U.S. Department of Energy. 2015. *Quadrennial Technology Review 2015*, Appendix 6I: Process Heating. https://www.energy.gov/sites/prod/files/2016/06/f32/QTR2015-6I-Process-Heating.pdf

Process Cooling and Refrigeration

California's large food processing industry makes considerable use of refrigeration/cold storage and freezing. These applications rely on many of the same technologies used in commercial-sector refrigeration systems—namely, heat pumps and large-scale chillers. Hence, many of the technology opportunities discussed for the buildings sector are relevant for industrial cooling and refrigeration. In situations where there is a source of waste heat, absorption or adsorption chillers could be used to provide thermal compression of refrigerant instead of mechanical compression.

Converting Waste Heat to Electricity

Waste heat is generated from a variety of industrial systems. The largest sources of waste heat for most industries are exhaust and flue gases and heated air, but waste heat can also be found within liquids and solids. Improved waste heat recovery is a major focus of industrial energy conservation efforts and also R&D. In general, the least expensive option for utilizing waste heat is to re-use this energy in an on-site thermal process. In some cases, however, a waste heat to power system may be an economically attractive option. Such systems would have the potential to reduce purchased electricity by industry.

A variety of waste heat to power technologies are in use in industry. R&D opportunities in advanced high efficiency power generation systems include:[48]

- High turndown systems for use in applications where the waste heat stream heat content (in terms of Btu/hr) changes significantly (due to mass flow or temperature fluctuations).
- Systems with non-water cooled condensers to avoid the need for water and cooling towers.

Thermoelectric electricity generation systems, which allow for direct electricity generation, are under development for heat-to-electricity conversion.[49] New material classes could allow for waste heat recovery with better efficiency or use with higher-temperature heat sources. Other key identified R&D needs include the development of high-performance heat exchange surfaces and high-heat flux interface materials. The need to reduce the cost of power generated by thermoelectric waste heat recovery could be met by using lower cost materials as well as automated methods of thermoelectric assembly. Researchers at LBNL and Stanford have recently developed a thermoelectric waste-heat recovery system based on wafer-scale arrays of porous

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[48] Based on: U.S. Department of Energy. 2015. *Quadrennial Technology Review 2015*, Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing. https://www.energy.gov/sites/prod/files/2017/03/f34/qtr-2015-chapter6.pdf

[49] U.S. Department of Energy. *Quadrennial Technology Review 2015*, Appendix 6G: Direct Thermal Energy Conversion Materials, Devices, and Systems. https://www.energy.gov/sites/prod/files/2015/12/f27/QTR2015-6G-Direct-Thermal-Energy-Conversion-Materials-Devices-and-Systems.pdf

silicon nanowires.[50] The results provide material design guidelines for creating potentially cost-effective silicon nanowire-based thermoelectric energy converters.

Water Sector

In the last 25 years, energy use in California's water and wastewater systems has increased almost 40% and 75%, respectively. Currently, approximately 6% of electricity is consumed in the water sector for supplying and treating water for use in the state, or collecting water after use (i.e., wastewater) and treating it for safe disposal or reuse.[51]

An estimated breakdown of uses for electricity in the water sector is shown in Figure 2.3. Three-quarters of water sector electricity is used for pumping. Electricity used for pumping can be managed by minimizing water demand and with better sized and controlled pumps and motors. Prioritizing local and decentralized water supplies can also reduce pumping distances for supply and distribution. However, treatment processes often benefit from strong economies of scale so tradeoffs must be carefully considered. Around 8% of all electricity, and about half of electricity for wastewater treatment is used for aeration.

To reduce electricity consumption in water systems, two areas show particular promise:

- autonomous control systems,
- more efficient decentralized water treatment to serve rural and disadvantaged communities.

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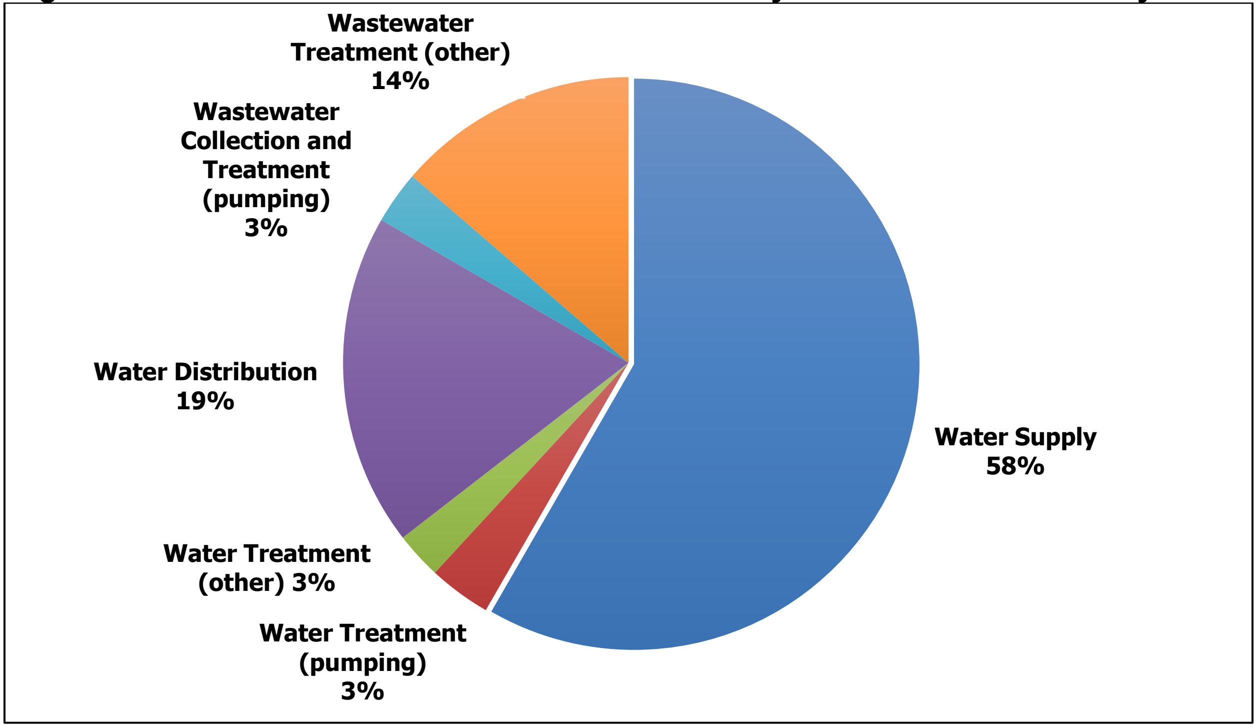
[50] Yang, L., D. Huh, R. Ning, et al. 2021. "High thermoelectric figure of merit of porous Si nanowires from 300 to 700 K." *Nat Commun* 12, 3926. https://doi.org/10.1038/s41467-021-24208-3

[51] Kenway, S.J. et al. 2019. "Defining Water-Related Energy for Global Comparison, Clearer Communication, and Sharper Policy." *Journal of Cleaner Production* 236 (November): 117502. https://doi.org/10.1016/j.jclepro.2019.06.333.

Figure 2.3: Estimated End-Use Shares of Electricity in California's Water Systems



Source: Estimated by LBNL using data from: "California's Water 2016" from the Public Policy Institute of California; Navigant (2006); Pabi, S. et al. (2013)

Autonomous Controls

As in other industries, process control using advanced sensors, combined with artificial intelligence (AI) and machine learning with adaptive controls, has the potential to greatly reduce electricity use across the water sector, potentially improving performance for both pumping and treatment steps. This will require infrastructure, software, and networked solutions for sensing, instrumentation, control, modeling and platforms. Autonomous systems must account for the high variability in operating conditions, water quality characteristics, flow regimes, and treatment train design and flexibility (e.g., ability to ramp processes up and down) seen in water and wastewater systems in California.

To date, more effort has been made to use AI and machine learning for knowledge generation rather than functional control.[52] The paucity of high-quality data about California's diverse water systems generally, and often by the water agencies themselves, as well as concerns about privacy and cybersecurity, are barriers to developing this technology. Additionally, industry fragmentation and the limited technical, managerial, and financial capacity of smaller water systems make it difficult to develop technology that is affordable for the communities that most need it.

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[52] Garrido-Baserba, M. et al. 2020. "The Fourth-Revolution in the Water Sector Encounters the Digital Revolution." *Environmental Science & Technology* 54 (8): 4698–4705. https://doi.org/10.1021/acs.est.9b04251

Nonetheless, there has been varying success developing and commercializing autonomous controls systems within the water sector, including some of the technologies listed in Table 2.20. Overall, adaptable, reliable, integrated, and generalizable autonomous monitoring and control systems that are cost effective for both small and large water systems are still in early stages of development.

Table 2.20: Technology Innovations for Autonomous Control of Water Systems

Technology	Technical Maturity
Leak detection and asset management for systems with sufficient knowledge of their water and wastewater conveyance infrastructure	High
Cost-effective smart metering for all customers	Medium
Control systems that allow responsive grid integration of pumping activities	Medium
Rainfall prediction and controls to automate and optimize operations of reservoirs	Medium
Leak detection and asset management based on statistical models to assist systems with incomplete data about their water and wastewater conveyance infrastructure	Low
Control systems that allow responsive grid integration of treatment processes and facilities	Low
Generalizable, secure, and resilient sensors that can be distributed and networked through the Internet-of-Things	Low
Models and platforms for real-time fault detection, feedback control, and optimization of treatment processes	Low
Reliably monitoring water quality from decentralized treatment systems through indicators and surrogates	Low

Sources: Garrido-Baserba, M. et al. (2020). Eggimann, S. et al. (2017). Mauter, Meagan and P. Fiske (2020). Technical maturity estimated by LBNL.

Efficient Decentralized Water Treatment to Serve Rural and Disadvantaged Communities

Many of the water and wastewater systems that rural areas have relied on are inadequate and are contributing to growing concerns about water justice and equity.[53] Connecting these rural areas to larger centralized systems will provide desirable outcomes in some cases. However, relying solely on consolidation to address this issue will impact the autonomy of these already disenfranchised communities and miss an opportunity to invest in decentralized treatment approaches that can improve

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[53] Balazs, C. et al. 2021. *Achieving the Human Right to Water in California: An Assessment of the State's Community Water Systems*. California Environmental Protection Agency.

resilience.[54] Reliable decentralized water treatment requires improved autonomous control to ensure effective treatment and safe performance of these systems.

Water Supply and Treatment

Water in rural areas, especially in the Central Valley, is most commonly obtained from pumped groundwater either through community water systems or on a household level. Approximately 2 million Californians use water from household wells and 97% of community water systems in the San Joaquin Valley are groundwater dependent with limited options for alternate water supplies. Groundwater is increasingly less reliable, with more degraded quality due to over-pumping and pollution from human and natural sources, much of which occurs in rural and disadvantaged areas (

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[54] Rabaey, K., T. Vandekerckhove, A. v.d.Walle, and D. L. Sedlak. 2020. "The Third Route: Using Extreme Decentralization to Create Resilient Urban Water Systems." *Water Research* 185 (October): 116276.

Figure 2.4). The Sustainable Groundwater Management Act alone may not address these problems.[55] Removing common pollutants (e.g., nitrates, pesticides, arsenic, and industrial chemicals) may require multiple treatment processes to remove all constituents. There is a need for more reliable and affordable technologies that can be deployed for small treatment facilities and point-of-entry or point-of-use applications. These new technologies will require significantly reduced life-cycle costs through fewer cleanings, reduced maintenance, and/or lower costs for capital and replacement parts. Examples include composite materials that can remove a broader array of constituents in a single step; small-scale membrane treatment; solar-powered thermal desalination; and materials that enable low-energy moisture harvesting.

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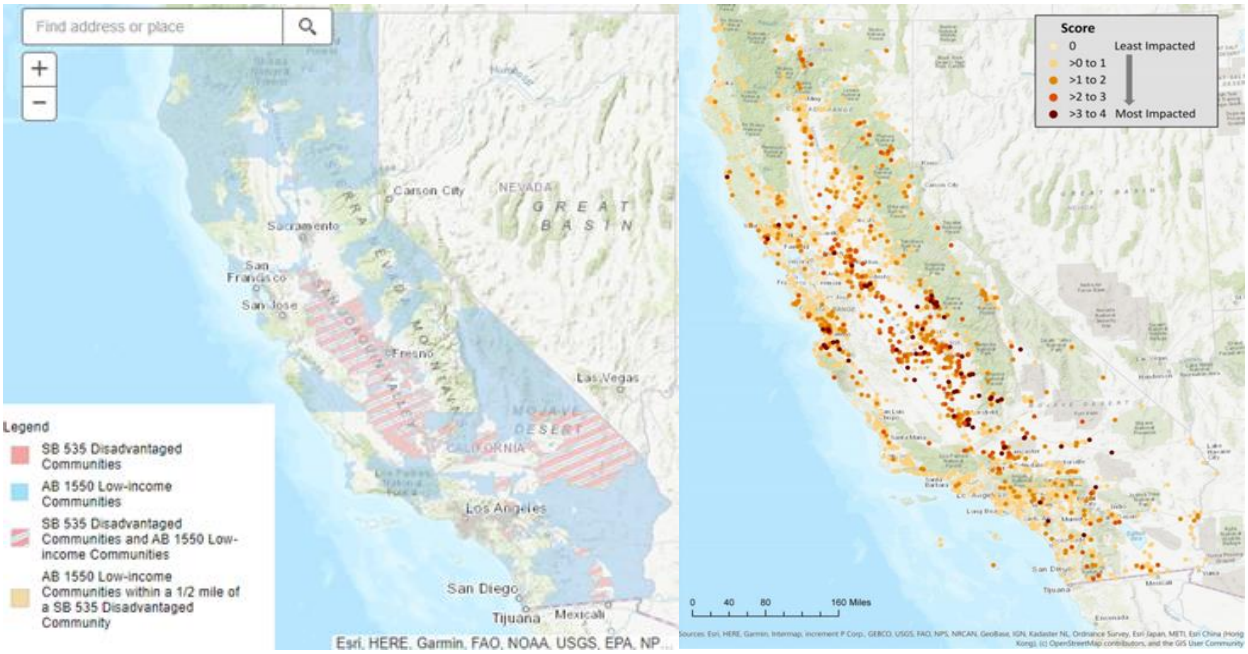
[55] https://waterfdn.org/wp-content/uploads/2020/06/Groundwater-Management-and-Safe-Drinking-Water-in-the-San-Joaquin-Valley-Brief-6-2020.pdf

Figure 2.4: Groundwater Pollution Prevalence (left) and Low Income and Disadvantaged Communities (right)



Source: Balazs et al. (2021) (left); California Air Resources Board, *https://ww3.arb.ca.gov/cc/capandtrade/auctionproceeds/communityinvestments.htm*

Wastewater Treatment

Wastewater treatment in rural areas often consists of passive treatment in household septic tanks. Though many California communities are phasing out septic tanks, about 10% of Californians still rely on them. Septic tanks that are poorly maintained create public health concerns, contaminate local water supplies, contribute to climate change with methane emissions, and don’t allow for short-term reuse of the water to reduce pressure on existing water supplies. Cost-effective and reliable technologies are needed to improve the performance of the wastewater systems and provide additional recovery of water and other resources that can be reused nearby (e.g., energy, nutrients). For wastewater systems serving small communities, engineered passive treatment processes can minimize aeration needs while also limiting nutrient discharges are needed. Potential approaches include improved constructed wetlands and algae-based treatment processes that provide reliable, year-round treatment as well as sewer bioaugmentation. At the household or neighborhood scales, onsite treatment systems that provide water for non-potable uses would be beneficial, such as improved membrane bioreactors or bioelectrochemical systems. Systems that combine small-scale water and wastewater treatment to provide onsite potable reuse in a reliable and affordable manner would be especially desirable.

Strategic Considerations for California

Buildings. Strategies to develop technologies that can reduce energy use for space heating and cooling need to take into account the distribution of buildings among climate zones and likely changes in climate. Most new homes in California will be built in areas that already have high demand for air conditioning, which will rise as global warming proceeds. Much of the existing housing stock is in the coastal metropolitan areas, where air conditioning is less common and heating demand is likely to decline.

Innovations in windows and building envelope will be easiest to apply in new buildings. For retrofit, window and envelope technologies that are too complex and/or costly are not likely to be cost-effective, but if envelope retrofits can be integrated into re-siding projects there is an opportunity to add insulation and air barriers. There is a need for products that work well together and add minimal extra work. Many older residential buildings, as well as manufactured homes, have thinner building envelopes than standard new construction. High R/in insulation materials for walls could allow for a thin insulating layer that could reduce energy use in these homes.

In transitioning space heating from natural gas-fired equipment to electric heat pumps, it will be important for heat pumps to incorporate low-GWP refrigerants or to dispense with refrigerants in novel systems. Demand for space heating peaks in the winter when output from solar electric generators is at its annual lowest. To minimize the burden on the electricity system, next-generation heat pumps need to have higher heating-side efficiency, which has received less attention than the cooling efficiency. For air conditioning, new evaporative cooling technologies hold potential if their water use can be managed.

When equipment is used affects the strategic value of improving energy efficiency. Because residential lighting primarily occurs in the evening when solar electricity generation is not available, improving lighting efficiency in homes is especially important. Higher lighting efficiency would also be beneficial to indoor farming in California, which has the potential to reduce energy use for water pumping and transport of high-value farm products.

Advanced building construction technologies and techniques could facilitate the construction of net-zero-energy buildings and allow for less-costly retrofits. They could support the goal of deploying cost-effective zero-carbon or near-zero-carbon modular and manufactured homes, particularly in under-resourced communities. In addition to saving energy, advanced building construction technologies and techniques have the potential to reduce the cost of housing construction and shorten construction time. In so doing, they could play an important role in alleviating California's housing crisis.

Industry. Motor systems are the main target for improving electricity use efficiency in industry. Because of the energy savings possible with VSDs and VFDs, a key focus of technology development is expanding the range of potential applications through use of wide-bandgap semiconductors. In addition, improvements to electric motors can be realized through the application of technologies such as advanced magnetic materials, improved insulation materials, aggressive cooling techniques, high speed bearing designs, and improved conductors or superconducting materials.

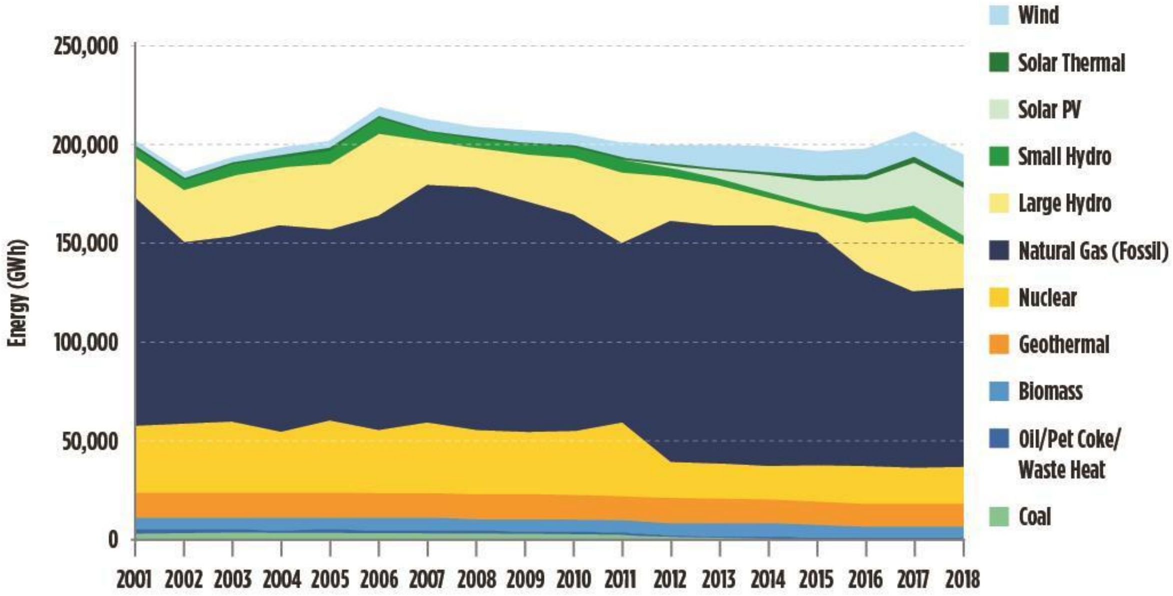
Water Sector. Process control using advanced sensors, combined with artificial intelligence and machine learning with adaptive controls, has the potential to greatly reduce electricity use across the water sector, potentially improving performance for both pumping and treatment steps. This will require infrastructure, software, and networked solutions for sensing, instrumentation, control, modeling and platforms. For rural areas, especially in the Central Valley, there is a need for more reliable and affordable technologies that can be deployed for small treatment facilities and point-of-entry or point-of-use applications.

CHAPTER 3: Renewable Electricity Generation

Introduction

Over the past two decades, California's traditional renewable electricity sources—hydroelectric power and geothermal—have maintained roughly the same share of total in-state electricity generation. In the last decade, however, the share of newer renewable electricity sources—wind and solar—has grown considerably (see Figure 3.1). In 2019, the combined share of all renewable sources was 32%.[56]

Figure 3.1: California In-State Electricity Generation by Fuel Type



Source: CEC. Final 2019 Integrated Energy Policy Report.

Legislation passed in 2018 (SB 100) established 2045 targets for renewable and zero-carbon energy procurement equal to 100 percent of retail sales and 100 percent of electricity procured to serve state agencies.[57] The bill also increased the state's Renewable Portfolio Standards to require 60 percent of retail sales from renewables by the end of 2030.

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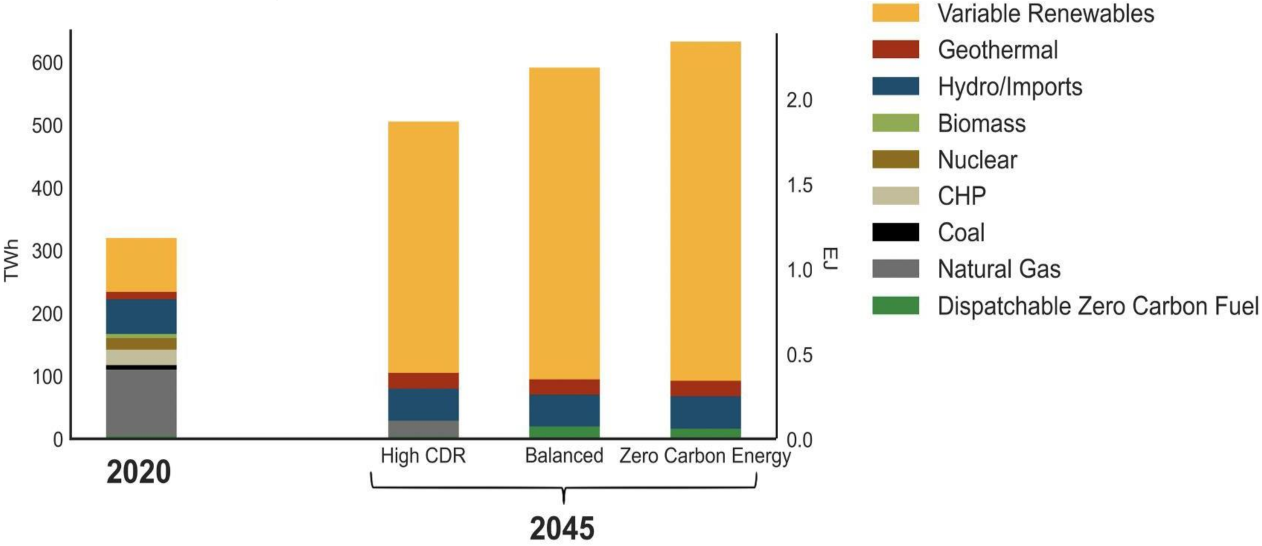
[56] The shares of solar and wind were 14% and 7%, respectively. https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/2019-total-system-electric-generation

[57] SB 100 allows transmission and distribution losses (which represent about 7.2% of total generation) and non-retail loads to be supplied by non-zero-carbon resources.

Reaching these targets will require a large and rapid increase in renewable electricity generation. When one considers the substantial growth in electricity demand that will come from electrification of motor vehicles and end uses in buildings, and the need to keep electricity prices low enough to encourage electrification, the challenge becomes even greater.

Decarbonization scenarios developed for the California Air Resources Board (CARB) show electricity demand growing from 300 terawatt-hours (TWh) in 2020 to a low case of 440 TWh or a high case of 540 TWh in 2045.[58]



shows the sources of electricity generation in each scenario that meet the forecast demand. The enormous growth in renewable electricity generation stands out clearly.

Figure 3.2: California Electricity Generation in 2020

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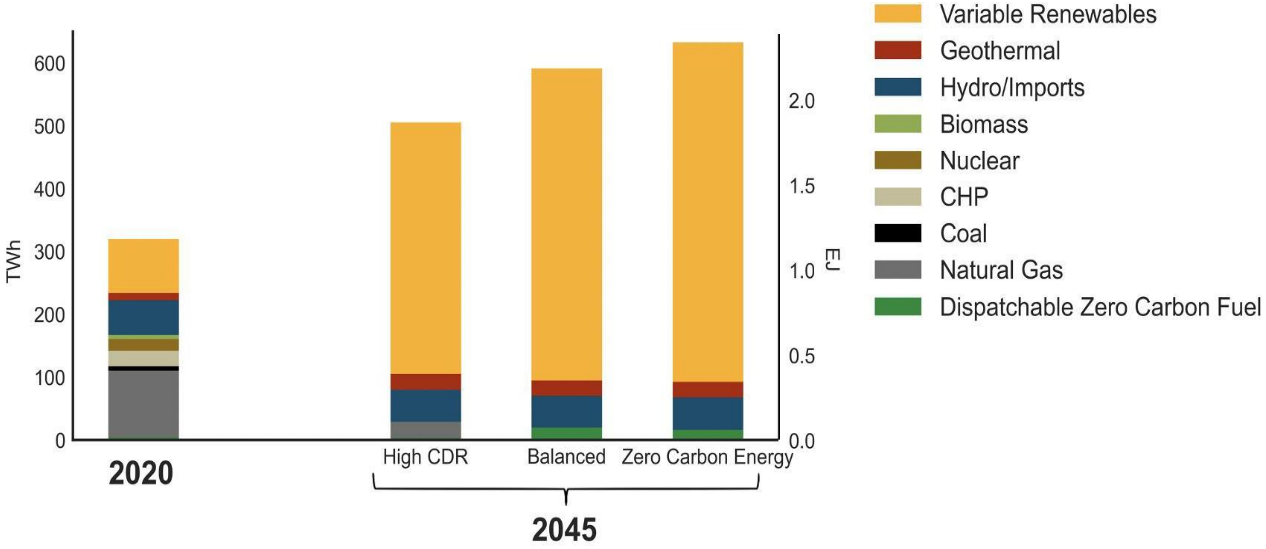
[58] Energy and Environmental Economics. 2020. *Achieving Carbon Neutrality in California: PATHWAYS Scenarios Developed for the California Air Resources Board*. The "High CDR" scenario relies heavily on CO_2 removal strategies to achieve carbon neutrality, while such strategies are minimized in the "Zero Carbon Energy" scenario.

and in Zero-Carbon Scenarios in 2045



Source: Energy and Environmental Economics (2020)

Achieving a four- or five-fold increase in renewable electricity supply in 25 years will be challenging. Some of the renewable electricity used in California can come from out-of-state, but lack of long-distance transmission may constrain the amount that can be imported. Building adequate transmission capacity is also an issue within the state. Most of the expected renewable generation will come from solar PV, whose variable nature poses challenges for maintaining adequate and reliable electricity supply. In addition to electricity storage, some amount of firm zero-carbon electricity generation will likely be needed to maintain reliability and reduce overall costs.[59] Emerging options include geothermal electricity, hydrogen made from renewable electricity ("green hydrogen" – discussed in the next chapter), natural gas with carbon capture and storage, and possibly advanced nuclear power designs.

Technology innovation can play a key role in rapid expansion of renewable electricity generation by:

- Improving resource utilization through higher efficiency of generation;
- Reducing the cost of renewable electricity;
- Expanding the renewable resources that can be utilized for electricity generation.

Solar Photovoltaics

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[59] In contrast to variable renewable electricity sources, dispatchable or firm sources can be called on as needed by grid operators. For an analysis of how clean firm power could help to meet California's goals at lower cost, see: Cohen, Armond, et al. 2021. "Clean Firm Power is the Key to California's Carbon-Free Energy Future." *Issues in Science and Technology*. https://issues.org/california-decarbonizing-power-wind-solar-nuclear-gas/

In the past decade improvements in PV technology have driven down the price of solar electricity substantially.[60] This development, combined with an increase in the average capacity factor of utility-scale PV systems and access to lower-cost financing, has made electricity from solar PV cost competitive with other power sources in many parts of the world.

A major driver for innovation has been the push for improved cell efficiency. Increasing cell efficiency is key for competitive module manufacturing, as it directly decreases costs by reducing the quantities required for a given output. Higher levels of cell efficiency reduce the number of modules that need to be transported to the installation site, the necessary land area and the length of wires and cables required.

The efficiency of silicon-based modules, which dominate the current market, has increased from around 16% in 2010 to a high of 20% in 2020.[61] A number of new or nonstandard cell architectures—such as back-contact cells—are growing in importance because they offer significantly higher efficiency. Nonstandard cell architectures tend to use high-quality monocrystalline wafers and more sophisticated processing to achieve module efficiencies of 22%–23%. Thin-film technologies using cadmium telluride and copper indium gallium selenide (CIGS) have come close to silicon's efficiency and cost, but cadmium telluride and CIGS both depend on rare elements, which may limit their use. While improvements, including continued gains in efficiency, are expected for the existing PV technology, other technologies have the potential to push efficiency further and lower costs.

In 2016, DOE's Solar Energy Technologies Office set cost goals for solar PV power for 2030 that are 50% less than the 2020 goals. In March 2021, DOE accelerated its utility-scale solar cost targets – setting a new goal of driving down the current average cost of 4.6 cents/kWh to 3 cents/kWh by 2025 and 2 cents/kWh by 2030.[62] If the goals for utility-scale solar PV are achieved, the electricity generated would be among the least expensive options for new power generation, and would be below the cost of most fossil fuel-powered generators.

Multijunction Solar Cells

Multijunction solar cells (referred to as tandem cells when two different cells are used) are stacks of individual cells, one on top of the other, that each selectively convert a specific band of light into electrical energy, leaving the remaining light to be absorbed and converted to electricity in the cell below. An upper layer with a wide bandgap can make the most of visible light, whereas most of the infrared shines through so that it

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[60] The focus of this section is utility-scale and distributed PV applications. Technologies that are mainly suited for other applications, such as organic PV, are not discussed.

[61] Champion Photovoltaic Module Efficiency Chart. NREL. https://www.nrel.gov/pv/module-efficiency.html

[62] U.S. Department of Energy Announces Goal to Cut Solar Costs by More than Half by 2030. 2021. https://www.energy.gov/articles/doe-announces-goal-cut-solar-costs-more-half-2030

can be absorbed by a second layer with a narrower bandgap. Materials with bandgaps that are relatively easy to tune are well-suited for tandem cells.

Multijunction devices can be realized via deposition of thin-film devices on top of conventional silicon cells or in all-thin-film form using layers of semiconductors deposited sequentially. Typical multijunction cells use two or more absorbing junctions, and the theoretical maximum efficiency increases with the number of junctions. Early research on multijunction devices leveraged the properties of semiconductors comprised from elements in the III and V columns of the Periodic table. Three-junction devices using III-V semiconductors have reached efficiencies of greater than 45% using concentrated sunlight. This architecture can also be transferred to other solar cell technologies, and multi-junction cells made from various materials are being investigated.

Although multijunction III-V cells have higher efficiencies than competing technologies, such solar cells are considerably more costly because of current fabrication techniques and materials. The high costs may be partially offset by using concentrating optics, with current systems primarily using Fresnel lenses. The concentrating optics increase the amount of light incident on the solar cell, thus leading to more power production. Using concentrating optics requires the use of dual-axis sun-tracking, which affects the cost of the system.

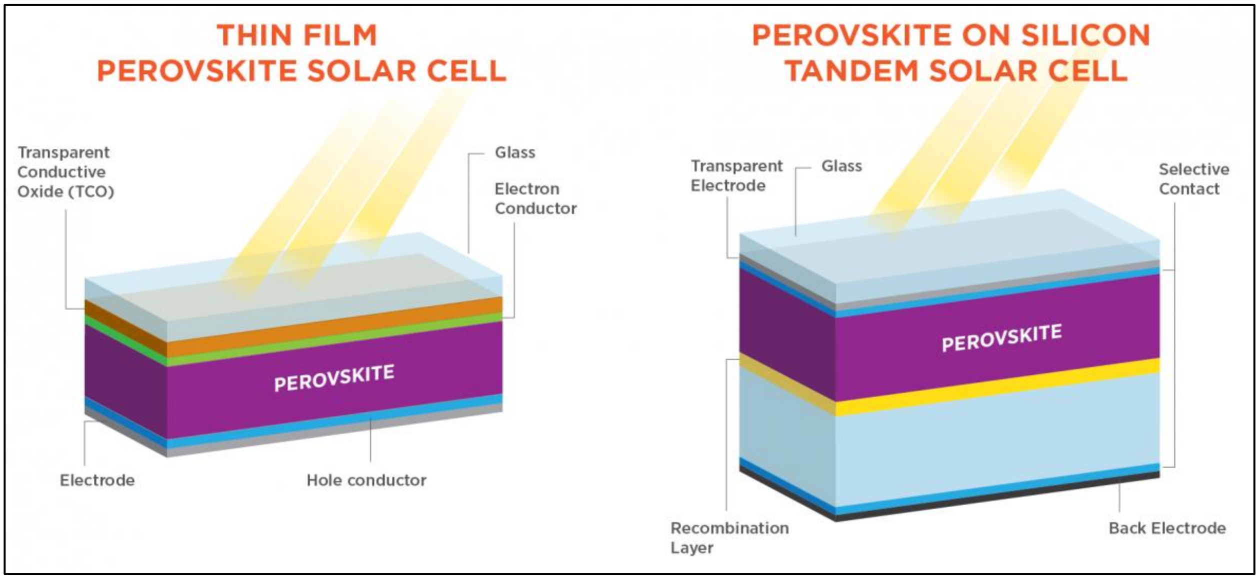
Active research efforts are directed at lowering the cost of electricity generated by these solar cells through approaches such as developing new substrate materials, absorber materials, and fabrication techniques; increasing efficiency; and extending the multi-junction concept to other PV technologies. Developing reliable low-cost solutions for tracking and concentration is also an active area of research to support cost reductions for PV systems using multi-junction cells.

Perovskite Solar Cells

Recently, there has been considerable interest in a class of solar cells that use perovskites, a family of materials with a specific crystal structure and excellent light absorption. Perovskite solar cells have shown remarkable progress in recent years with rapid increases in conversion efficiency, from reports of about 3% in 2006 to over 25% in 2020.

Perovskites could be used in a thin-film solar cell, but tandem device architectures appear more interesting (Figure 3.3). Perovskite solar cells convert ultraviolet and visible light into electricity very efficiently, meaning they could be excellent tandem partners with absorber materials such as crystalline silicon that efficiently convert lower-energy light. In 2018, British researchers set a record efficiency of 27.3% for perovskite–silicon tandem cells, which are nearing commercial status.[63]

Figure 3.3: Perovskite Solar Cells



Source: U.S. Department of Energy

The perovskite materials being investigated have tunable bandgaps, which means they can be custom-designed to complement the absorption of their partner material. Innovative tandem architectures such as perovskite-perovskite and perovskite–CIGS hold the potential to achieve efficiencies above 30% at reasonable cost and thus are garnering extensive interest.[64] A spin-off from Oxford University aims to build all-perovskite cells with two or more layers, targeting an eventual efficiency of 37%.[65]

While perovskite solar cells have become highly efficient in a very short time, a number of challenges remain before they can become a competitive commercial technology. The stability of perovskite solar cells is limited compared to that of leading PV technologies. They don't stand up well to moisture, extended periods of light, or high heat. To increase stability, researchers are studying the degradation in both the perovskite materials and the contact layers. Additional barriers to commercialization are the potential environmental impacts related to the perovskite absorber, which is lead-

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[63] Oxford PV takes record perovskite tandem solar cell to 27.3% conversion efficiency. 2018. *PVTECH*. https://www.pv-tech.org/news/oxford-pv-takes-record-perovskite-tandem-solar-cell-to-27.3-conversion-effi.

[64] Tian, Xueyu, S. Stranks, F. You. 2020. Life cycle energy use and environmental implications of high-performance perovskite tandem solar cells, *Science Advances* Vol. 6, no. 31. https://advances.sciencemag.org/content/6/31/eabb0055.full

[65] News Feature: The solar cell of the future. 2019. *PNAS* January 2, 2019 116(1) 7-10. https://www.pnas.org/content/116/1/7

based. Current and potential materials are being studied to evaluate, reduce, mitigate, and potentially eliminate toxicity and environmental concerns.

Perovskite cells are built with layers of materials, either printed or coated from liquid inks or vacuum-deposited. Producing uniform, high-performance perovskite material in a large-scale manufacturing environment is difficult and has resulted in a substantial difference in performance between small-area cell efficiency and large-area module performance. The future of perovskite manufacturing will likely depend on solving this challenge, which remains an active area of work within the PV research community.

As perovskite PV is commercialized, there must be balance among demonstrating high power conversion efficiency and high stability, utilizing scalable manufacturing processes, and scaling from individual cells to multi-cell modules with larger active areas. In its efforts to advance perovskite solar PV technologies, DOE is funding (1) research projects to advance perovskite efficiency and stability at the cell or mini-module scale beyond the current state of the art technology, (2) research projects to address challenges with manufacturing perovskite modules at relevant scale and throughput, and (3) a neutral, independent validation center that can be used to verify perovskite device performance and address acceptance and bankability challenges.[66]

Novel Optics

Novel optics are at an early stage but hold the potential to boost the efficiency of PV cells. Nanostructured materials could provide better anti-reflection coatings, which allow more sunlight to enter a solar cell. A Dutch research group is using nanocylinders, which are made from an insulating material instead of a semiconductor. Rather than absorbing light, they simply have a different refractive index than the surrounding material. As a result, certain wavelengths of light bounce off the array, whereas others are transmitted. In a perovskite–silicon tandem cell, nanocylinders form a separate layer between the perovskite and silicon. As light enters the cell, the perovskite layer absorbs most of the short-wavelength light—but some of it passes through without being captured. The nanocylinders have the right spacing to reflect this unabsorbed light back into the perovskite layer, allowing it a second chance to be absorbed. Similar methods could improve light trapping in many forms of solar cell, bouncing the light back and forth until it is absorbed.

Summary

Table 3.1 summarizes some of the key technology innovations for solar photovoltaics.

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[66] https://www.energy.gov/articles/department-energy-announces-20-million-advance-perovskite-solar-technologies

Table 3.1: Technology Innovations for Solar Photovoltaic Energy

Technology	Description	Technical Maturity
Multijunction Solar Cells		
III-V Multijunction Solar Cells	Advanced III-V solar cell architectures, growth and processing of ultrahigh-efficiency III-V multijunction solar cells, and growth of challenging new III-V alloys.	TRL 4
Low-cost III-V Solar Cells	Reduced cost of manufacturing III-V solar cells; achieve single-junction cells with efficiencies >25% and tandems with efficiencies >30% for one-sun and low-concentration applications.	TRL 4
Hybrid Tandem Solar Cells	High-efficiency III-V/silicon tandem solar cells with epitaxial and stacking/bonding approaches.	TRL 5-9
Perovskite Solar Cells		
Unique Perovskite Deposition Processes	Novel methods for growth and deposition of high-quality perovskite films.	TRL 4
Perovskites at Scale	Techniques and processes that enable rapid, inexpensive deposition of high-quality perovskite films, allowing perovskite PV to be manufactured consistently and cost-effectively in an industrial environment.	TRL 4
Alternative Perovskite Chemistry	Alternative thin film and quantum dot chemistries to the common methylammonium lead halide perovskite devices, with potential to improve the performance of perovskite films by demonstrating both increased stability and efficiency.	TRL 4
Improved Perovskite Film Performance	Film deposition methods, chemistry improvements, and engineering of the perovskite active layer and device architecture to push commercial perovskite device efficiencies to 20% and beyond.	TRL 4
Improved Perovskite Film Stability	Technologies that improve perovskite device resistance to performance degradation over time. These technologies include methods of depositing perovskite films, encapsulant coatings, contact layer compositions, and novel film chemistries.	TRL 4
Improved Perovskite Film Contact Layers	Improvements to hole-selective, electron-selective, or other material layers found in perovskite-based optoelectronic devices.	TRL 4
Novel Perovskite Device Architecture	New perovskite solar cell device designs that capitalize on the unique properties of the perovskite layer to create low-cost devices with improved efficiency and reliability.	TRL 4

Source: NREL, High-Efficiency Crystalline Photovoltaics. https://www.nrel.gov/pv/high-efficiency-crystalline-photovoltaics.html. Perovskite Solar Cells. https://www.nrel.gov/pv/perovskite-patent-portfolio.html. Estimates of technical maturity were provided by subject experts at NREL.

Technology Roadmap Initiatives for California

The CEC's recent Utility-Scale Renewable Energy Generation Technology Roadmap recommends two initiatives to advance solar PV in California.[67]

- Field Test Tandem Material PV Cells

  This initiative would establish field-testing programs to accelerate acquisition of real-world experience with promising novel technologies, such as perovskite thin-film cells on top of crystalline silicon cells. Field testing will proof the designs in real-world environment and provide information on degradation and failure mechanisms.

- Increase PV Material Recovery from Recycling Processes

  Crystalline silicon PV modules typically contain some amounts of potentially hazardous materials, 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 help develop innovative designs, processes, and techniques for economically reclaiming much of the materials in end-of-life PV modules. 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.

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[67] Schwartz, Harrison, Sabine Brueske. 2020. *Utility-Scale Renewable Energy Generation Technology Roadmap*. California Energy Commission. Publication Number: CEC-500-2020-062. https://ww2.energy.ca.gov/2020publications/CEC-500-2020-062/CEC-500-2020-062.pdf

Concentrating Solar Power

Concentrating solar power (CSP) refers to systems in which large areas of mirrors reflect and concentrate solar energy onto a receiver, which contains a fluid that transfers the thermal energy to a heat engine that drives an electrical generator.[68] California has around 1.2 gigawatts (GW) of CSP capacity, but development activity has stalled.

An advantage of CSP is that energy captured during the day can charge a thermal energy storage medium and then can be used to run the generator after sundown, providing value to the grid. The decreasing cost of PV+battery storage has brought the viability of CSP into question, however. Technical challenges, including increasing the temperatures at which CSP plants operate, as well as the thermal efficiency of plant materials such as heat exchangers and receivers, need to be addressed in order to significantly reduce costs. Additionally, increasing the lifetime of plant materials, either through more resilient materials or less corrosive heat transfer fluids, has the potential to significantly reduce O&M costs.

DOE's Solar Energy Technologies Office has a 2030 target of 5 cents/kWh for CSP baseload plants with a minimum of 12 hours of energy storage, and 10 cents/kWh for CSP peaker plants, which would have a lower capacity factor and fewer hours of energy storage.[69] Achieving these targets will require innovations in system design associated with the solar field cost and use of higher temperatures to raise power block conversion efficiency to over 50%. These advances are the subject of research in heliostat design, heat-transfer and thermal storage media, and power cycle efficiency.[70]

In 2016, DOE hosted a workshop of stakeholders that defined three potential pathways for the next generation CSP plant based on the form of the thermal carrier in the receiver: molten salt, particle, or gaseous. Prior analysis by DOE had selected the supercritical carbon dioxide (sCO_2) Brayton cycle as the best-fit power cycle for increasing CSP system thermo-electric conversion efficiency. This technology transforms heat energy to electrical energy through the use of supercritical CO_2 (CO_2 held above a critical temperature and pressure, which causes it to act like a gas while having the density of a liquid) rather than through a steam-Rankine cycle system commonly used

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[68] CSP technologies can also be used as heat in a variety of industrial applications, such as water desalination, enhanced oil recovery, food processing, chemical production, and mineral processing.
[69] https://www.energy.gov/eere/solar/goals-solar-energy-technologies-office. The values refer to the levelized cost of energy, and are based upon systems installed in an average solar resource location for the United States. The cost in 2018 for CSP baseload plants was 9.8 cents/kWh.
[70] Murphy, Caitlin, Yinong Sun, Wesley Cole, Galen Maclaurin, Craig Turchi, and Mark Mehos. 2019. *The Potential Role of Concentrating Solar Power within the Context of DOE's 2030 Solar Cost Target*. National Renewable Energy Laboratory. NREL/TP-6A20-71912. https://www.nrel.gov/docs/fy19osti/71912.pdf

in today's CSP and other power plants. DOE is building the world's first and largest indirectly heated, high-temperature sCO_2 test facility (10 MWe) in Texas.[71]

The workshop led to a roadmap that addresses and prioritizes R&D gaps.[72] Table 3.2 summarizes the main areas of technology development. Within each of the thermal carrier pathways, there are components that are at different stages of development for this high-temperature application.

Following on the roadmap, U.S. DOE is funding projects that explore new system designs and innovative concepts in the collector, receiver, thermal storage, heat transfer fluids, and power cycle subsystems.[73] U.S. DOE plans to select one of the thermal carrier pathways to scale up to a demonstration project.

Technology Roadmap Initiatives for California

The CEC's Utility-Scale Renewable Energy Generation Technology Roadmap recommends two CSP initiatives that are seen as complementary to U.S. DOE's R&D program.[74]

- Improve Cleaning Systems for CSP Mirrors

  CSP mirrors need high reflectivity for good performance, but they are easily soiled with wind-blown sand and dust. Because soiling can reduce plant energy production substantially, frequent cleaning is necessary. 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 use.

- Advance Materials and Working Fluids for High Temperature Thermal Energy Storage

  This initiative addresses key challenges involved in finding 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 that are stable at such high temperatures, together permitting CSP power cycles with more than 50 percent efficiency.

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[71] https://www.energy.gov/sco2-power-cycles/pilot-plant-supercritical-co2-power-cycles

[72] Mehos, Mark, et al. 2017. *Concentrating Solar Power Gen3 Demonstration Roadmap*. National Renewable Energy Laboratory. https://www.energy.gov/sites/prod/files/2017/04/f34/67464.pdf

[73] Concentrating Solar-Thermal Power. https://www.energy.gov/eere/solar/concentrating-solar-power

[74] Schwartz and Brueske, op cit.

Table 3.2: Technology Innovations for Concentrating Solar Power

Technology Area	Description	Technical Maturity
Thermal Carrier in the Receiver		
Molten-salt Systems	Increase in hot-salt system temperature to approximately 720°C brings significant material challenges. Knowledge around the selection of a high-temperature molten salt is needed, especially with regard to its impact on containment materials that can achieve acceptable strength, durability, and cost targets at the high temperature.	TRL 4-5
Falling Particle	Unlike conventional receivers that employ fluid, particle receivers use solid particles that are heated by concentrated sunlight. The heated particles may be stored in an insulated tank and used to heat a secondary working fluid for the power cycle. Although many of the components are mature, the unique application for solarized sCO_2 systems at high temperatures and pressures offers unique challenges that need to be addressed. Heating the particles with concentrated sunlight poses additional challenges with efficient particle heating, flow control and containment, erosion and attrition, and conveyance.	TRL 4-5
Gas Phase	Gas-phase receivers use a stable, intermediate-pressure, heat-transfer fluid in a closed-loop configuration to transfer energy to and from thermal storage The gas-phase technology pathway relies on an inert, stable gas-phase heat transfer fluid, such as CO_2 or helium, operating within a high-pressure receiver. This pathway relies on thermal energy storage options such as a phase-change material or particle storage.	TRL 4-5
Power Cycle		
Supercritical CO_2 Brayton Cycle	R&D needs include development of high efficiency CO_2 expansion turbines and low cost heat exchangers that are able to attain large heat transfer duties with small temperature differences between the hot and cold sides of the exchanger. Goals are: Net thermal-to-electric efficiency > 50%; Power-cycle system cost < $900/kW; Dry-cooled heat sink at 40 C ambient; Turbine inlet temperature > 700 C.	TRL 4-5

Source: Mehos, et al. (2017)

Wind Power

The rise of wind energy in the last two decades has been driven largely by technological advances that have made wind turbines more efficient at lower cost. Improvements included design of longer blades and taller towers that capture more energy from the wind, developments in drive train designs, and use of improved controls and sensors. In recent years, the focus has shifted from individual turbine performance to overall system performance characteristics. Technology innovation centers on developing enhanced micro-siting strategies, improved resource forecasting, and complex control systems for arrays of wind turbines. These enhanced technologies broaden the range of viable wind sites by facilitating greater energy capture at high wind speeds as well as economical energy capture at lower wind speeds.

In 2016 U.S. DOE prepared a roadmap of actions to develop next-generation wind energy technology.[75] This roadmap lays out the areas where technology innovation could advance wind energy (see Table 3.3). The categories are fairly broad, so specific technologies in each area are at different levels of maturity. Many of the technologies are commercial, but improvements and cost reduction are possible.

Offshore Wind Energy

Offshore wind energy has seen rapid growth in Europe in the past decade and is in the early stages of growth in the U.S. Development of offshore wind energy has taken place in relatively shallow water (depths <60 meters). The estimated technical capacity of wind resources off the coast of California is 160 GW, but only 9 GW of that total is located in areas with water depths that are suited for fixed bottom deployments.

Floating offshore wind platforms would allow development of higher-speed and more consistent wind resources than their fixed-bottom counterparts can access. Designs for the first wave of precommercial floating wind turbines adapted substructure concepts directly from the offshore oil and gas industry and relied on mature wind turbine designs intended for land-based or fixed-bottom offshore applications. The next phase for floating offshore wind technology is now underway with precommercial pilot plants, improved turbines adapted for floating applications, and more advanced substructures. Cost analysis indicates that economic viability will require further optimization, innovation, and up-scaling to commercial plant sizes.

Modeling by researchers at the National Renewable Energy Laboratory (NREL) shows that significant cost reductions will come from a disciplined combination of complementary innovations, which may be technologies (e.g., downwind turbines), design features (e.g., rapid disconnect cables), or installation and operational strategies.[76] The researchers have described a long-term vision for a research program and design methodology that may be able to push floating wind plants toward a lower levelized cost of energy than fixed-bottom offshore wind. The method involves a fully integrated systems-engineering and techno-economic design approach to capture the complex interactions between the physics, manufacturing, installation, and operation of floating wind turbines. It will require engineering tools to design systems comprising innovative technical and operational building blocks that span disciplines. Areas of

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[75] U.S. Department of Energy. 2018. *Wind Vision Detailed Roadmap Actions, 2017 Update*. https://www.energy.gov/sites/prod/files/2018/05/f51/WindVision-Update-052118-web_RMB.pdf

[76] Garret Barter, Robertson, Amy, Musial, Walter. 2020. A systems engineering vision for floating offshore wind cost optimization. *Renewable Energy Focus.* Vol. 34, Sept. 2020, pp. 1-16. https://www.sciencedirect.com/science/article/pii/S1755008420300132#bib0025

research include novel substructure designs, novel anchoring methods, alternative materials, and floating plant controls.

ARPA-E's ATLANTIS (short for Aerodynamic Turbines Lighter and Afloat with Nautical Technologies and Integrated Servo-control) program seeks to (1) design radically new floating offshore wind turbines (FOWT) by maximizing their rotor-area-to-total-weight ratio while maintaining or ideally increasing turbine generation efficiency; (2) build a new generation of computer tools to facilitate FOWT design; and (3) collect real data from full and lab-scale experiments to validate the FOWT designs and computer tools.[77]

In California, a recent CEC-funded study developed priority recommendations that would lead to cost-effective offshore wind projects in California. The study identified a number of research, development, and deployment opportunities to remove or reduce technological, manufacturing, logistics, and supply chain barriers to deployment; lower the development risk of offshore energy projects; and identify opportunities for early pilot demonstration projects.[78]

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[77] Aerodynamic Turbines Lighter and Afloat with Nautical Technologies and Integrated Servo-control. https://arpa-e.energy.gov/technologies/programs/atlantis

[78] Sathe, Amul, Andrea Romano, Bruce Hamilton, Debyani Ghosh, Garrett Parzygno. (Guidehouse). 2020. *Research and Development Opportunities for Offshore Wind Energy in California*. California Energy Commission. Publication Number: CEC-500-2020-053. https://ww2.energy.ca.gov/2020publications/CEC-500-2020-053/CEC-500-2020-053.pdff

Table 3.3: Technology Innovations for Wind Energy

Technology Area	Description	Technical Maturity
Cost-Effective Turbine Technology for Very Low Wind Speeds	High-capacity-factor wind turbines with tall towers and large blades will allow greater geographic diversity of wind energy supply, minimizing the need for new transmission lines.	Medium
Larger Wind Turbines	Design and manufacture of very large blades and towers, while overcoming logistical challenges such as transportation and installation, will allow significant reduction in the number of turbines needed to meet deployment goals.	Medium
Advanced Rotors	Stronger, lighter materials to enable larger rotors; improve aerodynamic designs, novel rotor architectures, active blade elements, aeroelastic tailoring, sweep, noise reduction devices, active aerodynamic controls, and downwind, lower solidity rotors.	Medium
Improved Drivetrain and Power Electronics	Advanced generator designs; alternative materials for rare-earth magnets and power electronics; improve grid support through power electronics; improve reliability of gearboxes.	Medium
Advanced Control Systems	Advanced control systems that reduce structural loads on turbines, increase energy capture, and operate the wind plant in an integrated manner to increase efficiency and support grid stability.	Low
Tall Towers	Taller towers that reach higher wind speeds and enable larger rotors will allow increased energy capture for a given land area, allowing development of lower wind speed sites.	Medium
Next-Generation Foundations and Installation Systems	New foundation designs that will efficiently support taller towers are needed for both land-based and offshore turbines. New installation systems must be developed to mitigate the limitations of conventional crane technologies.	Low
Improved Distributed Wind Technology	Optimized technology design for low to moderate wind resources, where distributed wind applications are typically located.	Medium
Floating Wind Turbines	Cost-effective wind turbine technology that can be deployed in water depths up to 700 meters.	Low

Source: U.S. Department of Energy (2018). Technical maturity estimated by NREL subject expert.

Wind Energy Cost Goals

U.S. DOE's latest cost goals for different types of wind power show significant reductions from current levels (Table 3.4).

Table 3.4: Wind Energy Cost Goals (U.S. DOE)

Levelized cost in cents/kWh			
	2020	**2025**	**2030**
Land-Based Wind	3.7	3.2	2.3
Offshore Wind			
Fixed-bottom	8.6	7.0	5.0
Floating	13.5	9.5	7.0
Distributed Wind	10.5	7.2	5.0

Source: U.S. Department of Energy. Wind Energy Technologies Office Multi-Year Program Plan Fiscal Years 2021—2025.

Leveraging Supercomputing to Advance Wind Power Plants

A 2017 report from NREL describes how the wind plant of the future will use a collection of technologies that allow wind power plants and the turbines within them to not only respond to the atmosphere as an efficient, integrated system, but also to control the airflow within the plant to maximize power production.[79] This approach is made possible by recent advances in supercomputing technology, which turns large sets of atmospheric and wind turbine operation data into a high-fidelity model. Industry can then use these scientific insights to design new wind turbine components, sensors, and controls. Future wind power plants would include:

- High-fidelity modeling and state-of-the-art sensors to accurately estimate wind power plant energy production, reducing uncertainty and increasing the predictability of electricity production;
- Integrated wind plant design, real-time active control of turbines, and operational strategies to increase reliability and extend turbine lifetimes;
- Innovative design of wind turbines and components such as rotors and drivetrains to optimize performance and enhance energy capture, including larger rotors and taller towers to capture higher-potential wind energy in the Earth's upper atmosphere; and

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[79] Dykes, Katherine, et al. 2017. *Enabling the SMART Wind Power Plant of the Future Through Science-Based Innovation*. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy17osti/68123.pdf

- Controllable, dispatchable, and predictable grid support services for grid resilience and stability, including precise forecasting of wind energy production for short-term grid operation and planning.

NREL estimates that by incorporating these innovations, the unsubsidized cost of wind energy could drop to 50% of 2017 levels, equivalent to $23 per megawatt-hour, by 2030.

Technology Roadmap Initiatives for California

Land-based wind represents one of the more established forms of renewable energy generation in the state, but the majority of land-based wind resource areas are currently saturated with older, smaller wind turbines. The CEC's Utility-Scale Renewable Energy Generation Technology Roadmap recommends two initiatives for land-based wind power. They focus on pathways to increasing deployment of larger turbines on rugged terrain by increasing conversion efficiency and lowering installation costs.

- Advance Construction Technologies for Land-based Wind Turbines

  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 techniques, and modified spiral welding.

- Demonstrate New Blades that Improve Conversion Efficiency

  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.

The Technology Roadmap recommends two initiatives that focus on pathways to develop and deploy floating offshore wind technologies. They take advantage of research and development occurring throughout the world on floating system designs and emphasize scale-up.

- Pilot Demonstration of Floating Offshore Platform Manufacturing

  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.

- Design Port Infrastructure to Deploy Floating Offshore Wind Technologies

  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. 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. Port development is necessary to unlock the potential of local manufacturing by providing an outlet to assemble and transport turbine components to offshore locations.

The CEC Roadmap also recommends an initiative to integrate wave energy systems with floating offshore platforms. While the cost of electricity from wave power remains high, a synergy exists between floating offshore wind systems and wave energy devices. Combined wave and wind systems could lower the overall cost of deployment of the hybrid system and therefore drive down the combined cost of electricity.

Geothermal Power

Geothermal power is the largest source of non-variable renewable power in California and has been a major part of its energy mix for 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. Estimates of potential additional capacity in California range from 5 to 35 GW for conventional geothermal generation and as high as 68 GW with the inclusion of enhanced geothermal systems.

Traditionally, geothermal power has been limited to sites with concentrated sources relatively close to the surface. A far larger potential exists in enhanced geothermal systems (EGS), which are man-made geothermal reservoirs. In EGS, 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 for use in electricity generation. To achieve the required permeability underground for the heat transfer medium to go from the injection well to the production well, hydraulic fracturing is required.

Geothermal resources are unique among renewable energy technologies in that significant exploration and capital expenditure are required to locate, characterize, and prove a resource. Improved resource and site characterization are key for increasing geothermal deployment. Progress is needed in detecting subsurface signals to remotely identify and characterize underground attributes. The geothermal industry would benefit from technology breakthroughs in non-invasive, lower-cost geophysical and remote-sensing technologies.

Once geothermal resources are identified and characterized at a level that justifies a more capital-intensive investment toward development, technology advances in drilling and wellbore integrity will play a critical role in lowering the costs of development. The geothermal industry encounters high-strength, hard-rock environments with distributed fracture permeability and extremely high temperatures, in some cases combined with corrosive environments. Adapting technologies from the oil and gas industry has a role to play, but R&D on technologies that improve drilling processes and efficiencies in geothermal-specific environments can fill gaps that technology transfer cannot.

Major advances in reservoir and subsurface engineering will be required to enable the cost-effective creation of EGS reservoirs and sustain their productivity once created. Enhanced and innovative tools and techniques can also ensure optimal resource use, improve well life cycles, and enhance overall performance of geothermal wells.

Uniquely among renewable power sources, geothermal systems typically operate in a baseload configuration. Flexible operating modes are also being considered for geothermal systems, which would allow them to provide ramping capabilities for the grid. Flexible-mode geothermal energy production may involve rapid changes in geothermal production, such as reducing the production by half within tens of minutes and after a few hours again restoring full production. Converting production from (steady) base-load to (variable) flexible production may result in significant changes to the system related to corrosion and mineral deposition (scaling) in wells, mechanical damage fatigue to well components or the reservoir. A better understanding of the impacts of flexible-mode production on the reservoir-wellbore system is needed to assure safe and sustainable production.[80]

Table 3.5 presents emerging technology innovations in three areas:

Improved Detection of Subsurface Signals: Tools and technologies that provide greater understanding of subsurface characteristics vital to geothermal development, including temperature, permeability, and chemistry

Improved Geothermal Drilling and Wellbore Integrity: New designs and approaches that enhance drilling efficiency and reduce well costs

Improved Geothermal Energy Resource Recovery: Methods that allow developers to better access geothermal heat and efficiently bring that heat to the surface

There is also a need for improved methods and tools that allow developers to monitor and model geothermal resources.

Technology Roadmap Initiatives for California

The CEC's Utility-Scale Renewable Energy Generation Technology Roadmap recommends two initiatives for geothermal power.

- Improve Materials to Combat Corrosion from Geothermal Brines

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[80] Comprehensive Physical-Chemical Modeling to Reduce Risks and Costs of Flexible Geothermal Energy Production. https://eesa.lbl.gov/projects/comprehensive-physical-chemical-modeling-to-reduce-risks-and-costs-of-flexible-geothermal-energy-production-epic/

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. Further advancement and testing of metal alloys may reveal lower cost and more corrosion-resistant materials.

- Advance Techniques to Assess Potential EGS Development Sites

  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.

Table 3.5: Technology Innovations for Geothermal Energy

Technology	Description	Technical Maturity
Improved Detection of Subsurface Signals		
Exploration tools that identify undiscovered resources and improve the ability to identify prospective enhanced geothermal resources	New and innovative exploration technologies and capabilities to characterize subsurface permeability, temperature, and chemistry, along with major geologic structures and stress states in areas where no surface expression exists. Advances in machine learning could produce new capabilities for characterizing the subsurface through automated pattern identification and data interpretation.	TRL 3-6
Improved resolution of existing geophysical methods	Improving existing resistivity-based geophysical methods; enhancing application of seismic reflection to geothermal environments; and developing innovative geophysical technologies and methods that show promise for identifying, imaging, and targeting permeability in geothermal settings.	TRL 4-8
Improved Geothermal Drilling and Wellbore Integrity		
Adapting technology from the oil and gas industry	Leveraging tools and technologies from the oil and gas industry for deployment in the geothermal industry could result in significant improvements in exploration and drilling success rates.	TRL 4-6
New drilling technologies and tools specific to geothermal environments	Technology advancements in drilling hardware (e.g., drill bits, drill strings), well construction materials (e.g., casing, cements), and drilling systems and methodologies (e.g., mud programs, advancing and cementing casing, innovative drilling approaches).	TRL 2-5
Improved well life cycles	New and hardened construction materials that can withstand higher temperatures and corrosive environments. Tools and systems to monitor wellbore integrity once a well is completed and in service.	TRL 2-5
Improved Geothermal Energy Resource Recovery		
Stimulation methods for improved geothermal resource recovery	Improved methods for existing stimulation technologies. Innovative technologies and approaches to well and reservoir stimulation.	TRL 5-8
Improved zonal-isolation techniques	Technologies, methodologies, and best practices that ensure reliable zonal isolation in geothermal environments.	TRL 3-5
Advanced real-time fracture mapping	Advanced real-time, integrated fracture mapping that enables operators to monitor progress in reservoir stimulation.	TRL 2-3

Source U.S. Department of Energy. 2019. The GeoVision Roadmap: A Pathway Forward; Technical maturity estimated by subject expert at DOE Golden Field Office

Biomass Power

Solid biomass combustion is one of the older operating renewable sources in California and uses a variety of technologies and feedstocks. Installed generating capacity has been more or less flat at around 1 GW since 2000.

There are a variety of bioenergy technologies for electricity generation that fall into two major pathways: direct combustion of biomass, and combustion of biomass-derived gases including biogas, which is primarily methane, and syngas, which is primarily a blend of carbon monoxide and hydrogen. Biogas is generated in anaerobic digesters and landfills among other sources. Syngas can be generated from various biomass sources through pathways such as gasification and pyrolysis. Biogas and syngas must be upgraded to renewable natural gas (RNG) for use in compressed gas vehicles or for injection into pipelines; RNG is fully interchangeable with conventional natural gas. Raw syngas and biogas do not necessarily need to be upgraded to the same standards if used onsite for electricity generation (depending on emissions regulations).

Common sources of biomass feedstock come from municipal waste, agricultural waste and residue, and forest residues and thinning. The source and security of feedstock delivery is important to ensure consistent production from bioenergy sources.

While bioenergy for electricity generation has less technical potential than other renewable resources,[81] it is uniquely positioned to offset fossil fuel usage with products that can be dropped into fossil fuel setups. RNG could provide a renewable fuel for gas-fired power plants used to handle rapid load changes associated with large-scale deployment of variable renewable electricity sources.

Bio-energy power generation combined with CO_2 capture and storage (BECCS) as a way to remove large quantities of CO_2 from the atmosphere has featured prominently in many scenarios or pathways aimed at achieving targets for achieving net zero CO_2 emissions. Biomass pyrolysis or gasification with soil biochar storage is another option for carbon sequestration under evaluation. A European research project evaluated 28 BECCS technology combinations.[82] Eight technologies that were short-listed for further analysis represented a wide range of technical maturity ranging from TRL 4 (bench-scale test rig) to TRL 6-7 (demonstration). The differences are mainly due to the assumed CO_2 capture technologies.

Two key issues for BECCS are the sustainability of large-scale deployment relative to other land and biomass needs, and the availability of geological reservoirs to store the captured CO_2. Potential geological reservoirs for CO_2 include saline aquifers and depleted oil and gas reservoirs.

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[81] The CEC Utility-Scale Renewable Energy Generation Technology Roadmap estimated that the potential electricity generation possible from bioenergy if the entire technical capacity is captured is 21,500 GWh, which would be enough electricity to provide 6.6 percent of SB100 goals for 2045.

[82] Bhave, Amit, et al. 2017. Screening and techno-economic assessment of biomass-based power generation with CCS technologies to meet 2050 CO_2 targets. *Applied Energy* 190 pp. 481–489.

Technology Roadmap Initiatives for California

The CEC's Utility-Scale Renewable Energy Generation Technology Roadmap recommends two initiatives for bioenergy that focus on ways to increase production of biogas and syngas.

- Improve Cleaning Methods to Produce High Quality Biomass-Derived Syngas

  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. 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.

- Deploy Thermal Hydrolysis Pretreatment to Increase Biogas Production

  Thermal hydrolysis pretreatment can be used as a precursor to anaerobic digestion to increase biogas production and improve the breakdown of organic material. Thermal hydrolysis pretreatment can potentially improve the ability to dewater sludge, increase methane production, increase digester loading rates and produce bio-solids ready for land disposal.

Grid-Forming Controls for a Renewables-Dominant Grid[83]

Historically, the dynamical behavior and stability properties of power systems have been dominated by the inherent physical characteristics and control response of large synchronous machines. This is set to change as the percentage of the electricity mix that comes from renewable resources continues to grow. These generation resources differ in two main aspects. First, they are typically smaller in size than synchronous resources and are connected through the distribution system and also directly to the transmission grid. Second, they are predominantly connected to the power system through power electronic inverters.

The increase in power electronic-connected resources, and associated loss of large spinning electromechanical synchronous generation, is forcing a re-examination of how to ensure the stability of systems with high penetration of renewable resources. A recent DOE-sponsored report[84] examined the associated challenges and open research questions that must be addressed to achieve widespread adaption of inverter-based renewable generation resources.

Synchronous machines regulate their terminal voltage and respond to changes in grid frequency by adjusting their power output. Collectively, they *form* the power system. In

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[83] This section was prepared by Ciaran Roberts, Energy Storage and Distributed Resources Division, LBNL.

[84] Lin, Yashen, Joseph H. Eto, Brian B. Johnson, Jack D. Flicker, Robert H. Lasseter, Hugo N. Villegas Pico, et al. 2020. *Research Roadmap on Grid-Forming Inverters*. National Renewable Energy Laboratory. NREL/TP-5D00-73476. https://www.nrel.gov/docs/fy21osti/73476.pdf.

contrast, today's inverter-based resources operate in what is known as *grid-following* mode. They use a phase-locked loop to measure an external grid voltage and use this measurement within their control loops to control their injection into the grid. In the absence of an existing stable voltage signal, an inverter in grid-following mode cannot operate. Additionally, in the absence of a synchronous generator, a collection of grid-following inverters cannot independently support the operation of a microgrid, nor can they support the restoration of the grid following a blackout.

With the continual displacement of synchronous generation by renewable resources, other forms of controlling inverters that replicate the *forming* capability inherently provided by synchronous generators must be considered. This mode of controlling inverters is referred to as *grid-forming controls*. Grid-forming controls are being considered for their ability to increase the stability of power systems with large penetrations of inverter based-resources. They can operate in the absence of synchronous machines, as well as support the restoration of microgrids and the bulk power system following a blackout.

The DOE report and accompanying workshop[85] identified five research needs and technology challenges related to grid-forming inverters that must be addressed to ensure widespread adoption of renewable electricity generation:

- Frequency control
- Voltage control
- System protection
- Fault ride-through and voltage recover
- Modeling and simulation

Current research projects include the design of non-phase-locked-loop controls for grid-forming inverters[86] and utility-scale validations of hybrid power plants with grid-forming inverters.[87] In September 2021 DOE awarded $25 million to a new public-private consortium dedicated to the development of grid-forming inverters powerful enough to distribute renewable energy across multiple states.

Strategic Considerations for California

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[85] The Workshop on Grid-forming Inverters for Low-Inertia Power Systems was held at the University of Washington in Seattle on April 29–30 2019. See: https://lowinertiagrids.ece.uw.edu/.

[86] Wang, Jing, Blake Lundstrom, and Andrey Bernstein. 2020. *Design of a Non-PLL Grid-Forming Inverter for Smooth Microgrid Transition Operation* (Preprint). National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy20osti/75332.pdf

[87] Renewables Rescue Stability as the Grid Loses Spin. https://www.nrel.gov/news/features/2020/renewables-rescue-stability-as-the-grid-loses-spin.html

California has abundant and diverse resources for renewable electricity generation, but the various sources each have different characteristics that will influence their role in the state's future electricity supply.

Solar PV has the largest potential of any renewable energy type in California, very good prospects for cost reduction, and can be installed feasibly across the entire state. Because electric output waxes and wanes with the sun, however, it needs to be complemented with electricity storage and demand flexibility to ensure sufficient power when solar output is low or not available. The ability of CSP to provide power in the evening could make it a useful renewable source for California, but technical progress is necessary for it to be competitive with PV+battery storage.

To restart growth of California's land-based wind production, emerging manufacturing, transportation, and installation technologies offer a pathway to overcoming barriers preventing developers from building larger turbines in more remote areas. Floating offshore wind platforms are at an early stage of development, but offshore wind power holds great potential. The average peak generation of California's offshore wind resources occurs at the end of the day and evening, characteristics that are complementary to the state's solar resource. California could potentially become one of the first global manufacturing centers for floating offshore wind infrastructure.

New technologies that can limit corrosion and access new areas for geothermal development would enable geothermal energy to provide greater amounts of reliable energy while developing its capabilities as a flexible resource. There is growing interest in geothermal energy in parts of the oil and gas industry,[88] and it may be possible to transition parts of California's oil and gas production industry to geothermal resource exploration and production.

Biomass could fuel some dispatchable electricity to California's power grid, but RNG may also be in demand for use in other sectors, so it will be important to evaluate how to best allocate the available resources.

Potential innovations exist that would improve prospects for all of the renewable technologies, but advances in solar PV technology have the potential to make this technology by far the least-cost source of supply. To maintain reliability with heavy reliance on such a variable resource, however, the development of cost-effective electric storage capacity and dispatchable low-carbon generation sources is critical.

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[88] https://www.heatbeat.energy/post/if-oil-and-gas-becomes-geothermal-what-does-geothermal-become

CHAPTER 4: Electricity Storage for the Grid

Introduction

As the share of electricity that comes from variable sources such as solar PV and wind power increases, the ability to store significant amounts of renewable electricity becomes increasingly important. Storage not only helps to maintain the reliability of the grid. It also can significantly enhance the value of renewable electricity, reduce curtailment, and thereby improve the economics of deploying large amounts of renewables.

Installations of large-scale energy storage projects using lithium-ion (Li-ion) batteries paired with renewable electricity generation are increasing in California and elsewhere. These batteries can be readily deployed anywhere, have high round-trip charge-discharge efficiencies, and their cost has steadily declined. Current electricity storage projects typically provide up to 4 hours of storage, but Li-ion batteries could potentially provide storage durations up to or beyond 12.[89]

Electricity storage with duration under 10 hours may be sufficient to ensure system reliability until the share of variable renewable generation is much higher than it is now. Depending on the characteristics of the region, between about 50% and 80% of annual energy from solar and/or wind may be feasible with storage durations of ≤10 hours.[90] However, significant amounts of storage with durations of >10 hours to the low hundreds of hours, and/or flexible (firm) low-carbon generation, would be needed to achieve renewables penetration beyond 80%.

Electricity system modeling indicates that introduction of long-duration (>10 hours) electricity storage significantly reduces total system costs relative to wind/solar systems with only shorter-duration batteries.[91] Long-duration electricity storage (LDES) minimizes expensive short-term storage that would otherwise be needed to compensate for the diurnal cycle of sunlight, and reduces the over-building of generation that would otherwise be needed to compensate for the seasonal variation in solar insolation. In addition, LDES could enhance grid resiliency in the face of increasing extreme weather events and wildfires.

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[89] *Duration* refers to the amount of time a storage system can discharge at its rated power capacity.

[90] Albertus, Paul, Joseph Manser, Scott Litzelman. 2020. Long-Duration Electricity Storage Applications, Economics, and Technologies. *Joule*, Vol. 4, 22-32. https://doi.org/10.1016/j.joule.2019.11.009

[91] Dowling, Jacqueline, et al. 2020. Role of Long-Duration Energy Storage in Variable Renewable Electricity Systems. *Joule*, Vol. 4, 1-22. https://doi.org/10.1016/j.joule.2020.07.007.

The Role of Different Storage Durations

A recent report from NREL describes four phases of electricity storage deployment with progressively longer durations.[92]

Phase 2, which is now underway, is characterized by the deployment of storage with 2–6 hours of discharge duration to serve as peaking capacity. These storage assets derive much of their value from the replacement of traditional peaking resources, but they also derive value from time-shifting/energy arbitrage of energy supply.

Phase 3 is less distinct, but is characterized by lower costs and technology improvements that enable storage to be cost-competitive while serving longer-duration (6–12 hour) peaks. Storage in this phase might provide additional sources of value, such as transmission deferral and additional time-shifting of solar and wind generation to address diurnal mismatches of supply and demand.

Phase 4 characterizes a possible future in which storage with durations from days to months is used to achieve very high levels of renewable energy in the power sector (>80%), or as part of multisector decarbonization.

Recent research that used a detailed long-run electricity system planning model to explore thousands of combinations of five generic LDES parameters across multiple scenarios found that the storage duration of LDES systems should be greater than 100 hours to maximize LDES system value and reductions in total electricity costs.[93] The researchers note that while technologies techno-economically suited to 10–24 hour duration can be a useful complement to available lithium-ion battery technologies, much longer durations are required for LDES to have a significant impact on the cost and composition of low-carbon power systems.

Cost Considerations for Electricity Storage

The upfront capital cost of a storage technology can be described in terms of the specific *power* cost--the portion of the costs that scale with the rate that energy can be moved into or out of storage (e.g., kW), and the specific *energy* cost---the portion of the costs that scale with the volume of energy that can be stored (e.g., kWh). As shown in Figure 4.1, shorter-duration storage technologies like batteries tend to have relatively high cost per kWh, while longer-duration technologies have higher costs per kW but

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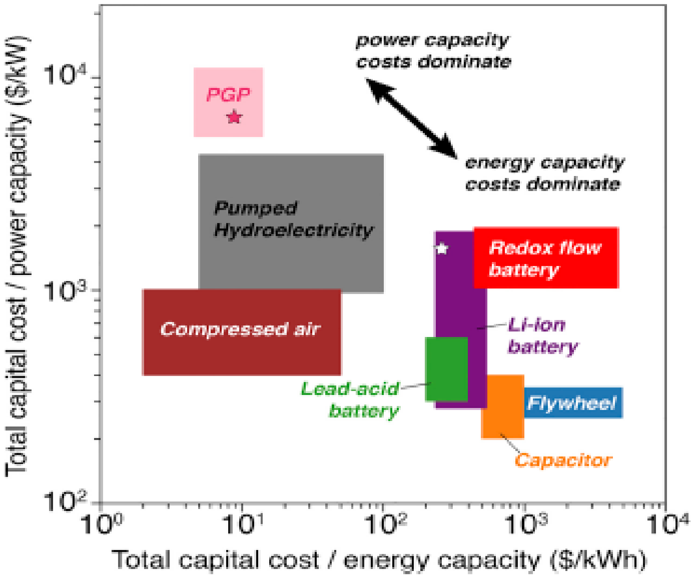
[92] Denholm, Paul, Wesley Cole, A. Will Frazier, Kara Podkaminer, and Nate Blair. 2021. *The Four Phases of Storage Deployment: A Framework for the Expanding Role of Storage in the U.S. Power System*. National Renewable Energy Laboratory. NREL/TP-6A20-77480. https://www.nrel.gov/docs/fy21osti/77480.pdf

[93] Sepulveda, N.A., J.D. Jenkins, A. Edington, D.S. Mallapragada, and R.K. Lester. 2021. The design space for long-duration energy storage in decarbonized power systems. *Nature Energy* 6, 506–516. https://doi.org/10.1038/s41560-021-00796-8

much lower cost per kWh.[94] Long-run electricity system modelling indicates that energy capacity cost is the greatest driver of LDES system value.

Figure 4.1: Energy Storage Technology Capital Costs by Capacity



The total capital cost by capacity for each storage technology is depicted with a box representing a range of values found in the literature. The height shows the range in capital costs divided by installed power capacities for typical systems and the width represents the range in capital costs divided by the usable energy storage capacities for typical systems. PGP = power to gas (e.g., hydrogen) to power.

Source: Dowling, et al. (2020)

The duration and number of annual discharges strongly influence the cost targets for economic viability of a storage system. One recent study used a discounted cash flow framework to estimate that acceptable installed energy capital costs range from just a few dollars per kWh for 100-hr duration (50% round trip efficiency) to around $75/kWh for 10-hr duration (80% round trip efficiency).[95] However, the authors note that the breadth of value propositions for storage, along with the ongoing evolution of storage valuation in electricity markets, makes it difficult to establish a single set of technical and economic metrics that, if met, would result in wide-scale deployment of LDES technologies. They also note that as power grids incorporate larger fractions of variable energy resources, the value of capacity and ancillary grid support services such as frequency and voltage regulation may have an outsized impact on the economic viability of storage projects.

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[94] The capital cost per kWh is different from the levelized cost of storage per kWh. The levelized cost of storage is a function of a storage asset's capital and operating costs as well as its operational profile and energy output over its useful lifetime.

[95] Albertus, et al., op. cit.

U.S. DOE recently issued an Energy Storage Grand Challenge Roadmap that lays out aggressive cost targets that are focused on markets of significant size with substantial growth potential.[96] The target for long-duration stationary applications is a levelized cost of storage of $0.05/kWh, which would facilitate commercial viability for storage across a wide range of uses. Both operational cost and manufacturing cost declines are required to enable domestic manufacturers to produce technologies that are cost competitive. The DAYS (Duration Addition to electricitY Storage) program at the Advanced Research Projects Agency-Energy (ARPA-E), which supports LDES technologies, also has an objective of achieving a levelized cost of $0.05/kWh across the full range of storage durations.[97]

In 2021, U.S. DOE established the Long Duration Storage Energy Earthshot initiative, which seeks to reduce the cost of grid-scale energy storage by 90% (from a 2020 Li-ion battery baseline) for systems that deliver 10+ hours of duration within the decade.[98] The Long Duration Storage Shot will consider all types of technologies – whether electrochemical, mechanical, thermal, chemical carriers, or any combination – that have the potential to meet the necessary duration and cost targets. The diversity of storage options with different costs, efficiencies, design characteristics, and siting constraints may result in complementary technologies occupying specific niches.[99]

Electrochemical Storage Technologies (Batteries)

Electrochemical storage systems use electrochemical reactions to convert and store energy, encompassing a range of battery chemistries and designs. The ability to install an electrochemical storage system in many locations is one of the technology's greatest advantages. Electrochemical energy storage technologies tend to have relatively high energy capacity costs ($/kWh), but the costs of Li-ion batteries have been steadily declining, primarily driven by mass production for automotive applications.

Advanced Lithium-Ion Batteries and Lithium Supply

Li-ion batteries are expected to maintain a cost advantage over other storage technologies for short and medium-duration storage.[100] U.S. DOE is supporting work on several new types of lithium-ion technology (e.g., silicone anodes, solid state electrolytes, lithium metal) to achieve a cost of <$100/kWh by 2028, with an ultimate

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[96] U.S. Department of Energy. December 2020. *Energy Storage Grand Challenge Roadmap*. https://www.energy.gov/energy-storage-grand-challenge/downloads/energy-storage-grand-challenge-roadmap

[97] Duration Addition to electricitY Storage (DAYS) Overview. https://arpa-e.energy.gov/sites/default/files/documents/files/DAYS_ProgramOverview_FINAL.pdf

[98] Long Duration Storage Shot. https://www.energy.gov/eere/long-duration-storage-shot

[99] Sepulveda, et al., op. cit.

[100] Schmidt, Oliver, Sylvain Melchior, Adam Hawkes, Iain Staffell. 2019. Projecting the Future Levelized Cost of Electricity Storage Technologies. *Joule*, Vol. 3, Issue 1, pp. 81-100. https://www.sciencedirect.com/science/article/pii/S254243511830583X?via%3Dihub

goal of $80/kWh. While much of the R&D is focused more on the needs of electric vehicles, other innovations could enhance batteries more suited for grid storage.

The rapid growth in demand for Li-ion batteries has led to investigation of novel cathode materials. Recently, lithium transition metal oxides with a cation-disordered rocksalt-type structure have emerged as potential high energy density cathodes. These compounds can be reasonable ionic and electronic conductors when prepared with excess lithium content, a realization which has led to the investigation of a large range of compositions in this structure space.[101] Several cation-disordered rocksalt cathodes have demonstrated very high specific capacities and energy densities well exceeding commercially-available layered lithium transition metal oxide cathodes.

Lithium extraction and refinement currently involves multi-step processes that use large quantities of reagents, require significant waste management, and are energy inefficient, contributing to the overall cost and negative environmental impact of lithium extraction. Multidisciplinary R&D efforts that integrate scientific research, engineering innovation, manufacturing, and process improvement can improve the economics and environmental footprint of processing from existing resources while enabling the use of new sources of lithium that are not yet commercially viable.

The key role of Li-ion batteries in both electrification of vehicles and electricity storage has prompted interest in development of domestic lithium supply. Recent estimates show that California's Imperial County, home of the Salton Sea geothermal resource area, could satisfy more than one-third of today's global lithium demand.[102] Given the potential to develop a domestic supply chain of lithium, California Assembly Bill 1657 authorized the CEC to convene a Blue-Ribbon Commission on Lithium Extraction in California, charged with "reviewing, investigating, and analyzing certain issues and potential incentives…regarding lithium extraction and use in California…" A unique aspect of the "Lithium Valley" vision is the potential to produce lithium as a by-product of geothermal energy. Development of Lithium Valley could bring significant employment opportunities to the region, and expand to include co-location of battery manufacturing.

A range of activities are envisioned to unlock this resource and develop "Lithium Valley." Technological advancements are needed in energy-efficient lithium separation and purification for the unconventional resources found in the western United States

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[101] Clement, R.J., Z. Lun and G. Ceder. 2020. Cation-disordered rocksalt transition metal oxides and oxyfluorides for high energy lithium-ion cathodes. *Energy Environ. Sci.,* 13,345-373. https://pubs.rsc.org/en/content/articlehtml/2020/ee/c9ee02803j

[102] Alston, Ken, Mikela Waldman, Julie Blunden, Rebecca Lee and Alina Epriman. 2020. *Building Lithium Valley*. New Energy Nexus. https://www.newenergynexus.com/wp-content/uploads/2020/10/New-Energy-Nexus_Building-Lithium-Valley.pdf

and the Salton Sea geothermal brine in particular.[103] The most mature technologies for the direct extraction of lithium from geothermal brines are in the realm of solid adsorbents. Solvent extraction with crown ethers is a promising area for developing a direct lithium extraction technology, but both fundamental and applied research is needed to advance and validate this technology. Crown ether technology has not been proven against geothermal brines, but if this technology can be validated, it has the potential to reduce the need for extensive pretreatment and simplify extraction processes. Other promising low TRL technologies include ion-imprinted polymers and cyclic siloxanes.

Various research groups are exploring methods to efficiently and selectively extract lithium. These include the use of renewable and recyclable hydrogen manganese oxide-modified cellulose film to absorb lithium, a solar-powered electrolysis technique using a sodium super ionic conductor (NASICON) solid-state electrolyte as the selective membrane for lithium extraction, and an electrochemical process based on Li-ion battery cathode materials.

Flow Batteries

A flow battery, or redox flow battery (after reduction–oxidation), is a type of electrochemical cell where chemical energy is provided by two chemical components dissolved in liquids contained within the system and separated by a membrane or porous separator. The electrochemical energy is typically stored in two soluble redox couples contained in external electrolyte tanks. The basic design is flexible in the chemistries it can accommodate.

Flow batteries are attractive for grid applications because the power and energy capacity can be designed separately. The power (kW) of the system is determined by the size of the cells and the number of cells in a stack, whereas the energy storage capacity (kWh) is determined by the concentration and volume of the electrolyte. Both energy and power can be easily adjusted for storage from a few hours to days. Compared to conventional containerized rechargeable batteries, redox flow batteries also offer long operational lifetimes with deep discharge capabilities, enhanced calendar life, simplified manufacturing, and improved safety characteristics, but lower volumetric energy density.

Although significant improvements in cell performance have been demonstrated on multiple types of conventional flow battery chemistries, it appears likely that the next generation of systems will utilize different materials than those being used today.[104] Pathways that could enable lower costs include the use of inherently lower-cost

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[103] Stringfellow, William and Patrick Dobson. 2021. Technology for Lithium Extraction in the Context of Hybrid Geothermal Power. PROCEEDINGS, 46th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 15-17, 2021.

[104] Perry, Michael L. and Adam Z. Weber. 2016. 'Advanced Redox Flow Batteries: A Perspective,' *Journal of the Electrochemical Society*, 163 (1), A5064-A5067. https://doi.org/10.1149/2.0101601jes

materials, as well as materials that can enable significantly higher energy densities (Wh/L) and/or power densities (W/m^2). This could entail using lower-cost, easy-to-synthesize, redox-active organic molecules, or overcoming limitations with inherently earth-abundant materials. Both aqueous and non-aqueous options are being pursued.

Researchers have developed an air-breathing aqueous sulfur battery that employs exceptionally low cost materials. The researchers believe that a modest reduction in stack resistance over current laboratory results would allow a power cost of $1,000–2,000/kW to be reached. At this power cost, estimated energy capacity costs are ~$100/kWh for durations of one day, and ~$30/kWh for durations of one week.[105] The researchers note that the scalability and cost of the battery could be significantly improved through development of low-cost, low-resistance membranes and non-platinum group metal catalysts.

The Joint Center for Energy Storage Research, a U.S. DOE Energy Innovation Hub, has pursued non-aqueous flow batteries that utilize dissolved or suspended redoxmers as charge-storing fluids.[106] Non-aqueous electrolytes enable a broader window of electrochemical stability, which is advantageous from both an energy-density and cell-voltage perspective. However, non-aqueous electrolytes also have disadvantages, such as higher solvent costs, higher viscosities, and lower ionic conductivities.

LBNL researchers have worked with partners to explore different hydrogen-based flow battery chemistries including iron-ion/hydrogen,[107] hydrogen/bromine,[108] and hydrogen/cerium,[109] each of which is being commercialized in different parts of the world. These battery chemistries provide facile reactions in aqueous conditions with advantages of possible low cost, assuming that deficiencies such as corrosivity are ameliorated.

Flow batteries using zinc-air chemistry are another promising approach. Zinc-air batteries offer high energy density, low operational temperature, high efficiency, and safe operation.[110] Compared to other metal anodes, zinc is an inexpensive, abundant

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[105] Li, Zheng, et al., 2017. Air-Breathing Aqueous Sulfur Flow Battery for Ultra low-Cost Long-Duration Electrical Storage, *Joule* 1, 306–327. https://doi.org/10.1016/j.joule.2017.08.007

[106] Trahey, Lynn, F. Brushett, N. Balsara, G. Ceder, L. Cheng, et al. 2020. Energy storage emerging: A perspective from the Joint Center for Energy Storage Research. *PNAS* 117 (23) 12550-12557. https://www.pnas.org/content/117/23/12550#sec-2

[107] Tucker, Michael C., Venkat Srinivasan, Philip N. Ross, and Adam Z. Weber. 2013. 'Performance and Cycling of the Iron-Ion/Hydrogen Redox Flow Cell with Various Catholyte Salts', *Journal of Applied Electrochemistry*, 43, 637-644. https://doi.org/10.1007/s10800-013-0553-2

[108] Cho, Kyu Taek, Michael C. Tucker, and Adam Z. Weber. 2016. 'A Review of Hydrogen/Halogen Flow Cells,' *Energy Technology*, 4, 655-678). https://doi.org/10.1002/ente.201500449

[109] Tucker, Michael C., Alexandra Weiss, and Adam Z. Weber. 2016. 'Improvement and analysis of the hydrogen cerium redox flow cell,' *Journal of Power Sources*, 327, 591-598 https://doi.org/10.1016/j.jpowsour.2016.07.105

[110] Abbasi, Ali, et al. 2020. Discharge profile of a zinc-air flow battery at various electrolyte flow rates and discharge currents. *Scientific Data* 7. https://www.nature.com/articles/s41597-020-0539-y

and non-toxic element with greater stability in aqueous environments. A Canadian company is commercializing zinc-air flow batteries for >8 hours electricity storage.[111]

ARPA-E's DAYS program is funding several novel flow battery designs suited to long-duration storage:[112]

- Aqueous sulfur system (mentioned above)
- A new approach to the zinc bromine battery. Taking advantage of the way zinc and bromine behave in the cell, the battery eliminates the need for a separator to keep the reactants apart when charged, and allows all the electrolyte to be stored in a single tank, instead of multiple cells.
- A new flow battery chemistry using inexpensive and readily available sulfur-manganese based active materials. Technology development aims to overcome challenges of system control and unwanted crossover between the two active materials through the flow membrane.

Table 4.1 presents some of the promising technology innovations for flow batteries.

Table 4.1: Technology Innovations for Flow Batteries

Technology	Description	Technical Maturity
Air-Breathing Aqueous Sulfur Battery	A long-duration energy storage system that takes advantage of the low cost and high abundance of sulfur in a water-based solution.	TRL 4-5
Hydrogen-Based Flow Battery Chemistries	These battery chemistries provide facile reactions in aqueous conditions with advantages of possible low cost, assuming that deficiencies such as corrosivity are ameliorated.	TRL 3-5
Sulfur-Manganese Flow Battery	Technology development aims to overcome challenges of system control and unwanted crossover between the two active materials through the flow membrane.	TRL 2-4
Zinc Bromine Battery	The battery eliminates the need for a separator to keep the reactants apart when charged, and allows all the electrolyte to be stored in a single tank.	TRL 5

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[111] New zinc-air battery is 'cheaper, safer and far longer-lasting than lithium-ion' https://www.rechargenews.com/transition/new-zinc-air-battery-is-cheaper-safer-and-far-longer-lasting-than-lithium-ion/2-1-812068

[112] Duration Addition to electricitY Storage (DAYS). https://arpa-e.energy.gov/sites/default/files/documents/files/DAYS%20Project%20Descriptions%20FINAL.pdf

Technology	Description	Technical Maturity
Redoxmer-Based Flow Batteries	Nonaqueous flow batteries that utilize dissolved or suspended redoxmers (redox active organic monomer, oligomers, polymers, and colloids) as charge-storing fluids.	TRL 2-3
Size-Selective Polymeric Membranes	Polymers of intrinsic microporosity are a new class of nanoporous membranes capable of size-screening redoxmers in redox flow batteries. These potentially inexpensive polymer membranes can be functionalized to enable charge selectivity, in addition to size selectivity.	TRL 2

Technical maturity estimated by LBNL subject experts.

Other Batteries for Grid Electricity Storage

The requirements of stationary batteries are quite different from those of power batteries used in EVs. Long cycle life (>8000 full cycles), low cost, and high energy efficiency (>90% at system level) are the most important parameters to consider. Sodium-ion batteries and potassium-ion batteries, which rely on naturally abundant sodium and potassium resources, are likely to provide a significant advantage in terms of cost for stationary applications such as power grids.[113]

U.S. DOE is supporting research into replacing the traditional materials in lithium-ion technologies with more abundant sodium while retaining the lithium-ion manufacturing process. Because sodium-ion is relatively heavier, energy densities are lower than lithium-ion, but stationary storage applications have less need for high energy densities than do vehicle applications. R&D is focused on identifying materials and cell chemistries that can enable sodium-based systems to have comparable life cycle performance to today’s lithium-ion batteries while eliminating the cost and supply chain constraints of lithium.

Table 4.2 presents two battery types that are being considered for grid applications. Sodium-sulfur and sodium-metal-halide (or Zebra) batteries use a molten-sodium anode and require particular cell architectures and high temperature to function. A promising zinc-based chemistry currently being developed for grid-scale applications is based on the traditional zinc-manganese oxide alkaline batteries. Modifications to the chemistry have enabled reversible charging of the cells. When combined with an estimated materials cost of <$20/kWh, a long shelf life, and an established manufacturing supply chain in the United States, these batteries are a potential candidate for low-cost grid storage.

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[113] Tian, Yaosen, et al. 2021. Promises and Challenges of Next-Generation “Beyond Li-ion” Batteries for Electric Vehicles and Grid Decarbonization. *Chemical Reviews* 2021, 121, 3, 1623–1669. https://doi.org/10.1021/acs.chemrev.0c00767

Table 4.2: Technology Innovations for Other Batteries for Grid Applications

Technology	Description	Technical Maturity
Sodium-Metal-Based	Research is working on novel metal-halide-based chemistries and designs that operate between 150–200°C. This lower temperature operation enables use of lower-cost materials and mass-producible manufacturing processes.	TRL 8-9[1]
Zinc-Manganese Oxide	This chemistry uses a zinc anode and a manganese-oxide cathode, modified to enable reversible charging of the cells. R&D is focused on improving materials utilization and development of lower-cost materials.	TRL 4

[1] The basic technology is relatively mature but improvements are sought.

Source: U.S. Department of Energy (December 2020). Technical maturity estimated by LBNL subject expert.

Chemical Storage Technologies

Chemical energy storage includes hydrogen and other energy-dense chemicals. The most prominent chemical storage technology involves hydrogen. In hydrogen energy storage for grid applications, hydrogen (H_2) is produced via electrolysis and then stored in tanks, pipes, or underground caverns. The hydrogen is then used in a fuel cell or combined cycle to generate electricity.

An advantage of hydrogen energy storage systems is that the storage capacity can be scaled independently from the power and hydrogen production rates. Hydrogen can be stored underground in large quantities the same way natural gas is stored today – e.g., in aquifers and depleted natural gas reservoirs, which opens up opportunities for seasonal energy storage. Hydrogen used as a multi-day storage resource can provide carbon-free grid support during worst-case scenario grid events that are increasingly arising from natural disasters and weather extremes.

Compared to other electricity storage technologies, an advantage of hydrogen energy storage is the flexibility to deploy the hydrogen generated to other markets and customers, potentially adding value to the system. In addition, the rapid response times of some electrolyzers can provide grid services including voltage and frequency stabilization.

Technologies and infrastructure for hydrogen production, storage, and utilization exist today at various levels of maturity and cost. Use of hydrogen for electricity storage is but one of the applications driving hydrogen technology development.[114] Large-scale

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[114] For an overview of the potential for hydrogen production, transport, storage, and utilization in multiple energy sectors, see: Ruth, Mark, et al. 2020. *The Technical and Economic Potential of the H2@Scale Concept within the United States*. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy21osti/77610.pdf

systems for hydrogen production, transport, storage, and utilization are in the process of being validated in Europe, Asia, and the U.S. While major components are advanced enough to enable these efforts, continued cost reductions through technology improvements and economies of scale will be needed to support market adoption.

Hydrogen Production

Electrolyzers use electricity to split water into hydrogen and oxygen. They can be broadly classified as low-temperature or high-temperature based on their operating temperature ranges.

Low-temperature electrolysis, generally operated below 100°C, includes liquid alkaline, proton exchange membrane (PEM), and anion exchange membrane (AEM) technologies. Liquid alkaline electrolysis systems have been established for over 100 years and have a large manufacturing base. They have cost advantages for large-scale hydrogen production for general use, but have limited flexibility to follow changing electrical demand on the grid and cannot be used to internally pressurize the hydrogen.

PEM electrolyzer technologies offer high current density, reduced footprint, higher efficiency than alkaline electrolyzers, and inherent electrochemical hydrogen compression. Compared to alkaline electrolysis, PEM electrolysis has the advantage of quickly reacting to the fluctuations typical of renewable power generation. PEM electrolysis has an efficiency of about 80% in working application, in terms of hydrogen produced per unit of electricity used to drive the reaction (higher heating value). Estimates for durability are about 40,000 hours. PEM electrolyzers are available today at the multi-megawatt scale, but RD&D is still required to reduce their cost and improve the efficiency and durability.

AEM electrolysis replaces a conventional diaphragm with an anion exchange membrane. Compared to PEM electrolysis, a major advantage of AEM electrolysis is the replacement of conventional noble metal electrocatalysts with low cost transition metal catalysts.[115] The process is also effective at smaller scales, making it potentially suitable for decentralized applications. AEM electrolysis technology is at an early stage of development. Progress requires basic and applied research, technology development and integration, and testing at a laboratory scale of small demonstration units that can be used to validate the technology (from TRL 2–3 currently to TRL 4–5).[116]

High-temperature electrolysis typically operates above 550°C and uses electricity and heat to produce hydrogen. The heat requirement means that the technology is better suited to thermal electricity generation such as nuclear power than to renewables. The

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[115] Vincent, Immanuel and D. Besarabov. 2018. "Low cost hydrogen production by anion exchange membrane electrolysis: A review." *Renewable and Sustainable Energy Reviews.* Vol. 81, Part 2, pp. 1690-1704. https://www.sciencedirect.com/science/article/pii/S1364032117309127#!

[116] Miller, Hamish, et al. 2020. Green hydrogen from anion exchange membrane water electrolysis: a review of recent developments in critical materials and operating conditions. *Sustainable Energy Fuels*, 4, 2114-2133. https://pubs.rsc.org/en/content/articlelanding/2020/se/c9se01240k#!divAbstract

leading high-temperature electrolysis technology under development utilizes solid oxide electrolysis cells (SOECs), which offer the advantage of higher-efficiency hydrogen production. Performance and durability improvements as well as increased scale-up efforts have led to a hundredfold increase in gas production capacity within the past decade and to commissioning of the first industrially-relevant SOEC plants.[117] Because high operating temperatures lead to fast degradation of active materials and balance-of-system components, increasing lifetime is a key goal of current research efforts for this technology.

The key areas for innovation for electrolyzer technology are new catalysts using inexpensive and abundantly available materials, improvements in the membrane electrode assemblies and porous transport layers, and protecting the bipolar contact plates through advanced coatings. Liquid alkaline technology would benefit from higher current density operation and improved efficiencies, while PEM technology would benefit from thinner membranes and precious metal catalyst reduction.

The U.S. DOE-sponsored consortium H2 from the Next-generation of Electrolyzers of Water (H2NEW) will conduct R&D to enable large-scale manufacturing of affordable electrolyzers. H2NEW will focus on materials and component integration, manufacturing, and scale-up to help support large industry deployment of durable, efficient, and low-cost electrolyzers for hydrogen production.

Advanced manufacturing processes for electrolyzers are also receiving more attention.[118] Among emerging manufacturing technologies, roll-to-roll coating, additive manufacturing for production of some components in the fuel cell and electrolyzer stacks, and automation of the stack assembly line provide potential solutions for higher production volumes and lower-cost parts.

In terms of long-range research, the U.S. DOE-funded HydroGEN consortium is working on next-generation advanced water splitting technologies, including EM electrolyzers, photoelectrochemical water splitting, proton-conducting ceramic SOECs, and solar thermochemical production.[119] Each of these are at the TRL 1-3 stage and require new materials with increased efficiency and durability, but they provide the promise of making hydrogen from renewable resources directly.

Hydrogen Storage

Although hydrogen has the highest energy content by weight of conventional fuel, in gaseous form the volumetric energy density is low, which makes storage challenging.

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[117] Hauch, A. et al. 2020. Recent advances in solid oxide cell technology for electrolysis. *Science* 09 Oct 2020: Vol. 370, Issue 6513. https://science.sciencemag.org/content/370/6513/eaba6118

[118] Mayyas, Ahmad and Margaret Mann. 2019. Emerging Manufacturing Technologies for Fuel Cells and Electrolyzers, *Procedia Manufacturing* 33 (2019) 508–515. https://doi.org/10.1016/j.promfg.2019.04.063

[119] HydroGEN: Advanced Water Splitting Materials. https://www.h2awsm.org/

Traditional storage relies on high pressure tanks and/or liquefaction, which can carry high energy penalties.

Large-scale hydrogen storage options:

- Hydrogen may be stored as gas or a liquid in pure molecular form without any significant physical or chemical bonding to other materials;
- Molecular hydrogen may be adsorbed onto or into a material, held by relatively weak physical bonds;
- Atomic hydrogen may be chemically bonded (absorbed) as metal hydrides or chemical hydrides.
- Conversion into a chemical compound that acts as a carrier.

The most widely used hydrogen storage solution is to contain the compressed gas in a metal container. While there is little experience with the large-scale storage of hydrogen in metallic vessels, it is a relatively common practice for natural gas, and the same types of vessels could be applied for storage of hydrogen. For larger tanks for bulk storage of hundreds of tons of hydrogen, novel designs, materials, and controls to accommodate fuel supply requirements are being investigated. Surface hydrogen storage facilities have limited storage and discharge capacity today, however.

Underground formations are an option for storing very large amounts of hydrogen gas. Salt caverns offer low construction costs, low leakage rates, and fast withdrawal and injection rates. However, they are geographically constrained to the presence of evaporitic formations with suitable thickness and extent. Porous saline aquifers and depleted hydrocarbon reservoirs offer storage capacities several orders of magnitude larger than salt caverns, and provide a geographically more independent and flexible solution for large-scale hydrogen storage. A range of scientific issues need to be addressed in order to enable large-scale underground hydrogen storage in porous media, including the fluid flow behavior of hydrogen in subsurface reservoirs, geochemical reactions caused by the introduction of hydrogen, biotic reactions enabled by the presence of excess hydrogen, and the geomechanical response of the reservoir and caprock to cyclic injection and withdrawal operations.[120]

The other H_2 storage technologies are still at relatively early stages of development. Much of the research activity is conducted under the U.S. DOE funded HyMARC (Hydrogen Materials Advanced Research Consortium).[121] With metal hydrides, the chemical bonds are much stronger than the physical bonds involved in the adsorption of hydrogen, which allows hydrogen to be stored at high density even at ambient conditions. However, more energy is needed to release the chemically bonded

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[120] Heiemann, Niklas, et al. 2021. Enabling large-scale hydrogen storage in porous media – the scientific challenges. *Energy Environ. Sci.*, Issue 2, 2021. https://pubs.rsc.org/en/content/articlelanding/2021/EE/D0EE03536J#!divAbstract

[121] https://www.hymarc.org/

hydrogen. The chemical carriers require efficient catalysts to put in and take out the hydrogen but are generally liquids at normal conditions, thereby simplifying their transport and storage, as well as heat and mass transfer during dehydrogenation and hydrogenation processes. Liquid chemical hydrogen carriers compatible with large-scale storage and transport include common compounds such as ammonia and Toluene. Physical absorption systems such as highly porous metal-organic frameworks can store hydrogen at lower pressures than traditional gas storage, but RD&D is still required for efficient and economical storage.

Conversion to Electricity

Conversion of the stored chemical energy to electricity can be achieved using combined cycle gas turbines and combustion turbines or fuel cell technologies. Recently, major players in the worldwide power-generation industry have been focusing more attention on hydrogen turbines, particularly for large-scale electricity generation. Industry has developed materials and systems to increase the concentration of hydrogen that can be combusted – eventually to 100%.[122] Although a number of issues need to be addressed, hydrogen turbines are likely to be the technology of choice for large-scale hydrogen power-to gas-to power projects.[123]

Fuel cell systems can generate electricity at efficiencies ranging from 40% to 60%, depending on the technology. Fuel cells operate quietly and have fewer moving parts. Polymer electrolyte membrane fuel cells typically operate at about 80°C and can respond quickly to changing loads, making them suitable for distributed generation, backup, or portable power applications that require fast start-up times or must react to variable loads. Solid oxide fuel cells operate at much higher temperatures (typically 800°C to 1,000°C) and may be more suitable for use in modular and utility-scale stationary power systems where there may be higher contaminants and CO concentrations. They can operate at higher efficiencies but are not dynamic and require long times for start-up and shut-down. While these challenges can be overcome with newer generation metal-supported cells, such research is still at a low TRL level.

The California Stationary Fuel Cell Roadmap prepared by the National Fuel Cell Research Center at UC Irvine envisions that in the medium term, distributed stationary fuel cell systems could be operating to support capacity and distribution deferral throughout the utility grid network, replace combustion systems and improve the

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[122] Mitsubishi Hitachi Power Systems has announced that their hydrogen turbines will be able to combust 100% hydrogen by 2025.

[123] For example, the IPP Renewed project in Utah plans to pair renewable energy-powered hydrogen production and underground storage in a salt cavern with new gas-fueled electricity generating units capable of utilizing hydrogen for 840 megawatts net generation output. The turbines will be designed to utilize 30 percent hydrogen fuel at start-up, transitioning to 100 percent hydrogen fuel by 2045 as technology improves. The primary offtaker of the dispatchable renewable electricity will be Los Angeles Department of Water & Power. https://www.ipautah.com/ipp-renewed/

reliability and stability of the network's high use of renewable power generation.[124] Depending on cost reductions, the long run could see deployment of fuel cell systems for large-scale, 100 MW-class power generation at central plants.

A recent NREL techno-economic analysis of long-duration energy storage and flexible power generation technologies suggested that using heavy-duty vehicle PEM fuel cells in stationary service could reduce power production capital costs relative to conventional stationary PEM fuel cells without introducing the need for frequent fuel cell stack replacements throughout the project life due to the low power generation capacity factor for seasonal LDES.[125] The authors note that seasonal energy storage systems may only be discharged 5%–10% of the time, equivalent to 13,000–26,000 h over a 30-year lifetime and similar to the demonstrated fuel cell lifetimes of more than 20,000 h achieved in transit buses.

An advanced approach combines electrolysis and fuel cell functions into a single unit, which is referred to as a reversible (or regenerative) fuel cell. A *discrete* reversible fuel cell (RFC) system uses separate electrolyzer and fuel cell stacks, while the combination of these two processes into a single stack is commonly termed a *unitized* reversible fuel cell (Figure 4.2). Some advantages of carrying out fuel cell and electrolyzer operations in a single stack include significantly decreased cost, a smaller footprint, and system simplification.

In the near term, it is expected that RFC systems will consist of discrete electrolyzer and fuel cell stacks. These systems will require MW-scale fuel cells capable of intermittent operation. Unitized RFCs are at an earlier stage of R&D and must overcome challenges with the availability of materials that are stable and perform efficiently in both modes of operation. Work is underway on cell, stack, and system architectures that provide flexibility and durability with switching operation modes.

A key challenge for unitized RFCs is to obtain a roundtrip energy efficiency close to that of a discrete system. Researchers at LBNL recently demonstrated an optimized unitized RFC in constant-electrode configuration that achieved 57% and 60% round-trip efficiency with air and O_2 as the reductant gases, respectively.[126] Their assessments suggest that the primary challenge to unitized RFCs will be to engineer catalyst layers and systems that are stable in both charge and discharge operating modes and to decrease the time in switching between modes.

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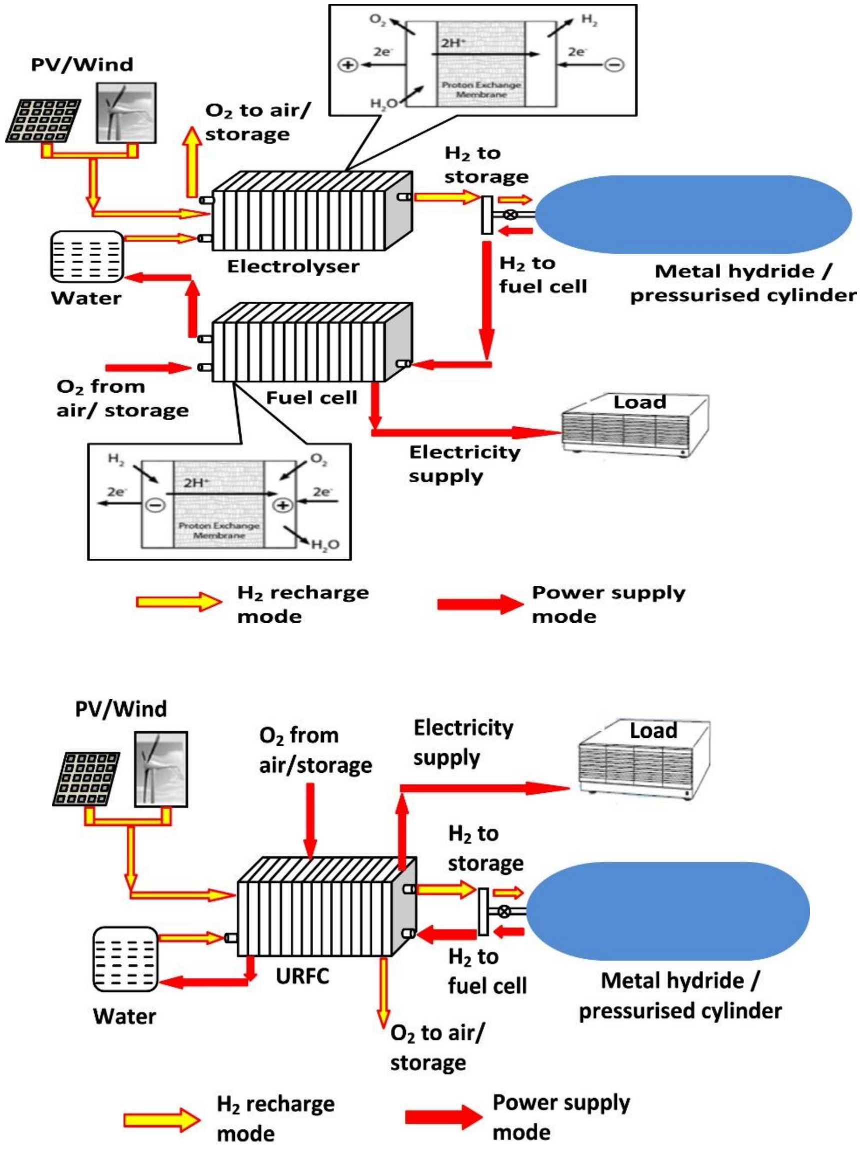
[124] *California Stationary Fuel Cell Roadmap*. March 2020. National Fuel Cell Research Center, UC Irvine. http://www.nfcrc.uci.edu/PDF_White_Papers/California_Stationary_Fuel_Cell_Roadmap_Long_Version_062420.pdf

[125] Hunter, Chad, et al. 2021. Techno-economic analysis of long-duration energy storage and flexible power generation technologies to support high-variable renewable energy grids. *Joule* 5, 2077–2101. https://doi.org/10.1016/j.joule.2021.06.018

[126] Regmi, Y., et al. 2020. A low temperature unitized regenerative fuel cell realizing 60% round trip efficiency and 10 000 cycles of durability for energy storage applications. *Energy & Environmental Science* Issue 7. https://pubs.rsc.org/en/content/articlelanding/2020/EE/C9EE03626A#!divAbstract

Figure 4.2: Schematic Diagram of a Discrete Reversible PEM Fuel Cell System with Storage (Top) and a Unitized PEM Fuel Cell System with Storage (Bottom)



Source: Paul and Andrews (2017)

Summary

Table 4.3 summarizes technology innovations for hydrogen electricity storage. Storage of hydrogen as gas or a liquid is not included because the technology is relatively mature, and deployment is mainly constrained by geographic factors or cost issues. Combustion turbines and conventional fuel cells are not included because the technologies are relatively mature.

Table 4.3: Summary of Technology Innovations for Hydrogen Electricity Storage

Technology	Description	Technical Maturity
Hydrogen Production via Electrolysis		
Proton Exchange Membrane	Key advantages of PEM systems are high power density and cell efficiency, provision of highly compressed hydrogen, and flexible operation. Disadvantages include expensive platinum catalyst and fluorinated membrane materials, and high system complexity due to high pressure operation and water purity requirements. R&D targets reducing system complexity and reducing capital costs through less expensive materials and more sophisticated stack manufacturing processes.	Early market
Anion Exchange Membrane	A major advantage of AEM electrolysis is the replacement of conventional noble metal electrocatalysts with low cost transition metal catalysts. AEM electrolysis requires further investigation and improvements, specifically regarding its power efficiency, membrane stability, robustness, ease of handling, and cost reduction.	Low
Solid Oxide Electrolyzer Cells	SOECs use solid ion-conducting ceramics as the electrolyte, enabling operation at significantly higher temperatures. Potential advantages include high electrical efficiency, low material cost and the options to operate in reverse mode as a fuel cell. Current research is focused on stabilizing existing component materials, developing new materials and lowering the operation temperature to 500–700 °C.	Medium
Hydrogen Storage		
Adsorption Onto or Into a Material	Hydrogen storage via adsorption exploits physical bonding between molecular hydrogen and a material with a large specific surface area. Low temperatures and elevated pressures must typically be applied to achieve significant hydrogen storage densities using adsorption.	Low
Metal Hydrides	Chemical bonding with metal hydrides allows hydrogen to be stored at high density even at ambient conditions.	Low
Chemical Carriers	Chemical carriers are generally liquids at normal conditions, thereby simplifying their transport and storage, as well as heat and mass transfer during dehydrogenation and hydrogenation processes.	Low
Conversion of Hydrogen to Electricity		
Discrete Reversible Fuel Cell	A discrete reversible fuel cell uses separate electrolyzer and fuel cell stacks.	Medium
Unitized Reversible Fuel Cell	A unitized reversible fuel cell combines an electrolyzer and fuel cell. Unitized RFCs must overcome challenges with the availability of materials that are stable and perform efficiently in both modes of operation.	Low to Medium

Technical maturity estimated by LBNL subject experts.

Mechanical Storage Technologies

Mechanical storage systems use mechanical methods to convert and store electrical energy.[127] These systems include pumped water, compressed air, and gravity storage systems. The advantages of mechanical solutions, in general, are their long lifetime, long duration, and low technology risk. Mechanical storage is scalable to large sizes, but its energy density is considerably lower than electrochemical storage, and thus above-ground systems have larger spatial footprints, and may necessitate large earthworks or engineering projects to achieve appreciable capacities. New approaches may help overcome the challenges to mechanical energy storage.

Pumped Storage Hydro

Pumped hydro systems provide the long lasting, reliable, predictable energy storage that utility asset planners seek. Both in California and in the U.S., pumped hydroelectric power has been the traditional method for electricity storage, but it is limited by geographic location and effects on downstream water flows.

The most significant constraint on traditional pumped storage hydro (PSH) deployments is obtaining suitable available land for the upper and lower reservoirs. Closed-loop systems that are not connected to a natural water source have less environmental impact and greater flexibility in siting options, and are the predominant technology being explored for future developments. U.S. DOE's HydroNEXT initiative focuses on lowering costs, improving performance, and promoting environmental stewardship in the context of closed-loop PSH systems.[128] Round-trip efficiency (RTE), historically around 70%, have been improved over the years, and R&D efforts by U.S. DOE target systems capable of >80% RTE.

New PSH designs could reduce capital investment requirements, expand siting possibilities, and shorten the development timeframe for new facilities. One design being explored has a novel configuration that does not require an underground powerhouse, which is one of the more costly, risky, and environmentally impactful aspects of PSH construction.[129] Installation of the submersible pump turbine in a vertical "well," rather than a traditional underground powerhouse, reduces construction cost and project risk and also allows installation under geologic conditions not suitable for an underground powerhouse.

Another design under development couples a ternary PSH system with sophisticated transmission monitoring and control equipment to address renewable energy integration issues. The ternary PSH system consists of a separate turbine and pump

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[127] This section is based in part on U.S. Department of Energy, Energy Storage Grand Challenge Draft Roadmap, Appendix 3.

[128] https://www.energy.gov/eere/water/articles/energy-department-awards-98-million-next-generation-hydropower-technologies

[129] Novel Design Configuration Increases Market Viability for Pumped-Storage Hydropower in the United States. 2020. NREL. https://www.nrel.gov/news/program/2020/psh-ensures-resilient-energy-future.html

stacked (or horizontally mounted) on a single shaft with an electric machine that can operate as either a generator or motor. The system can operate both the pump and the turbine simultaneously, whereas all other PSH plants operate in either generating mode or pumping mode.[130]

ARPA-E is funding a California startup that is developing a modified PSH system using rocks beneath the Earth's surface.[131] The system will pump pressurized water into gaps in underground rocks. When energy is needed later, the induced strain in the surrounding rock will force water back through a generator to produce electricity.

Compressed Air Energy Storage

Compressed air energy storage (CAES) systems use electricity to compress air and store it in a reservoir, either underground in a suitable cavern or in an above-ground pressure vessel. When electricity is needed, the compressed air is heated, expanded, and directed through a generator to produce electricity.

Current CAES plants heat the air with fossil fuel when the system is discharged. Much recent research has focused on adiabatic CAES, in which the heat at the compressor outlets is removed from the air via heat exchangers, stored in separate thermal energy stores, and then utilized to heat the cool compressed air in discharge operation. While technical literature consistently refers to its potential as a promising energy storage solution, several design challenges need to be overcome for adiabatic CAES to become a viable energy storage option. A recent review concluded that the adoption of a whole-system design approach, relating component performance to feasible designs across the system, would be highly valuable.[132] In terms of component development, the simultaneous development of higher-outlet-temperature compressors and lower-inlet-temperature turbines is vital.

Traditional CAES systems have operated using solution-mined salt caverns, but geological conditions with salt domes or bedded salt conducive to solution-mining to make caverns are rare. In contrast, sedimentary rocks with pore space filled by groundwater and sometimes by oil and natural gas are ubiquitous in sedimentary basins around the world. The same pore space that is occupied by these fluids can provide the volume needed for "porous media" CAES. Simulated operation of a prototypical porous media CAES wellbore–reservoir system representing a depleted hydrocarbon reservoir validated the feasibility of this approach.[133] In 2017, PG&E demonstrated technical

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[130] Corbus, D., et al. 2018. *Transforming the U.S. Market with a New Application of Ternary-Type Pumped-Storage Hydropower Technology*, Preprint. NREL. https://www.nrel.gov/docs/fy18osti/71522.pdf

[131] Duration Addition to electricitY Storage (DAYS). https://arpa-e.energy.gov/sites/default/files/documents/files/DAYS%20Project%20Descriptions%20FINAL.pdf

[132] Barbour, Edward and Daniel Pottie. 2021. "Adiabatic compressed air energy storage technology." *Joule* 5, 1914–1920.

[133] Oldenburg, Curtis and Lehua Pan. 2013. Porous Media Compressed-Air Energy Storage (PM-CAES): Theory and Simulation of the Coupled Wellbore–Reservoir System. *Transp Porous Med* 97:201–221. DOI 10.1007/s11242-012-0118-6

feasibility for porous media CAES in a depleted natural gas reservoir. A dedicated research effort is needed to reduce uncertainties that could allow economical bulk storage to be realized.[134] Such research could lead to widespread re-purposing of depleted gas reservoirs for utility-scale energy storage.

Another CAES approach involves purpose-built caverns, which allows for flexibility in siting. It uses a column of water above the cavern to maintain static pressure during charge and discharge.[135] Thermal storage is used to capture the heat of compression, which is used for increasing the available energy during discharge. A British company is advancing a technology that cryogenically cools air and stores liquid air in insulated, low pressure vessels. Exposure to ambient temperatures causes rapid re-gasification and a 700-fold expansion in volume, which is then used to drive a turbine and create electricity.[136]

Gravity Storage Systems

A new breed of gravity storage solutions, using the gravitational potential energy of a suspended mass, seeks to replicate the cost and reliability benefits of pumped hydro, without the siting limitations.[137] The initial capital cost of these technologies is driven by the type of mass, the type of elevation gain, and the mechanism to move and store the mass as it transitions through the elevation gain. The metric of greatest importance is cost per kg of stored material.

Several companies are developing different types of gravity-based energy storage systems. For example, Energy Vault's storage plants consist of a 35-story crane with six arms, surrounded by a tower consisting of thousands of bricks made from recycled concrete, each weighing about 35 tons. This plant will "store" energy by using electricity to run the cranes that lift bricks from the ground and stack them atop of the tower, and "discharge" energy by reversing that process. Specially engineered control software ensures the bricks are placed in exactly the right location each time. The modular system is capable of 4-8 MW of continuous power discharge for 8-16 hours.

Summary

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[134] A description of the technical studies needed is given in a proposal developed by LBNL: "Bulk Energy Storage--Bringing New Value to California's Depleted Natural Gas Reservoirs." https://eesa.lbl.gov/wp-content/uploads/2014/11/Bulk-Energy-Storage_LBNL_041019.pdf

[135] https://www.hydrostor.ca/

[136] https://highviewpower.com/technology/

[137] Fyke, Aaron. 2019. The Fall and Rise of Gravity Storage Technologies. *Joule* 3, 620–630. https://www.cell.com/joule/pdf/S2542-4351(19)30041-8.pdf

Table 4.4 summarizes technology innovations for mechanical energy storage.

Table 4.4: Technology Innovations for Mechanical Energy Storage

Technology	Description	Technical Maturity
Pumped storage hydro	New technologies such as small modular PSH systems can reduce the geographical footprint and enable MW-scale PSH systems to be deployed, while advances in ternary PSH systems improve capacity utilization and increase response time and efficiency.	High
Compressed air energy storage	Novel approaches include use of thermal storage technology to capture and reuse the heat that is generated during air compression, storing liquified air in above-ground tanks, and purpose-built caverns.	Medium to High
Gravity storage systems	Designs use the gravitational potential energy of a suspended mass to store energy.	Medium to High

High-Temperature Thermal Energy Storage

High-temperature reservoir thermal energy storage (TES) systems can use excess electricity to heat a storage medium to high temperature. The heat can then be used to generate electricity.

In the context of grid energy storage, TES technologies have received less attention because the conversion of heat to electricity tends to occur at low efficiency (~35–40%) and high cost for conventional turbine-based heat engines. The storage of energy as heat can be far cheaper than storing electricity in batteries, however, and using heat at very high temperatures can maximize the efficiency of electricity generation. High-temperature thermal energy storage systems are at an early stage of development but hold the potential to provide electricity at a low cost per kWh and a round-trip efficiency of 50% or more.

In the case of concentrating solar-thermal power technologies, solar heat is used to heat the TES material, molten salts. New technologies under development use electricity to resistively heat a storage medium, which allows for a much higher storage temperature. Different high-temperature storage media have been proposed, including molten silicon and carbon blocks.

There are also different proposed approaches to convert the heat to electricity. One conceptual design involves pumping molten silicon through an array of tubes which emit light.[138] The light/heat is then converted back into electricity using multi-junction photovoltaic cells that convert the visible and near infrared light. Figure 4.3 illustrates the proposed system.

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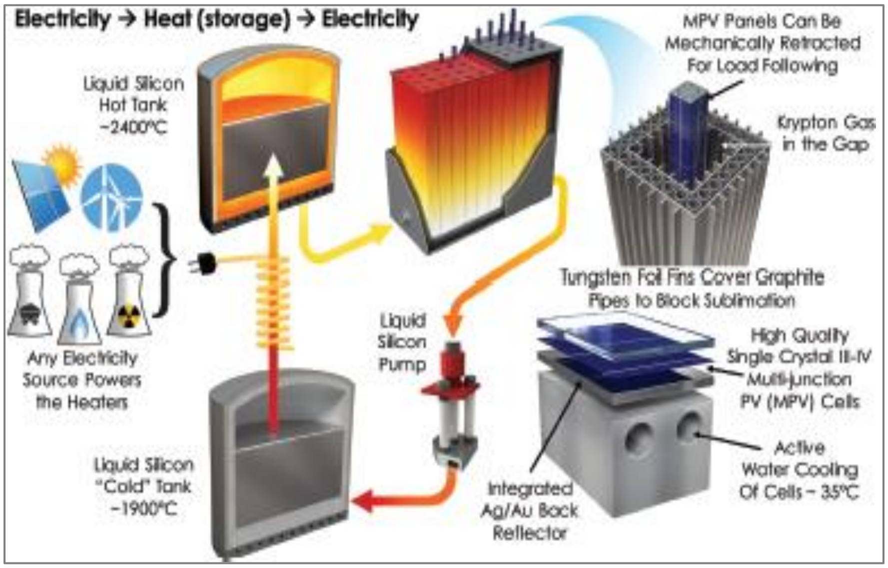
[138] Amy, Caleb, et al. 2019. Thermal energy grid storage using multi-junction photovoltaics. *Energy Environ. Sci.*, 12, 334. https://pubs.rsc.org/en/content/articlelanding/2019/ee/c8ee02341g#!divAbstract

Another approach under development stores thermal energy in inexpensive carbon blocks.[139] To charge the battery, excess electricity will heat the blocks to temperatures exceeding 2000°C (3632°F) via resistive heating. To discharge energy, the hot blocks are exposed to thermophotovoltaic panels that are similar to traditional solar panels but specifically designed to efficiently use the heat radiated by the blocks. The system involves a thermophotovoltaic heat engine capable of efficiently and durably converting high-temperature heat into electricity. It will seek to double panel efficiency through new materials and smart system design.

Figure 4.3: Thermal Energy Grid Storage Using Multi-Junction Photovoltaics



Source: Amy, et al. (2019)

ARPA-E's DAYS program is funding several high-temperature thermal energy storage systems:[140]

- A high temperature, low cost thermal energy storage system that uses a high performance heat exchanger and closed loop Brayton cycle turbine to generate power. Electric heaters will warm stable, inexpensive solid particles to temperatures greater than 1100°C during charging. To discharge the system, the particles will be fed through the heat exchanger, heating a working fluid to drive the gas turbine attached to a generator.
- A modular thermal storage system that uses electricity to heat up a bed of magnesium manganese oxide particles to high temperatures. Once heated, the particles will release oxygen and store the heat energy in the form of chemical

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[139] Solid State Thermal Battery. https://arpa-e.energy.gov/technologies/projects/solid-state-thermal-battery

[140] Duration Addition to electricitY Storage (DAYS). https://arpa-e.energy.gov/sites/default/files/documents/files/DAYS%20Project%20Descriptions%20FINAL.pdf

energy. When power is needed, the system will pass air over the particle bed, starting a chemical reaction that releases heat to drive a gas turbine generator.

- Improved Laughlin-Brayton cycle energy storage. When the system is charging, an electrically driven heat pump will accumulate thermal energy in a molten salt solution, which can then be discharged later by heating gas and sending it through the generation turbine. The system uses a reversible turbine design, in which each turbine acts as the compression stage for the other, whether during charging or discharging.
- Long-duration electrical energy storage using a CO_2-based pumped thermal energy storage system. The system that uses a CO_2 heat pump cycle to convert electrical energy to thermal energy by heating a "reservoir" of low cost materials such as sand or concrete. The reservoir will retain heat that will be converted back into electricity on demand. To generate power, liquid CO_2 will be pumped through the high-temperature reservoir to a supercritical state, after which it will expand through a turbine to generate electricity from the stored heat.
- A system that stores thermal energy in inexpensive carbon blocks and uses a thermophotovoltaic heat engine to convert high-temperature heat into electricity (described above).

Strategic Considerations for California

The bulk of California's future renewable electricity supply is expected to come from solar PV, whose production rises and falls with the sun. Given that peak demand is moving toward the evening, it will be imperative to store electricity to meet demand and minimize curtailment of PV generation. In addition, because PV production is lowest in the winter, seasonal storage will become more important if electrification of heating and water heating becomes widespread. Finally, long-duration electricity storage can play a key role in enhancing the resiliency of the power grid to unexpected shortfalls in electricity supply.

A recent study prepared for the California Energy Storage Alliance estimated that meeting the state's goals could require up to 11 GW of long-duration electricity storage by 2030, and 45 to 55 GW by 2045.[141] The analysis shows how LDES in the 10-hour range can significantly reduce the need for natural gas based generation during the night and early morning. Storage with 100-hour minimum duration for seasonal shifting of energy is shown to be critical for achieving a zero-carbon electric sector.

Detailed techno-economic analysis of potential electricity storage technologies by NREL[142] and others indicates that a number of technologies could be competitive

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[141] Strategen Consulting. 2020. *Long Duration Energy Storage for California's Clean, Reliable Grid*. https://www.storagealliance.org/longduration.

[142] Hunter, Chad, et al. 2021. Techno-economic analysis of long-duration energy storage and flexible power generation technologies to support high-variable renewable energy grids. *Joule* 5, 2077–2101. https://doi.org/10.1016/j.joule.2021.06.018

depending on the energy storage duration and realized capital cost improvements. The diversity of storage options with different costs, efficiencies, design characteristics, and siting constraints may result in complementary technologies occupying specific subniches. With so many options available, independent evaluation will be important to identify which technologies capable of storing energy for long durations have a realistic pathway to the ultra-low costs for energy capacity and requisite combination of efficiency and power costs to be competitive. Initiatives like the U.S. DOE Long Duration Storage Energy Earthshot will provide information that will help to focus R&D and demonstrations on the most promising candidates.

The CEC is funding an evaluation of different scenarios for the deployment of long-duration storage to meet the state's mandates to decarbonize the electricity sector in California by 2045.[143] The objective is to develop a better understanding of the role that long-duration energy storage can and should play in the future of California's grid, and the optimal durations and locations to support a variety of applications.

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[143] https://www.energy.ca.gov/solicitations/2020-01/gfo-19-308-assessing-long-duration-energy-storage-deployment-scenarios-meet

CHAPTER 5: Managing Flexible Loads for a Low-Carbon Electricity System

Introduction

In the past 20 years California's electricity system has evolved towards a structure in which many energy resources are "distributed" rather than centralized. These distributed energy resources (DER) include on-site electricity generation (such as rooftop PV systems) and flexible electricity loads that are responsive to the needs of the grid.

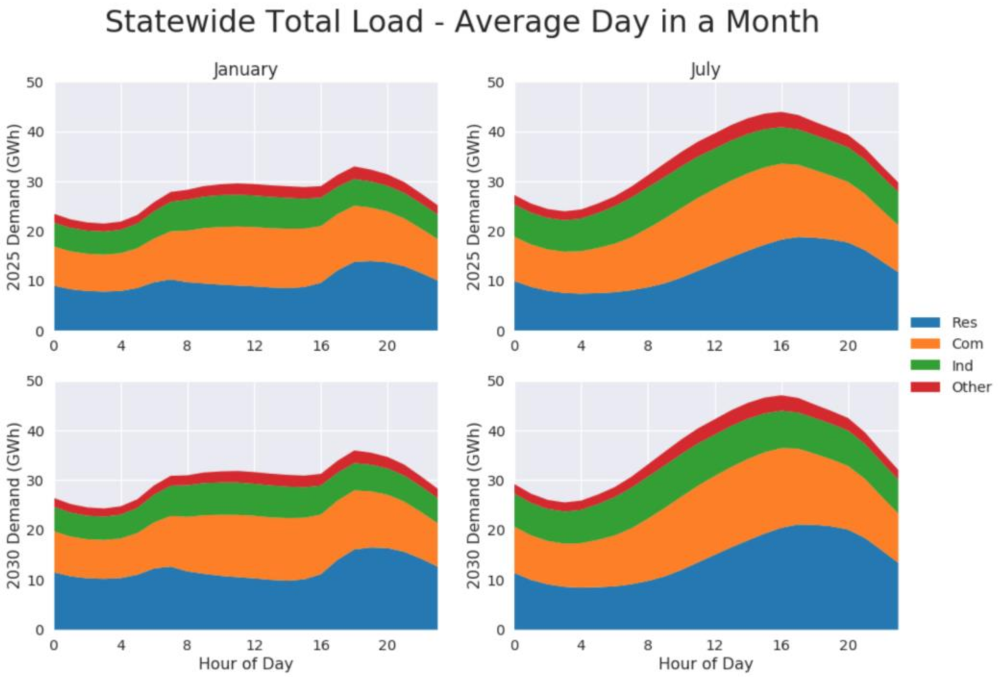
As previously discussed, a major challenge for California's electricity system is the growing mismatch between the daily and seasonal availability of solar electricity generation and the expected peak demands on the system. In general, solar PV generation rises from sunrise to noon and then declines until sunset. However, projected peak demand in the summer rises during the course of the afternoon and is still quite high by 8 p.m., and projected demand in the winter is highest between 4 p.m. and 8 p.m. (Figure 5.1). Electrification of space heating would worsen the problem in the winter, and growing use of air conditioning would increase demand in the late afternoon and evening in the summer. Electrification of other end uses such as water heating and cooking would exacerbate the problem, as would electrification of motor vehicles if a significant amount of electric vehicle (EV) charging takes place when vehicle owners return home from work.

Increasing electricity storage capacity on the grid is one way to address these problems. Another way is to increase the flexibility of electricity demand such that demand can be reduced (*shed*) during peak periods or *shifted* from peak to off-peak periods in response to the needs of the grid. Technologies to enable such load (demand) flexibility are discussed in the first section of this chapter.

Management of EV charging is another important strategy. In addition to avoiding charging during periods of peak demand, EV batteries could potentially store electricity during periods when supply is in excess, and discharge the electricity to meet on-site demand or feed into the grid later. Integration of EVs is the subject of the second part of this chapter.

A third strategy, covered in the last part of this chapter, pertains to coordinating the control of distributed energy resources across multiple buildings, or community scale DERs, to collectively provide grid services.

Figure 5.1: Projected Total Daily California Statewide Load in 2025 and 2030



The sectors are residential, commercial, industrial, and other.

Source: Gerke, et al. (2020)

This chapter considers three types of demand-side management strategies that can provide grid services: Shed Load, Shift Load, and Modulate Load.[144] Table 5.1 describes these demand flexibility strategies and their key characteristics.

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[144] Efficiency is also an important strategy and is considered in Chapter 2.

Table 5.1: Mapping Demand-Side Management Strategies to Grid Services

Strategy	Grid Services	Description of Change
Shed Load	Contingency Reserves	Load reduction for a short time to make up for a shortfall in generation.
	Generation: Energy Generation: Capacity T&D: Non-wires solutions	Load reduction during peak periods in response to grid constraints or based on TOU pricing structures.
Shift Load	Generation: Capacity T&D: Non-Wires Solutions	Load shifting from peak to off-peak periods in response to grid constraints or based on TOU pricing structures.
	Contingency Reserves	Load shift for a short time to make up for a shortfall in generation.
	Avoid Renewable Curtailment	Load shifting to increase energy consumption at times of excess renewable generation output.
Modulate Load	Frequency Regulation	Load modulation in real time to closely follow grid signals. Advanced telemetry is required for output signal transmission to grid operator; must also be able to receive automatic control signal.
	Voltage Support	
	Ramping	Load modulation to offset short-term variable renewable generation output changes.

Source: U.S. Department of Energy (2019). Grid-interactive Efficient Buildings Technical Report Series; Overview of Research Challenges and Gaps.

Buildings

The electricity demand from buildings results from a variety of electrical loads that are operated to serve the occupants' needs. However, many of these loads are flexible to some degree. With proper communications and controls, loads can be managed to draw electricity at specific times and at different levels, while still meeting service levels, occupant productivity and comfort requirements. The increased flexibility can benefit the grid[145] while providing value to owners through reduced utility bills and increased resilience, among other benefits.

Demand response can be dispatchable or non-dispatchable, depending on who has the authorization to modify the building's controls. Dispatchable demand response relies on communication and control technologies that respond directly to signals from the grid operator, utility, or a third-party aggregator. Non-dispatchable demand response activates at the discretion of the building owner in response to price signals. Currently, predetermined time-of-use (TOU) electricity prices and demand charges are common

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[145] Grid services can reduce generation costs by offsetting generation capacity investments and other costs, and can reduce delivery costs by offsetting T&D capacity investments or by reducing equipment maintenance.

forms of non-dispatchable demand response, but dynamic real-time pricing is a future opportunity that will provide incentives for the use of advanced control strategies.

U.S. DOE has conducted analysis of the potential for buildings to provide grid services through demand flexibility.[146] Table 5.2, Table 5.3, and Table 5.4 summarize how a set of studies characterized the potential of various technologies to provide demand flexibility (load shed or load shift).[147] Most of the technologies with high potential are described in the following sections.

Table 5.2: Evaluation of Technology Capabilities to Provide Demand Flexibility: Windows and Opaque Envelope

Technology Area	Technology	Load Shed	Load Shift
Windows	Dynamic Glazing	High	Low
	Automated Attachments	High	Low
	Photovoltaic Glazing	Medium	n.a.
Opaque Envelope	Tunable Thermal Conductivity Materials	Medium	n.a.
	Thermally Anisotropic Materials	High	Low
	Thermal Storage	Medium	High
	Moisture Storage and Extraction	Medium	Medium
	Variable Radiative Technologies	Medium	n.a.

High Capability: Well suited to provide the demand-side management (DSM) strategy and the corresponding grid services or possesses high potential through continued R&D.
Medium Capability: Able to provide the DSM strategy, but in a limited capacity.
Low Capability: May be able to provide the DSM strategy, but it is not well suited.

Source: U.S. Department of Energy. 2019. Grid-interactive Efficient Buildings Technical Report Series; Windows and Opaque Envelope.

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[146] U.S. Department of Energy. 2020. *Grid-interactive Efficient Buildings: Projects Summary*. https://www.energy.gov/sites/prod/files/2020/09/f79/bto-geb-project-summary-093020.pdf.

[147] It should be noted that the ratings are qualitative and are based on estimated theoretical technological potentials, available research studies, and expert guidance. No lab testing or experimental pilot tests have been performed as part of this evaluation. The capability of technologies to provide load modulation or energy efficiency is not shown here.

Table 5.3: Evaluation of Technology Capabilities to Provide Demand Flexibility: HVAC, Water Heating, Appliances, Refrigeration, and Related Technologies

Technology Area	Technology	Load Shed	Load Shift
HVAC	Smart Thermostats	Medium	High
	Separate Sensible and Latent Space Conditioning	Medium	Medium
	Liquid Desiccant Thermal Energy Storage	Medium	High
	Advanced Controls for HVAC Equipment with Embedded Thermostat	Low	High
Water Heating	Water Heaters with Smart, Connected Controls	Low	High
Appliances	Modulating/advanced Clothes Dryers	Low	Medium
	Advanced Dishwasher and Clothes Washer Controls	n.a.	High
	Advanced Controls for Commercial Refrigeration	Low	High
	Water Circulation (pumps)	Low	High
	Misc. HVAC (e.g., ceiling fans)	Medium	High

High Capability: Well suited to provide the demand-side management (DSM) strategy and the corresponding grid services or possesses high potential through continued R&D.
Medium Capability: Able to provide the DSM strategy, but in a limited capacity.
Low Capability: May be able to provide the DSM strategy, but it is not well suited.

Source: U.S. Department of Energy. 2019. Grid-interactive Efficient Buildings Technical Report Series; Heating, Ventilation, and Air Conditioning (HVAC); Water Heating; Appliances; and Refrigeration.

Table 5.4: Evaluation of Technology Capabilities to Provide Demand Flexibility: Lighting and Electronics

Technology Area	Technology	Load Shed	Load Shift
Lighting	Advanced Sensors and Controls	Medium	n.a.
Electronics	Battery-Powered Electronics	n.a.	Medium

Medium Capability: Able to provide the DSM strategy, but in a limited capacity.

Source: U.S. Department of Energy. 2019. Grid-interactive Efficient Buildings Technical Report Series; Lighting and Electronics.

Windows

Buildings can adjust solar heat gain to actively reduce heating/cooling needs through dynamic windows with automatic shading. In the near future, dynamic windows will be integrated with shading, lights, and HVAC systems through advanced control algorithms such as model predictive control to manage heating, cooling and lighting energy.[148] Controllable dynamic windows would be compatible with other end-use control systems using the standard interoperability protocols for daylighting and electric lighting integration. As discussed in Chapter 2, development of dynamic windows includes novel solar photovoltaic windows[149] and electrochromic windows.[150] These windows could enable buildings to provide flexibility in heating and cooling loads in addition to the lighting load. Table 5.5 describes windows technologies for managing the electric load.

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[148] Gehbauer, C., D. H. Blum, T. Wang, and E. S. Lee. 2020. "An assessment of the load modifying potential of model predictive controlled dynamic facades within the California context." *Energy Build.* 210: 109762. https://doi.org/10.1016/j.enbuild.2020.109762.

[149] Peng, J., D. C. Curcija, A. Thanachareonkit, E. S. Lee, H. Goudey, and S. E. Selkowitz. 2019. "Study on the overall energy performance of a novel c-Si based semitransparent solar photovoltaic window." *Appl. Energy* 242: 854–872. https://doi.org/10.1016/j.apenergy.2019.03.107.

[150] Sarwar, S., S. Park, T. T. Dao, M.-soo Lee, A. Ullah, S. Hong, and C. H. Han. 2020. "Scalable photo electrochromic glass of high performance powered by ligand attached TiO_2 photoactive layer." *Sol. Energy Mater. Sol. Cells* 210: 110498. https://doi.org/10.1016/j.solmat.2020.110498.

Table 5.5: Windows Technology Innovations to Manage Electric Load

Technology	Description	Technical Maturity	Technical Potential
Dynamic windows with smart control	Smart control of windows with shading, coordinated with the lighting and HVAC systems	TRL 4–6	Dynamic windows with smart controls can reduce critical coincident peak demand as much as 43% for a perimeter office.
Novel solar photovoltaic window	Solar photovoltaic window with high energy conversion efficiency and visible transmittance	TRL 3–5	Integration of dynamic solar photovoltaic windows in a commercial building can reduce peak demand by up to 30% in a perimeter office.
Novel electrochromic window	Novel application of a photoactive layer for photoelectrochromic devices	TRL 3–5	For commercial buildings located in the northern hemisphere, electrochromic glazing is estimated to reduce peak demand by 20%–30% for east, south, and west thermal zones.

Lighting

Connected lighting technologies can be used to adjust lighting levels up and down and modulate lighting power demand with minimal impact on occupant visual comfort. Dimming the light is the most common shed strategy for demand response. Innovations for next generation lighting systems include (1) communications interoperability between daylighting systems, lighting, and HVAC; (2) advanced sensor integration and control; and (3) low cost, high efficiency hybrid daylight/solid state lighting (SSL) systems that can respond to pricing signals.[151] Recent development of a self-powered low-cost sensor and controller for lighting applications, which is capable of distributed intelligence and communications, has demonstrated energy savings in laboratory

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[151] U.S. Department of Energy. 2019. *Grid-interactive Efficient Buildings Technical Report Series - Lighting and Electronics*. https://www.energy.gov/eere/buildings/downloads/grid-interactive-efficient-buildings-technical-report-series-lighting-and

testing.[152] Table 5.6 summarizes the technical maturity and benefit of lighting technology innovations for managing the electric load.

Table 5.6: Lighting Technology Innovations to Manage Electric Load

Technology	Description	Technical Maturity	Technical Benefit
Low-cost sensor and controller integrated lighting device	Sensors integrated directly or embedded into the lighting device/LED lamp or luminaire for better data communication and demand response capabilities necessary to provide many grid services	TRL 4–6	In addition to enabling users to shed lighting loads, the technology can provide fast response grid services through shedding and modulating, though in limited capacities that are not disruptive to occupant productivity, comfort, or safety.
Hybrid daylight SSL systems	Technology integration of daylight systems with photosensors and automated dimming controls to adjust electric lighting for quick response grid services	TRL 4–6	SSL displays can provide some DR capabilities, mainly by shedding load during peak periods through modulating light output and other energy consuming components.
New design of hybrid daylight SSL systems	Improved design of hybrid daylight SSL systems and materials to minimize daylight transmitting and material efficiency losses and allow for lower installation costs	TRL 3–5	Its primary grid service contribution is load reduction through heating and cooling energy savings.
Lighting fixtures: embedded demand response communication and control protocols	Automated demand response capability by dimming the lights in response to a grid signal	TRL 4–6	Provide a "plug-and-play" solution to enable the lighting to participate grid services.

Previous studies have demonstrated the load shed potential by switching off or dimming the lights in response to grid signals with minimal impact on the occupant visual

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[152] Brown, R. E., P. Schwartz, B. Nordman, J. Shackelford, A. Khandekar, N. Jackson, A. Prakash, et al. 2019. *Developing Flexible, Networked Lighting Control Systems That Reliably Save Energy in California Buildings.* California Energy Commission. https://eta.lbl.gov/publications/developing-flexible-networked

comfort.[153] Estimates of the demand response (DR) potential from DR-capable lighting are a 20%–40% kW reduction with no or low daylight, and up to a 60% kW reduction with high daylight.[154] A DR potential study conducted by LBNL estimated the available DR capacity in commercial lighting as 156 MW per year for load shed and ~220 MW per year for load modulation.[155]

In addition to providing load shedding for demand response, lighting systems with advanced sensors and controls also offer the opportunity for additional building-level energy savings by sharing their data with other building systems. Advanced sensors and controls and spectral tunable SSL technologies also can provide health benefits for the occupants. These systems can be designed to engage human physiological responses, including alertness, productivity, and human circadian rhythms that aid in sleep and wake cycles. Quantification of the impact these features may have on workforce productivity requires more research since lighting controls that are used to promote human health and well-being may conflict with the grid service objectives.

Building Envelope

Energy storage systems that can store and discharge thermal energy can be integrated into a building envelope. Thermal storage systems can store energy as sensible heat (e.g., raising and lowering the temperature of a concrete slab) or latent heat (e.g., by driving a phase transition in a phase change material). In addition to shifting the timing of heating and/or cooling energy demand, thermal storage can improve thermal comfort by reducing the magnitude of temperature swings, and in some cases it can offset energy use by recharging using nighttime air or solar heat gain and can reduce the size of space-conditioning equipment.

Phase change materials. Envelope-based energy storage systems charge and discharge in response to ambient temperatures and can shift load to off-peak hours either in heating or cooling modes. Due to the transition of the peak period from midday to evening hours, traditional passive phase change materials (PCM) systems may not be fully utilized to shift heating/cooling loads. To tackle this barrier, new research integrates solid state tunable thermal storage and switching into the building envelope, and provides thermal demand flexibility by controlling PCM charging and discharging during operation.[156] A similar study of "thermal switches" has demonstrated

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[153] Newsham, G. R., S. Mancini, and R. G. Marchand. 2008. "Detection and Acceptance of Demand-Responsive Lighting in Offices with and without Daylight." *LEUKOS* 4(3). http://doi.org/10.1582/LEUKOS.2007.004.03.001.

[154] Yin, R., J. Page, and D. Black. 2016. Demand Response with Lighting in Office, Retail, and Hospitality Buildings in the SD&E Service Area. LBNL Report to SDG&E.

[155] Alstone, P., J. Potter, M.A. Piette, et al. 2017. *2025 California Demand Response Potential Study – Charting California's Demand Response Future: Final Report on Phase 2 Results*. Lawrence Berkeley National Laboratory, LBNL-2001113.

[156] Prasher, R.S., R. Jackson, and C. Dames. 2019. Solid State Tunable Thermal Energy Storage and Switches for Smart Building Envelopes. 2019 BTO Peer Review.

the performance of active insulation systems with integrated thermal mass in reducing heating/cooling energy consumption and peak loads while improving thermal comfort compared to the traditional precooling using building thermal mass.[157]

PCMs are used in buildings for different purposes, including thermal load shaving and shifting, cooling/heating load reduction, thermal comfort, control of building material temperature, and increase in building durability, efficiency, and energy saving.[158]

Operation of PCM systems during peak periods can improve thermal comfort. They also can help improve flexibility with respect to long-term changes in climate conditions, because they can adjust their operating ranges to reflect actual conditions, rather than the design conditions when the building envelope was specified.

Control of thermally activated building system (TABS) for demand response. A TABS has radiant tubing embedded in a structural slab, or in a topping slab on top of a structural slab without insulation to separate the two slabs.[159] For a radiant slab cooling system, the cooling demand can be shifted from the on-peak period to the off-peak period by adjusting the water flow or temperature into the slab.[160] A low threshold of the water flow or temperature is required to avoid condensation on the slab.

Table 5.7 summarizes the technical maturity and potential of building envelope technology innovations for managing the electric load.

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https://www.energy.gov/sites/default/files/2019/05/f62/bto-peer%E2%80%932019-lbnl-nrel-solid-state-tunable-tes.pdf

[157] Mumme, S., N. James, M. Salonvaara, S. Shrestha, D. Hun. 2020. "Smart and efficient building envelopes: Thermal switches and thermal storage for energy savings and load flexibility." *ASHRAE Transactions*, 126, 140–148.

[158] Al-Yasiri, Q., and M. Szabó. 2021. "Incorporation of phase change materials into building envelope for thermal comfort and energy saving: A comprehensive analysis." *Journal of Building Engineering,* Vol. 36. https://doi.org/10.1016/j.jobe.2020.102122.

[159] Paliaga, G., F. Farahmand, and P. Raftery. 2017. TABS Radiant Cooling Design and Control in North America: Results from Expert Interviews 0–62.

[160] Jin, W., J. Ma, C. Bi, Z. Wang, C. B. Soo, and P. Gao. 2020. "Dynamic variation in dew-point temperature of attached air layer of radiant ceiling cooling panels." *Build. Simul.* 13: 1281–1290. https://doi.org/10.1007/s12273-020-0645-y.

Table 5.7: Building Envelope Technology Innovations to Manage Electric Load

Technology	Description	Technical Maturity	Technical Potential
Novel phase change material	Solid state tunable thermal storage that can be actively controlled by charging and discharging to provide demand flexibility	TRL 3–5	Such a PCM application in Southern California can potentially save 10%–30% compared to existing cooling energy consumption.
Control of thermally activated building systems for demand response	Increased ability to shift or shed load—both response time and magnitude—by adjusting the water flow or temperature into the slab. Components and assemblies with areas of high and low thermal conductivity that allow heat to be routed through the envelope to a heat sink such as a plumbing loop	TRL 4–6	The optimal control of TABS could reduce peak heating and cooling load by 10% and 36%[161]

HVAC Equipment

Smart thermostat. Some large-scale smart thermostat deployment already exists in demand response programs on the electricity retail and wholesale markets. Though smart thermostats have two-way communication capabilities between the vendor and customer, real-time HVAC power use is still invisible for the vendor or utility. The centralized approach involves a large number of local variables and constraints that make numerical computations impracticable for controlling a large number of smart thermostats. A distributed control structure with good performance could aggregate large numbers of smart thermostats in response to a real-time price signal or a fast demand response program.[162] The use of smart thermostats in residential HVAC can provide as much as 2 MW per year of load shed and 32–43 MW per year of load shifting in California’s electricity market.

PCM-coupled HVAC system. Recently there are new developments of PCM-coupled HVAC systems to achieve a more grid-interactive capability. A low-cost novel PCM can be coupled with an HVAC system to be controlled dynamically.[163] The residential HVAC

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[161] Chung, W.J., S.H. Park, M.S. Yeo, and K.W. Kim. 2017. “Control of thermally activated building system considering zone load characteristics.” *Sustainability* 9: 1–14. https://doi.org/10.3390/su9040586.

[162] Totu, L.C., J. Leth, and R. Wisniewski. 2013. “Control for large scale demand response of thermostatic loads.” *Proc. Am. Control Conf.* 5023–5028. https://doi.org/10.1109/acc.2013.6580618.

[163] Jiang, Z., J. Cai, P. Hlanze, H. Zhang. 2020. "Optimized Control of Phase Change Material-Based Storage Integrated in Building Air-Distribution Systems." *2020 American Control Conference,* pp. 4225-4230, https://doi.org/10.23919/ACC45564.2020.9147514.

load can provide a large flexible resource for load shedding or shifting. The PCM-coupled HVAC system is capable of storing the cooling during the daytime and reducing the peak demand during the evening hours. The next generation of PCM applications will be dynamic and modular, as well as being grid-interactive.[164,165]

Water Heating

Electric thermal storage water heaters can draw excess electricity generated from renewables and store it for later use. The next generation of thermal storage water heaters in buildings will need to incorporate grid interactive and advanced control capabilities. Recent development of grid-interactive water heater technologies can provide real-time monitoring, load forecasting, and machine learning algorithms-based controlling to maximize the amount of capacity available for grid services while minimizing any impact on a customer's hot water supply. Thermal storage water heaters will be most important for the residential sector, since most commercial buildings are not occupied during evening peak hours. Most of the value is in load shifting. Smart connected water heater controllers offer some load shedding by allowing temperatures to drift when curtailed, but this is generally followed by a period of increased demand. Table 5.9 summarizes the technical maturity and potential of water heating technology innovations for managing the electric load.

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[164] Kaur, S., M. Bianchi, N. James, L. Berkeley, S. Kaur, M. Bianchi, and N. James. 2020. 2019 Workshop on Fundamental Needs for Dynamic and Interactive Thermal Storage Solutions for Buildings.

[165] Dutton, S. 2019. Hybrid HVAC with Thermal Energy Storage Research and Demonstration. 2019 BTO Peer Review.

Table 5.8 summarizes the technical maturity and potential of HVAC technology innovations for managing the electric load.

Water Heating

Electric thermal storage water heaters can draw excess electricity generated from renewables and store it for later use. The next generation of thermal storage water heaters in buildings will need to incorporate grid interactive and advanced control capabilities.[166] Recent development of grid-interactive water heater technologies can provide real-time monitoring, load forecasting, and machine learning algorithms-based controlling to maximize the amount of capacity available for grid services while minimizing any impact on a customer's hot water supply. Thermal storage water heaters will be most important for the residential sector, since most commercial buildings are not occupied during evening peak hours. Most of the value is in load shifting. Smart connected water heater controllers offer some load shedding by allowing temperatures to drift when curtailed, but this is generally followed by a period of increased demand. Table 5.9 summarizes the technical maturity and potential of water heating technology innovations for managing the electric load.

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[166] Starke, M., J. Munk, H. Zandi, T. Kuruganti, H. Buckberry, J. Hall, and J. Leverette. 2020. Real-time MPC for residential building water heater systems to support the electric grid. 2020 IEEE Power Energy Soc. Innov. Smart Grid Technol. Conf. https://doi.org/10.1109/ISGT45199.2020.9087716.

Table 5.8: HVAC Technology Innovations to Manage Electric Load

Technology	Description	Technical Maturity	Technical Potential
Smart thermostat	Distributed control of a large number of smart thermostats in response to real-time pricing or fast demand response	TRL 4–6	Can provide load shifting, including management of complex scheduling and day-ahead service requests, while optimizing operations to minimize impacts on customer comfort.
Hybrid evaporative precooling	Relatively fast response to switch from vapor-compression to evaporative cooling modes	TRL 3–5	Well suited to providing efficiency value through substantial improvements to coefficient of performance, but limited load shedding and load shifting/leveling value.
Separate sensible and latent cooling system	Separate sensible and latent cooling and variable capacity control can allow buildings to shed load and operate at lower energy consumption levels during peak demand events.	TRL 3–5	Systems could shed load by reducing the sensible cooling stage and only operating the high-efficiency latent cooling stage to maintain occupant comfort during peak events and allow for longer curtailment periods without causing discomfort. Some systems may offer load shifting by using liquid desiccants and other materials.
Low-cost novel PCM coupled with HVAC system	New application of PCM in HVAC plants or coupled with HVAC supply air duct to give heating/cooling flexibility	TRL 4–6	Optimized control of PCM-based storage integrated in building air-distribution systems can lower peak demand by 30%.[167]
Modular thermal energy storage	Modular and scalable thermal energy storage cell that can be easily deployed like building blocks to shift the peak cooling demand from high noon to off-peak hours.	TRL 5–7	Can be deployed in small and medium businesses on a large scale.

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[167] Jiang, Z., J. Cai, P. Hlanze, and H. Zhang. 2020. Optimized Control of Phase Change Material-Based Storage Integrated in Building Air-Distribution Systems. Proc. Am. Control Conf. 4225–4230. https://doi.org/10.23919/ACC45564.2020.9147514.

Table 5.9: Water Heating Technology Innovations to Manage Electric Load

Technology	Description	Technical Maturity	Technical Potential
Grid-interactive heat pump water heater	Integrated or add-on connected, smart controls that enable remote, two-way communication for operator-controlled dispatch and programmable setbacks.	TRL 5–7	Each water heater shifts relatively small amounts of load away from the evening peak (estimated to be between 0.3 kW and 0.6 kW).

Resilience: Advanced water heater controls can be used to preheat water in anticipation of a winter storm or hurricane when an outage may be possible. Assuming water pressure is still sufficient from the potable water supply (which may require on-site energy storage or backup generation), users could have some hot water available during the outage.

Whole-Building Controls, Sensors, Modeling and Analytics

Sensors and Control. Building automation systems utilize analytics supported by sensors and controls to manage various end uses in response to utility price signals or events. The development of low-cost, low-power wireless sensors has promoted the implementation of advanced energy-saving and demand control strategies in buildings and has made retrofitting additional sensors more economical. [168] Sensors can be deployed to monitor indoor and outdoor environmental conditions, as well as equipment and system operation and health. The primary technological challenge is to connect and synchronize various sensors and meters as an integrated system for grid interactive control. Existing work has demonstrated the use of a unified metadata schema for efficient building operation and demand response participation[169], however it is still in the early development stage.

Advanced Control Algorithms. A variety of statistical, modeling, data mining, and machine-learning techniques can be utilized to study recent and historical data to make optimal control sequences. Field demonstration studies have proven that advanced building control, such as model predictive control (MPC), can reduce energy use and

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[168] Joshi, P. 2016. *Low-cost Manufacturing of Wireless Sensors for Building*. Oak Ridge National Laboratory.

[169] Balaji, B., A. Bhattacharya, G. Fierro, J. Gao, J. Gluck, D. Hong, A. Johansen, et al. 2016. Brick: Towards a unified metadata schema for buildings. Proc. 3rd ACM Conf. Syst. Energy-Efficient Built Environ. BuildSys 41–50. https://doi.org/10.1145/2993422.2993577.

cost while maintaining acceptable indoor environmental conditions.[170] However, the widespread application of MPC in buildings is still in the early stages.

Several technologies are in development to tackle the challenges associated with MPC:

- Appropriate hardware and software infrastructure with compatible communication interfaces[171]
- User-friendly, control-oriented, accurate, and computationally efficient building modeling
- Automated design, tuning, and deployment of MPC[172]
- Plug-and-play implementation, and robust operation of MPC.[173]

Associated areas of importance include privacy and cyber-security issues and user trust.

A recent project developed a hierarchical, occupancy-responsive MPC to reduce the energy use in buildings.[174] The MPC includes (1) efficient optimization algorithms to reduce computation time, (2) model learning techniques to reduce setup time, and (3) model calibration techniques to improve the model accuracy. The quality of the MPC implementation depends largely on the model accuracy. In other words, if the model prediction accuracy is below the acceptable threshold, the optimized control sequence may lead to ineffective or even worse operations.

Advanced communication for grid participation. In recent years, there has been a shift away from utility-sponsored price-signal demand response programs to greater participation in the grid, with grid operators such as CAISO providing mechanisms for demand response resources to bid into their wholesale electricity market. Although there are several pilot field demonstration projects proving the use of the concept "transactive energy"[175] to turn DERs into grid assets,[176] it is still in the early stages of market deployment. The implementation of transactive energy will have to incorporate

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[170] Drgoňa, J., J. Arroyo, I. Cupeiro, D. Figueroa, K. Blum, D. Arendt, E.P. Kim, et al. 2020. All you need to know about model predictive control for buildings. *Annu. Rev. Control* https://doi.org/10.1016/j.arcontrol.2020.09.001.

[171] Fierro, G., and D. E. Culler. 2015. Poster abstract: XBOS: An eXtensible Building Operating System. BuildSys 2015 - Proc. 2nd ACM Int. Conf. Embed. Syst. Energy-Efficient Built, 119–120. https://doi.org/10.1145/2821650.2830311.

[172] Blum, D., and M. Wetter. 2017. MPCPy: An Open-Source Software Platform for Model Predictive Control in Buildings. Proc. 15th Conf. Int. Build. Perform. Simul.

[173] Le Floch, C., S. Bansal, C. J. Tomlin, S. J. Moura, and M. N. Zeilinger. 2019. "Plug-and-play model predictive control for load shaping and voltage control in smart grids." *IEEE Trans. Smart Grid* 10: 2334–2344. https://doi.org/10.1109/TSG.2017.2655461.

[174] Piette, M. A. Hierarchical Occupancy-Responsive Model Predictive Control (MPC) at Room, Building and Campus Levels 1–24. LBNL. https://www.energy.gov/eere/buildings/downloads/hierarchical-occupancy-responsive-model-predictive-control-mpc-room

[175] For more information: https://www.gridwiseac.org/about/transactive_energy.aspx.

[176] GridWise Architecture Council. 2018. *Transactive Energy Systems Research, Development and Deployment Roadmap*. Pacific Northwest National Laboratory, PNNL-26778.

highly secure and efficient technical platforms that allow machine-to-machine transactions through standard interfaces.[177]

Table 5.10 summarizes the technical maturity of communication and control technology innovations for managing the electric load.

Table 5.10 Communication and Control Technology Innovations to Manage Electric Load

Technology	Description	Technical Maturity
Model predictive control	Use of a model to make optimal building control sequences under a set of constraints, i.e., model predictive control	TRL 4–6
Building operating system services	A building operating system that provides secure monitoring and control of digital resources embedded in the built environment	TRL 4–6
Distributed control and sensing software platform	Converting the sensing and meter data streams to actionable information that improves building operations, manages energy consumption, and enables true integration of buildings with the electric grid	TRL 4–6
Transactive energy techniques	Techniques for managing the generation, consumption, or flow of electric power within an electric power system through the use of economic or market based constructs while considering grid reliability constraints.	TRL 4–6

Industry and Agriculture

Although the operational demands of processes are of paramount importance for industry and agriculture, there are opportunities to shift electric load without compromising production.

Innovative application of phase change materials. Refrigerated warehouses are a significant electricity load in the food processing industry. An innovative way of using PCM in refrigerated warehouses is to utilize the sensing of stored product temperature and surrounding air temperature to control active charging and discharging of the PCM during the operation. The system could monitor the air and the weather conditions, as well as the stored product temperature, and optimize the discharging and charging

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[177] Lian, J., Y. Sun, K. Kalsi, S. E. Widergren, D. Wu, and H. Ren. 2018. *Transactive System: Part II: Analysis of Two Pilot Transactive Systems Using Foundational Theory and Metrics*. Pacific Northwest National Laboratory, PNNL-27235.

control operations in real time. A modular, long-duration and controllable PCM can provide greater energy efficiency and demand flexibility while maintaining the same level of stored food quality.[178] A grid-interactive PCM controller can provide other value streams in grid services to increase the cost effectiveness of PCM deployment in refrigerated warehouses.

Agricultural irrigation pumping. Agricultural irrigation pumping on farms can be a resource for utilizing on-site intermittent renewable energy resources (solar/wind) and reducing operating cost through the use of the cheapest electricity at any time.[179] The schedule of agricultural irrigation pumping can be postponed or interrupted, as long as the requirements of different crops for soil moisture are ensured. New IoT-based smart irrigation systems have been developed by incorporating a number of sensors (i.e., soil moisture, water pumping, water temperature, weather forecast) and advanced control solutions (i.e., real-time irrigation intelligence) to reduce operational cost and enable demand flexibility.[180] Irrigation pumps with variable frequency drives (VFD) and automation have the best potential to participate in DR and load shifting, while requiring limited customer interaction with the controls.

Table 5.11 summarizes the technical maturity and potential of technology innovations for managing the electric load in industry and agriculture.

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[178] GTM Creative Strategies. 2020. Storing Energy in the Freezer: Long-Duration Thermal Storage Comes of Age. https://www.greentechmedia.com/articles/read/storing-energy-in-the-freezer-long-duration-thermal-storage-comes-of-age.

[179] Aghajanzadeh, A., and P. Therkelsen. 2019. "Agricultural demand response for decarbonizing the electricity grid." *J. Clean. Prod.* 220: 827–835. https://doi.org/10.1016/j.jclepro.2019.02.207.

[180] García, L., L. Parra, J. M. Jimenez, J. Lloret, and P. Lorenz. 2020. "IoT-based smart irrigation systems: An overview on the recent trends on sensors and IoT systems for irrigation in precision agriculture." *Sensors (Switzerland)* 20. https://doi.org/10.3390/s20041042.

Table 5.11: Technology Innovations to Manage Electric Load in Industry and Agriculture

Technology	Description	Technical Maturity	Technical Benefits
Novel and modular phase change material	Novel modular, grid-interactive PCM that can be deployed in refrigerated warehouses.	TRL 5–7	Can provide ~30% decrease in peak demand.
Vapor compression systems with variable speed/frequency drive	Optimal control of variable frequency drives to compressors to achieve capacity control for energy efficiency and demand response in industrial refrigeration systems.	TRL 4–6	Industrial loads with VFD can provide 11 MW per year of load modulation service.
Industrial refrigeration advanced control systems	Cloud-based performance monitoring and intelligent control system to achieve both energy efficiency and demand response.	TRL 5–7	Statewide demand response potential for the refrigerated warehouse sector in California is estimated to be more than 22 MW.[181]
New IoT-based smart irrigation systems	Use of sensing, two-way communication and advanced control solutions (i.e., real-time irrigation intelligence) to provide the maximum capacity in grid service participation.	TRL 5–7	Water pumping in California's industrial and agricultural sectors can provide 240 MW per year of load shed and ~1,780 MWh-year of load shift.[182]

Electric Vehicles

With proper management, EVs can be a flexible load that stores electricity when grid assets are underutilized or renewable generation is abundant, and decreases demand at peak times when power generation is most expensive and grid congestion is more likely. Two main technologies can use electric vehicles as a flexible load:

- V1G: *uni-directional* controlled charging by adjusting the rate of charging of vehicles or charging infrastructure
- Vehicle-to-grid (V2G): *bi-directional* charging and discharging control of vehicles in response to grid signals.

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[181] Scott, D., R. Castillo, K. Larson, B. Dobbs, and D. Olsen. 2015. *Refrigerated Warehouse Demand Response Strategy Guide.* LBNL-1004300.

[182] Alstone, P., J. Potter, M. A. Piette, et al. 2017. *2025 California Demand Response Potential Study – Charting California's Demand Response Future: Final Report on Phase 2 Results*. LBNL-2001113.

To meet the potential of this resource, the communication interoperability between the EV charging infrastructure and the grid needs to be improved to provide maximum demand flexibility while meeting charging needs. The development of V2G technology allows the aggregation of electric vehicles for grid ancillary services such as frequency regulation.[183] This requires a real-time telemetry system and control algorithm to provide fast charging and discharging load modulation of the aggregated electric vehicles in response to grid regulation signals.

Coordinated Charging of EVs

Development of smart charging control solutions has been focused on centralized control,[184] hierarchical control,[185] and decentralized control architectures.[186] As the EV users decide their charging patterns, decentralized control does not guarantee that the global optimal solution for the entire system is reached. To achieve the optimal charging control of large numbers of electric vehicles without too much computation burden, a hierarchical control framework can be used to manage a large number of EVs through aggregators while meeting grid constraints and customer requirements.[187]

Centralized charging control utilizes a central controller to provide a global optimal solution that considers the grid and EV constraints. It is suitable for a simple application like a commercial parking garage or a building with few charging stations installed. When the application becomes complex with the increase of the vehicle count on a large scale, the implementation of a centralized charging control is computationally challenging and requires advanced communications between the central hub and vehicles.

In addition to the technical needs for the coordinated charging control of EVs, future research should focus on understanding consumer driving and charging issues,

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[183] DeForest, N., J. S. MacDonald, and D. R. Black. 2018. "Day ahead optimization of an electric vehicle fleet providing ancillary services in the Los Angeles Air Force Base vehicle-to-grid demonstration." *Appl. Energy* 210: 987–1001. https://doi.org/10.1016/j.apenergy.2017.07.069.

[184] Yin, R., D. Black and Bin Wang. 2020. "Characteristics of Electric Vehicle Charging Sessions and Its Benefits in Managing Peak Demands of a Commercial Parking Garage," 2020 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids. doi: 10.1109/SmartGridComm47815.2020.9302987

[185] Xu, Z. et al. 2016. "A hierarchical framework for coordinated charging of plug-in electric vehicles in China." *IEEE Transactions on Smart Grid* 7(1): 428–438. Kaur, K., N. Kumar, and M. Singh. 2018. "Coordinated power control of electric vehicles for grid frequency support: MILP-based hierarchical control design." *IEEE Transactions on Smart Grid* 10(3). https://ieeexplore.ieee.org/document/8334637

[186] Moeini-Aghtaie, M. et al. 2013. PHEVs centralized/decentralized charging control mechanisms: requirements and impacts. In: North American Power Symposium (NAPS). Ma, Z., D. S. Callaway, and I. A. Hiskens. 2013. "Decentralized charging control of large populations of plug-in electric vehicles." *IEEE Trans Control Syst Technol* 21(1): 67–78.

[187] Nguyen, H. N., C. Zhang, J. Zhang, and L.B. Le. 2017. "Hierarchical control for electric vehicles in smart grid with renewables." In Proceedings of the 13th IEEE International Conference on Control Automation, 898–903. https://doi.org/10.1109/ICCA.2017.8003180.

including the choice of charging infrastructure, range anxiety, and incentives for using grid-interactive control.

Wireless Electric Vehicle Charging

The application of wireless EV charging technology can be separated into *stationary* wireless charging and *dynamic* wireless charging, which enables power exchange between the vehicle and the grid while the vehicle is moving.

Many companies have introduced stationary wireless charging systems with charging power ranging from 3.6 kW to 7.2 kW. Dynamic wireless charging is the next stage of wireless charging, where the charging equipment is installed under the road, and the vehicles can charge their batteries while driving.[188] The first demonstration of slow dynamic Inductive Power Transfer at 20 kW was conducted by ORNL in 2016. Since then, the bi-directional wireless charging technology for light-duty applications has been scaled up to 120 kilowatts in a recent demonstration. This technology could turn an electric vehicle into mobile energy storage to integrate renewable energy generation, reduce peak electricity demand, or provide grid ancillary services.[189] As part of future road infrastructures, dynamic wireless vehicle charging could be integrated with renewable energy resources along the highways.

Connective Mobility

Vehicles are increasingly exchanging data with a central hub and with one another through cellular, Wi-Fi, satellite, and other means. At present, there are mostly entertainment and convenience offerings on the market, but maintenance and safety functionalities are emerging. The future development of connective mobility among EVs and charging stations can reduce energy consumption and emissions and improve mobility in the transportation system at multiple scales.[190] Connective electric vehicles can coordinate between each other to get real-time traffic conditions and available charging stations without waiting at congested charging stations. This conventional way of addressing the electric vehicles is referred to as a *charging station-based e-mobility system.* Actually, electric vehicles can be observed as dynamic movable storage that can provide flexibility at any available charging station in response to grid price or event signals.

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[188] Li, G. et al. 2018. Direct vehicle-to-vehicle charging strategy in vehicular ad-hoc networks. In: 2018 9th IFIP International Conference on New Technologies, Mobility and Security. Kosmanos, D. et al. 2018. "Route optimization of electric vehicles based on dynamic wireless charging." *IEEE Access* 6: 42551–65. Foote, A. et al. 2019. System design of dynamic wireless power transfer for automated highways. In: IEEE Transportation Electrification Conference and Expo.

[189] Laporte, S., G. Coquery, V. Deniau, A. De Bernardinis, and N. Hautière. 2019. "Dynamic wireless power transfer charging infrastructure for future EVs: From experimental track to real circulated roads demonstrations." *World Electr. Veh. J.* 10: 1–22. https://doi.org/10.3390/wevj10040084.

[190] Adler, M. W., S. Peer, and T. Sinozic. 2019. "Autonomous, connected, electric shared vehicles (ACES) and public finance: An explorative analysis." *Transp. Res. Interdiscip. Perspect.* 2: 100038. https://doi.org/10.1016/j.trip.2019.100038.

EV Integration with Buildings

Integration of EVs with distributed renewable resources is a promising approach for addressing grid issues such as capacity shortage, voltage instabilities, and power quality. For instance, when the on-site solar PV generates less electricity on cloudy days, the EV charging load can be curtailed through automated active load management, along with the real-time monitoring and forecasting of building load and weather.[191,192,193]

With on-site generation (i.e., solar PV) and EV charging stations installed behind the meter, real-time predictive energy allocations between the building, solar PV, and EV charging stations becomes very challenging considering building load variability, intermittent solar PV generation, and uncertainties of the plug-in duration and energy consumption for each individual EV. This challenge is driving the development of predictive control of EV for integration with buildings. Recent studies have demonstrated novel scheduling control of EVs using a two-stage operation. This operation combines day-ahead operations (energy transaction from the day-ahead market) and real-time predictive allocation to regulate the EV charging behaviors, considering the uncertainties within individual EV charging sessions. The real-time strategy allocates the energy to each individual EV in a decentralized fashion. The goal is to achieve the minimum operational cost with additional benefit from participation in the wholesale electricity market.

In the California market, a study estimated that residential electric vehicles can provide shift DR service ranging from 30 to 38 MWh/year from battery electric vehicles (BEVs) and 59 to 83 MWh/year from plug-in hybrid electric vehicles (PHEVs) in 2025.[194] For commercial EVs, available shift DR resources include 7 to 8 MWh/year for BEVs, 2 to 3 MWh/year for PHEVs, and an additional 3 MWh/year for BEVs charging at work.

Table 5.12 summarizes technology innovations for EV load management.

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[191] Traube, J., F. Lu, D. Maksimovic, J. Mossoba, M. Kromer, P. Faill, S. Katz, et al. 2013. "Mitigation of solar irradiance intermittency in photovoltaic power systems with integrated electric-vehicle charging functionality." *IEEE Trans. Power Electron.* 28: 3058–3067. https://doi.org/10.1109/TPEL.2012.2217354.

[192] Pillai, J. R., S. H. Huang, B. Bak-Jensen, P. Mahat, P. Thogersen, and J. Moller. 2013. "Integration of solar photovoltaics and electric vehicles in residential grids." *IEEE Power Energy Soc. Gen. Meet.* https://doi.org/10.1109/PESMG.2013.6672215.

[193] Taibi, E., C. Fernández del Valle, and M. Howells. 2018. "Strategies for solar and wind integration by leveraging flexibility from electric vehicles: The Barbados case study." *Energy* 164: 65–78. https://doi.org/10.1016/j.energy.2018.08.196.

[194] Alstone, P., J. Potter, and M. A. Piette. 2017. *2025 California Demand Response Potential Study - Charting California's Demand Response Future: Final Report on Phase 2 Results.* LBNL-2001113.

Table 5.12: Technology Innovations for Electric Vehicle Load Management

Category	Technology	Description	Technical Maturity
Grid service market	Advanced telemetry infrastructure for communication and fast control of bi-directional electric vehicles	Advanced communication and control technologies for bi-directional electric vehicles and charging stations can provide additional grid service products (e.g., frequency regulation) in the electricity market.[195]	TRL 5–6
	Interoperability communication and control of large-scale electric vehicles for renewables integration	Aggregation of EVs as grid-scale energy storage to reduce grid operating costs and renewable energy curtailment.	TRL 3–4
	Automated active load management system	Smart charging and discharging control along with the variability in building operation for reducing the operational cost.	TRL 4–6
Connective mobility	Vehicle-to-infrastructure [V2I] and vehicle-to-vehicle [V2V] communications	Use of sensing, perception, and computing for V2I and/or V2V communication to reduce the energy consumption and emissions, and to improve mobility in the transportation system at multiple scales.	TRL 3–5

Vehicle-to-Building and Vehicle-to-Home for Backup Power

Usually, people use backup generators or batteries as backup power to power critical loads in commercial buildings and homes during electric grid outages such as public safety power shutoffs. For EV owners, an alternative for dealing with a blackout is to turn their EV into an emergency power source with bi-directional EV charging technology. To send the power from the EV's battery to the building, an AC/DC inverter is needed, either in the onboard bi-directional charger or the offboard bi-directional charger (e.g., public vehicle charging station). A recent U.S. DOE-funded study provides a comprehensive assessment of on- and off-board V2G technology performance on battery and the grid.[196] With the considerations of cost, safety, certification, and integration, bi-directional DC charging is more favorable for the application of Vehicle-

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[195] Giubbolini, Luigi. 2020. *Grid Communication Interface for Smart Electric Vehicle Services*. California Energy Commission. CEC-500-2020-028.

[196] Chhaya, Sunil. 2020. Comprehensive Assessment of On- and Off-Board V2G Technology Performance on Battery and the Grid. 2020 U.S. Department of Energy Vehicle Technologies Office Annual Merit Review.
https://www.energy.gov/sites/prod/files/2020/06/f75/elt187_chhaya_2020_o_5.12.20_1106AM_LR.pdf

to-Building and Vehicle-to-Home. This type of system is ready for commercial deployment in the market.

Coordinated Controls Across Distributed Energy Resources

From the perspective of a utility or grid operator, coordinating DERs to increase the flexibility and reliability of the grid is very beneficial, but very challenging. Coordinated controls can also serve the purpose of increasing the reliability of the grid services provided, a necessary requirement for adoption as a resource in the utility markets. Several novel technologies could help advance such coordination.

Distributed Energy Resource Management System (DERMS). A DERMS is a platform which uses a real-time communications infrastructure to monitor, control, coordinate and manage distributed energy assets connected to the utility at the distribution or local feeder level. There are already many mature DERMS platforms in the market to provide end-to-end communications and controls across multiple buildings and DERs. The new DERMS development focuses on "plug and play" DER to make grid integration simple and reliable, as well as new features of artificial intelligence (AI) and machine learning to improve the performance and reliability of the grid services while minimizing or eliminating any negative impacts to the occupants or customers. These innovations will allow grid operators, utilities, and aggregators to maximize DERs operation capabilities through automated grid optimization.[197]

Interoperability in Connected Communities. A recent research report defines “Connected Communities” as collections of buildings and DERs that incorporate integrated energy management strategies at the multi-building scale.[198] Connected communities have significant value to customers and utility/system operators in terms of energy bill savings, demand response/ancillary services, resilience, GHG reductions, and reduced the need for new capacity for generation, transmission and distribution infrastructures. However, there are still some technical challenges, especially the interoperability of DER technologies.

Enabling communications interoperability among a diversity of DER technologies and systems, customers, electricity markets, and grid stakeholders requires a common language for machine-to-machine communications. To tackle this issue, the Grid Modernization Laboratory Consortium proposed an “Energy Services Interface” that

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[197] Antonopoulos, I., et al. 2020. “Artificial intelligence and machine learning approaches to energy demand-side response: A systematic review.” *Renewable and Sustainable Energy Reviews*, Vol. 130.
[198] Olgyay, Victor, Seth Coan, Brett Webster, and William Livingood. 2020. *Connected Communities: A Multi-Building Energy Management Approach.* National Renewable Energy Laboratory. NREL/TP-5500-75528. https://www.nrel.gov/docs/fy20osti/75528.pdf.

could universally integrate different DER technologies within the electric system.[199] The Energy Services Interface is in laboratory testing phase.

Advanced Power Electronics and Smart Inverters. Smart inverters have become mainstream in recent years along with the increasing DER penetrations.[200] The communication function enables the collection of many smart inverters that can be aggregated into a virtual power plant and managed by a third party or utility company through a distributed energy resources management system. Smart inverters will need to be versatile and able to adapt to different grid control architectures, such as centralized or decentralized. In addition, the new generation of smart inverters will have self-awareness, adaptability, autonomy, collaboration, and plug-and-play capabilities, which are supported and implemented by the various control functions.

Table 5.13: Technology Innovations for Coordinated Management Across Distributed Energy Resources

Technology	Description	Technical Maturity
Distributed Energy Resource Management System	The platform provides ”plug-and-play” DER to the grid, and has built-in new functions of artificial intelligence and machine learning	TRL 5–7
Energy Service Interface	A common interface and data model that integrates different DER technologies	TRL 2–3
Advanced Power Electronics and Smart Inverters	Advanced communication and control capability that easily enables the aggregation of DERs	TRL 5-6

Strategic Considerations for California

Buildings, Industry and Agriculture

Load modifying programs result in a more favorable load shape, reducing resource procurement requirements, mitigating over-generation, and moderating ramps in demand. The combination of demand response and energy efficiency can together contribute to reliable and efficient management of the future electricity grid in

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[199] https://gmlc.doe.gov/sites/default/files/resources/GMLC%20ESI%20Webinar%20Slides_180514.pdf

[200] Xue, Y., et al. 2018. "On a Future for Smart Inverters with Integrated System Functions," 2018 9th IEEE International Symposium on Power Electronics for Distributed Generation Systems, pp. 1-8, https://doi.org/10.1109/PEDG.2018.8447750.

California. To meet the state's future needs, the following load modifying technologies appear to have the most potential:

- Energy flexible loads
  - Advanced sensing and control (i.e., MPC) of flexible loads in buildings to modify the building load
  - Distributed control of smart thermostats for HVAC load shedding and shifting
  - Distributed control of grid-interactive heat pump water heaters to modify the water heating load that will grow with electrification
- Energy storage
  - Solid state tunable thermal storage that can be deployed in the building envelope to modify the heating/cooling load
  - Novel PCM coupled with building HVAC systems
- Water pumping in agriculture
  - IoT-based smart irrigation systems for water pumping load shedding and shifting

Electric Vehicles

California aims to have 5 million zero-emission vehicles on the road by 2030 and the majority of them will be EVs.[201] Integrating these electric loads into the grid while reducing CO_2 emissions and maintaining reliability will be a major challenge. Innovative technologies are critical to meeting the challenge.

We consider the following technologies to be the most important for California:

- Vehicle-grid integration communication protocol
  - Open, reliable, secure communication protocols for vehicle grid integration that can bridge all vehicle-grid integration protocols (IEEE 2030.5, OpenADR 2.0b, and Open Charge Point Protocol 2.0)
- Vehicle-to-grid service participation
  - An embedded automated smart charging feature that receives the EV rates to help integrate EVs with the grid by shifting on-peak charging to off-peak hours or reducing the charging power to a lower level
  - Advanced and smart charging control algorithms for the distributed/centralized coordinated control of EVs for grid service participation (e.g., demand response, ancillary service)
- Vehicle-to-Building and Vehicle-to-Home for behind-the-meter DER integration, peak demand management, and resilient backup power

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[201] Executive Order B-48-18 (issued on January 26, 2018) increases the state's ZEV goal to five million cars by 2030. It also establishes a goal of 250,000 ZEV charging stations, including 10,000 direct-current fast chargers, and 200 hydrogen fueling facilities in the state by 2025.

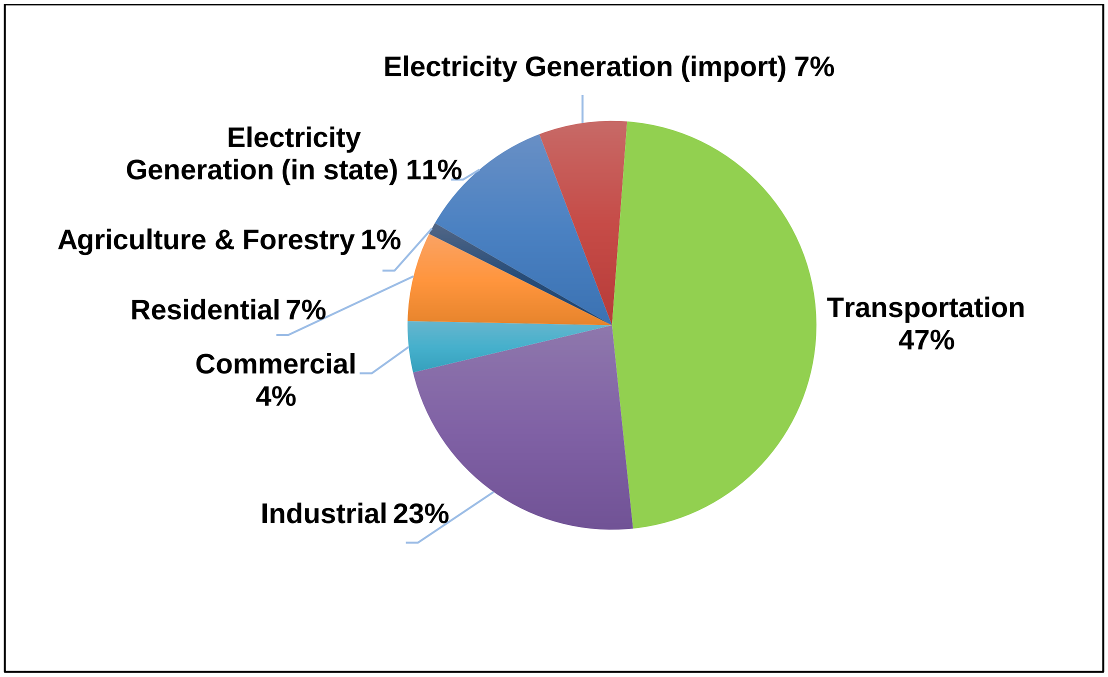
  - Advanced telemetry infrastructure for communication and fast control of bi-directional EVs
  - A bi-directional capable V2G system that has a low-cost inverter, simplified telecommunication and protocol, and smart charging control

CHAPTER 6: Electrification to Reduce CO_2 Emissions

Introduction

The preceding chapters have dealt with electricity demand and supply. Although these sectors are important, they account for a relatively small share of California's CO_2 emissions. Transportation is by far the largest source of CO_2 emissions in California, followed by industry (Figure 6.1). Within industry, oil and gas production and petroleum refining account for just over half of all emissions. The residential and commercial sectors combined account for only 11% of total emissions.

Figure 6.1: California CO_2 Emissions by Sector in 2018



Source: California Air Resources Board GHG Inventory

Over time, the share of electricity generation will decline as renewable energy takes on a predominant role. As electric vehicle market penetration continues to increase, demand for traditional transportation fuels like gasoline and diesel will decrease, likely resulting in fewer emissions from oil and gas production and petroleum refining. State regulatory policy could also further curtail oil and gas production.[202]

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[202] Decarbonization scenarios developed for the CARB show final energy demand in oil and gas production and petroleum refining declining from ~0.85 exajoules (EJ) in 2020 to ~0.2 EJ in 2045.

The transition from petroleum products to either electricity or hydrogen fuel cells for motor vehicles is emerging as a major focus of the state's GHG reduction policy. The technologies needed to facilitate this shift are relatively mature, though there is considerable RD&D activity to improve performance and reduce costs. These technologies have not been covered by the CEC's EPIC program, however, and were outside the scope of this report. Technologies related to the integration of electric vehicles into the electric grid are discussed in Chapter 5.

To displace fossil fuels in the industrial and buildings sectors, there are several options whose relevance varies between the sectors, as shown in Table 6.1.

Table 6.1: Decarbonization Strategies for Industry and Buildings

Strategy	Industry	Buildings
Electrification of end uses currently reliant on fossil fuels	Most relevant for low-temperature process heating, but other applications are possible	Available for all end uses
Solar thermal heating	Possible for some process heating	Possible for water heating and space heating
Replacement of natural gas with renewable natural gas (RNG) and/or green hydrogen (or other energy carriers)	Possible if cost declines substantially	RNG or hydrogen blended in gas distribution network is possible
Use fossil fuels with carbon capture and storage	Possible if cost is competitive with use of hydrogen	Unlikely

Consideration of the relative merits of different decarbonization strategies is beyond the scope of this report. While this chapter discusses potential electric technologies, one should bear in mind that strategies other than electrification may prove more cost-effective for decarbonization, particularly for high-temperature industrial applications.[203]

Energy and Environmental Economics. 2020. *Achieving Carbon Neutrality in California: PATHWAYS Scenarios Developed for the California Air Resources Board*.

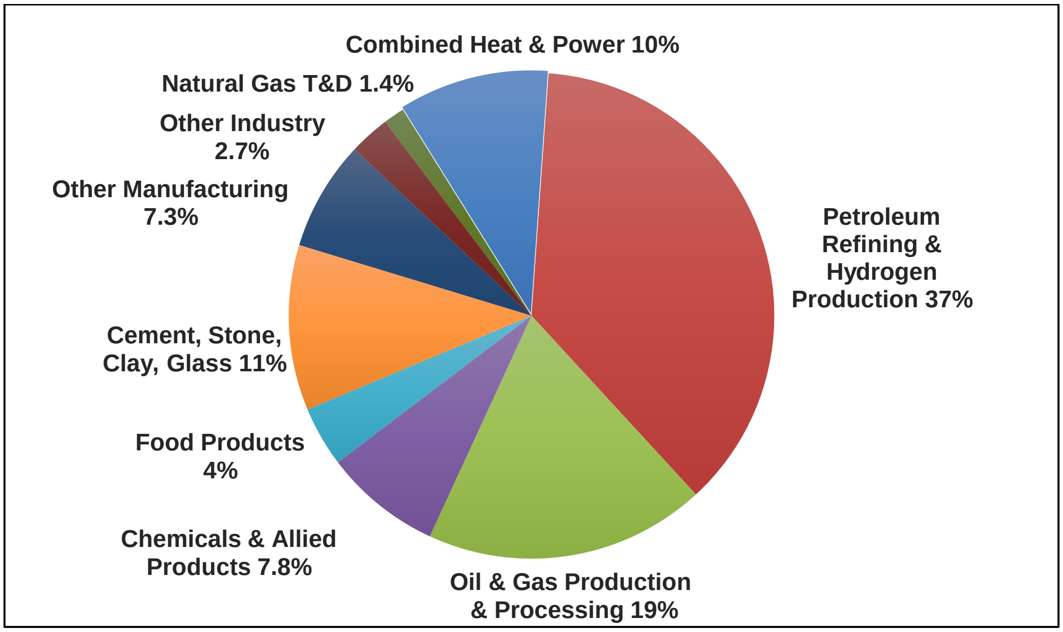
[203] For discussion of decarbonization strategies for industry, see: McKinsey&Company. 2018. *Decarbonization of industrial sectors: The next frontier*; Friedmann, S. Julio, Zhiyuan Fan, and Ke Tang. 2019. *Low-Carbon Heat Solutions for Heavy Industry: Sources, Options, and Costs Today*. Columbia Center on Global Energy Policy; Gregory Thiel and Addison Stark. 2020. "To decarbonize industry, we must decarbonize heat." *Joule.* https://doi.org/10.1016/j.joule.2020.12.007

Total electrification costs include equipment replacement but also substantial electrical infrastructure upgrades in many cases to support the new technology. Some of the pathways described in Table 6.1 can work with existing equipment in place, albeit with new infrastructure to support fuel replacement. An additional consideration is that industrial applications require high reliability, and often 24/7 supply.

Industrial Electrification

The industrial sector includes manufacturing, petroleum refining, and oil and gas production and processing. Oil and gas production and processing and petroleum refining accounted for over half of total industrial CO_2 emissions in California in 2018 (Figure 6.2). Over time, however, these emissions are likely to decline due to electrification of transportation, as mentioned previously. The next largest industries for CO_2 emissions are cement, chemicals, and food products.

Figure 6.2: California Industry CO_2 Emission Shares in 2018



Source: California Air Resources Board GHG Inventory
Includes process-related emissions but not indirect emissions from purchased electricity.

As noted above, electrification may not be the least-cost option for decarbonizing many industrial applications. In decarbonization scenarios for 2045 prepared for the California Air Resources Board, the analysts chose to replace natural gas with direct hydrogen combustion for conventional boilers due to the higher cost of replacing conventional gas-fired boilers with electric resistance boilers.[204] For process heating, they assumed carbon capture and sequestration (CCS) would be adopted for industries that require

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[204] Energy and Environmental Economics, op. cit.

high-temperature heat, such as cement, glass, and primary metal manufacturing. They assumed that the remaining process heat in applications with lower temperature heating requirements would be met with electric heating technologies, though use of hydrogen or other energy carriers could be a suitable option for many applications and may be more cost effective. The latter approach would fit well with the experience, value chain, and transportation elements of the chemical and refining industries. It would also avoid some of the expensive changes in existing infrastructure based on fossil fuels and steam.

There are many electric technologies that are commercially available for industrial applications. The top cross-cutting beneficial electrification opportunities include low- to mid-temperature process heat, machine drives, and intermittent fuel switching (e.g., hybrid boilers).[205] Industry-specific electrification opportunities exist in specialized materials production, heating/drying, surface curing, and melting.

Process Heating[206]

In the U.S., process heating uses more energy than any other manufacturing application. Process heating is employed in a variety of ways, with fluid heating and distillation, drying, metal refining, and calcining being the top uses. The low-temperature range (<150 °C) offers the best opportunity for electrification. This range accounts for nearly all of the process heat energy used in the food industry and for over half of the total process heat energy used in the chemicals industry.

Although the cost of electricity can be a barrier to adoption of electro-technologies, they have demonstrated benefits over fuel-based process heating for applications such as curing and drying through infrared, microwave, and radio frequency technologies, and for heating and melting though induction systems. Electric process heating can increase the proportion of useful heat energy delivered to the product by delivering energy directly where it is needed. Electric process-heating techniques are flexible, and process parameters can often be monitored and actively controlled.

Electro-technologies also offer opportunities to increase speed and throughput as well as improve product quality. For example, microwave volumetric heating of a flowing liquid (or suspensions) in food manufacturing can efficiently heat products while minimizing thermal damage to heat sensitive components. It also provides a means of microbial inactivation (pasteurization and sterilization) for food products with the advantage of more rapid, uniform heating.[207]

There are a number of electric technology options for providing process heat, depending on the temperature range and process parameters. Although R&D needs still

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[205] Rightor, E., A. Whitlock, and R. Neal Elliot. July 2020. *Beneficial Electrification in Industry*. American Council for an Energy-Efficient Economy. https://www.aceee.org/research-report/ie2002

[206] This section draws on Rightor et al., op. cit.

[207] U.S. Department of Energy. 2015. *Quadrennial Technology Review 2015, Process Heating Technology Assessment*.

exist in promising technologies such as inductive, dielectric, arc, plasma and electron beam heating, these technologies are in themselves commercially available. However, their use is often limited to niche applications where other heating technologies do not offer sufficient product quality or processing speed. The integration of electrical heating technologies into the various production processes remains a significant challenge.

Industrial heat pumps are of interest due to their high efficiency. They offer potential replacement for some applications in the low-temperature range, and can supply heat for process heating or preheating, process water heating and cooling, steam production, and product drying. Considerable R&D is focused on heat pumps with heat sink temperatures above 120°C. The heat pump cycles examined are mainly single-stage and in some cases contain an internal heat exchanger for superheating or an economizer for vapor injection into the compressor.[208] Heat pumps with a heat sink temperature of 160°C are expected to reach market maturity in the next few years. Case studies of a multi-stage steam compression cycle and a reversed Brayton cycle indicate that supply temperatures up to 280°C may be technically and economically feasible in some applications, and higher temperatures might be reached depending on the availability of suitable heat sources.[209] If these technologies prove viable, they could greatly expand the potential market for industrial heat pumps. In addition, new approaches to designing working fluids from the molecule up can result in optimal working fluids for new, high-temperature cycles.[210]

Energy-Intensive Industries

Energy-intensive industries such as steel, petroleum refining, chemicals and cement generally require high temperatures and are more difficult to electrify. While steel production is not present in California, the others are important industries.

Chemicals

Production of commodity chemicals such as ammonia, ethylene, and methanol emit GHGs through combustion of fossil fuels. There are many possible routes for electricity to drive a chemical reaction, and electrochemical methods have some advantages over traditional thermochemical methods.[211] For example, in ammonia production, the currently practiced thermochemical Haber-Bosch process requires high temperatures

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[208] Arpagaus, Cordin, et al. 2018. "High Temperature Heat Pumps: Market Overview, State of the Art, Research Status, Refrigerants, and Application Potentials". International Refrigeration and Air Conditioning Conference. Paper 1876. https://docs.lib.purdue.edu/iracc/1876

[209] Zühlsdorf, B., F. Bühler, M. Bantle, and B. Elmegaard. 2019. "Analysis of Technologies and Potentials for Heat Pump-Based Process Heat Supply above 150°C." *Energy Conversion and Management*: X 2 (April): 100011. www.sciencedirect.com/science/article/pii/S2590174519300091?via%3Dihub

[210] Yu, Peiyuan, Anubhav Jain & Ravi S. Prasher. 2019. Enhanced Thermochemical Heat Capacity of Liquids: Molecular to Macroscale Modeling. *Nanoscale and Microscale Thermophysical Engineering*, 23:3, 235-246, DOI: 10.1080/15567265.2019.1600622

[211] Schiffer, Zachary J. and Karthish Manthiram. 2017. Electrification and Decarbonization of the Chemical Industry. *Joule* 1, 10–14.

and pressures that mandate large-scale, centralized reactors to achieve economic viability. Electrification may allow nitrogen and water to form ammonia at low temperatures and pressures that are conducive to modularity. Ammonia synthesis reactors also have the added benefit of being much smaller and potentially located adjacent to renewable electricity sources.

In the energy-intensive production of ethylene, microwave-enhanced cracking technology takes advantage of radiative heat transfer by high-frequency electromagnetic energy to cause direct, volumetric heating of the reactants. It is expected to save 30%–50% of direct process energy requirements compared to conventional furnace energy consumption in the cracking process step. The potential for operating naphtha or gas steam crackers with electricity is being investigated by a consortium of six chemical companies in Europe.[212]

In the Netherlands, a collaboration between researchers and industry includes a program working on the direct electrosynthesis of chemical building blocks and higher value products.[213] The program focuses on: (1) electro-organic synthesis using electro-oxidation and electro-reduction to convert renewable feedstock to specialty chemical building blocks, (2) electro-reduction of CO_2 to C1 building blocks, focusing on formic acid, CO and ethylene as key feedstock for other reactions, and (3) paired electrosynthesis where a product is produced at both cathode and anode of the electrochemical cell.

Electrochemical conversion of CO_2 into chemical feedstocks offers a way to turn waste emissions into valuable products. Research and development into electrocatalytic materials for CO_2 reduction has intensified in recent years, with advances in selectivity, efficiency, and reaction rate progressing toward practical implementation.[214] A variety of chemical products can be made from CO_2, such as alcohols, oxygenates, synthesis gas (syngas), and olefins—staples in the global chemical industry.

The development of new catalysts is essential to electrification of the chemical industry. There are opportunities to develop catalysts for CO_2 reduction with improved activity, selectivity, and stability for liquid products such as methanol. For a wide range of reaction chemistries, efforts at the inter-section of atomically and molecularly precise catalysts, *in situ* spectroscopy, and computational modeling of surfaces will have great impact on electro-catalyst discovery.[215]

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[212] https://www.borealisgroup.com/news/petrochemical-giants-form-consortium-cracker-of-the-future-and-sign-agreement

[213] https://www.voltachem.com/research/power-2-chemicals

[214] De Luna, P., C. Hahn, D. Higgins, S. Jaffer, T. Jaramillo. 2019. What would it take for renewably powered electrosynthesis to displace petrochemical processes? *Science* 26 Apr 2019: Vol. 364, Issue 6438, DOI: 10.1126/science.aav3506

[215] Friend, C.M., and B. Xu 2017. Heterogeneous catalysis: a central science for a sustainable future. *Acc. Chem. Res*. 50, 517–521.

Cement

Decarbonization strategies for cement production are receiving growing attention. A collaboration in Sweden between the state-owned energy company Vattenfall and cement producer Cementa concluded that electrification of the heating in the cement process appears to be technically possible, but would entail an approximate doubling of the production cost for the cement.[216] A study into how a pilot plant can be constructed is underway.

Deep decarbonization of cement manufacturing will require remediation of both the CO_2 emissions due to the decomposition of limestone and those from combustion of fossil fuels in calcining and sintering. Researchers have developed an electrochemically-based process for producing clinker that can be used in Portland cement. The electrochemical decarbonation reactor simultaneously functions as an electrolyzer and a chemical reactor, as it also produces a stream of O_2/CO_2 at the anode and H_2 at the cathode.[217] The CO_2 can be captured directly without the need for expensive CCS processes like amine scrubbing. The O_2/CO_2 stream could also be used as oxy-fuel in the kiln. The flue gas from oxy-fuel combustion has a higher concentration of CO_2, which would make carbon capture more efficient. The hydrogen produced could be used as fuel to power the reactor or other operations at the cement plant. The H_2 or CO_2 could also be used as feedstocks in other processes. A simple economic analysis suggests that if low-cost renewable electricity is available, the electrochemical process would be cost-competitive with conventional cement plants that used amine scrubbing of the flue gas for carbon capture and sequestration.

Another approach has been proposed in which the exhaust from partial or full oxy-fuel cement plants would be coupled to a chamber in which CO_2 in a molten carbonate electrolyte would be transformed by electrolysis into carbon nanotubes at a steel cathode, and oxygen at a nickel anode that is looped back to improve cement line energy efficiency and production rate.[218] Carbon nanotubes have many applications in electronics, optics and other material sciences and technologies.

Summary

Table 6.2 summarizes a number of technology innovations for electrification of industrial processes.

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[216] https://group.vattenfall.com/press-and-media/pressreleases/2019/vattenfall-and-cementa-take-the-next-step-towards-a-climate-neutral-cement

[217] Ellis, Leah, et al. 2020. Toward electrochemical synthesis of cement—An electrolyzer-based process for decarbonating $CaCO_3$ while producing useful gas streams. *PNAS* 117 (23) 12584-12591. https://www.pnas.org/content/117/23/12584

[218] Licht, Stuart. March 2017. Co-production of cement and carbon nanotubes with a carbon negative footprint. *Journal of CO_2 Utilization*, Volume 18, pp. 378-389. https://www.sciencedirect.com/science/article/abs/pii/S2212982016302852

Table 6.2: Technology Innovations for Electrification of Industrial Processes

Technology	Description	Technical Maturity
Industrial heat pump	Advanced designs could provide a heat sink temperature of 160°C.	Medium
	Multi-stage steam compression cycle and a reversed Brayton cycle may supply temperatures up to 280°C.	Low
Electrochemical processes for chemicals industry	A variety of electrochemical processes have potential to replace traditional thermochemical methods. Electrocatalysis can be implemented throughout the chemical supply chain and could include electrosynthesis of basic building blocks, higher-value fine chemicals in combination with biocatalytic processes, and supplementation of traditional thermocatalysis pathways.	Low to Medium
Electrochemically-based process for producing clinker for cement	The electrochemical decarbonation reactor simultaneously functions as an electrolyzer and a chemical reactor. The CO_2 can be captured directly without the need for expensive CCS processes like amine scrubbing.	Low

Buildings Electrification

CO_2 emissions from the residential and commercial sectors are primarily from natural gas combustion. Space heating accounts for approximately 40% of fuel consumption, and water heating accounts for 34% (Table 6.3).

Table 6.3: On-site Fuel Consumption in California Buildings in 2016

	Residential (%)	Commercial (%)	Total (%)
Space Heating	25	15	40
Water Heating	24	10	34
Other	15	11	26
Total	64	36	100

Fuel is primarily natural gas, with some propane. Water heating includes hot water for clothes washers and dishwashers. In residential buildings, “Other” is mainly cooking and clothes drying. In commercial buildings, “Other” is mainly cooking.

Source: Synapse Energy Economics (2018)

Electrification is an important element of a potential strategy to reduce GHG emissions in California's buildings stock, and could yield other benefits. For homes, electrification could improve safety by substituting for gas appliances. In the case of cooking, electrification could also reduce exposure to indoor air pollutants from gas cooking appliances.

Space Heating

Heat pumps in various configurations are a mature technology that is available to replace natural gas equipment in residential and commercial buildings. The main barriers to their adoption are lack of familiarity on the part of builders and building owners and their high initial cost in many retrofit situations, especially where electrical work is needed to accommodate their power demand.

New types of heat pumps discussed in Chapter 2 could play a role in facilitating electrification of space heating if they increase heating-side efficiency or reduce overall cost. In addition, building efficiency measures that reduce the heating load can help to minimize the size of the heat pump (decreasing cost), and reduce the time that a heat pump might need to rely on its electric resistance backup heating to meet demand on very cold days.

Water Heating

Heat pump water heaters have been on the market for a shorter time than HVAC heat pumps, but are by now a mature technology. The main emerging innovation is a unit that can run on 120V, which would allow a less costly retrofit for older homes that lack 240V service. One prototype 120V heat pump water heater dispenses with a backup electric resistance heating element, and instead stores hot water at a higher setpoint.

Other End Uses

For cooking, the efficient, electrified replacement technology is an induction stove (or individual burners). Compared to other electric and gas surfaces, induction cooktops are much safer because there is no radiant heat source, red hot coil or open flame that may ignite flammable materials or fumes.

Efficient electrification of clothes drying can be accomplished with a heat pump clothes dryer. The technology is mature and the main barrier is the higher purchase cost.

A new clothes drying technique under development uses high frequency ultrasonic vibrations generated by piezoelectric transducer instead of thermal heating to mechanically extract moisture from the fabric. U.S. DOE and GE have developed a prototype ultrasonic clothes dryer that can dry a load in about half the time a traditional dryer will take, and is three to five times more efficient than a traditional electric dryer.[219] The first applications are likely to be in the industrial and commercial sectors.

Strategic Considerations for California

Industry. Electrification is an option for many industrial processes, especially those that require low-temperature heat, but it may be less cost-effective than use of hydrogen produced from renewable electricity or carbon capture and sequestration. Electro-technologies that improve industrial processes will be most attractive. In addition, innovations for industrial heat pumps that increase the temperature of heat supplied could greatly expand the potential market for this very efficient technology.

A significant barrier to the adoption of electro-technologies by industry in California is the fact that the ratio of electricity to natural gas prices in the industrial sector in terms of delivered energy is among the highest in the nation. Cost considerations are a priority for industries who participate in national or international markets. Policies that would raise the price of natural gas, such as strict caps on CO_2 emissions or carbon fees, could improve the ability of electricity to compete and help create a level playing field for the different strategies for decarbonizing industry.

Buildings. The technical and economic barriers to electrification in the buildings sectors are much lower than in industry. For space heating and water heating, heat pumps are a mature technology, but new approaches and refrigerants with very low global warming potential could improve efficiency and help meet GHG reduction goals.

Electrification in homes could pose problems for the electricity grid, however. Electric space heating, water heating, and cooking could all add to the system peak demand in the 5 p.m. to 9 p.m. period, when renewable electricity is less available. As discussed in Chapter 5, some of the load could potentially be shifted off peak for space heating and water heating, but not for cooking. Another issue is that electric space heating would be in most demand in the winter, when solar electricity is at its lowest level.

Addressing this issue may require significant incentives for load shifting, along with smart controls that communicate well with grid operators. Household battery storage systems coupled with on-site solar PV could help to reduce the demands placed on the grid. For the electricity system as a whole, meeting peak demands associated with electrification in buildings may require a large investment in electricity storage and demand flexibility strategies for daily needs, and in long-duration electricity storage to meet seasonal needs.

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[219] https://www.utilitydive.com/news/ge-doe-roll-out-ultrasonic-clothes-dryer-prototype-to-reduce-energy-consum/440893/

CHAPTER 7: Enhancing Reliability and Resilience of Electricity Supply

Introduction

Climate change has had a severe impact on California's natural resources, threatening the resiliency of the state's power system. Severe droughts, floods, heatwaves, and increasing numbers of devastating wildfires in recent years are testing the reliability of the state's electric power infrastructure and its resilience to power disruptions.[220]

In California, the electric power system is evolving toward more dispersed renewable energy resources with more rooftop PV, battery storage, and wind that can provide localized improvements in electric reliability and resilience. Along with this significant increase of variable renewable energy, the balancing of power in the bulk power system has also evolved from time scales of daily to hourly, minute, second, and milli-second time scales, raising concerns around system frequency and inertia that help maintain grid reliability.[221] Innovative technologies in these areas can help address these concerns and support the state's climate policies.

Some of the energy technologies that can help improve reliability and resilience in the electricity distribution system have been presented in earlier sections of this report that covered electricity storage and load management. Additional emerging technologies that can support that goal, some of which derive from outside the energy sector, are presented herein this chapter.

Note: The TRLs presented in the tables in this chapter are rough approximations based on the author's reading of the literature.

Artificial Intelligence and Machine Learning

While machine learning and the broader techniques of artificial intelligence (AI) are commonly utilized in areas like supercomputing, online shopping, and smart devices (e.g., Siri, Alexa), these capabilities are not widely utilized in the utility sector.[222]

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[220] There are conflicting definitions of resilience and how it relates to, and differs from, reliability. In the Draft Proposed EPIC Interim Investment Plan 2021, CEC staff used the following conceptual definitions for discussing EPIC interim research initiatives: *Resilience* investments advance technologies, knowledge, and strategies to plan for, manage through, and recover from large-area or long-duration outages. *Reliability* investments advance technology, knowledge, and operational strategies that reduce the frequency or impact of small-scale or short-duration disruptions in electric service.

[221] U.S. Department of Energy. 2017b. *Transforming the National Electricity System: the 2nd Installment of the Quadrennial Energy Review*. https://www.energy.gov/sites/prod/files/2017/02/f34/Quadrennial%20Energy%20Review--Second%20Installment%20%28Full%20Report%29.pdf

[222] Wolfe, F. 2017. How Artificial Intelligence Will Revolutionize the Energy Industry. http://sitn.hms.harvard.edu/flash/2017/artificial-intelligence-will-revolutionize-energy-industry/

Machine learning and AI have the potential to optimize generation, demand, operations and maintenance of energy assets, better understand energy usage patterns, and provide better stability and efficiency of the power system. With the recent wildfires in California, this technology area has the potential to better predict vulnerable locations that could cause fires and their potential spread. The following represent some promising areas for further research and development.

AI-Driven Smart Grid Controls

AI methods are being used to develop technologies that can provide useful insights into predictive analytics from advanced metering infrastructure (AMI) such as customer usage behavior, marketing, dynamic pricing and distribution planning and scheduling.[223] These technologies can be particularly beneficial for targeting demand response (DR) programs, giving utilities and customers the ability to more quickly and efficiently respond to periods of peak demand in real time and providing for a more stable and reliable system.[224]

Augmented and Virtual Reality

Just starting to emerge in the utility sector, augmented and virtual reality could significantly improve how utilities respond to power outages or damage to equipment, enabling digital enhancements of service territory landscape to more efficiently assess and diagnose problems in the system. Some augmented or virtual reality technologies allow utility crewmen to view superimposed digital information on a smart device to help pinpoint the exact location of a problem.[225] [226]

AI for Grid Performance and Cybersecurity

Incorporating AI in grid planning can help make the bulk power system more reliable and resilient. The use of AI can not only help system planners by providing enhanced situational awareness of the electric distribution system, it can also enhance load and price forecasting models by considering a wider set of possible scenarios to help system operators better pinpoint conditions and make more reliable decisions. This is particularly true given a grid landscape with a growing number of distributed and

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[223] Itron. 2020. Itron and Innowatts Collaborate to Deliver AI-Powered AMI Predictive Insights to Electric Utilities. https://investors.itron.com/news-releases/news-release-details/itron-and-innowatts-collaborate-deliver-ai-powered-ami

[224] Antonopoulus, I. et al. 2020. Artificial intelligence and machine learning approaches to energy demand-side response: A systematic review. *Renewable and Sustainable Energy Reviews*, Volume 130, September 2020, 109899. https://www.sciencedirect.com/science/article/pii/S136403212030191X

[225] Joshi, N. 2019. AR And VR in the Utility Sector. https://www.forbes.com/sites/cognitiveworld/2019/09/29/ar-and-vr-in-the-utility-sector/?sh=2621bd0966a1

[226] Florida Power and Light. 2020. Advanced Smart Grid Technology. https://www.fpl.com/smart-meters/smart-grid.html

variable generating sources that can produce billions of potential failure scenarios of varying degree.[227] [228]

Another aspect of monitoring grid performance is the use of AI and machine learning to enhance cybersecurity.[229] Improved machine learning techniques like artificial neural networks, Decision Tree, and support vector machines have been discussed in the literature as effective approaches in power system studies, yet less so in practice.

With increasing internet-connected devices in the electric power system comes additional ways to exploit their weaknesses. California's government is taking this issue seriously—imposing the nation's first cybersecurity standards for IoT devices under SB 327.[230] LBNL is working on several U.S. DOE-funded projects that focus on developing tools for monitoring and protecting power grid control system devices.[231] This work specializes in smart technologies, such as state-of-the-art sensors that help automate electric grid protections and responses against cyberattacks. For example, if a large number of smart inverters get compromised, it can lead to software manipulations that can compromise the voltage and potentially resulting in blackouts in extreme cases. To mitigate this, researchers are exploring the behaviors of inverters and noting when voltages are oscillating and helping respond with voltage settings that are less aggressive. This research shows there are significant potential benefits of leveraging smart technologies in the fight against cyberattacks. [232] [233]

Deep Learning

Deep learning involves using more complex multi-layered learning algorithms to address the poorer performance of AI as a result of bad input data, which can help improve forecast planning models, for example. This technology also has the ability to handle big data that result from smart metering, which can enhance the reliability of the power

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[227] Nunes, C. 2019. Artificial intelligence can make the U.S. electric grid smarter. https://www.anl.gov/article/artificial-intelligence-can-make-the-us-electric-grid-smarter

[228] Wolfe, 2017, op cit.

[229] Alimi, O., K. Ouahada, A. Abu-Mahfouz. 2020. A Review of Machine Learning Approaches to Power System Security and Stability. IEEE Access. https://ieeexplore.ieee.org/document/9121208.

[230] CA Legislature. 2018. California Senate Bill No. 327, Chapter 886: An act to add Title 1.81.26 (commencing with Section 1798.91.04) to Part 4 of Division 3 of the Civil Code, relating to information privacy. https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180SB327

[231] Berkeley Lab Cybersecurity R&D. 2020. Cybersecurity for Energy Delivery Systems Projects. https://dst.lbl.gov/security/research/ceds/

[232] Peisert, S. and D. Arnold. 2018. Cybersecurity via Inverter-Grid Automated Reconfiguration (CIGAR). https://www.energy.gov/sites/prod/files/2018/12/f58/LBNL%20-%20CIGAR.PDF

[233] Roberts, C. et al. 2019. Learning Behavior of Distribution System Discrete Control Devices for Cyber-Physical Security. https://www.cs.ucdavis.edu/~peisert/research/2019-TSG-Infer-Control.pdf

system with better understanding of the underlying data. This technology has been demonstrated in various areas, but not yet in the energy industry.[234] [235]

AI Limitations and Need for Better Data and Data Measurement

While AI shows great promise, the learning algorithms are only as good as the quality of the measured data that feed AI tools. A recent U.S. DOE report highlighted that real operational data are not readily available for research and development and are often deemed proprietary to the collecting entity.[236]

Further, there is a shortage of people or workforce in the industry as well as at national laboratories and universities with expertise to help address this issue. Although not a "technology" per se, materials and tools to ensure that energy industry workers have the skills to use these next generation technologies successfully are lacking. More needs to be done to promote the hiring of more data scientists with expertise in data analytics for power and energy.

Algorithms are being developed that identify misleading information and improve the quality of the information collected. NREL and U.S. DOE are collaborating to use AI to improve data center efficiency in supercomputing as well as energy usage by focusing on detecting anomalous or potentially erroneous data measurements.[237] Advanced techniques have recently been tested to detect bad data that combine advanced machine learning called extreme learning machine together with density-based spatial clustering algorithms.[238] Combining these techniques has shown promising results in the ability to quickly and efficiently detect anomalous data.

Research is underway to develop methods to detect anomalous or erroneous data measurements, some of which involve AI. Bad data can result from meter failures, communication errors, asynchronous measurements, human error, and data attacks, all of which can result in threats to the reliability of the power system. Machine learning and AI are reliant on measured data, limiting their ability to perform well if the data input is bad. This problem has a double-edged sword, as machine learning and AI rely

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[234] Pouyanfar, Samira, et al. 2108. A Survey on Deep Learning: Algorithms, Techniques, and Applications. https://www2.cs.duke.edu/courses/cps274/compsci527/spring20/papers/Pouyanfar.pdf

[235] Wang, Y., Q. Chen, T. Hong, C. Kang. 2019. Review of Smart Meter Data Analytics: Applications, Methodologies, and Challenges. *IEEE Transactions on Smart Grid*, vol. 10 (3). https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8322199&tag=1.

[236] SEAB AIML Working Group. 2020. Preliminary findings of the SEAB to Secretary of Energy Dan Brouillette regarding the Department of Energy and Artificial Intelligence. https://www.energy.gov/sites/prod/files/2020/04/f73/SEAB%20AI%20WG%20PRELIMINARY%20FINDINGS_0.pdf

[237] NREL and HPE Team Up to Apply AI for Efficient Data Center Operations. 2019. https://www.nrel.gov/news/program/2019/nrel-and-hpe-team-up-to-apply-ai-for-efficient-data-center-operations.html

[238] Huang, Heming, et al. 2018. Robust Bad Data Detection Method for Microgrid Using Improved ELM and DBSCAN Algorithm. https://ascelibrary.org/doi/10.1061/%28ASCE%29EY.1943-7897.0000544

not only on historical data to train the model, but also on new measured data to provide foresight.[239] To detect false data injections in power systems, machine learning methods are being used to help identify bad data in the system.[240]

Table 7.1 summarizes various technology innovations for AI to help improve the reliability and resilience of the power system.

Table 7.1: AI Technology Innovations to Enhance Reliability and Resilience

Technology	Description	Technical Maturity
AI-driven smart grid control technologies	Using AI on AMI smart grid data to better understand customer behavior and help improve the performance of DR programs	TRL 3-5
Augmented and virtual reality technologies	Tools that provide virtual or enhanced reality that can help utility crewmen to more quickly and accurately assess power outages or equipment damage	TRL 4-7
AI for grid performance	AI that advances techniques like artificial neural networks for use in computational models to improve event classification for load and price forecasting	TRL 2-4
Deep learning technologies	Next generation AI techniques that apply multiple layers of complex thinking or randomized model averaging to improve performance and an ability to handle big data from smart meters	TRL 3-5
Workforce training tools	The utility industry needs improved techniques to train the next generation utility workforce in use of advanced techniques	TRL 3-5
Data measurement technologies to improve AI	Methods to detect anomalous or erroneous data measurements, some of which involve AI.	TRL 2-5

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[239] Redman, T. C. 2018. If Your Data Is Bad, Your Machine Learning Tools Are Useless. https://hbr.org/2018/04/if-your-data-is-bad-your-machine-learning-tools-are-useless

[240] Yu, B. et al. 2020. "The data dimensionality reduction and bad data detection in the process of smart grid reconstruction through machine learning." *PLoS ONE* 15(10): e0237994. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0237994

Big Data Analytics

An essential component of the smart grid is the AMI. With nearly 11 million smart meters installed in California representing 70% of electricity customers, utilities now have an overwhelming amount of insightful metered data.[241] When used well, data from smart meters allow for faster power outage detection and restoration of service, and empower customers to control their usage when coupled with time-based rates.[242] With the shift toward a smart electric grid capable of two-way flow of power and data, utilities have the potential to improve the efficient scheduling of energy use and improve reliability by better analyzing this data. However, traditional approaches of data analysis are inadequate to handle the high frequency and volume of data from various distributed sources. Current practices tend to aggregate the data for computational ease, but this may overlook valuable insights.[243] While data analytics may be readily used in some industries, use in the energy industry is still in its early stages.[244] A recent study suggests three broad applications for data analytics using smart metered data: load analysis, load forecasting, and load management.[245]

Dynamic Energy Management Systems

Dynamic energy management systems (DEMs) utilize sophisticated simulations that can provide globally optimal solutions based on randomization techniques. While DEMs are considered conventional for traditional energy system applications, they are still new for the smart grid due to their complexity to run in real-time and solve more complicated optimization problems.[246] The challenge is developing systems that can assess load patterns in real time from an abundance of AMI data and provide powerful analysis to optimize bi-directional power flow. An important aspect includes a sophisticated communications system that is able to efficiently and dynamically communicate within the system.[247] Systems that can communicate interactively with multiple sources (smart

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[241] York, D. 2020. Smart meters gain popularity, but most utilities don't optimize their potential to save energy. https://www.aceee.org/blog-post/2020/01/smart-meters-gain-popularity-most-utilities-dont-optimize-their-potential-save

[242] California Public Utilities Commission (CPUC). The Benefits of Smart Meters. https://www.cpuc.ca.gov/General.aspx?id=4853#:~:text=In%20California%2C%20the%20CPUC%20authorized,million%20electric%20meters%20and%204.2

[243] IEEE Smart Grid Big Data Analytics, Machine Learning and Artificial Intelligence in the Smart Grid Working Group. Big Data Analytics in the Smart Grid. https://smartgrid.ieee.org/images/files/pdf/big_data_analytics_white_paper.pdf

[244] Walton, R. 2020. Most utilities aren't getting full value from smart meters, report warns. https://www.utilitydive.com/news/most-utilities-arent-getting-full-value-from-smart-meters-report-warns/570249/

[245] Guerrero-Prado, J. et al. 2020. The Power of Big Data and Data Analytics for AMI Data: A Case Study. *Sensors* v20 (11). https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7309066/

[246] Han, D. et al. 2017. Dynamic energy management in smart grid: A fast randomized first-order optimization algorithm. https://www.sciencedirect.com/science/article/abs/pii/S0142061517306518

[247] Júnior, F. et al. 2018. Design and Performance of an Advanced Communication Network for Future Active Distribution Systems. *Journal of Energy Eng*. Vol 144 (3). https://ascelibrary.org/doi/pdf/10.1061/%28ASCE%29EY.1943-7897.0000530

meters, schedulers, solar radiation sensors, wind speed meters, relays, etc.) allow for more effective decisions that can enhance reliability and resilience.

Related to this, advanced distributed energy resource management systems (DERMS) represent software-based solutions designed to address integration of DERs like solar, energy storage, and demand response while improving reliability and power quality. These advanced energy management systems are able to adjust outputs of PVs or energy storage devices to ensure reliable power supply. A recent PG&E research project focused on enhancing the situational awareness and economically optimizing the use of DERs.[248]

Multivariate Data Fusion

Multivariate data fusion is an emerging research area that focuses on incorporating external sources of data with smart meter data like weather in order to enhance understanding of customer behavior. This emerging topic suggests smart meter data analytics should no longer be limited to electricity consumption data. For example, joint load forecasting for electricity, heating, and cooling can be conducted simultaneously with weather information to assess multiple energy systems to gain improved predictability into customer behavior.[249]

Table 7.2 summarizes technology innovations for big data analytics to help improve the reliability and resilience of the power system.

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[248] Kuga, R. et al. 2019. Electric Program Investment Charge (EPIC), EPIC 2.02 – Distributed Energy Resource Management System; EPIC 2.02 DERMS. Grid Integration and Innovation. Pacific Gas & Electric. https://www.pge.com/pge_global/common/pdfs/about-pge/environment/what-we-are-doing/electric-program-investment-charge/PGE-EPIC-2.02.pdf

[249] Wang, Y, Q. Chen, T. Hong, C. Kang. 2019. Review of Smart Meter Data Analytics: Applications, Methodologies, and Challenges. *IEEE Transactions on Smart Grid*. Vol 10 (3). https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8322199&tag=1.

Table 7.2: Big Data Analytics Technology Innovations to Enhance Reliability and Resilience

Technology	Description	Maturity Level
Dynamic energy management systems	Techniques that are able to accommodate bi-directional, smart meter data and assess load patterns by applying complex simulations and algorithms	TRL 4-5
Multivariate data fusion	Assessing both smart meter data with external data sources like weather or economic information for improved understanding of customer behavior	TRL 3-5

Advanced Microgrids and Islanding

Microgrids have been around for decades, yet they have recently received more attention as a means of providing a local and reliable source of electricity using distributed clean energy resources like solar PV and wind that can also disconnect and function as an electrical island. These DERs, however, do pose a concern for grid stability with, for example, potential fluctuations in voltage when the microgrid islands from or reconnects to the grid.[250] Current research is focusing, among other things, on the advancement of automation techniques and advanced control technologies to help ensure stable operation of the microgrid once islanded.

Autonomous Energy Grids

An autonomous energy grid (AEG) is an emerging "intervention" that can self-organize and control itself using advanced machine learning and simulation to create resilient, reliable, and affordable optimized energy systems. AEGs represent a set of controls and optimization strategies that rely on microgrids as a building block and can operate without an operator, envisioning a future where the power system is a network of autonomous microgrids.[251] [252]

Detection of Unplanned Islanding

Big-data-based approaches are being used to detect, locate, and help stabilize unplanned microgrid islanding events.[253] Research has focused on geospatial and

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[250] DOE. 2019. Microgrids and Power Quality. https://www.energy.gov/sites/default/files/2019/11/f68/22-fupwg-fall-2019-starke.pdf

[251] NREL. 2020. Autonomous Energy Grids. https://www.nrel.gov/grid/autonomous-energy.html

[252] Dyson, M. and B. Li. 2020. Reimagining Grid Resilience: A Framework for Addressing Catastrophic Threats to the US Electricity Grid in an Era of Transformational Change. https://rmi.org/insight/reimagining-grid-resilience/

[253] Jiang, H. et al. 2017. Big Data-Based Approach to Detect, Locate, and Enhance the Stability of an Unplanned Microgrid Islanding. https://ascelibrary.org/doi/10.1061/%28ASCE%29EY.1943-7897.0000473

temporal characteristics associated with the plethora of data from smart grid sources including DERs in the microgrid as well as phasor measurement units (PMUs), fault disturbance recorders, and micro-PMUs in order to better pinpoint locations of unplanned islanding.

Table 7.3 summarizes the various technology innovations for microgrids and islanding to help improve the reliability and resilience of the power system.

Table 7.3: Microgrid and Islanding Technology Innovations to Enhance Reliability and Resilience

Technology	Description	Maturity Level
Autonomous Energy Grids	Aggregated microgrids that include controls and optimization strategies that can be operated autonomously	TRL 2-4
Islanding detection	Use of big-data analytics to detect, locate, and stabilize unplanned microgrid islanding events	TRL 3-5

Grid Monitoring and Modeling

The power grid is considered one of the most critical pillars of infrastructure necessary for society to function. Grid monitoring and modeling is central to maintaining stability and reliability of that power grid. Advances in grid monitoring include improved ability to detect and respond to more granular perturbations in the system, improved voltage, current and frequency monitoring, and modeling that is able to adjust to an evolving power system with more distributed energy resources. Better grid monitoring and modeling can help enhance the reliability and resilience of the electric power system.

Advanced Grid Monitoring Technologies

Efforts are underway to advance the way power quality is monitored. The Gridsweep probe, for example, is a promising technology in the prototype development phase that is designed to detect very small oscillation perturbations in the electric system that can cause problems with connected equipment and operations that can lead to potentially adverse effects on grid stability. The probe is particularly relevant to California with the increased penetration of dispersed energy resources.[254] In another example, research is being conducted to detect instability in the power system using an approach that could

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[254] McEachern Laboratories. 2021. GridSweep instrument. https://gridsweep.com/

help prevent a potential cascading outage based on a measurement index to estimate the dynamic response of the system.[255]

Synchrophasor Technologies

Phasor measurement units (PMUs) measure voltage, current and frequency more frequently than conventional supervisory control and data acquisition (SCADA) systems. They provide grid operators with greater situational awareness to help prevent power interruptions.[256] [257] Current research is exploring the use of machine learning techniques to more rapidly analyze the greatly increased volume of data produced by PMUs. Application of these techniques is expected to improve the efficiency, reliability and resilience of the power system.[258] [259]

Integrated Transmission and Distribution Modeling

Traditionally, simulations considered the bulk power or transmission system separate from the distribution system. An emerging area of research focuses on modeling the behavior of the bulk power system in the presence of PV and other forms of distributed energy systems within the distribution system. The modeling must consider the behavior of both systems in an integrated fashion as well as take into account details that formerly were only considered when modeling each system separately.

Table 7.4 summarizes technology innovations related to power quality that can help improve the reliability and resilience of the power system.

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[255] Bai, F. et al. 2016. A measurement-based approach for power system instability early warning. *Protection and Control of Modern Power Systems*. Vol 1 (4).

[256] PJM. 2020. Synchrophasor Technology Improves Grid Visibility. https://www.pjm.com/-/media/about-pjm/newsroom/fact-sheets/synchrophasor-technology.ashx?la=en

[257] Advanced Machine Learning for Synchrophasor Technology. https://gmlc.doe.gov/projects/gm0077

[258] Chertkov, M. 2017. Advanced Machine Learning for Synchrophasor Technology. https://www.energy.gov/sites/prod/files/2017/07/f35/9.%20Chertkov%20GMLC%200077%20June%2013%202017.pdf

[259] Robertson, R. 2020. Advanced Synchrophasor Protocol Development and Demonstration Project. https://www.osti.gov/biblio/1597102

Table 7.4: Grid Monitoring Technology Innovations to Enhance Reliability and Resilience

Technology	Description	Maturity Level
Advanced grid monitoring technologies	Hardware, software, or simulation techniques that advance the detection of oscillation perturbations that can affect grid stability	TRL 3-4
Advanced synchrophaser technologies	Advanced synchrophasor research using machine learning to better forecast load	TRL 4-5
Integrated T&D modeling	Modeling approaches that consider both transmission and distribution systems to allow for dynamic real-time feedback	TRL 2-4

Bi-directional Electricity Storage

Chapter 4 described the importance of electricity storage as the power grid becomes more reliant on variable renewable sources. Energy storage technologies are an attractive means of enhancing reliability and resilience. Storage technologies have become popular in recent years over diesel backup generators because of their ability to provide cleaner power year round, not just during times of emergency. Despite the higher costs, the ability of storage to operate during resilience events like severe weather or earthquakes make them an attractive option.[260] Realizing this benefit, the CEC EPIC program is exploring an investment plan to further electric storage capability to enhance resilience in the state.[261]

Strategic Considerations for California

To help address the challenges to the reliability of the state's electric power infrastructure, the state issued Executive Order B-30-15 to require climate change to be addressed in strategic planning exercises across all sectors. This includes developing adaptive approaches to enhance resilience in the face of an uncertain climate.

Facilitating the adoption and use of innovative technologies that enhance resilience in the power system is critical, including increased use of AI and machine learning in power system operation and monitoring including improved big data analytics.

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[260] NREL. 2018. Valuing the Resilience Provided by Solar and Battery Energy Storage Systems. https://www.nrel.gov/docs/fy18osti/70679.pdf

[261] California Energy Commission. 2020. Staff Workshop for the Initial Public Workshop for Comments on Long Duration Energy Storage Scenarios. https://www.energy.ca.gov/event/workshop/2020-12/staff-workshop-initial-public-workshop-comments-long-duration-energy-storage

Autonomous energy grids should be explored as the state's power system continues to evolve. The CEC's EPIC program funds activities that support a more decentralized electric grid and enhance the resiliency of the electric system. The program demonstration of emerging technologies that will help address grid needs. Under this program, Pacific Gas & Electric, the state's largest investor-owned utility, is exploring new emerging technologies that are using data analytics and applying machine learning to proactively identify assets nearing end-of-life so they can be replaced before failing.[262] Autonomous peak shaving capability from energy storage resources was also developed and piloted.[263] In 2020, PG&E explored automated drones to help investigate alerts from distribution system sensors, particularly in high-fire threat locations.[264]

Further investments in projects that enhance the reliability and resiliency of the state's electric power system should be explored, especially those that address the imminent and growing threats to our natural resources. The California Resilience Challenge is supporting 12 projects to help local communities across the state strengthen their resilience to climate change.[265] One project directly intended to help the local power system is with the Western Riverside Council of Governments (WRGC). In collaboration with its 19 member jurisdictions, the WRCG is developing a comprehensive plan designed to enhance resilience to public safety power shutoffs, power shortages and emergencies. The plan will identify specific projects and strategies to develop independent energy sources in each jurisdiction, including back-up generators, energy storage, and development of local power microgrids.

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[262] PG&E. 2021. Electric Program Investment Charge Project Reports. https://www.pge.com/en_US/about-pge/environment/what-we-are-doing/electric-program-investment-charge/closeout-reports.page

[263] PG&E. 2021. Electric Program Investment Charge Project Reports. https://www.pge.com/en_US/about-pge/environment/what-we-are-doing/electric-program-investment-charge/closeout-reports.page

[264] Pacific Gas & Electric. 2020. PG&E Tests and Demonstrates New Technologies on Electric Grid to Increase Safety, Further Mitigate Wildfire Risk. Media report. https://www.pgecurrents.com/2020/08/25/pge-tests-and-demonstrates-new-technologies-on-electric-grid-to-increase-safety-further-mitigate-wildfire-risk/

[265] California Resilience Challenge. https://resilientcal.org/winners/

CHAPTER 8: Cross-Cutting Areas of Technology Innovation

There are a number of areas of technology innovation that could have benefits across multiple sectors of the energy economy. They involve smart manufacturing techniques, advanced materials that could improve performance and lower the cost of energy-producing and energy-using technologies, novel manufacturing techniques that could reduce energy use, recycling of various materials that could dramatically reduce the embodied energy and carbon emissions associated with materials production, and advances in computing that will have impacts in a multitude of areas. This chapter provides an overview of some important parts of the broader landscape of innovation that could help to meet clean energy goals.

Smart Manufacturing: Advanced Sensors, Controls, and Platforms

Smart manufacturing technologies enable the extensive application of data for the optimization of enterprises and manufacturing supply chain.[266] They have the potential to transform the entire manufacturing supply chain – from extraction of materials at mines, through commodities, to finished products. The benefits of smart manufacturing technologies go far beyond electricity savings, but such savings can be an outcome.

Smart manufacturing technologies include infrastructure, software, and networked solutions for sensing, instrumentation, control, modeling and platforms for manufacturing applications. These technologies interact in machine-to-plant-to-enterprise-to-supply-chain ecosystem applications of real-time data and models that are networked for enterprise and ecosystem optimization, as well as monitoring, diagnostics, enterprise/ecosystem analytics, and integrated performance metrics.

Data from advanced sensor systems form the basis for process control applications, decision work flows, and enterprise and supply chain optimization. Smart manufacturing optimizes manufacturing processes while minimizing excess production at each manufacturing step. A networked, open-architecture, open-access, and open-application data platform combined with "plug-and-play" capabilities enables integration and customization across smart technologies while ensuring that a standard of performance is met at a low implementation cost.

Energy management is a critical aspect of smart manufacturing. Many manufacturing facilities have some form of energy management system, which provides a standard

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[266] This section is drawn from: U.S. Department of Energy. 2016. *Advanced Manufacturing Office Multi-Year Program Plan*, Draft; U.S. Department of Energy. 2015. *Quadrennial Technology Review 2015*, Advanced Sensors, Controls, Platforms and Modeling for Manufacturing.

process to incorporate energy considerations and energy management into daily operations to improve their energy performance. While such continual process improvement protocols are effective frameworks for managing energy in manufacturing, there is a need for physical and computational platforms for cost-effectively implementing energy management in real-time across manufacturing processes, facilities, enterprises and supply-chains. As smart manufacturing equipment becomes more advanced and less costly, more types of equipment and plant operations will be monitored at a more granular level to enable greater energy savings, emission reductions, and productivity benefits.

The Clean Energy Smart Manufacturing Innovation Institute (CESMII),[267] sponsored by U.S. DOE, has activities that include:

- Inferential modeling for driving out energy waste
- Energy management systems for subtractive and additive precision manufacturing
- Smart manufacturing of cement
- Energy efficient material processing through automated process monitoring and controls
- Smart manufacturing for chemical processing: energy efficient operation of air separation unit.

Advanced Materials Manufacturing[268]

Conventional materials development, based largely on labor-intensive iterations of synthesizing and testing materials, can take 10-20 years from initial discovery to commercialization of a new material. An advanced system of computational, experimental, and data tools could be employed to research and validate new materials at a significantly accelerated rate. This acceleration of the materials development cycle has significant potential to enable lifecycle energy savings and more efficient clean energy technologies. Lightweight materials that improve vehicle fuel economy and energy conversion materials that improve potential for waste heat recovery exemplify the range of potential benefits across the entire manufacturing supply chain.

The U.S. DOE Advanced Manufacturing Office (AMO) focuses on materials for use in additive manufacturing, lightweight structural applications, low resistance conductor materials and novel low cost soft magnetic materials to reduce weight, size and losses in transformers, waste heat recovery systems, catalysts, and highly selective

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[267] https://www.cesmii.org/

[268] Drawn from: U.S. Department of Energy. 2016. *Advanced Manufacturing Office Multi-Year Program Plan*, Draft. https://www.energy.gov/sites/prod/files/2017/01/f34/Draft%20Advanced%20Manufacturing%20Office%20MYPP_1.pdf

membranes with atomically precise pores for water purification, fuel cells, and industrial separation processes.

Areas of interest for advanced materials manufacturing include:

Scalable manufacturing processes for a range of materials with 50% or greater improved thermal or electrical conductivity. Materials with improved thermal or electrical conductivity could save energy in manufacturing processes and product use through a variety of applications. For instance, metals with higher electrical conductivity could reduce the amount of electrical materials necessary in certain devices, resulting in lifecycle energy savings through lightweighting in automotive and aerospace applications. Metals with improved thermal conductivity could increase heat exchanger efficiency. Recently, significant conductivity improvements in metals such as copper, iron, and aluminum have been achieved through the infusion of carbon nanoparticles into the material. Opportunity exists to apply a similar process to significantly increase the conductivity of numerous alloys.

New process technologies that can provide production quantities of commercial-scale atomically precise products. Atomically precise manufacturing refers to the concept of producing macro-scale material components in which individual atoms are positioned exactly relative to other atoms, without impurities or other defects. Defects and inclusions in conventional materials result in substantially inferior properties than what is theoretically possible. New advances in material design and manufacturing could result in materials that approach these theoretical strength levels. These materials could be applied to reduce weight and create lifecycle energy savings in automotive and other applications. Other application areas for atomically precise manufacturing include the creation of separation membranes that could greatly reduce the energy intensity of water desalination, or atomically precise catalysts which could reduce the energy required for chemical reactions.

For further discussion of the challenges and opportunities for advanced materials manufacturing, see the *Quadrennial Technology Review 2015 (QTR 2015), Technology Assessment: Advanced Materials Manufacturing*.[269]

Advanced Composite Materials[270]

Lightweight, high strength-to-weight ratio, and high-stiffness composite materials have been identified as an important cross-cutting technology in U.S. manufacturing. These materials have the potential to improve the energy efficiency of the transportation sector, enable more efficient power generation, improve the storage and transport of low-carbon fuels, and improve manufacturing processes. Yet high-volume, large-scale production will only be economically viable with lower-cost carbon fibers and

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[269] Available online at: http://energy.gov/sites/prod/files/2016/04/f30/QTR2015-6B-Advanced-Materials-Manufacturing.pdf.

[270] Drawn from *Advanced Manufacturing Office Multi-Year Program Plan*, op. cit.

advancements to technologies including fast-curing resin systems, innovative recycling technologies, effective characterization methods, and process design and control solutions.

Targeted markets are high volume carbon, glass and emerging fiber composite manufacturing with end use applications including lightweight vehicles, compressed gas storage, wind turbine blades, and industrial applications (such as high temperature insulation and membranes).

The Institute for Advanced Composites Manufacturing Innovation is working through industrial partnerships to develop lower-cost, higher-speed, and more-efficient manufacturing and recycling processes for advanced composite materials.[271] Areas of innovation in advanced composites manufacturing include:

- Advanced carbon fiber technologies via alternative precursors, efficiency processes, and interface engineering.
- Demonstrating production of high-value intermediates and composites from reclaimed carbon fiber.
- Application of materials characterization capabilities to technology advancement and benchmarking.
- Application of additive manufacturing to reclaimed structural fiber composites fabrication and rapid prototyping.

For more information, see the *QTR 2015 Technology Assessment: Composite Materials*.[272]

Advanced Materials for Harsh Service Conditions[273]

Harsh and extreme service environments (e.g., high temperature or chemically-reactive environments) can drive or accelerate key failure modes of a product, device, or component. All thermal power systems involve subjecting materials in turbines, boilers, and heat exchangers to high temperatures, often in combination with aggressive chemical environments and mechanical loads. Cyclical variations in chemistry also pose a challenge, such as in pipes that can transport natural gas and hydrogen in the same line. Stringent application demands for future products that will provide energy savings, emissions reductions, and other benefits will require new materials and new processing solutions.

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[271] https://iacmi.org/

[272] Available online at: http://energy.gov/sites/prod/files/2015/12/f27/QTR2015-6E-Composite-Materials.pdf.

[273] Drawn from *Advanced Manufacturing Office Multi-Year Program Plan*, op. cit.

Material degradation ranging from gradual performance loss to catastrophic failure can result from a complex combination of conditions which is difficult to replicate experimentally or predict computationally. Current barriers include lack of in-situ characterization technologies; poor understanding of time dependence of reactions and transformations under non-steady state conditions; lack of predictive capability in a multi-scale environment; and a lack of data and informatics for integrated computational materials engineering.

Key challenges exist in:

Manufacturing. Conceptual solutions for materials exist for virtually any harsh condition, but the pathway to manufacture them cost effectively does not. Cost-effective manufacturing includes production of materials and assembly of parts, which requires integration of materials in structures (joining, coating, sealing, lubrication, etc.) and consideration of the supply chain.

Materials discovery. Accelerated materials discovery is needed to meet the demands for future power systems. Surfaces and interfaces are the first line of defense against chemical attack, contact mechanical loads, and thermal resistance. Bulk structures need to be resilient against temperature, un-desired phase changes, and other micro-structural changes. Accelerating the materials development timeline will require the use of modeling at various scales to identify potential material solutions. At the federal level, the Materials Genome Initiative is a multi-agency initiative designed to support U.S. institutions in the effort to discover, manufacture, and deploy advanced materials twice as fast, at significantly lower cost.

For further discussion of the applications, challenges, and opportunities for materials in harsh environments from an energy perspective, see *QTR 2015, Technology Assessment: Materials for Harsh Service Conditions*.[274]

Additive Manufacturing[275]

Additive manufacturing (AM) is the process of producing objects from computer-aided design model data, usually adding layer upon layer, in contrast to conventional subtractive manufacturing methods that involve the removal of material from a starting work piece. Emerging AM technologies are projected to have a transformational impact on manufacturing by dramatically reducing materials and energy use, eliminating production steps, enabling simpler component designs, eliminating costly part tooling, and supporting increased distributed manufacturing at the point-of-use. Additive manufacturing can provide life-cycle benefits in multiple sectors compared to

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[274] Available online at: http://energy.gov/sites/prod/files/2016/04/f30/QTR2015-6B-Advanced-Materials-Manufacturing.pdf

[275] Drawn from: U.S. Department of Energy. *Quadrennial Technology Review 2015*, Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing.

conventional manufacturing by reducing the amount of required raw material, reducing the ultimate weight of a component, and minimizing part count.

To realize the full potential of additive manufacturing, technology solutions are needed to improve dimensional accuracy, improve the mechanical and physical properties of the finished part, increase throughput, and reduce the minimum feature size that can be fabricated. Key technical challenges include:

Process control: Feedback control systems and metrics are needed to improve the precision and reliability of the manufacturing process and to increase throughput while maintaining consistent quality. Feedback control is especially challenging for AM processes with rapid deposition rates. The ability to tailor the material microstructure in situ could improve performance properties.

Tolerances: Some potential applications would require micron-scale accuracy in printing.

Finish: The surface finishes of products manufactured using additive technology require further refinement. With improved geometric accuracy, finishes may impart improved tribological (related to friction, lubrication, and wear) and aesthetic properties.

Material compatibility: Materials that can be used with additive manufacturing technologies are currently limited to a relatively small set of compatible materials. There is a need for new polymer and metal materials formulated for additive manufacturing to provide materials properties such as flexibility, conductivity, transparency, safety, and low embodied energy.

For more information, see *QTR 2015, Technology Assessment: Additive Manufacturing*.[276]

Recovery, Re-Use, Remanufacturing and Recycling

Recovery, re-use, remanufacturing and recycling (Re-X) of various materials could dramatically reduce the embodied energy and carbon emissions associated with industrial-scale materials production and processing.

Co-funded by U.S. DOE, the REMADE Institute, in partnership with industry, academia, trade associations, and national laboratories, is broadly focused on all material processing industries across the entire material value chain, including production, remanufacturing, and recycling.[277] The Institute is focused on driving down the cost of technologies essential to reuse, recycle and remanufacture materials such as metals, fibers, polymers and electronic waste.

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[276] Available online at: https://www.energy.gov/sites/prod/files/2015/11/f27/QTR2015-6A-Additive%20Manufacturing.pdf.

[277] https://remadeinstitute.org/

The Institute has five key areas of concentration:

Systems Analysis & Integration – Data collection, standardization, metrics, and tools for understanding material flow

Design for Reuse and Disassembly – Design tools to improve material utilization and reuse at End-of-Life

Manufacturing Materials Optimization – Technologies to reduce in-process losses, reuse scrap materials, and utilize secondary feedstocks in manufacturing

Remanufacturing and End-of-life Reuse – Efficient and cost effective technologies for cleaning, component restoration, condition assessment, and reverse logistics

Recycling & Recovery – Rapid gathering, identification, sorting, separation, contaminant removal, reprocessing and disposal

For more information, see the REMADE Institute Technology Roadmap.[278]

Advanced Power Electronics Using Wide Bandgap Semiconductors[279]

A wide range of devices, machines, and systems—from handheld electronic devices like smartphones and laptop computers to electric vehicles and grid-scale renewable energy systems—rely on semiconductor power electronics capable of converting power and controlling electrical energy (i.e., tuning voltage, current, and frequency) from the point of energy generation to distribution. Wide bandgap (WBG) semiconductors, which are used in LED light fixtures and many TVs, can improve energy efficiency in the next generation of power electronics while also reducing cost and system size.280 Silicon-based power electronics usually range between 85% and 97% efficient; WBG devices reduce losses by half or more, raising efficiencies to between 95% and 99%.[281]

WBG semiconductors are able to operate at higher voltages and power densities than silicon-based semiconductors, allowing the same amount of power to be delivered with fewer chips and smaller components. In addition, these more powerful WBG semiconductors can operate at higher frequencies, which helps to simplify system circuitry and reduce system costs. Furthermore, WBG semiconductors tolerate heat

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[278] https://remadeinstitute.org/technology-roadmap

[279] Based on: https://www.energy.gov/eere/amo/power-america

[280] A bandgap is the term used for the amount of energy needed to release electrons in semiconductor materials so that the electrons can move freely, enabling the flow of electricity. WBG semiconductors have bandgaps significantly greater than those of silicon semiconductors. Electrical current applied to WBG semiconductors will excite fewer electrons across the gap, enabling superior current control and reducing energy losses.

[281] Armstrong, Kristina, Sujit Das and Laura Marlino. April 2017. *Wide Bandgap Semiconductor Opportunities in Power Electronics*. Oak Ridge National Laboratory. https://info.ornl.gov/sites/publications/Files/Pub104869.pdf

better than silicon. As a result, WBG-based power electronic chips can operate in harsher conditions without degrading the semiconductor material. This greater thermal tolerance (300°C vs. 150°C) reduces the need for bulky insulation and additional cooling equipment, allowing for more compact system designs and saving energy. Collectively, these performance properties of WBG semiconductors will enable technology developers to continue designing increasingly more compact, efficient, reliable, and affordable power electronics in the decades ahead.

Chapter 2 discussed the potential for WBG semiconductors to expand the use of variable-frequency drives into a wider range of industrial motor system sizes and applications. While this is the largest area in terms of potential electricity savings, other important areas where WBG semiconductors can save electricity are:

Consumer Electronics and Data Centers: Power converters for data centers and consumer electronics (such as laptops, smart phones, and tablets) account for nearly 4% of U.S. electricity use today, and the demand for these facilities and products continues to rise. WBG chips could eliminate up to 90% of the energy losses in today's rectifiers that perform these conversions.

Conversion of Renewable Power: Renewable energy generated by wind turbines and solar photovoltaic systems must be converted from DC to AC prior to upload to the electric grid. A WBG chip provides the required conversion in the inverter.

The most technologically mature WBG semiconductors that could be used in power electronics are silicon carbide (SiC) and gallium nitride (GaN). These have enabled the development of compact (i.e., high power density), energy-efficient power components that operate at higher temperature, voltage, and frequency conditions. Compared to silicon, SiC-based power devices can operate at higher temperatures with higher thermal conductivity, higher breakdown voltage at lower on-stage resistance, faster switching speed, lower conduction and switching on-state loss, and exceptional radiation hardness. Advantages of GaN-based power devices include higher electron mobility and lower losses at higher frequencies, which can enable smaller devices with increased power density.

DOE is sponsoring an R&D consortia—PowerAmerica (also called the Next Generation Power Electronics National Manufacturing Innovation Institute)—that is working to move WBG semiconductor technologies from laboratory prototypes to working demonstration models and, finally, commercialized products.[282] In addition, ARPA-E’s CIRCUITS (Creating Innovative and Reliable Circuits Using Inventive Topologies and Semiconductors) program seeks to accelerate the development and deployment of efficient, lightweight, and reliable power converters based on WBG semiconductors.[283] CIRCUITS projects seek to establish the building blocks of this class of power converter by advancing higher efficiency designs that exhibit enhanced reliability and superior

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[282] https://poweramericainstitute.org/

[283] https://arpa-e.energy.gov/technologies/programs/circuits

total cost of ownership. In addition, a reduced form factor (size and weight) will drive adoption of higher performance and more efficient power converters relative to today's state-of-the-art systems. Past ARPA-E programs led to a new generation of devices that operate at much higher powers, voltages, frequencies, and temperatures than traditional silicon-based semiconductor devices. CIRCUITS projects build on these earlier programs by designing circuit topologies optimally suited for WBG attributes to maximize overall electrical system performance.

Innovations stemming from CIRCUITS projects have the potential to affect high-impact applications wherever electrical power is generated or used, including the electric grid, industrial motor controllers, automotive electrification, heating, ventilation and air conditioning, solar and wind power systems, data centers, aerospace control surfaces, wireless power transfer, and consumer electronics. A project focused on data center power delivery is being conducted by UC-Berkeley.[284] The project team is developing a prototype device that converts power from a universal grid input (110-240 V at 50-60 Hz) to 48 V DC, the standard for datacenter and telecom supply. The team hopes that this GaN-based converter will enable a complete redesign of the power delivery network for future datacenters, while achieving a three-fold reduction in energy loss and 10 times improvement in power density over traditional conversion circuits.

Autonomous WBG-Based Power Conversion Modules

While some WBG-based devices are commercially available, many applications of WBG semiconductors are still in development. One potential device is an autonomous WBG-based power conversion module that could be flexibly assembled for a wide array of energy conversion applications.[285]

The power converters used in a variety of applications are typically specialized and are custom designed and manufactured for the requisite voltage and power ratings. The design, manufacture, and installation of a unique power conversion system for each niche application leads to increased balance-of-systems costs, requiring specialized components, tooling, and installation knowledge. Moreover, the smaller production and installation volume for each sector hinders the ability to leverage economies of scale.

An autonomous, plug-and-play, mass-manufactured WBG-based power conversion module could be flexibly assembled for a wide array of energy conversion applications. Each module is a self-contained, bi-directional ac/dc power converter that can be easily connected with other modules for use in bi-directional ac-to-dc, dc-to-ac, dc-to-dc, or ac-to-ac applications that require different voltage and power ratings. Interconnected modules do not require a supervisory or centralized controller, which greatly reduces installation complexity and increases system robustness by eliminating a single point-of-failure. The modules utilize intelligent, decentralized controllers to autonomously

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[284] https://arpa-e.energy.gov/technologies/projects/data-center-power-delivery

[285] The technology development team includes researchers at Lawrence Berkeley National Laboratory, Stanford University, Enphase Energy, and Power Integrations, Inc.

coordinate with neighboring modules, and can automatically share power, handle faults, and provide coordinated actions such as grid ancillary services. The modules would utilize planar and printed circuit board-integrated passive components in order to reduce costs and maximize manufacturability. It would utilize WBG devices to maximize voltage handling capability and to miniaturize the system volume.

Autonomous plug-and-play WBG-based power conversion modules could provide:

- Up to 25% balance-of-systems cost reduction. The plug-and-play nature of the module simplifies installation and eliminates the need for custom power conversion designs. Moreover, the module utilizes advanced manufacturing techniques that drive down costs.
- Broad application capability enables greater economies of scale. The module can be utilized in a wide array of applications, including transportation, renewable energy integration, lighting, and utility-scale energy storage.
- Increased system reliability. If a module fails, adjacent modules will automatically reconfigure to isolate the fault and continue operation in a reduced state. The subsequent repair of the system will only involve the replacement of the faulty module, and not the entire system.

Energy Efficient Advanced Computing[286]

The scaling down in the size of complementary metal-oxide-semiconductor (CMOS) devices has increased the energy efficiency, storage capacity, and lowered the cost of integrated circuits consistently since the 1970s; the pace of the scaling is known as Moore's Law. CMOS device dimensions are expected to reach their physical limit within a decade. In order to continue the growth in computing power, basic and applied research is needed to accelerate the development of energy-efficient IT beyond the scaling limit of CMOS technology. This development will enable low-power computing and low-cost smart grid, building electronics, and next-generation sensors and electronics for a broad swath of industries.

Materials and devices: Novel materials and technologies are needed, such as carbon nanotube based transistors and other nanoscale devices. New materials and devices for ultra-efficient computing include low voltage transistor concepts such as the tunnel field-effect transistor, and energy efficient memory such as optical non-volatile photonic storage and spin transfer torque random access memory.

Manufacturing: To develop and deploy appropriate manufacturing technologies for new devices, innovation is needed in nano-manufacturing methods such as extreme

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[286] Based on: *Advanced Manufacturing Office Multi-Year Program Plan*, op. cit.

ultraviolet lithography, heterogeneous integration of advanced photonics and wide bandgap devices, and in three-dimensional (3-D) stacking of integrated circuits.

Systems: Simultaneous innovations in materials, devices, and system architectures are required to achieve beyond exascale computing capability.

Technical targets of the AMO's program plan include:

- Develop and demonstrate technologies that will enable 10 times improvement in computing energy efficiency over 2015 state of the art by 2025
- Develop and demonstrate manufacturing technologies that expand the limits of three-dimensional integrated circuits
- Develop and demonstrate processors at 100x higher processing speeds than 2015 commercial processors
- Develop and demonstrate optoelectronic interconnects with a chip footprint one-tenth of 2015 technology.

Advances in high-performance computing depend on achieving exascale, the next leap forward in computing.[287] The exponential increase in memory, storage, and compute power made possible by exascale systems will drive breakthroughs in energy production, storage, and transmission; materials science; additive manufacturing; chemical design; artificial intelligence and machine learning; cancer research and treatment; earthquake risk assessment; and many other areas.

For more information, see: Exascale Computing Project, https://www.exascaleproject.org/

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[287] Exascale computing refers to computing systems capable of at least one exaflop or a billion billion calculations per second (10^{18}). That is 50 times faster than the most powerful supercomputers being used today and represents a thousand-fold increase over the first petascale computer that came into operation in 2008.

CHAPTER 9: Conclusion

The preceding chapters have provided abundant evidence that the landscape of clean energy technology innovation is full of promising solutions to the challenges of moving toward an electricity system, and economy, that is far less reliant on fuels that contribute to global warming. Some of the technologies described are close to commercialization by clean energy startups, while others are still in development at research institutions and universities. Not all will make it all the way through the innovation pipeline to mainstream adoption, and other technologies that are little known today may prove to be significant.

Ranking or prioritizing the technologies with respect to their potential importance to meeting California's GHG reduction goals was beyond the scope of this report. Furthermore, any prioritization of emerging technologies needs to take into account other goals of public policy, such as enhancing public health, promoting economic development, and addressing equity concerns. However, some observations are possible.

Renewable electricity generation. Rapidly expanding renewable electricity generation is the centerpiece of decarbonization strategies, not only to reduce CO_2 emissions from electricity supply but also to support electrification of vehicles and other uses. Solar PV has the best prospects for providing the bulk of California's needs, so technologies that can reduce cost per kWh (through improved efficiency or other means) are highly important. Innovative tandem architectures using perovskites hold the potential to achieve efficiencies above 30% at reasonable cost and are garnering extensive interest. R&D is underway to advance perovskite efficiency and stability at the cell or mini-module scale, and to address challenges with manufacturing perovskite modules at relevant scale and throughput. While still at a nascent stage, floating offshore wind technology has a large potential and its daily generation profile would be complementary to solar PV. Innovation is needed in manufacturing, assembly and installation processes for the various components. California has an opportunity to become a leading manufacturing center for floating offshore wind technology.

Electricity storage. An electricity system dominated by renewable electricity sources presents reliability challenges due to their intermittency. Electricity storage of various durations will be essential to provide electricity when sufficient renewable generation is not available, and can enhance the value of renewable electricity. To provide storage durations longer than is feasible for lithium-ion batteries, a number of technologies have potential. These include flow batteries, mechanical energy storage systems, and high-temperature thermal energy storage systems. For seasonal storage and provision of firm electricity, hydrogen is the leading candidate. Electrolyzers that can produce hydrogen from renewable electricity at lower cost are a critical need, and not only in the context of electricity storage. Advanced fuel cells could generate electricity from stored hydrogen at scales smaller than combustion turbines.

Management of flexible electric loads will become more important to better match demand with the availability of renewable electricity or stored electricity. There is a need for advanced communications and controls that can manage loads to draw electricity at specific times and levels, while still meeting occupant productivity, service levels and comfort requirements. At the whole-building level, innovations in advanced sensors, controls, and communication for grid participation could enhance the ability of buildings to meet the needs of building occupants and the grid. Another priority is proper management of EVs, which can facilitate their use as a flexible load that stores electricity when renewable generation is abundant and decreases demand at peak times. To meet the potential of this resource, the communication interoperability between the EV charging infrastructure and the grid needs to be improved to provide maximum demand flexibility while meeting charging needs. For optimal charging control of large numbers of EVs, a hierarchical control framework can be used to manage EVs through aggregators while meeting grid needs and customer requirements.

Increasing the efficiency of electricity use is important to ensure that growth in electricity demand does not outpace expansion of renewable electricity supply. As the climate grows warmer, energy use for air conditioning will rise, and as building heating becomes electrified, heat pumps will add to demand in the winter. Innovation in vapor compression heat pumps that use refrigerants with very low global warming potential, or in non-vapor compression systems that dispense with refrigerants, is needed. Because residential lighting occurs in the evening when solar electricity generation is not available, improving lighting efficiency in homes is important. Advanced building construction technologies and techniques could facilitate the construction of net-zero-energy buildings and allow for less-costly retrofits. They could support the goal of deploying cost-effective zero-carbon or near-zero-carbon modular and manufactured homes, particularly in under-resourced communities. In addition to saving energy, advanced building construction technologies and techniques have the potential to reduce the cost of housing construction and shorten construction time. In so doing, they could play an important role in alleviating California’s housing crisis.

Electrification. Large shares of California’s CO_2 emissions come from transportation and industry, and to a lesser extent, from buildings. For buildings and light vehicles, and possibly for some industry and heavy vehicles, electrification may be the most viable way to reduce emissions. Electrification is an option for many industrial processes, especially those that require low-temperature heat, but it may be less cost-effective than use of hydrogen produced from renewable electricity or carbon capture and sequestration. Electro-technologies that improve industrial processes will be most attractive. In addition, innovations for industrial heat pumps that increase the temperature of heat supplied could greatly expand the potential market for this very efficient technology. The technical and economic barriers to electrification in the buildings sectors are much lower than in industry, but innovations that reduce the equipment and installation costs of heat pumps would help to support electrification across the income spectrum.

Reliability and resilience. As the electricity system becomes more dependent on variable generating resources and management of distributed electricity loads and storage, new approaches will be necessary to ensure that electricity is available when needed and that the system is able to withstand and recover from threats related to climate change and other forces. One promising technology area not yet widely utilized in the utility sector is machine learning and artificial intelligence. Increased application in this sector could help optimize generation, improve demand response programs, operations and maintenance of energy assets, better understand energy usage patterns, and provide better stability and efficiency of the power system. Digital enhancements of service territory landscape using virtual reality can improve situational awareness and more efficiently assess and diagnose problems in the system.

Cross-cutting areas of technology innovation. Areas of technology innovation that could have benefits across multiple sectors of the energy economy include smart manufacturing techniques, advanced materials that could improve performance and lower the cost of energy-producing and energy-using technologies, novel manufacturing techniques that could reduce energy use, recycling of various materials that could dramatically reduce the embodied energy and carbon emissions associated with materials production, and advances in computing that will have impacts in a multitude of areas. Given the leading role played by California research institutions and the private sector in many of these areas, there is an opportunity to support innovations that help build a dynamic economy and also reduce greenhouse gas emissions.

Nurturing the Innovation Pipeline

In its recent report on clean energy innovation, the International Energy Agency stated that "If governments and companies want to move more quickly towards net-zero emissions, progress on early stage technologies needs to be accelerated."[288] In the U.S., a report from the National Academies of Sciences, Engineering and Medicine on accelerating decarbonization of the energy system called for a tripling of federal investment in clean energy R&D and demonstration in order to provide new technology options, reduce costs for existing options, and better understand how to manage a socially-just energy transition.[289]

The National Academies report noted that there is a critical gap in government funding between basic research and commercialization. One method being explored is to scale up funding for entrepreneurial research fellows. This approach is showing promise in the current lab-embedded entrepreneurship program configuration, such as Cyclotron

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[288] International Energy Agency. 2020. *Clean Energy Innovation*. https://www.iea.org/reports/clean-energy-innovation.

[289] National Academies of Sciences, Engineering and Medicine. 2020. *Accelerating Decarbonization of the U.S. Energy System*. https://nap.edu/resource/25932/interactive/

Road at Lawrence Berkeley National Laboratory or Chain Reaction at Argonne National Lab. Since 2015, Cyclotron Road fellows have collaborated with more than 70 Berkeley Lab scientists, and the organizations they've founded have raised more than $315 million in follow-on funding, hired more than 330 employees, and introduced new products across industries.[290] Cyclotron Road works in close partnership with an independent non-profit, Activate, which provides specialized entrepreneurship training and a curriculum designed to help innovators bring their innovations to market.

A related tech-to-market program focuses on building technologies. IMPEL+, which stands for Incubating Market-Propelled Entrepreneurial Mindsets at the Labs and Beyond, recruits early-stage innovators, mentors them to develop strong entrepreneurial skill sets, and enables access to public and private tech-to-market pipelines.[291] IMPEL+ is funded by U.S. DOE's Building Technologies Office and implemented by LBNL.

The U.S. DOE's Energy Program for Innovation Clusters is designed to encourage the robust growth of regional energy innovation ecosystems across the U.S.[292] The program provides funds to innovation-accelerating organizations focused on stimulating energy hardware development and related supportive ecosystems.

In California, the CEC supports an initiative called the California Energy Innovation Ecosystem.[293] The ecosystem provides entrepreneurs with access to the networks, funding opportunities, mentoring, facilities, and expertise needed to take their inventions from the idea stage to the impact stage. It includes the CalSEED Initiative, which gives entrepreneurs starting capital to develop their ideas into proof-of-concepts and early prototypes. The ecosystem also includes four innovation clusters that collectively provide entrepreneurial support services —such as laboratory equipment and buildings, business plan development, and connections to investors —throughout the state. The CEC also sponsors CalTestBed, a voucher program that provides clean energy entrepreneurs access to nearly 30 testing facilities throughout the state to conduct independent technology testing and validation.

The National Academies report noted that the demonstration stage is particularly underfunded. This poses a problem because the first several large demonstrations of an emerging technology often entail a level of technical and financial risk beyond what the private sector can support. The CEC provides some support for demonstrations through its Bringing Rapid Innovation Development to Green Energy (BRIDGE) program. The BRIDGE program seeks to help clean energy start-up companies build on their previous public funding awards to attract needed private investment to move toward

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[290] https://cyclotronroad.lbl.gov/

[291] https://impel.lbl.gov/impel

[292] https://www.energy.gov/technologytransitions/energy-program-innovation-clusters

[293] https://www.energy.ca.gov/programs-and-topics/topics/research-and-development/energy-innovation-ecosystem

commercialization. Its activities include providing non-dilutive, matching investments in promising clean energy companies alongside investors and commercial partners. In 2020, awards totaling $28.8 million were given to companies working on energy efficiency, energy storage, artificial intelligence/machine learning/advanced sensing, advanced power electronics/power conditioning, and zero- and negative-carbon emission generation.

Activities to support innovation in clean energy technologies are expanding at national, international, and state levels. Private sector investment in climate tech start-ups is growing rapidly. A consequence of the growth of activity is that it can be difficult to comprehend the status of technology development and R&D. The National Academies report stated that owing to the lack of reporting, it is unclear how much firms are investing in clean energy RD&D and whether public investments duplicate private investments. The Academies committee recommended that all firms receiving funds from the government be required to report on their aggregate investments in RD&D annually, by type of investment (basic energy sciences, applied RD&D) and category (e.g., solar, wind, smart grid, fission, negative emission, efficiency). Efforts to better understand the growing universe of clean energy startups, and of activity by incubators, accelerators, venture capital, and private equity would also be helpful. Establishment of a "clearinghouse" where interested parties could find up-to-date information on current clean energy R&D in various areas would help both public and private actor to deploy their funds and other support in the most effective manner.

LIST OF ACRONYMS

Term	Definition
AEG	Autonomous energy grid
AEM	Anion exchange membrane
AI	Artificial intelligence
AI/ML	Artificial intelligence and machine learning
AM	Additive manufacturing
AMI	Advanced metering infrastructure
AMO	Advanced Manufacturing Office (DOE)
ARPA-E	Advanced Research Projects Agency-Energy
BECCS	Bio-energy power generation combined with CO_2 capture and storage
BEVs	Battery electric vehicles
CAES	Compressed air energy storage
CCS	Carbon capture and sequestration
CEC	California Energy Commission
CO_2	Carbon dioxide
COP	Coefficient of performance
CSP	Concentrating solar power
DC	Direct current
DEMs	Dynamic energy management systems
DER	Distributed energy resources
DERMS	Distributed energy resource management systems
DR	Demand response
EGS	Enhanced geothermal system
EPIC	Electric Program Investment Charge
EV	Electric vehicle
GHG	Greenhouse gas

Term	Definition
GW/GWh	Gigawatts (10^9 watts)/ Gigawatt-hours (10^9 watt-hours)
GWP	Global warming potential
H_2	Hydrogen
HVAC	Heating, ventilation and air conditioning
IGU	Insulated glass unit
kW/kWh	kilowatts (10^3 watts)/ kilowatt-hours (10^3 watt-hours)
LBNL	Lawrence Berkeley National Laboratory
LDES	Long-duration electricity storage
LED	Light emitting diode
L-ion	Lithium-ion
MPC	Model predictive control
MW/MWh	Megawatts (10^6 watts)/ megawatt-hours (10^6 watt-hours)
NREL	National Renewable Energy Laboratory
NVC	Non-vapor compression
OLED	Organic light emitting diode
PCM	Phase change materials
PEM	Proton exchange membrane
PHEVs	Plug-in hybrid electric vehicles
PMUs	Phasor measurement units
PSH	Pumped storage hydro
PV	Photovoltaic
QTR 2015	Quadrennial Technology Review 2015
R&D	Research and development
RD&D	Research, development and demonstration
RFC	Reversible fuel cell
RNG	Renewable natural gas

Term	Definition
RNG	Renewable natural gas
RTE	Round-trip efficiency
SOEC	Solid oxide electrolysis cell
SSL	Solid-state lighting
TABS	Thermally activated building system
TES	Thermal energy storage
TOU	Time-of-use
TRL	Technology Readiness Level
TWh	terawatt-hours (10^{12} watt-hours)
U.S. DOE	United States Department of Energy
V2G	Vehicle-to-grid
VCC	Vapor compression cycle
VFD	Variable frequency drive
VIPs	Vacuum-insulated panels
VSD	Variable speed drive
WBG	Wide-bandgap

REFERENCES

Abbasi, Ali, et al. 2020. "Discharge profile of a zinc-air flow battery at various electrolyte flow rates and discharge currents." *Scientific Data* 7. https://www.nature.com/articles/s41597-020-0539-y

Adler, M.W., S. Peer, and T. Sinozic. 2019. "Autonomous, connected, electric shared vehicles (ACES) and public finance: An explorative analysis." *Transp. Res. Interdiscip. Perspect.* 2: 100038. https://doi.org/10.1016/j.trip.2019.100038.

Aghajanzadeh, A., and P. Therkelsen. 2019. "Agricultural demand response for decarbonizing the electricity grid." *J. Clean. Prod.* 220: 827–835. https://doi.org/10.1016/j.jclepro.2019.02.207.

Albertus, Paul, Joseph Manser, Scott Litzelman. 2020. "Long-Duration Electricity Storage Applications, Economics, and Technologies." *Joule*, Vol. 4, Issue 1, pp. 21-32. https://doi.org/10.1016/j.joule.2019.11.009

Alimi, O., K. Ouahada, A. Abu-Mahfouz. 2020. "A Review of Machine Learning Approaches to Power System Security and Stability". IEEE Access. https://ieeexplore.ieee.org/document/9121208.

Alston, Ken, Mikela Waldman, Julie Blunden, Rebecca Lee and Alina Epriman. 2020. *Building Lithium Valley*. New Energy Nexus. https://www.newenergynexus.com/wp-content/uploads/2020/10/New-Energy-Nexus_Building-Lithium-Valley.pdf

Alstone, P., J. Potter, and M. A. Piette. 2017. *2025 California Demand Response Potential Study - Charting California's Demand Response Future: Final Report on Phase 2 Results.* Lawrence Berkeley National Laboratory, LBNL-2001113.

Al-Yasiri, Q., and M. Szabó. 2021. "Incorporation of phase change materials into building envelope for thermal comfort and energy saving: A comprehensive analysis." *Journal of Building Engineering*, Vol. 36*.* https://doi.org/10.1016/j.jobe.2020.102122.

Amy, Caleb, et al. 2019. "Thermal energy grid storage using multi-junction photovoltaics." *Energy Environ. Sci*., 12, 334. https://pubs.rsc.org/en/content/articlelanding/2019/ee/c8ee02341g#!divAbstract

Antonopoulos, I., et al. 2020. "Artificial intelligence and machine learning approaches to energy demand-side response: A systematic review." *Renewable and Sustainable Energy Reviews*, Vol. 130.

Antonopoulus, I. et al. 2020. "Artificial intelligence and machine learning approaches to energy demand-side response: A systematic review". *Renewable and Sustainable*

Energy Reviews, Volume 130, September 2020, 109899. https://www.sciencedirect.com/science/article/pii/S136403212030191X

Armstrong, Kristina, Sujit Das and Laura Marlino. April 2017. *Wide Bandgap Semiconductor Opportunities in Power Electronics*. Oak Ridge National Laboratory. https://info.ornl.gov/sites/publications/Files/Pub104869.pdf

Arpagaus, Cordin, et al. 2018. "High Temperature Heat Pumps: Market Overview, State of the Art, Research Status, Refrigerants, and Application Potentials". International Refrigeration and Air Conditioning Conference. Paper 1876. https://docs.lib.purdue.edu/iracc/1876

Bai, F., et al. 2016. "A measurement-based approach for power system instability early warning". *Protection and Control of Modern Power Systems*. Vol 1 (4).

Balaji, B., A. Bhattacharya, G. Fierro, J. Gao, J. Gluck, D. Hong, A. Johansen, et al. 2016. Brick: Towards a unified metadata schema for buildings. Proc. 3rd ACM Conf. Syst. Energy-Efficient Built Environ. BuildSys 41–50. https://doi.org/10.1145/2993422.2993577.

Balazs, C., et al. 2021. *Achieving the Human Right to Water in California: An Assessment of the State's Community Water Systems*. California Environmental Protection Agency. https://oehha.ca.gov/media/downloads/water/report/hrtwachievinghrtw2021f.pdf

Berkeley Lab Cybersecurity R&D. 2020. Cybersecurity for Energy Delivery Systems Projects. https://dst.lbl.gov/security/research/ceds/

Bhave, Amit, et al. 2017. "Screening and techno-economic assessment of biomass-based power generation with CCS technologies to meet 2050 CO_2 targets". *Applied Energy* 190 pp. 481–489.

Blum, D., and M. Wetter. 2017. "MPCPy: An Open-Source Software Platform for Model Predictive Control in Buildings". *Proc. 15th Conf. Int. Build. Perform. Simul.*

Brown, R., P. Schwartz, B. Nordman, J. Shackelford, A. Khandekar, N. Jackson, A. Prakash, et al. 2019. *Developing Flexible, Networked Lighting Control Systems That Reliably Save Energy in California Buildings.* California Energy Commission. https://eta.lbl.gov/publications/developing-flexible-networked

Brown, Rich, Peter Schwartz, Bruce Nordman, Jordan Shackelford, Aditya Khandekar, Erik Page, Neal Jackson, et al. 2019. *Developing Flexible, Networked Lighting Control Systems That Reliably Save Energy in California Buildings*. California Energy Commission. https://escholarship.org/uc/item/4ck0216d

California Public Utilities Commission. "The Benefits of Smart Meters". https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/infrastructure/the-benefits-of-smart-meters

Chandrappa, N. and S. Banerjee. 2017. "The Next Generation of Power Quality Monitoring Technology—Helping Industrial Equipment Stay Healthy". https://www.analog.com/media/en/technical-documentation/tech-articles/The-Next-Generation-of-Power-Quality-Monitoring-Technology-Helping-Industrial-Equipment-Stay-Healthy.pdf

Chertkov, M. 2017. "Advanced Machine Learning for Synchrophasor Technology". https://www.energy.gov/sites/prod/files/2017/07/f35/9.%20Chertkov%20GMLC%200077%20June%2013%202017.pdf

Chhaya, Sunil. 2020. "Comprehensive Assessment of On- and Off-Board V2G Technology Performance on Battery and the Grid". 2020 U.S. Department of Energy Vehicle Technologies Office Annual Merit Review. https://www.energy.gov/sites/prod/files/2020/06/f75/elt187_chhaya_2020_o_5.12.20_1106AM_LR.pdf

Cho, Kyu Taek, Michael C. Tucker, and Adam Z. Weber. 2016. "A Review of Hydrogen/Halogen Flow Cells". *Energy Technology*, 4, 655-678. https://doi.org/10.1002/ente.201500449

Choi, S. et al. 2018. "Review: Recent advances in household refrigerator cycle technologies". *Applied Thermal Engineering* 132 pp. 560–574.

Chung, W.J., S.H. Park, M.S. Yeo, and K.W. Kim. 2017. "Control of thermally activated building system considering zone load characteristics." *Sustainability* 9: 1–14. https://doi.org/10.3390/su9040586

Clement, R.J., Z. Lun and G. Ceder. 2020. "Cation-disordered rocksalt transition metal oxides and oxyfluorides for high energy lithium-ion cathodes". *Energy Environ. Sci.,* 13,345-373*.* https://pubs.rsc.org/en/content/articlehtml/2020/ee/c9ee02803j

Cohen, Armond, et al. 2021. "Clean Firm Power is the Key to California's Carbon-Free Energy Future." *Issues in Science and Technology*. https://issues.org/california-decarbonizing-power-wind-solar-nuclear-gas/

Compressed Air Energy Storage: The Path to Innovation. 2019. Chinese Academy of Sciences. http://en.cnesa.org/latest-news/2019/9/29/compressed-air-energy-storage-becoming-a-leading-energy-storage-technology

Corbus, D., et al. 2018. *Transforming the U.S. Market with a New Application of Ternary-Type Pumped-Storage Hydropower Technology*, Preprint. NREL. https://www.nrel.gov/docs/fy18osti/71522.pdf

De Luna, P., C. Hahn, D. Higgins, S. Jaffer, T. Jaramillo. 2019. "What would it take for renewably powered electrosynthesis to displace petrochemical processes?". *Science* 26 Apr 2019: Vol. 364, Issue 6438, https://doi.org/10.1126/science.aav3506

DeForest, N., J. S. MacDonald, and D. R. Black. 2018. "Day ahead optimization of an electric vehicle fleet providing ancillary services in the Los Angeles Air Force Base vehicle-to-grid demonstration." *Appl. Energy* 210: 987–1001. https://doi.org/10.1016/j.apenergy.2017.07.069.

Denholm, Paul, Wesley Cole, A. Will Frazier, Kara Podkaminer, and Nate Blair. 2021. *The Four Phases of Storage Deployment: A Framework for the Expanding Role of Storage in the U.S. Power System*. National Renewable Energy Laboratory. NREL/TP-6A20-77480. https://www.nrel.gov/docs/fy21osti/77480.pdf

Dowling, Jacqueline, et al. 2020. "Role of Long-Duration Energy Storage in Variable Renewable Electricity Systems". *Joule*, Vol. 4, 1-22. https://doi.org/10.1016/j.joule.2020.07.007.

Drgoňa, J., J. Arroyo, I. Cupeiro, D. Figueroa, K. Blum, D. Arendt, E.P. Kim, et al. 2020. "All you need to know about model predictive control for buildings". *Annu. Rev. Control* https://doi.org/10.1016/j.arcontrol.2020.09.001.

Dutton, S. 2019. Hybrid HVAC with Thermal Energy Storage Research and Demonstration. 2019 BTO Peer Review.

Dykes, Katherine, et al. 2017. *Enabling the SMART Wind Power Plant of the Future Through Science-Based Innovation*. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy17osti/68123.pdf

Dyson, M. and B. Li. 2020. "Reimagining Grid Resilience: A Framework for Addressing Catastrophic Threats to the US Electricity Grid in an Era of Transformational Change". https://rmi.org/insight/reimagining-grid-resilience/

Eggimann, S., et al. 2017. "The Potential of Knowing More: A Review of Data-Driven Urban Water Management." *Environmental Science & Technology* 51 (5): 2538–53. https://doi.org/10.1021/acs.est.6b04267.

Ellis, Leah, et al. 2020. "Toward electrochemical synthesis of cement—An electrolyzer-based process for decarbonating $CaCO_3$ while producing useful gas streams". *PNAS* 117 (23) 12584-12591. https://www.pnas.org/content/117/23/12584

Energy and Environmental Economics. 2020. *Achieving Carbon Neutrality in California: PATHWAYS Scenarios Developed for the California Air Resources Board*. https://ww2.arb.ca.gov/sites/default/files/2020-10/e3_cn_final_report_oct2020_0.pdf

Fierro, G., and D. E. Culler. 2015. Poster abstract: XBOS: An eXtensible Building Operating System. BuildSys 2015 - Proc. 2nd ACM Int. Conf. Embed. Syst. Energy-Efficient Built, 119–120. https://doi.org/10.1145/2821650.2830311.

Florida Power and Light. 2020. Advanced Smart Grid Technology. https://www.fpl.com/smart-meters/smart-grid.html

Foote, A. et al. 2019. System design of dynamic wireless power transfer for automated highways. IEEE Transportation Electrification Conference and Expo.

Friend, C.M., and B. Xu 2017. "Heterogeneous catalysis: a central science for a sustainable future." *Acc. Chem. Res*. 50, 517–521.

Fyke, Aaron. 2019. The Fall and Rise of Gravity Storage Technologies. *Joule* 3, 620–630. https://www.cell.com/joule/pdf/S2542-4351(19)30041-8.pdf

Ganeshalingam, M., Arman Shehabi, Louis-Benoit Desroche. 2017. *Shining a Light on Small Data Centers in the U.S*. Lawrence Berkeley National Laboratory. https://eta-publications.lbl.gov/sites/default/files/lbnl-2001025.pdf

García, L., L. Parra, J. M. Jimenez, J. Lloret, and P. Lorenz. 2020. "IoT-based smart irrigation systems: An overview on the recent trends on sensors and IoT systems for irrigation in precision agriculture." *Sensors (Switzerland)* 20. https://doi.org/10.3390/s20041042.

Garrido-Baserba, M. et al. 2020. "The Fourth-Revolution in the Water Sector Encounters the Digital Revolution." *Environmental Science & Technology* 54 (8): 4698–4705.

Gehbauer, C., D. H. Blum, T. Wang, and E. S. Lee. 2020. "An assessment of the load modifying potential of model predictive controlled dynamic facades within the California context." *Energy Build.* 210: 109762. https://doi.org/10.1016/j.enbuild.2020.109762.

Gerke, B. F., G. Gallo, S. J. Smith, J. Liu, P. Alstone, S. Raghavan, P. Schwartz, et al. 2020. *The California Demand Response Potential Study, Phase 3: Final Report on the Shift Resource through 2030*. Lawrence Berkeley National Laboratory. https://doi.org/10.20357/B7MS40.

Giubbolini, Luigi. 2020. *Grid Communication Interface for Smart Electric Vehicle Services*. California Energy Commission. CEC-500-2020-028.

GridWise Architecture Council. 2018. *Transactive Energy Systems Research, Development and Deployment Roadmap*. Pacific Northwest National Laboratory, PNNL-26778.

GTM Creative Strategies. 2020. "Storing Energy in the Freezer: Long-Duration Thermal Storage Comes of Age." https://www.greentechmedia.com/articles/read/storing-energy-in-the-freezer-long-duration-thermal-storage-comes-of-age.

Guerrero-Prado, J. et al. 2020. "The Power of Big Data and Data Analytics for AMI Data: A Case Study." *Sensors* v20 (11). https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7309066/

Han, D. et al. 2017. "Dynamic energy management in smart grid: A fast randomized first-order optimization algorithm." *International Journal of Electrical Power & Energy Systems*, Volume 94, 2018. https://doi.org/10.1016/j.ijepes.2017.07.003.

Hauch, A. et al. 2020. Recent advances in solid oxide cell technology for electrolysis. *Science* 09 Oct 2020: Vol. 370, Issue 6513. https://science.sciencemag.org/content/370/6513/eaba6118

Heiemann, Niklas, et al. 2021. "Enabling large-scale hydrogen storage in porous media – the scientific challenges." *Energy Environ. Sci.*, Issue 2, 2021. https://pubs.rsc.org/en/content/articlelanding/2021/EE/D0EE03536J#!divAbstract

Huang, Heming, et al. 2018. Robust Bad Data Detection Method for Microgrid Using Improved ELM and DBSCAN Algorithm. https://ascelibrary.org/doi/10.1061/%28ASCE%29EY.1943-7897.0000544

IEEE Smart Grid Big Data Analytics, Machine Learning and Artificial Intelligence in the Smart Grid Working Group. Big Data Analytics in the Smart Grid. https://smartgrid.ieee.org/images/files/pdf/big_data_analytics_white_paper.pdf

Itron. 2020. Itron and Innowatts Collaborate to Deliver AI-Powered AMI Predictive Insights to Electric Utilities. https://www.itron.com/cn/company/newsroom/2020/01/28/itron-and-innowatts-collaborate.

Jiang, H. et al. 2017. Big Data-Based Approach to Detect, Locate, and Enhance the Stability of an Unplanned Microgrid Islanding. https://ascelibrary.org/doi/10.1061/%28ASCE%29EY.1943-7897.0000473

Jiang, Z., J. Cai, P. Hlanze, and H. Zhang. 2020. "Optimized Control of Phase Change Material-Based Storage Integrated in Building Air-Distribution Systems." Proc. Am. Control Conf. 4225–4230. https://doi.org/10.23919/ACC45564.2020.9147514.

Jiang, Z., J. Cai, P. Hlanze, H. Zhang. 2020. "Optimized Control of Phase Change Material-Based Storage Integrated in Building Air-Distribution Systems." *2020 American Control Conference,* pp. 4225-4230, https://doi.org/10.23919/ACC45564.2020.9147514.

Jin, W., J. Ma, C. Bi, Z. Wang, C. B. Soo, and P. Gao. 2020. "Dynamic variation in dew-point temperature of attached air layer of radiant ceiling cooling panels." *Build. Simul.* 13: 1281–1290. https://doi.org/10.1007/s12273-020-0645-y.

Joshi, N. 2019. AR And VR in the Utility Sector. https://www.forbes.com/sites/cognitiveworld/2019/09/29/ar-and-vr-in-the-utility-sector/?sh=2621bd0966a1

Joshi, P. 2016. *Low-cost Manufacturing of Wireless Sensors for Building*. Oak Ridge National Laboratory.

Júnior, F. et al. 2018. "Design and Performance of an Advanced Communication Network for Future Active Distribution Systems." *Journal of Energy Eng*. Vol 144 (3). https://ascelibrary.org/doi/pdf/10.1061/%28ASCE%29EY.1943-7897.0000530

Kaur, K., N. Kumar, and M. Singh. 2018. "Coordinated power control of electric vehicles for grid frequency support: MILP-based hierarchical control design." *IEEE Transactions on Smart Grid* 10(3)*.* https://ieeexplore.ieee.org/document/8334637

Kaur, S., M. Bianchi, N. James, L. Berkeley, S. Kaur, M. Bianchi, and N. James. 2020. 2019 Workshop on Fundamental Needs for Dynamic and Interactive Thermal Storage Solutions for Buildings.

Kenway, S.J. et al. 2019. "Defining Water-Related Energy for Global Comparison, Clearer Communication, and Sharper Policy." *Journal of Cleaner Production* 236 (November): 117502. https://doi.org/10.1016/j.jclepro.2019.06.333.

Kosmanos, D. et al. 2018. "Route optimization of electric vehicles based on dynamic wireless charging." *IEEE Access* 6: 42551–65.

Kuga, R. et al. 2019. Electric Program Investment Charge (EPIC), EPIC 2.02 – Distributed Energy Resource Management System; EPIC 2.02 DERMS. Grid Integration and Innovation. Pacific Gas & Electric. https://www.pge.com/pge_global/common/pdfs/about-pge/environment/what-we-are-doing/electric-program-investment-charge/PGE-EPIC-2.02.pdf

Laporte, S., G. Coquery, V. Deniau, A. De Bernardinis, and N. Hautière. 2019. "Dynamic wireless power transfer charging infrastructure for future EVs: From experimental track to real circulated roads demonstrations." *World Electr. Veh. J.* 10: 1–22. https://doi.org/10.3390/wevj10040084.

Le Floch, C., S. Bansal, C. J. Tomlin, S. J. Moura, and M. N. Zeilinger. 2019. "Plug-and-play model predictive control for load shaping and voltage control in smart grids." *IEEE Trans. Smart Grid* 10: 2334–2344. https://doi.org/10.1109/TSG.2017.2655461.

Lee, E.S., D.C. Curcija, T. Wang, C. Gehbauer, L. Fernandes, R. Hart, D. Blum, et al. 2020. *High-Performance Integrated Window and Façade Solutions for California*. California Energy Commission. Publication Number: CEC-500-2020-001. https://www.energy.ca.gov/publications/2020/high-performance-integrated-window-and-facade-solutions-california

Li, G. et al. 2018. Direct vehicle-to-vehicle charging strategy in vehicular ad-hoc networks. In: 2018 9th IFIP International Conference on New Technologies, Mobility and Security.

Li, Zheng, et al., 2017. Air-Breathing Aqueous Sulfur Flow Battery for Ultra low-Cost Long-Duration Electrical Storage, *Joule* 1, 306–327. https://doi.org/10.1016/j.joule.2017.08.007

Lian, J., Y. Sun, K. Kalsi, S. E. Widergren, D. Wu, and H. Ren. 2018. Transactive System: Part II: Analysis of Two Pilot Transactive Systems Using Foundational Theory and Metrics. Pacific Northwest National Laboratory, PNNL-27235.

Licht, Stuart. March 2017. Co-production of cement and carbon nanotubes with a carbon negative footprint. *Journal of* CO_2 *Utilization*, Volume 18, pp. 378-389. https://www.sciencedirect.com/science/article/abs/pii/S2212982016302852

Lin, Yashen, Joseph H. Eto, Brian B. Johnson, Jack D. Flicker, Robert H. Lasseter, Hugo N. Villegas Pico, et al. 2020. *Research Roadmap on Grid-Forming Inverters*. National Renewable Energy Laboratory. NREL/TP-5D00-73476. https://www.nrel.gov/docs/fy21osti/73476.pdf.

Ma, Z., D. S. Callaway, and I. A. Hiskens. 2013. "Decentralized charging control of large populations of plug-in electric vehicles." *IEEE Trans Control Syst Technol* 21(1): 67–78.

Mahone, Amber, Zachary Subin, Gabe Mantegna, Rawley Loken, Clea Kolster. 2020. *Achieving Carbon Neutrality in California: PATHWAYS Scenarios Developed for the California Air Resources Board*. Energy and Environmental Economics. https://ww2.arb.ca.gov/sites/default/files/2020-10/e3_cn_final_report_oct2020_0.pdf

Mahone, Amber, Zachary Subin, Jenya Kahn-Lang, Douglas Allen, Vivian Li, Gerrit De Moor, Nancy Ryan, et al. 2018. *Deep Decarbonization in a High Renewables Future: Updated Results from the California PATHWAYS Model.* California Energy Commission. Publication Number: CEC-500-2018-012. https://www.energy.ca.gov/publications/2018/deep-decarbonization-high-renewables-future-updated-results-california-pathways

Mauter, Meagan and P. Fiske. 2020. "Desalination for a Circular Water Economy." *Energy & Environmental Science*, Issue 10. https://doi.org/10.1039/D0EE01653E.

Mayyas, Ahmad and Margaret Mann, Emerging Manufacturing Technologies for Fuel Cells and Electrolyzers, *Procedia Manufacturing* 33 (2019) 508–515. https://doi.org/10.1016/j.promfg.2019.04.063

Mehos, Mark, et al. 2017. *Concentrating Solar Power Gen3 Demonstration Roadmap*. National Renewable Energy Laboratory. https://www.energy.gov/sites/prod/files/2017/04/f34/67464.pdf

Meier, Alan, Richard Brown, Daniel L. Gerber, Aditya Khandekar, Margarita Kloss, Hidemitsu Koyanagi, Richard Liou, et al. September 2020. *Efficient and Zero Net Energy-Ready Plug Loads*. California Energy Commission. https://ww2.energy.ca.gov/2020publications/CEC-500-2020-068/CEC-500-2020-068.pdf

Miller, Hamish, et al. 2020. Green hydrogen from anion exchange membrane water electrolysis: a review of recent developments in critical materials and operating conditions. *Sustainable Energy Fuels*, 4, 2114-2133. https://pubs.rsc.org/en/content/articlelanding/2020/se/c9se01240k#!divAbstract

Moeini-Aghtaie, M. et al. 2013. PHEVs centralized/decentralized charging control mechanisms: requirements and impacts. In: North American Power Symposium (NAPS).

Mongird, Kendall, Vilayanur Viswanathan, Jan Alam, Charlie Vartanian, Vincent Sprenkle. December 2020. *2020 Grid Energy Storage Technology Cost and Performance Assessment*. PNNL Publication No. DOE/PA-0204. https://www.pnnl.gov/sites/default/files/media/file/Final%20-%20ESGC%20Cost%20Performance%20Report%2012-11-2020.pdf

Morya, A.K., et al. March 2019. "Wide Bandgap Devices in AC Electric Drives: Opportunities and Challenges," *IEEE Transactions on Transportation Electrification*, vol. 5, no. 1, pp. 3-20. doi: 10.1109/TTE.2019.2892807.

Mumme, S., N. James, M. Salonvaara, S. Shrestha, D. Hun. 2020. "Smart and efficient building envelopes: Thermal switches and thermal storage for energy savings and load flexibility." *ASHRAE Transactions*, 126, 140–148.

Murphy, Caitlin, Yinong Sun, Wesley Cole, Galen Maclaurin, Craig Turchi, and Mark Mehos. 2019. *The Potential Role of Concentrating Solar Power within the Context of DOE's 2030 Solar Cost Target*. National Renewable Energy Laboratory. NREL/TP-6A20-71912. https://www.nrel.gov/docs/fy19osti/71912.pdf

National Fuel Cell Research Center. March 2020. *California Stationary Fuel Cell Roadmap*. National Fuel Cell Research Center, UC Irvine. http://www.nfcrc.uci.edu/PDF_White_Papers/California_Stationary_Fuel_Cell_Roadmap_Long_Version_062420.pdf

Navigant Consulting. 2006. *Refining Estimates of Water-Related Energy Use in California*. California Energy Commission, CEC-500-2006-118.

Newsham, G. R., S. Mancini, and R.G. Marchand. 2008. "Detection and Acceptance of Demand-Responsive Lighting in Offices with and without Daylight." *LEUKOS* 4(3). http://doi.org/10.1582/LEUKOS.2007.004.03.001.

Nguyen, H., C. Zhang, J. Zhang, and L.B. Le. 2017. "Hierarchical control for electric vehicles in smart grid with renewables." In *Proceedings of the 13th IEEE International Conference on Control Automation*, 898–903. https://doi.org/10.1109/ICCA.2017.8003180.

NREL. 2018. Valuing the Resilience Provided by Solar and Battery Energy Storage Systems. https://www.nrel.gov/docs/fy18osti/70679.pdf

Nunes, C. 2019. Artificial intelligence can make the U.S. electric grid smarter. https://www.anl.gov/article/artificial-intelligence-can-make-the-us-electric-grid-smarter

Oldenburg, Curtis and Lehua Pan. 2013. Porous Media Compressed-Air Energy Storage (PM-CAES): Theory and Simulation of the Coupled Wellbore–Reservoir System. *Transp Porous Med* 97:201–221. DOI 10.1007/s11242-012-0118-6

Olgyay, Victor, Seth Coan, Brett Webster, and William Livingood. 2020. *Connected Communities: A Multi-Building Energy Management Approach.* National Renewable Energy Laboratory. NREL/TP-5500-75528. https://www.nrel.gov/docs/fy20osti/75528.pdf.

Pabi, S., et al. 2013. Electricity Use and Management in the Municipal Water Supply and Wastewater Industries. Electric Power Research Institute.

Paliaga, G., F. Farahmand, and P. Raftery. 2017. TABS Radiant Cooling Design and Control in North America: Results from Expert Interviews. Center for the Built Environment, UC Berkeley.

Paul, B. and J. Andrews. 2017. PEM unitised reversible/regenerative hydrogen fuel cell systems: State of the art and technical challenges. *Renewable and Sustainable Energy Reviews*, Volume 79, pp. 585-599.

Peisert, S. and D. Arnold. 2018. Cybersecurity via Inverter-Grid Automated Reconfiguration (CIGAR). https://www.energy.gov/sites/prod/files/2018/12/f58/LBNL%20-%20CIGAR.PDF

Peng, J., D. C. Curcija, A. Thanachareonkit, E. S. Lee, H. Goudey, and S. E. Selkowitz. 2019. "Study on the overall energy performance of a novel c-Si based semitransparent solar photovoltaic window." *Appl. Energy* 242: 854–872. https://doi.org/10.1016/j.apenergy.2019.03.107.

Perry, Michael L. and Adam Z. Weber, 'Advanced Redox Flow Batteries: A Perspective,' *Journal of the Electrochemical Society*, 163 (1), A5064-A5067 (2016). https://doi.org/10.1149/2.0101601jes

PG&E. 2021. Electric Program Investment Charge Project Reports. https://www.pge.com/en_US/about-pge/environment/what-we-are-doing/electric-program-investment-charge/closeout-reports.page

Piette, M. A. Hierarchical Occupancy-Responsive Model Predictive Control (MPC) at Room, Building and Campus Levels 1–24. Lawrence Berkeley National Laboratory. https://www.energy.gov/eere/buildings/downloads/hierarchical-occupancy-responsive-model-predictive-control-mpc-room

Pillai, J. R., S. H. Huang, B. Bak-Jensen, P. Mahat, P. Thogersen, and J. Moller. 2013. "Integration of solar photovoltaics and electric vehicles in residential grids." *IEEE Power Energy Soc. Gen. Meet.* https://doi.org/10.1109/PESMG.2013.6672215.

PJM. 2020. Synchrophasor Technology Improves Grid Visibility. https://www.pjm.com/-/media/about-pjm/newsroom/fact-sheets/synchrophasor-technology.ashx?la=en

Pouyanfar, Samira, et al. 2108. A Survey on Deep Learning: Algorithms, Techniques, and Applications. https://www2.cs.duke.edu/courses/cps274/compsci527/spring20/papers/Pouyanfar.pdf

Prasher, R. S., R. Jackson, and C. Dames. 2019. Solid State Tunable Thermal Energy Storage and Switches for Smart Building Envelopes. 2019 BTO Peer Review. https://www.energy.gov/sites/default/files/2019/05/f62/bto-peer%E2%80%932019-lbnl-nrel-solid-state-tunable-tes.pdf

Rabaey, K., T. Vandekerckhove, A. v.d.Walle, and D. L. Sedlak. 2020. "The Third Route: Using Extreme Decentralization to Create Resilient Urban Water Systems." *Water Research* 185 (October): 116276.

Redman, T. C. 2018. If Your Data Is Bad, Your Machine Learning Tools Are Useless. https://hbr.org/2018/04/if-your-data-is-bad-your-machine-learning-tools-are-useless

Regmi, Y., et al. 2020. A low temperature unitized regenerative fuel cell realizing 60% round trip efficiency and 10 000 cycles of durability for energy storage applications. *Energy & Environmental Science,* Issue 7. https://pubs.rsc.org/en/content/articlelanding/2020/EE/C9EE03626A#!divAbstract

Rightor, E., A. Whitlock, and R. Neal Elliot. July 2020. *Beneficial Electrification in Industry*. American Council for an Energy-Efficient Economy. https://www.aceee.org/research-report/ie2002

Roberts, C., et al. 2019. Learning Behavior of Distribution System Discrete Control Devices for Cyber-Physical Security. https://www.cs.ucdavis.edu/~peisert/research/2019-TSG-Infer-Control.pdf

Robertson, R. 2020. Advanced Synchrophasor Protocol Development and Demonstration Project. https://www.osti.gov/biblio/1597102

Sarwar, S., S. Park, T.T. Dao, M.-soo Lee, A. Ullah, S. Hong, and C.H. Han. 2020. "Scalable photo electrochromic glass of high performance powered by ligand attached TiO_2 photoactive layer." *Sol. Energy Mater. Sol. Cells* 210: 110498. https://doi.org/10.1016/j.solmat.2020.110498.

Sathe, Amul, Andrea Romano, Bruce Hamilton, Debyani Ghosh, Garrett Parzygno. (Guidehouse). 2020. *Research and Development Opportunities for Offshore Wind Energy in California*. California Energy Commission. Publication Number: CEC-500-2020-053. https://ww2.energy.ca.gov/2020publications/CEC-500-2020-053/CEC-500-2020-053.pdf

Schiffer, Zachary J. and Karthish Manthiram. 2017. Electrification and Decarbonization of the Chemical Industry. *Joule* 1, 10–14.

Schmidt, Oliver, Sylvain Melchior, Adam Hawkes, Iain Staffell. 2019. Projecting the Future Levelized Cost of Electricity Storage Technologies. *Joule*, Vol. 3, Issue 1, pp. 81-100. https://www.sciencedirect.com/science/article/pii/S254243511830583X?via%3Dihub

Schwartz, Harrison, Sabine Brueske. 2020. *Utility-Scale Renewable Energy Generation Technology Roadmap*. California Energy Commission. Publication Number: CEC-500-2020-062. https://www.energy.ca.gov/publications/2020/utility-scale-renewable-energy-generation-technology-roadmap

Schwartz, Lisa, Max Wei, William R Morrow, III, Jeff Deason, Steven R Schiller, Greg Leventis, Sarah Josephine Smith, et al. 2017*. Electricity End Uses, Energy Efficiency, and Distributed Energy Resources Baseline*. Lawrence Berkeley National Laboratory. https://emp.lbl.gov/publications/electricity-end-uses-energy

Scott, D., R. Castillo, K. Larson, B. Dobbs, and D. Olsen. 2015. *Refrigerated Warehouse Demand Response Strategy Guide.* Lawrence Berkeley National Laboratory. LBNL-1004300.

SEAB AIML Working Group. 2020. Preliminary findings of the SEAB to Secretary of Energy Dan Brouillette regarding the Department of Energy and Artificial Intelligence. https://www.energy.gov/sites/prod/files/2020/04/f73/SEAB%20AI%20WG%20PRELIMINARY%20FINDINGS_0.pdf

Sepulveda, N.A., J.D. Jenkins, A. Edington, D.S. Mallapragada, and R.K. Lester. 2021. The design space for long-duration energy storage in decarbonized power systems. *Nature Energy* 6, 506–516. https://doi.org/10.1038/s41560-021-00796-8

Snyder, G. Jeffrey, et al., 2021. Distributed and localized cooling with thermoelectrics. *Joule,* Vol. 5, Issue 4. DOI: https://doi.org/10.1016/j.joule.2021.02.011

Starke, M., J. Munk, H. Zandi, T. Kuruganti, H. Buckberry, J. Hall, and J. Leverette. 2020. Real-time MPC for residential building water heater systems to support the electric grid. 2020 IEEE Power Energy Soc. Innov. Smart Grid Technol. Conf. https://doi.org/10.1109/ISGT45199.2020.9087716.

Strategen Consulting. 2020. *Long Duration Energy Storage for California's Clean, Reliable Grid*. https://www.storagealliance.org/longduration.

Stringfellow, William and Patrick Dobson. 2021. Technology for Lithium Extraction in the Context of Hybrid Geothermal Power. PROCEEDINGS, 46th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 15-17, 2021.

Synapse Energy Economics. 2018. *Decarbonization of Heating Energy Use in California Buildings*. https://www.synapse-energy.com/sites/default/files/Decarbonization-Heating-CA-Buildings-17-092-1.pdf

Taibi, E., C. Fernández del Valle, and M. Howells. 2018. "Strategies for solar and wind integration by leveraging flexibility from electric vehicles: The Barbados case study." *Energy* 164: 65–78. https://doi.org/10.1016/j.energy.2018.08.196.

Tian, Xueyu, S. Stranks, F. You. 2020. Life cycle energy use and environmental implications of high-performance perovskite tandem solar cells. *Science Advances* Vol. 6, no. 31. https://advances.sciencemag.org/content/6/31/eabb0055.full

Tian, Yaosen, et al. 2021. Promises and Challenges of Next-Generation "Beyond Li-ion" Batteries for Electric Vehicles and Grid Decarbonization. *Chemical Reviews* 2021, 121, 3, 1623–1669. https://doi.org/10.1021/acs.chemrev.0c00767

Totu, L.C., J. Leth, and R. Wisniewski. 2013. "Control for large scale demand response of thermostatic loads." *Proc. Am. Control Conf.* 5023–5028. https://doi.org/10.1109/acc.2013.6580618.

Trahey, Lynn, F. Brushett, N. Balsara, G. Ceder, L. Cheng, et al. 2020. Energy storage emerging: A perspective from the Joint Center for Energy Storage Research. *PNAS* 117 (23) 12550-12557. https://www.pnas.org/content/117/23/12550#sec-2

Traube, J., F. Lu, D. Maksimovic, J. Mossoba, M. Kromer, P. Faill, S. Katz, et al. 2013. "Mitigation of solar irradiance intermittency in photovoltaic power systems with integrated electric-vehicle charging functionality." *IEEE Trans. Power Electron.* 28: 3058–3067. https://doi.org/10.1109/TPEL.2012.2217354.

Tucker, Michael C., Alexandra Weiss, and Adam Z. Weber. 2016. 'Improvement and analysis of the hydrogen cerium redox flow cell,' *Journal of Power Sources*, 327, 591-598 https://doi.org/10.1016/j.jpowsour.2016.07.105

Tucker, Michael, Venkat Srinivasan, Philip N. Ross, and Adam Z. Weber. 2013. 'Performance and Cycling of the Iron-Ion/Hydrogen Redox Flow Cell with Various Catholyte Salts', *Journal of Applied Electrochemistry*, 43, 637-644. https://doi.org/10.1007/s10800-013-0553-2

U.S. Department of Energy. 2019. *Grid-interactive Efficient Buildings Technical Report Series - Lighting and Electronics*. https://www.energy.gov/eere/buildings/downloads/grid-interactive-efficient-buildings-technical-report-series-lighting-and

U.S. Department of Energy. 2020. *Grid-interactive Efficient Buildings: Projects Summary*. https://www.energy.gov/sites/prod/files/2020/09/f79/bto-geb-project-summary-093020.pdf.

U.S. Department of Energy. December 2020. *Energy Storage Grand Challenge Roadmap*. https://www.energy.gov/energy-storage-grand-challenge/downloads/energy-storage-grand-challenge-roadmap

U.S. Department of Energy. *Technology Readiness Assessment Guide*. https://www2.lbl.gov/dir/assets/docs/TRL%20guide.pdf

U.S. Department of Energy. 2016. *Advanced Manufacturing Office Multi-Year Program Plan*, Draft. https://www.energy.gov/sites/prod/files/2017/01/f34/Draft%20Advanced%20Manufacturing%20Office%20MYPP_1.pdf

U.S. Department of Energy. 2017a. *RD&D Opportunities for Commercial Buildings HVAC Systems*. https://www.energy.gov/sites/prod/files/2017/12/f46/bto-DOE-Comm-HVAC-Report-12-21-17.pdf

U.S. Department of Energy. 2017b. *Transforming the National Electricity System: the 2nd Installment of the Quadrennial Energy Review*. https://www.energy.gov/sites/prod/files/2017/02/f34/Quadrennial%20Energy%20Review--Second%20Installment%20%28Full%20Report%29.pdf

U.S. Department of Energy. 2018. *Wind Vision Detailed Roadmap Actions, 2017 Update*. https://www.energy.gov/sites/prod/files/2018/05/f51/WindVision-Update-052118-web_RMB.pdf

U.S. Department of Energy. December 2019. *Energy Savings Forecast of Solid State Lighting in General Illumination Applications*. https://www.energy.gov/sites/prod/files/2020/02/f72/2019_ssl-energy-savings-forecast.pdf

U.S. Department of Energy. January 2020. *2019 Lighting R&D Opportunities*. https://www.energy.gov/sites/prod/files/2020/01/f70/ssl-rd-opportunities2-jan2020.pdf

U.S. Department of Energy. May 2020a. DRAFT *Research and Development Opportunities Report for Opaque Building Envelopes*. https://www.energy.gov/eere/buildings/downloads/research-and-development-opportunities-report-opaque-building-envelopes

U.S. Department of Energy. May 2020b. DRAFT *Research and Development Opportunities Report for Windows*. https://www.energy.gov/eere/buildings/downloads/research-and-development-opportunities-report-windows

U.S. Department of Energy. February 2022. *2022 Solid-State Lighting R&D Opportunities*. https://www.energy.gov/sites/default/files/2022-02/2022-ssl-rd-opportunities.pdf

U.S. Department of Energy. *Quadrennial Technology Review 2015*, "Advanced Sensors, Controls, Platforms and Modeling for Manufacturing." https://www.energy.gov/sites/default/files/2015/11/f27/QTR2015-6C-Advanced-Sensors-Controls-Platforms-and-Modeling-for-Manufacturing.pdf

U.S. Department of Energy. *Quadrennial Technology Review 2015*, "Appendix 6G: Direct Thermal Energy Conversion Materials, Devices, and Systems." https://www.energy.gov/sites/prod/files/2015/12/f27/QTR2015-6G-Direct-Thermal-Energy-Conversion-Materials-Devices-and-Systems.pdf

U.S. Department of Energy. *Quadrennial Technology Review 2015*, "Appendix 6I: Process Heating." https://www.energy.gov/sites/prod/files/2016/06/f32/QTR2015-6I-Process-Heating.pdf

U.S. Department of Energy. *Quadrennial Technology Review 2015*, "Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing." https://www.energy.gov/sites/prod/files/2017/03/f34/qtr-2015-chapter6.pdf

Verma, S., H. Singh. 2020. Vacuum insulation panels for refrigerators. *International Journal of Refrigeration* 112 pp. 215–228.

Vincent, Immanuel and D. Besarabov. 2018. "Low cost hydrogen production by anion exchange membrane electrolysis: A review." *Renewable and Sustainable Energy Reviews.* Vol. 81, Part 2, pp. 1690-1704. https://www.sciencedirect.com/science/article/pii/S1364032117309127#!

Vossos, V., et al. 2019. *Direct Current as an Integrating and Enabling Platform for Zero-Net Energy Buildings*. California Energy Commission. https://ww2.energy.ca.gov/2019publications/CEC-500-2019-038/CEC-500-2019-038.pdf

Walton, R. 2020. Most utilities aren't getting full value from smart meters, report warns. https://www.utilitydive.com/news/most-utilities-arent-getting-full-value-from-smart-meters-report-warns/570249/

Wang, Jing, Blake Lundstrom, and Andrey Bernstein. 2020. *Design of a Non-PLL Grid-Forming Inverter for Smooth Microgrid Transition Operation* (Preprint). National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy20osti/75332.pdf

Wang, Y, Q. Chen, T. Hong, C. Kang. 2019. Review of Smart Meter Data Analytics: Applications, Methodologies, and Challenges. *IEEE Transactions on Smart Grid*. Vol 10 (3). https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8322199&tag=1.

Wang, Zhe, et al. 2020. Evaluating the comfort of thermally dynamic wearable devices. *Building and Environment*, Vol. 167, Jan. 2020. https://www.sciencedirect.com/science/article/abs/pii/S0360132319306535?via%3Dihub

Wei, M., H. Breunig, S. De La Rue Du Can, S. Meyers, Z. Taies. 2020. A Technology and Policy Assessment For California To Achieve Net Zero Greenhouse Gases By 2045. Lawrence Berkeley National Laboratory.

Wolfe, F. 2017. How Artificial Intelligence Will Revolutionize the Energy Industry. http://sitn.hms.harvard.edu/flash/2017/artificial-intelligence-will-revolutionize-energy-industry/

Xu, Z. et al. 2016. “A hierarchical framework for coordinated charging of plug-in electric vehicles in China.” *IEEE Transactions on Smart Grid* 7(1): 428–438.

Xue, Y., et al. 2018. "On a Future for Smart Inverters with Integrated System Functions," 2018 9th IEEE International Symposium on Power Electronics for Distributed Generation Systems, pp. 1-8. doi:10.1109/PEDG.2018.8447750.

Yang, L., D. Huh, R. Ning, et al. 2021. “High thermoelectric figure of merit of porous Si nanowires from 300 to 700 K.” *Nat Commun* 12, 3926. https://doi.org/10.1038/s41467-021-24208-3

Yin, R., D. Black and Bin Wang. 2020. “Characteristics of Electric Vehicle Charging Sessions and its Benefits in Managing Peak Demands of a Commercial Parking Garage,” 2020 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids. doi: 10.1109/SmartGridComm47815.2020.9302987

Yin, R., J. Page, and D. Black. 2016. Demand Response with Lighting in Office, Retail, and Hospitality Buildings in the SD&E Service Area. LBNL Report to SDG&E.

York, D. 2020. Smart meters gain popularity, but most utilities don’t optimize their potential to save energy. https://www.aceee.org/blog-post/2020/01/smart-meters-gain-popularity-most-utilities-dont-optimize-their-potential-save#:~:text=Donate-,Smart%20meters%20gain%20popularity%2C%20but%20most%20utilities%20don't%20optimize,their%20potential%20to%20save%20energy&text=Despite%20billions%20of%20dollars%20invested,to%20help%20customers%20save%20energy

Yu, B., et al. 2020. “The data dimensionality reduction and bad data detection in the process of smart grid reconstruction through machine learning.” *PLoS ONE* 15(10): e0237994. https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0237994

Yu, Peiyuan, Anubhav Jain & Ravi S. Prasher. 2019. Enhanced Thermochemical Heat Capacity of Liquids: Molecular to Macroscale Modeling. *Nanoscale and Microscale Thermophysical Engineering*, 23:3, 235-246. https://doi.org/10.1080/15567265.2019.1600622

Zühlsdorf, B., F. Bühler, M. Bantle, and B. Elmegaard. 2019. “Analysis of Technologies and Potentials for Heat Pump-Based Process Heat Supply above 150°C.” *Energy Conversion and Management*: X 2 (April): 100011. www.sciencedirect.com/science/article/pii/S2590174519300091?via%3Dihub