Energy Research and Development Division

FINAL PROJECT REPORT

Public Health Research Roadmap on Emerging Electricity Generating Systems

California Energy Commission

Edmund G. Brown Jr., Governor

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PREFACE

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

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solution, foster regional innovation and bring ideas from the lab to the marketplace. The California Energy Commission and the state's three largest investor-owned utilities – Pacific Gas and Electric Company, San Diego Gas and Electric Company and Southern California Edison Company – were selected to administer the EPIC funds and advance novel technologies, tools and strategies that provide benefits to their electric ratepayers.

The Energy Commission is committed to ensuring public participation in its research and development programs which promote greater reliability, lower costs and increase safety for the California electric ratepayer and include:

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

Public Health Research Roadmap on Emerging Electricity Generating Systems is the final report for the Public Health Research Roadmap on Emerging Electricity Generating Systems project (contract number EPC-15-034 conducted by the Public Health Institute's Center for Climate Change and Health. The information from this project contributes to Energy Research and Development Division's EPIC Program.

All figures and tables are the work of the author(s) for this project unless otherwise cited or credited.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

This report establishes a public health research roadmap aimed at anticipating and preventing potential unintended health impacts of emerging electricity generating, storing, and distributing systems (EES). Through expert interviews and bibliographic research, this Public Health Research Roadmap provides a compilation of resources and information from state of the art research on EES and their potential health impacts. This report focuses on renewable generation and electricity storage technologies along with innovations in distribution systems that are already being implemented or are likely to be part of California's electricity grid by 2030. These technologies were reviewed through a qualitative life cycle assessment to identify relevant exposures, hazards, and gaps in current understanding of the potential for adverse health impacts on California residents and workers in these emerging industries. The information was prioritized using public health and equity criteria to propose research priorities that address identified gaps. Recommendations span basic etiologic research (to establish relationships between health effects and new materials and processes) and prevention research to mitigate existing, known hazards through engineering and design in the development stage, green chemistry, education, training, and communications for workers, business, and the public.

Keywords: *renewable energy, solar, wind, geothermal, biomass, concentrated solar, smart grid, life cycle assessment, emerging energy systems, environmental impacts, health impacts*

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EXECUTIVE SUMMARY

Introduction

The goal of this project was to create a public health research roadmap aimed at anticipating and preventing potential unintended health impacts of emerging energy systems (EES). To mitigate the catastrophic effects of global climate change, California is leading the United States in reducing greenhouse gas (GHG) emissions from its energy, transportation, and land use sectors. As California advances the transition from fossil fuel electricity generation to renewable sources such as solar, wind, biomass, and geothermal, there is a need to understand the full spectrum of health impacts from this transition and to reduce any potential negative impacts. This report is focused on electricity generating, storing, and distributing technologies that are already implemented or likely to be a part of California's grid by 2030. These technologies are shown in **Table ES-1.**

Table ES-1. Technologies of Focus

Solar Photovoltaic (PV)	**Small Hydropower**
Polycrystalline Silicon (poly-Si) Monocrystalline Silicon (mono-Si) Cadmium Telluride (CdTe) Copper Indium Gallium Selenide (CIGS) Perovskite Solar Cells	Run-of-River In-Conduit **Marine Energy** Tidal Wave
Concentrating Solar Power (CSP)	**Storage**
Parabolic Trough Central Receiver Linear Fresnel Parabolic Dish **Wind** Onshore Offshore	Pumped Hydro Compressed Air Flywheels Conventional Batteries (Lithium-ion, Lead acid) High Temperature (Sodium/Sulfur) Flow Batteries (Vanadium-Redox) Proton Exchange Membrane Fuel Cells
Biomass	**Distribution and Additional Topics**
Anaerobic Digestion Direct Combustion Gasification **Geothermal** Direct Steam Flash Steam Binary	Microgrid Smart Grid / Smart Meter

Objectives

The primary goal of this project was to develop a research roadmap for emerging electricity generating systems with a public health and equity lens so that potential harms can be avoided and health benefits can be optimized.

Process

This report examines the potential health impacts of the technologies of focus across their life cycles – from material extraction to disposal – through a qualitative life cycle assessment methodology. The methods included literature review; interviews with leading researchers and stakeholders; public workshops; and a technical advisory committee convening. Criteria for prioritization was developed based on published public health prioritization schemes, and applied qualitatively to the full list of identified research needs.

Results

To date, there is a paucity of data and information on the health impacts of EES across the life cycle. But based on albeit incomplete information, the life cycle health impacts of EES have been determined to be significantly smaller than those of fossil fuel electricity production.

Across the life cycle of technologies in this report, there is the potential for health impacts on workers and the public through a range of different hazards (i.e. chemical, physical, electrical, etc.). However, there is a dearth of information available on the specific chemicals and processes used in many of these technologies and on the nature of protection for workers and fenceline communities, making a full characterization of these hazards difficult.

Moreover, climate change is the greatest health challenge of this century; strategies to reduce greenhouse gas emissions and slow climate change are thus of significant health benefit. **The health benefits of climate change mitigation and GHG emission reduction through shifting from fossil fuels to EES must thus be emphasized in any overall assessment of strategies to attain a healthy energy system**.

Solar Photovoltaics

The main hazards of concern across the life cycle of solar photovoltaics occur during the material extraction and manufacturing stages, much of which occurs outside of the United States. Hazard assessments of updated inventories of solar photovoltaic materials are necessary. In California, installation of utility-scale photovoltaics can lead to occupational and public exposure to *Coccidioides* fungal spores, which can cause Valley Fever, and requires further research. Disposal of solar photovoltaics is an additional concern and more research is needed on how recycling of components can be done sustainably and safely.

Concentrated Solar

Concentrated solar installations pose fewer risks related to material extraction and manufacture than solar photovoltaics. In California, installation of utility-scale concentrated solar power can lead to occupational and public exposure to *Coccidioides* fungal spores, which

can cause Valley Fever. These sites can also produce additional hazards to workers through extreme heat and heat transfer fluid leaks. Hazards during the disposal of heat transfer fluids are not well defined and will depend on the specific fluid composition. More research is needed to assess hazards across the life cycle of heat transfer fluids currently in use and development.

Wind

As more rare earth elements (i.e. dysprosium and neodymium) are mined and processed for developing direct drive turbines, there is the potential for health impacts on workers and communities. More information is needed on the potential for infrasound from wind turbines to disrupt sleep or lead to annoyance. To date, research has not provided convincing evidence to support the relationship between turbine infrasound and other health outcomes.

Biomass

The report assessed biomass feedstocks and conversion technologies used to produce electricity from forest, agricultural waste, urban waste streams. When considering impacts of biomass conversion, it is important to note alternative fates of feedstocks, as many could be consumed by wildfire, open burning practices, or in landfills, which are all associated with hazards. The transport of biomass feedstocks may entail hazards and emissions related to goods movement, but there is potential for informed build out of small, distributed systems using gasification technologies to prevent these. Emissions created throughout the energy conversion process are an additional concern, particularly if combustion facilities are sited in areas with existing poor air quality.

Geothermal

Emissions of hydrogen sulfide is a concern for workers and, potentially, surrounding communities, and improved emission controls are needed. Geothermal systems can also produce liquid and solid waste streams during their operation, which must be contained to prevent contamination of surrounding areas. As enhanced geothermal systems are further explored, care must be taken to prevent seismic impacts and leaching of geothermal materials to ground water reserves. Additionally, more information is needed on potential health impacts from material refining from geothermal brine (i.e. lithium, silica).

Small Hydropower and Marine Energy

Small hydropower systems may pose risks of flooding and diminished water quality depending on how facilities are sited and planned. The potential for health impacts on workers and surrounding communities depends on the specific context of each installation. Marine energy is expected to have limited development by 2030, though systems should be designed to limit impacts on coastal and indigenous communities who may rely on marine resources.

Storage Technologies

Apart from pumped hydropower storage, most electricity storage technologies will be new electrochemical storage arrays. Electrochemical battery storage systems include a number of rare and potentially hazardous materials and pose both chemical and fire risks. Hazard

assessments based on updated inventories of battery materials are necessary. Research is also necessary to improve and create healthy and safe recycling systems for these technologies.

Additional Health Concerns

Smart meters emit radiofrequency radiation when they are in use, with the amount dependent on the type of meter and its location. Because some houses and buildings may have multiple meters and may be equipped with a relay meter, better exposure assessment is required to ascertain radiofrequency exposure in a variety of real-world settings. More work is needed to understand the potential health impacts from radiofrequency radiation.

Equity Considerations

Employment is a key consideration when accessing potential equity considerations from emerging energy systems. Emerging electricity generating and storage systems employ a myriad of different workers across technology life cycles, and more work is needed to understand the *quality* of jobs created.. Equity considerations will also depend on where facilities are located. While new utility-scale facilities can offer opportunities for community economic development and living wage jobs, there will also be transport and land-maintenance related emissions across facility life cycles. These could exacerbate air quality concerns in areas already suffering from poor air infrastructure build out in the area and related impacts could be intensified in lower income or minority communities.

Research Roadmap

Table ES-2. Priority Research Needs

	High Priority Research Topics
Across Technologies	• Comparative health and health equity risk assessment across the life cycle of energy technology mixes projected for California in 2050 • Update identification and hazard assessment of materials used across technology life cycles, including environmental health, occupational safety, and community health impacts • Conduct routine life cycle hazard assessments of energy technologies • Identify, develop, and evaluate healthy, safe, and sustainable recycling methods for PV cells, wind turbine components, and electrochemical and chemical storage technologies • Expand research on safety-by-design in manufacturing processes • Develop strategies to reduce the risk of *Coccidioides* exposure associated with construction, maintenance, and operation of utility-scale energy facilities • Develop methods to test for presence of *Coccidioides* to facilitate risk-informed site selection • Conduct occupational and community exposure assessment across energy systems
Solar Photovoltaics	• Update identification and hazard assessment of chemicals used across the life cycle of PV cells and modules, including their environmental and occupational health and safety impacts ○ Determine potential community health impacts of material extraction, manufacturing, and disposal

	○ Determine occupational risks based on likelihood of exposure, dose, and toxicology of substance ○ Identify existing and emerging technologies that have relatively lower environmental and occupational risks ○ Develop green chemistry and safety-by-design manufacturing processes • Identify, develop, and evaluate healthy, safe, and sustainable recycling methods for PV cells
Biomass	• Monitor emissions from different gasification technology deployment scenarios, noting differences in electricity generating technologies (i.e. engines, microturbines, fuel cells) • Monitor emissions from operating biomass facilities, noting effectiveness of applied air emission mitigation technologies and workplace exposures, and develop improved mitigation systems • Model life cycle air emissions from different biomass energy deployment scenarios, noting baseline regional air quality and possible changes in conversion technology
Geothermal	• Develop technology to reduce hydrogen sulfide emissions from geothermal facilities • Perform a health impact assessment of proposed geothermal developments and facilities in Salton Sea region, including risks associated with fugitive dust creation and other impacts on surrounding communities
Storage	• Update identification and hazard assessment of chemicals used across the life cycle of electrochemical storage technologies, including their environmental and occupational health and safety impacts ○ Determine potential community health impacts of material extraction, manufacturing, and disposal ○ Determine occupational risks based on likelihood of exposure, dose, and toxicology of substance • Identify existing and emerging technologies that have relatively lower environmental risks • Further develop green chemistry and safety-by-design mechanisms • Identify, develop, and evaluate healthy, safe, and sustainable recycling methods for electrochemical storage technologies
Occupational Health	• Assess need for occupational health and safety regulations for emerging electricity generating system implementation in California ○ Worker and employer knowledge of hazards and related risk ○ Health and safety training practices ○ Implementation and enforcement of existing safety and health regulations
Equity	• Assess the *quality* of employment created throughout emerging energy system life cycles and identify strategies to incentivize access to high quality jobs that are safe and healthy with living wages and career opportunities in EES • Explore mechanisms to improve community engagement and participation in siting and planning of facilities • Develop mechanisms to promote equitable access to the benefits of EES • Analyze global health impacts of emerging energy systems and potential strategies to address them: ○ Examine the global health impacts of emerging energy systems ○ Assess best practices for addressing global impacts and the possible strategies to minimize/mitigate global impacts of emerging energy systems ○ Analyze whether and how California laws, regulations, and incentives address global impacts, or could be used to address

	global impacts of emerging energy systems ○ Identify changes needed to laws or regulations, or new initiatives needed for California to adequately address global impacts
	Medium Priority Research
Smart Meters	• Monitor exposures to extra-low-frequency electromagnetic radiation under a range of real-world conditions (e.g. multi-unit housing, relay units)
Concentrated Solar	• Assess potential health impacts of exposure during facility maintenance and end-of-life disposal of heat transfer fluids, including synthetic oils, molten salts, and supercritical CO_2 technologies
Wind Energy	• Improve infrasound exposure and impact assessment ○ Exposure assessment at various turbine-receptor distances ○ Epidemiological research on sleep disruption and annoyance from larger turbine design, controlling when possible for known confounders
Geothermal	• Identify health and environmental impacts of materials recovery (e.g. sulfur, lithium) from brine in California's geothermal plants
	Low Priority Research
Storage	• Assess occupational and public hazards during construction and maintenance of compressed air and flywheel facilities
Marine Energy	• Identify marine energy and offshore wind turbines impacts on California coastal fishing communities

As renewable energy and storage systems continue to expand, technologies and processes are constantly changing. Materials and hazards mentioned in this report may soon be phased out, and certain technologies of focus may be replaced by newer ones that are currently in early stages of research. Thus, in order to prevent potential harms and promote health benefits of emerging electricity generating technologies as new systems come online, it is critical to develop mechanisms to track new developments and assess their potential health impacts *before* wide-scale deployment.

Benefits to Californians

The research roadmap is meant to facilitate greater understanding of the potential health risks and benefits of emerging energy technologies that may be pursued to produce energy savings. That understanding could enable health-conscious implementation of new energy technologies and reduce adverse health impacts of energy systems. This roadmap takes a proactive stance to anticipate and research potential health impacts rather than responding only after injuries, illness, and death occur, working to build a healthier energy mix for Californians.

Chapter 1: Introduction and Methods

The primary goal of this project was to develop a public health research roadmap for emerging energy systems (EES), with an equity lens, in order to better anticipate and prevent potential harms and optimize potential health benefits of EES as these systems are expanded in California. The report focuses on electricity generation, storage, and distribution systems. Supporting goals were to reach out to a broad constituency of researchers and stakeholders to incorporate their expertise in crafting the research agenda and to build support for implementation.

The specific objectives of the project, developed with the Energy Commission, were to:

- Inventory and screen emerging energy technologies by experts in energy systems and public health
- Identify health impact pathways from emerging energy technologies over the technology lifecycle
- Develop and apply criteria to prioritize the research themes, gaps, and research
- Create a health impact matrix for emerging technologies by type, magnitude and severity of health risks (or benefits), type and size of population at risk, high risk process/materials, and control technology
- Formulate themes, information gaps, and research questions that correspond to the health impacts-technology matrix

Background

In order to mitigate the catastrophic effects of global climate change, California is leading the United States in reducing greenhouse gas (GHG) emissions from its energy, transportation, and land use sectors. As California advances the transition from fossil fuels electricity generation to renewable sources such as solar, wind, biomass, and geothermal, there is a need to understand the full spectrum of potential health impacts from this transition to reduce any potential adverse health impacts.

Governor Brown's Executive Order B-30-15 and California Senate Bill 32 have set the goal for California to cut greenhouse gas emissions to levels 40% below 1990 levels by 2030. To achieve these goals, Governor Brown and the legislature worked to increase energy generation from renewable sources. The Clean Energy and Pollution Reduction Act of 2015 (Senate Bill 350) requires that renewable energy sources provide 50% of California's energy by 2030. In 2011, Governor Brown set an additional goal of achieving 20,000MW of renewable generation in the state by 2020 – 8,000MW of which would be from large-scale facilities and 12,000MW from distributed generation (20MW or smaller).

According to many energy models, total demand for electricity in California is expected to grow from 306TWh in 2013 to 317-415TWh by 2030.[1] This is due to the expected increase in end-use electrification with energy efficiency improvements moderating the total demand increase.[2] For instance, as electric vehicles grow in use, electricity demand will also increase to charge these vehicles, requiring reliable electricity. To achieve its mitigation goals while accommodating greater electricity usage, California's regulatory system is focused on decarbonization of generation technologies, energy efficiency, and electrification of transportation. These goals will require additional updates to distribution and transmission systems, along with innovations in electricity storage.

As of December 2016, the California Energy Commission estimated that 27% of California's electricity retail sales were served by renewable generated sources in 2016.[3] These include solar, wind, biomass, geothermal, and small hydroelectric generation sources. From 2005 to 2015, California increased the number of large-scale renewable energy facilities from 5,900 to 15,900MW. From 2001 to 2015, total renewable capacity grew from 7,500MW to 19,000MW.[4] Figure 1 displays energy generation for California from renewables in 2016 compared to one study's projected renewable generation in 2030.[5]

This report addresses current knowledge and research gaps regarding the health impacts of emerging electricity generating, storing, and distributing technologies that are already implemented or likely to be a part of California's grid by 2030. The following sections discuss the study methods, research and assessment results, and recommendations for research necessary to inform the development of healthy energy systems.

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1 Chris Kavalec et al., "California Energy Demand 2016-2026, Revised Electricity Forecast, Volume 1: Statewide Electricity Demand and Energy Efficiency," Staff Report, Electricity and Natural Gas Demand Forecast (California Energy Commission, January 2016), http://docketpublic.energy.ca.gov/PublicDocuments/15-IEPR-03/TN207439_20160115T152221_California_Energy_Demand_20162026_Revised_Electricity_Forecast.pdf.

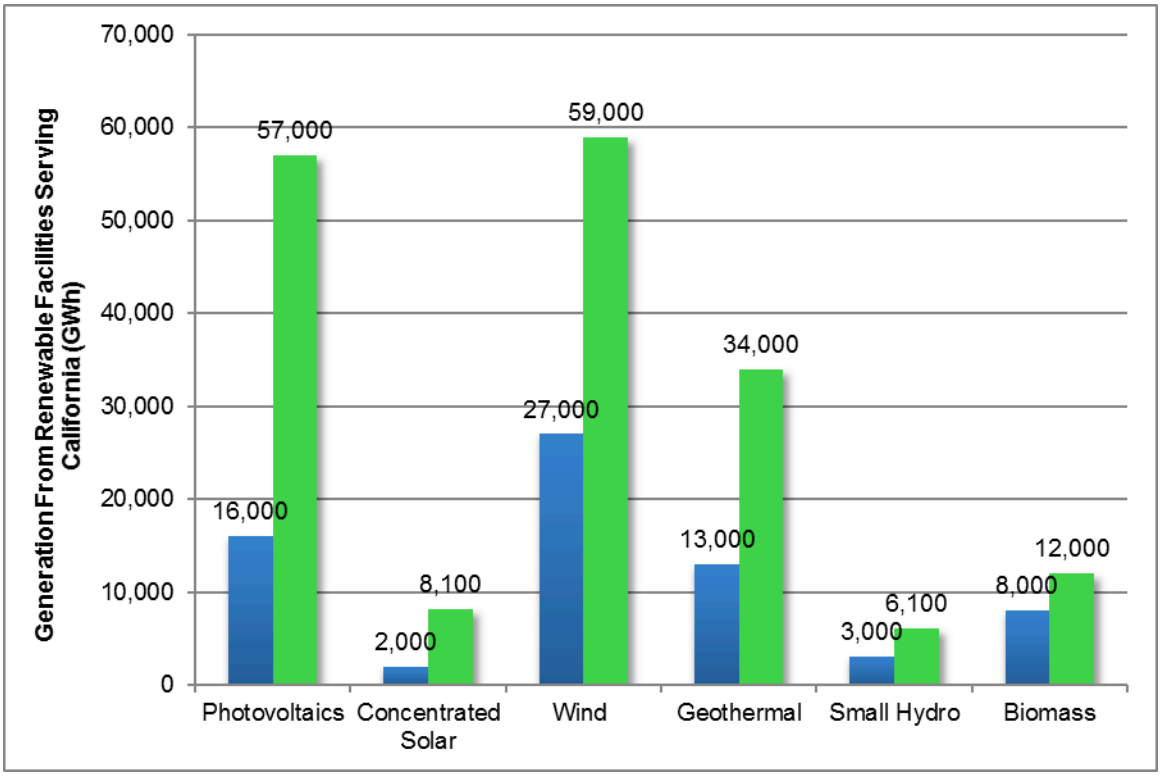
2 Sonia Yeh et al., "A Modeling Comparison of Deep Greenhouse Gas Emissions Reduction Scenarios by 2030 in California," Energy Strategy Reviews 13–14 (November 2016): 169–80, doi:10.1016/j.esr.2016.10.001.

3 CEC, "Renewable Energy – Overview December 2016" (California Energy Commission, December 2016), http://www.energy.ca.gov/renewables/tracking_progress/documents/renewable.pdf.

4 Jim Bartridge et al., "Draft 2016 Environmental Performance Report of California's Electrical Generation System," Staff Report (California Energy Commission, July 2016), https://efiling.energy.ca.gov/getdocument.aspx?tn=212338.

5 Gregory Brinkman, Jennie Jorgenson, and Marissa Hummon, "California 2030 Low Carbon Grid Study (LCGS): Phase I" (National Renewable Energy Laboratory, 2014), http://lowcarbongrid2030.org/wp-content/uploads/2014/10/LCGS_PhaseI_NRELslides.pdf; CEC, "Renewable Energy – Overview December 2016."

Figure 1. California Energy Generated from Renewables in 2016 (Blue) and Projected 2030 Renewable Generation (Green)



Source: Gregory Brinkman, Jennie Jorgenson, and Marissa Hummon, 'California 2030 Low Carbon Grid Study (LCGS): Phase I" (National Renewable Energy Laboratory, 2014; CEC, 'Renewable Energy – Overview December 2016'.

Methods

The project team utilized a variety of methods to explore what is currently known about the potential health impacts of EES and to identify and prioritize research gaps. These methods included a literature review, interviews with researchers and stakeholders, public workshops, and a technical advisory committee. This report describes the current state of knowledge on health impacts across technology life cycles qualitatively (explained in the section below) as available information permitted.

Literature review: Relevant research was compiled to create a literature review of existing studies to determine technologies of focus, understand life cycle processes, and identify health impacts from emissions and hazards across technology life cycles. This review included peer-reviewed articles and gray literature. Resources were compiled from health and engineering databases, expert interviews, and from government agency websites.

Subject matter expert and stakeholder interviews: To inventory existing and predicted EES for potential public health impacts, over 60 interviews were conducted with leading researchers and stakeholders in the fields of energy systems modeling, public health, occupational health and safety, environmental justice, and labor. These interviews provided information on the current state of knowledge in these fields as well as gaps that need further

investigation. The interviews were used to determine the technologies of focus for this report, and to understand the current state of knowledge and concerns regarding health and social externalities across these technologies' life cycles.

Public workshops: Two public workshops were conducted, one in Los Angeles and one in Sacramento (which was also webcast), to gather feedback and suggestions from stakeholders throughout the state. The workshop presentations focused on health impacts across the life cycle of the technologies of focus, and preliminary discussion of identified research needs for each technology group and across technologies. Comments from the workshops were integrated into the final analysis and report.

Technical advisory committee: Energy and health experts were convened as a technical advisory committee (TAC) to garner more specific feedback on research gaps. TAC participants also reviewed and provided comments on drafts of report sections relevant to their area of expertise.

Prioritization of research needs: A list of all research gaps identified by the project team, researchers, and stakeholders was compiled. Various public health prioritization schemes were reviewed, and a set of criteria based on these schemes was developed. However, data to support a formal application of these criteria is largely unavailable. The criteria were thus subjectively applied to the full list of research gaps by the research team to determine research priorities.

Technologies of Focus

The technologies included in this report were determined through literature review and interviews with energy system modelers to be those most likely to be online in the California energy mix by 2030. The technologies selected are displayed in Table 1.

This project focuses on technologies judged likely to be a part of California's energy grid by 2030, including technologies involved in producing, storing, and distributing electricity for grid applications. There are numerous technologies that are currently being researched and developed for future grid implementation (i.e. third-generation solar cells) that are not included in this report. Innovations in transport electrification and biofuels, carbon capture technologies, and energy efficiency technologies are likewise not included in this assessment.

As renewable energy and storage systems continue to expand, technologies and processes are constantly changing. Materials and hazards mentioned in this report may soon be phased out, and certain technologies of focus may be replaced by newer ones that are currently in early stages of research. Thus, in order to prevent potential harms and promote health benefits of EES as new systems come online, it is essential that mechanisms be implemented to track new developments and routinely assess their potential life cycle health impacts before wide-scale deployment.

Table 1. Technologies of Focus

Solar Photovoltaic (PV)	**Small Hydropower**
Polycrystalline Silicon (poly-Si) Monocrystalline Silicon (mono-Si) Cadmium Telluride (CdTe) Copper Indium Gallium Selenide (CIGS) Perovskite Solar Cells	Run-of-River In-Conduit **Marine Energy** Tidal Wave
Concentrating Solar Power (CSP)	**Storage**
Parabolic Trough Central Receiver Linear Fresnel Parabolic Dish **Wind** Onshore Offshore	Pumped Hydro Compressed Air Flywheels Conventional Batteries (Lithium-ion, Lead acid) High Temperature (Sodium/Sulfur) Flow Batteries (Vanadium-redox) Proton Exchange Membrane Fuel Cells
Biomass	**Distribution and Additional Topics**
Anaerobic Digestion Direct Combustion Gasification **Feedstock** Woody/forest Agricultural waste Urban Waste Landfill/waste water treatment plants Digester gas **Geothermal** Direct Steam Flash Steam Binary	Microgrid Smart Grid / Smart Meter

Health and Energy: Compared to What?

Energy and electricity production has greatly improved quality of life – providing for lighting, heating, cooling and refrigeration, and the manufacture of many useful products. However, our current energy system is associated with many significant and serious adverse impacts on human health and the environment, primarily due to the extraction and combustion of fossil fuels. While this report focuses on the life cycle health impacts of emerging energy systems, these impacts must be considered in the context of the health impacts of the electricity generation technologies that EES will replace. Based on available knowledge, the potential health impacts - across the life cycle - of EES appear to be very significantly smaller in magnitude than those attributable to fossil fuel electricity production.

In 2015, over 50% of California's electricity was produced from fossil fuels (see Figure 2).[6] While California relies more on natural gas than on coal and petroleum, all fossil fuel-based electricity production releases greenhouse gases, which are main contributors to global climate change.[7] In California, electricity production accounts for 19% of California's GHG emissions.[8] Electricity generation accounted for the 29% of total US greenhouse gas emissions in 2015.[9]

Across the life cycle, coal power plants generate 800-1000 grams of CO_2 per kWh (gCO_2/kWh) of electricity generated. Natural gas plants produce an estimated 600 gCO_2/kWh over the life cycle. There is emerging evidence that natural gas electricity production also produces significant methane emissions - a short-lived climate pollutant with a greater global warming potential than CO_2.[10] In comparison, renewable energy systems like wind, solar photovoltaic, concentrated solar, hydroelectric and geothermal power systems have been found to have life-cycle carbon dioxide emissions of less than 50 g of CO_2 per kilowatt hour (g CO_2 /kWh).[11] CO_2 emissions from biomass facilities are more complex to measure, and there is disagreement about how direct emissions from biomass combustion should be weighted against the amount of CO_2 sequestered when biomass resources are regrown.[12] Models are being

6 CEC, "Total System Electric Generation," Goverment Agency Website, California Energy Commission, (July 11, 2016), http://www.energy.ca.gov/almanac/electricity_data/total_system_power.html.

7 Edgar G. Hertwich, Jacqueline Aloisi de Larderel, and Sangwon Suh, "Green Energy Choices: The Benefits, Risks, and Trade-Offs of Low-Carbon Technologies for Electricity Production" (United Nations Environmnetal Programme, 2016), http://www.unep.org/resourcepanel/Portals/50244/publications/Summary_for_Policy_Makers_GHG_I.pdf.

8 ARB, "California Greenhouse Gas Emission Inventory - 2017 Edition," Goverment Agency Website, California Environmental Protection Agency Air Resources Board, (June 2017), https://www.arb.ca.gov/cc/inventory/data/data.htm.

9 EPA, "Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-2015" (U.S. Environmental Protection Agency, April 15, 2017).

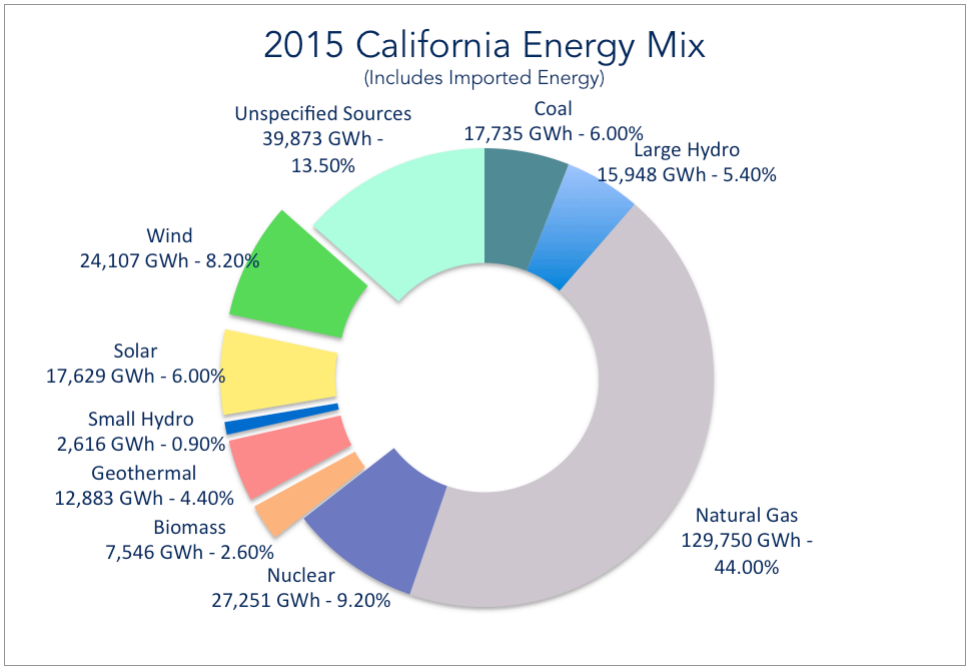
10 A.R. Brandt et al., "Methane Leaks from North American Natural Gas Systems," Science 343, no. 6172 (February 14, 2014): 733–35, doi:10.1126/science.1247045.

11 Hertwich, Aloisi de Larderel, and Suh, "Green Energy Choices: The Benefits, Risks, and Trade-Offs of Low-Carbon Technologies for Electricity Production."

12 Thomas Buchholz et al., "A Global Meta-Analysis of Forest Bioenergy Greenhouse Gas Emission Accounting Studies," GCB Bioenergy 8, no. 2 (March 2016): 281–89, doi:10.1111/gcbb.12245.

built to account for these considerations.[13] Because greenhouse gas emissions from human activities are the most significant driver of global climate change, California continues to advance policies to limit these emissions.[14]

Figure 2. 2015 California Energy Mix



Source: California Energy Commission, 2016 (http://www.energy.ca.gov/almanac/electricity_data/total_system_power.html)

Climate change is the greatest health challenge of the 21st century. Thus, the large contribution to greenhouse gas emissions of the current electricity generation sector must be seen as one of the gravest threats to public health.[15] Climate change will increase heat stress, floods, drought, and the frequency of intensity storms, which will impact air quality, the spread of disease vectors, nutrition, displacement, and mental health.[16] Climate change threatens key resources on which human life depends - air, food, water, shelter, and security.[17] Figure 3 shows these relationships in more detail.

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13 Francesco Cherubini et al., "CO2 Emissions from Biomass Combustion for Bioenergy: Atmospheric Decay and Contribution to Global Warming: GLOBAL WARMING POTENTIAL OF CO2 FROM BIOENERGY," GCB Bioenergy 3, no. 5 (October 2011): 413–26, doi:10.1111/j.1757-1707.2011.01102.x.

14 IPCC, "Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change" (Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2013), https://www.ipcc.ch/report/ar5/wg1/citation/WGIAR5_Citations_FinalRev1.pdf.

15 Anthony J. McMichael, Rosalie E. Woodruff, and Simon Hales, "Climate Change and Human Health: Present and Future Risks," The Lancet 367, no. 9513 (2006): 859–869.

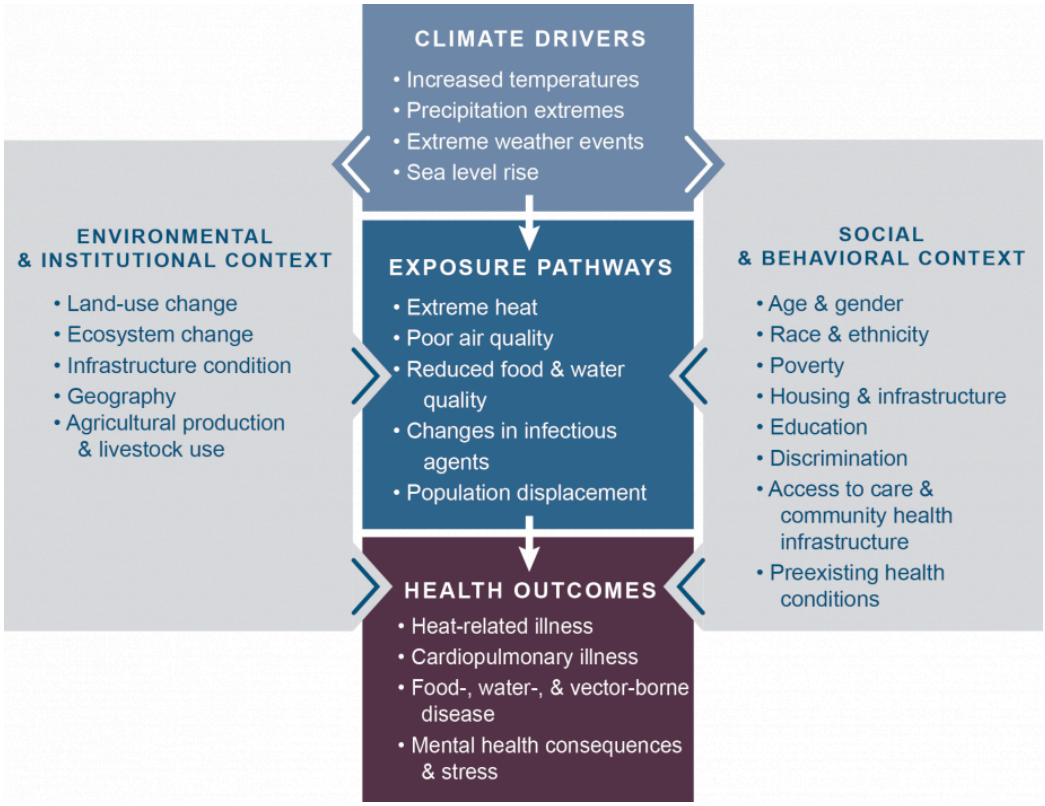
16 Nick Watts et al., "Health and Climate Change: Policy Responses to Protect Public Health," The Lancet Commissions 385 (May 21, 2015): 53.

17 Anthony Costello et al., "Managing the Health Effects of Climate Change," Lancet 373 (May 16, 2009): 1693–733.

The global population health benefits associated with reducing the ultimate magnitude of climate change are great. Climate mitigation is thus a public health priority. Switching from fossil-fuel electricity to EES is a key climate mitigation strategy. **Any health impacts of EES must be weighed against the significant health benefits of climate mitigation.**[18]

Apart from climate change related impacts, fossil fuel-based energy production also results in air pollution, including particulate matter (PM - a mixture of solid particles and liquid droplets), nitrous oxides (NOx), sulfur oxides (SOx), mercury, and other air toxics. Renewable electricity production from solar photovoltaics, wind, concentrated solar, small hydropower and geothermal result in PM emissions an order of magnitude less than those resulting from modern coal and natural gas facilities.[19] Fossil fuel electricity production is also associated with multiple other adverse health impacts, including from coal miner fatalities and pneumoconiosis, water contamination associated with both coal and natural gas extraction, and local release of benzene and VOCs in natural gas extraction and transport.[20]

Figure 3. Health Impacts of Climate Change



Source: USGCRP, 2016: The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment. http://dx.doi.org/10.7930/J0R49NQX

18 Thomas Gibon et al., "Health Benefits, Ecological Threats of Low-Carbon Electricity," Environmental Research Letters 12, no. 3 (March 1, 2017): 34023, doi:10.1088/1748-9326/aa6047.

19 Hertwich, Aloisi de Larderel, and Suh, "Green Energy Choices: The Benefits, Risks, and Trade-Offs of Low-Carbon Technologies for Electricity Production."

20 Ibid.

Renewable generation and storage technologies are also expected to improve fuel diversity and energy security, reduce water consumption in electricity generation facilities, and stabilize electricity prices.[21] EES offer new sources of employment and job training, offsetting and exceeding job losses in older energy production systems.[22] Each of these benefits is associated with additional health benefits, beyond the scope of this report to discuss.

All electricity-producing systems have health externalities across their life cycles. Figure 4 compares the life cycle health impacts of some of the electricity generating technologies included in this report. This chart uses disability adjusted life years (DALY) to quantify and estimate cumulative health impacts across technology life cycles. DALYs are used to account for years lost to illness, disability, or premature death within a particular population and are calculated by adding the number of years of life lost to the number of years lived with disability or illness.[23] This figure was adapted from an assessment of European energy systems that found that the majority of the DALY measures resulted from exposure to PM and toxics.[24] The cumulative life cycle impacts of renewable energy generation resources resulted in far fewer cumulative life years lost to premature death and disability than coal or natural gas.

This report also seeks to identify potential health equity concerns with the understanding that having access to safe and healthy homes, communities, and work environments have important impacts on physical and mental health. Equity considerations addressed include equitable facility siting, access to renewable energy jobs with living wages, and impacts on low-income and minority communities. Occupational health considerations, such as access to proper training for health and safety practices and enforcement of existing safety regulations, are also considered. Equitable access to the health and economic benefits of emerging electricity generating and storing systems are discussed.

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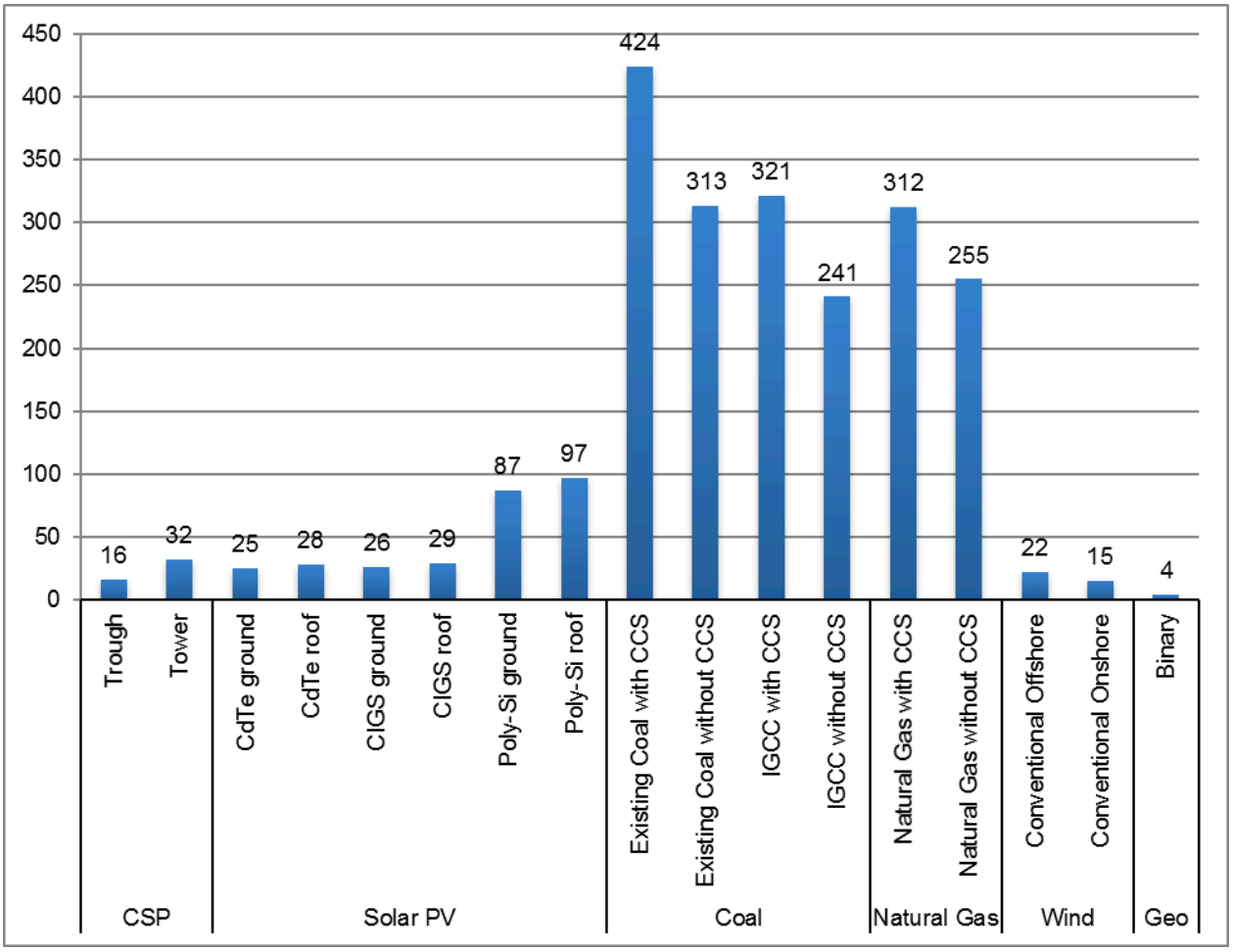
21 Ryan Wiser et al., "A Retrospective Analysis of the Benefits and Impacts of US Renewable Portfolio Standards," Lawrence Berkeley National Laboratory, National Renewable Energy Laboratory, 2016, http://climate-xchange.org/wp-content/uploads/2015/11/Renewable-Energy-Standards-Study.pdf.

22 Max Wei, Shana Patadia, and Daniel M. Kammen, "Putting Renewables and Energy Efficiency to Work: How Many Jobs Can the Clean Energy Industry Generate in the US?," Energy Policy 38, no. 2 (February 2010): 919–31.

23 Christopher J.L. Murray et al., "Disability-Adjusted Life Years (DALYs) for 291 Diseases and Injuries in 21 Regions, 1990–2010: A Systematic Analysis for the Global Burden of Disease Study 2010," Lancet 380 (2012): 2197–2223.

24 Hertwich, Aloisi de Larderel, and Suh, "Green Energy Choices: The Benefits, Risks, and Trade-Offs of Low-Carbon Technologies for Electricity Production."

Figure 4. Human Health Impact in Disability Adjusted Life Years (DALY) per TWh Electricity Generated



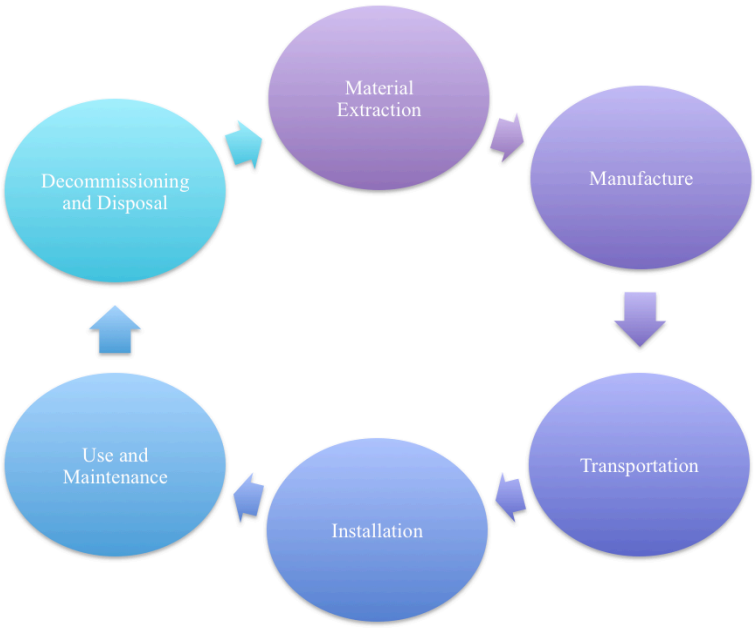
CSP – Concentrated Solar Power, Geo – Geothermal, CdTe – Cadmium Telluride Thin Films, CIGS – Copper Indium Gallium Selenide Thin Films, Poly-Si – Polycrystalline Solar Cells, IGCC – Integrated Gasification Combined Cycle CCS – Carbon Capture and Sequestration (results in higher health impacts due to energy input needed to produce and run CCS technologies)

Adapted from source: Edgar G. Hertwich, Jacqueline Aloisi de Larderel, and Sangwon Suh, "Green Energy Choices: The Benefits, Risks, and Trade-Offs of Low-Carbon Technologies for Electricity Production" United Nations Environmnetal Programme, 2016.

Life Cycle Assessment Overview

The report assesses EES technologies across the life cycle – from material extraction through disposal stages – using a qualitative assessment methodology. This section describes the life cycle stages and general health impacts expected for each life cycle stage across the technologies included in this report. The titles displayed in Figure 5 apply to most of the technologies, though biomass follows a somewhat different life cycle. Below we provide a brief overview of some of the potential health impacts associated with energy system life cycle stages across EES technologies.

Figure 5. Life Cycle Assessment Diagram



Source: Center for Climate Change and Health (2017)

In any assessment of potential health impacts across life cycles, evaluation of risk and potential health impact entails assessment of the inherent toxicity of materials used, likelihood of exposure, dose and frequency of exposure, route of exposure (i.e. inhalation, ingestion, or dermal contact), and whether there are any vulnerabilities to consider in the populations that may be exposed (i.e. age, genetics, medical conditions).[25] Additionally, populations may be exposed to multiple hazards, or to multiple sources of a particular hazard, resulting in cumulative impacts.[26]

While a quantitative life cycle assessment may combine health impacts through particular measures (i.e. DALYs explained above in Chapter 3), this report attempts to explain the current state of knowledge on health impacts across technology life cycles qualitatively, as available information permits. It should be noted that much of the information desired is not currently available. Below is a brief overview of some of the potential health impacts associated with stages of the energy systems life cycle across EES technologies.

LCA.1 Material Extraction

25 GEI Consultants, "Eagle Mountain Pumped Storage Project Draft Environmental Impact Report Volume I" (State Water Resources Control Board, July 2010), http://www.waterboards.ca.gov/waterrights/water_issues/programs/water_quality_cert/docs/eagle_mountain_pumped_ferc13123/2_eagltmtn_deir_vol1_2.pdf.

26 Ken Sexton and Dale Hattis, "Assessing Cumulative Health Risks from Exposure to Environmental Mixtures—Three Fundamental Questions," Environmental Health Perspectives 115, no. 5 (January 24, 2007): 825–32, doi:10.1289/ehp.9333.

The material extraction stage includes potential health impacts related to extracting or harvesting the materials needed for the technologies. This stage discusses exposures and hazards related to mining of materials used in technology components, as well as early processing stages for materials.

Mining is one of the most hazardous occupations in the world. Miners are at risk of severe injuries throughout their work but are also exposed to heavy metals, chemicals, and dust that can lead to the development of severe respiratory conditions (i.e. silicosis, pneumoconiosis), cancers, and mental health outcomes.[27] Extraction of primary materials may involve aboveground quarries or subsurface mining, both of which present unique hazards to workers and nearby communities.

Mining hazards differ by a myriad of characteristics, including minerals mined, mine type, geology, country, machinery used, and training and safety protocols followed. Research on potential risk is difficult due to this variability and a general dearth of related health and safety data. Mining is a critical component of international economies and can be an important source of employment and poverty-reduction. However, bodies like the United Nations recognize the need for further regulations and protections for miners.[28]

Mining can also have impacts on communities living near mining and smelting operations. These outcomes are less understood, overall, as it can be difficult to assess them in epidemiological studies and effects can be very context specific. Impacts can result from leaching of waste materials in local water supplies, soil contamination, and emissions of PM with heavy metal and other toxic components.[29]

Mining impacts can also be difficult to determine due to a lack of transparency in the mining sector, particularly from countries in Latin America, Asia, and Africa.[30] Material extraction for renewable technologies used in California likely occurs in these countries. More in-depth and long-term evaluation of the health impacts on miners and surrounding communities will be required to understand the scope of impacts.[31] Most life cycle assessments that include a human toxicity measure assume that available safety protocols for mining hazards are in place. However, these protections are not always present or functioning, particularly in developing countries.[32]

LCA.2 Manufacture

27 Carolyn Stephens, Mike Ahern, and others, "Worker and Community Health Impacts Related to Mining Operations Internationally: A Rapid Review of the Literature," Mining, Minerals and Sustainable Development, no. 25 (2001): 1–59.

28 "The Future We Want," Pub. L. No. 66/288 (2012), http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/66/288&Lang=E.

29 Stephens, Ahern, and others, "Worker and Community Health Impacts Related to Mining Operations Internationally."

30 Ibid.

31 Ibid.

32 Dustin Mulvaney, "Solar Energy Isn't Always as Green as You Think," IEEE Spectrum, November 13, 2014, http://spectrum.ieee.org/green-tech/solar/solar-energy-isnt-always-as-green-as-you-think.

The manufacturing stage of the life cycle involves the materials, processes, and systems involved in the actual production of the technologies. For example, in solar photovoltaics, this covers the stages from material processing to the completion of an entire photovoltaic module ready to be installed in a solar facility or on a rooftop. Across technologies, these processes are diverse, and health impacts are difficult to assess based on the lack of transparency across industries. Many of the processes are proprietary in nature, and the specific chemicals and exposures thereto are not publicly available knowledge.

Throughout manufacturing processes, workers may be exposed to chemical, physical, and radioactive hazards. These are discussed in detail in the following chapters. While, for many of the hazards discussed, there are known illness and injury prevention strategies, implementation of these strategies is highly variable in these industries and cannot be assumed – especially as these industries are expanding so quickly in a diverse group of countries with varying occupational safety regulations.

There are common materials across technologies that will not be covered in detail in this report. Steel, cement, concrete, and glass are used for piping, turbine components, and other system elements. The climate and health impacts from the production of these materials commonly used in manufactured goods are well known, but are outside the scope of this report.[33]

Manufacturing can also impact fence-line communities surrounding production facilities. Again, as information is limited on waste and air emissions from many of these facilities, it is difficult to assess the potential risk of chemical exposures, air emissions, or fire for surrounding communities. When manufacturing occurs outside of the US, potential risks are especially difficult to assess, but are likely to be significantly higher given the lack of occupational and environmental safeguards in many countries.

LCA.3 Transportation

Air pollutant emissions from the transportation of materials to and products from the manufacturing facility to their end-use site will be similar to those associated with any goods movement. For technologies that are shipped to the US from global manufacturers (i.e. solar photovoltaics), this transport will include emissions from large ships, rail, and heavy trucks. Domestic shipping will include rail and truck components. These will have varying GHG and

33 Lisa J. Hanle, Kamala R. Jayaraman, and Joshua S. Smith, “CO2 Emissions Profile of the U.S. Cement Industry” (13th International Emission Inventory Conference "Working for Clean Air in Clearwater, Clearwater, Fl: U.S. Environmental Protection Agency, 2004), https://www3.epa.gov/ttnchie1/conference/ei13/ghg/hanle.pdf; IARC, “Chemical Agents and Related Occupations: A Review of Human Carcinogens” (Lyon, France: International Agency for Research on Cancer, 2012), https://www.ncbi.nlm.nih.gov/books/NBK304416/pdf/Bookshelf_NBK304416.pdf; OSHA, “Worker Safety Series: Cement Manufacturing,” Goverment Ageny Website, United States Department of Labor, Occupational Safety and Health Administration, (2004), https://www.osha.gov/Publications/concrete_manufacturing.html; OSHA, “Basic Steel Products,” Goverment Ageny Website, United States Department of Labor, Occupational Safety and Health Administration, (2014), https://www.osha.gov/SLTC/basicsteel/standards.html; Radian, “Health Hazard Assessment Summary: Steel Mill Emissions” (U.S. Environmental Protection Agency, September 29, 1989); Michael Turner, “Mitigating Iron and Steel Emissions,” ed. Nico Tjabil (Columbia Climate Center, The Global Network for Climate Solutions, 2012), http://climate.columbia.edu/files/2012/04/GNCS-Iron-Steel.pdf.

criteria pollutant emissions, and trucks will have higher GHG emissions per ton transported than ship or rail.[34]

Diesel and pollutant emissions also affect local community air pollution, adding to cumulative environmental impacts especially in areas with poor air quality (Riverside, Imperial, Kern, San Bernardino Counties, etc.).[35] In order to prevent high pollution levels from PM emissions and criteria pollutants, utility-scale projects can implement requirements for use of certain lower emitting fuels and project vehicles with particular engines with catalysts and filters to reach California air quality standards.[36] Table 2 discusses common sources and health impacts from transportation emissions.[37]

Table 2. Health Impacts from Criteria Pollutants Emissions from Vehicle Exhaust

Pollutant	Sources	Health Effects
Nitrogen Oxides (NOx)	Power plants, motor vehicles, other industrial, commercial, and residential sources that burn fuels	Susceptibility to respiratory infections, irritation of lung and respiratory symptoms (e.g., cough, chest pain, difficulty breathing)
Sulfur Oxides (SOx)	Power plants, processing ores, motor vehicle emissions	Eye and throat irritation, coughing, respiratory tract problems, asthma exacerbation
Particulate Matter (PM)	Power plants, diesel engines, industries, windblown dust, wood stoves	Eye irritation, asthma exacerbation, bronchitis, lung damage, cardiovascular effects, cancer, heavy metal poisoning (will depend on PM components), potential reproductive impacts
Ozone (O3)	Vehicle exhaust, formed from other air pollutants (i.e. NOx) in the presence of sunlight	Eye and throat irritation, coughing, respiratory tract problems, asthma, lung damage
Carbon Monoxide	Motor vehicle exhaust and indoor sources include kerosene or wood burning stoves	Headaches, reduced mental alertness, heart attack, cardiovascular diseases, impaired fetal development, death (extreme acute exposure)

Source: Adapted from Sequoia Foundation, "A Health Impact Assessment of the Proposed Cabin Creek Biomass Energy Facility in Placer County, California," Health Impact Assessment 2007.

For some technologies, transport related emissions will be highest during the installation phase (i.e. solar photovoltaics), while for others, transport emissions will continue throughout the maintenance and use phase (i.e. larger, utility-scale biomass facilities). In areas

34 EPA, "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014" (U.S. Environmental Protection Agency, April 15, 2016), https://www.epa.gov/sites/production/files/2016-04/documents/us-ghg-inventory-2016-main-text.pdf.

35 Ricardo American Lung Association, "State of the Air 2016" (American Lung Association, 2016), http://www.lung.org/local-content/california/documents/state-of-the-air/2016/sota-2016-full-report.pdf.

36 Jeffrey D. Bryon, James D. Boyd, and Paul Kramer, "Ivanpah Solar Electric Generating System: Presiding Member's Proposed Decision," DOCKET NUMBER 07-AFC-5 (California Energy Commission, August 2010), http://www.circleofblue.org/wp-content/uploads/2010/09/California-Energy-Commission-Proposed-Ivanpah-Project-DecisionCEC-800-2010-004-PMPD.pdf.

37 Sequoia Foundation, "A Health Impact Assessment of the Proposed Cabin Creek Biomass Energy Facility in Placer County, California," Health Impact Assessment (Sequoia Foundation, 2007), www.placer.ca.gov/~/media/cdr/.../Biomass/.../HIAReport.as.

where a large number of facilities are being sited or built, the cumulative impact of these transport related emissions needs to be considered.

Workers involved in transporting these technologies to their end-use site in California will be exposed to physical hazards related to working with and moving heavy equipment during loading and unloading. Some of these materials will also have hazardous components requiring special handling. These hazards will differ based on the type of technology and transport.

LCA.4 Installation

Emerging electricity generating technologies are used in both utility-scale and distributed installations. For utility-scale projects, a major public health concern results from land clearing and preparation that involves leveling and removal of local vegetation, requiring herbicides and machinery. Land repurposing for large facilities can impact local cultural and ecological resources, and surrounding communities will be impacted by noise and fugitive dust. This can also expose workers and fence line communities to onsite and fugitive dust and potentially toxic herbicides.[38] Table 3 displays average land usage for different utility-scale energy facilities.

Another concern specific to Southern California and the US Southwest is the potential for occupational and public exposure to the hazardous fungus, *Coccidioides*. Though the actual dispersal of the fungus in Southwestern US soils is unknown, it has been documented throughout Southern California and the Central Valley.[39] Recently, *Coccidioides* spores have been found in areas previously thought to be outside of the fungi's endemic range, and researchers suggest this could be the result of climate change and intensified droughts, which increase dust production and spread.[40]

Human exposure to these fungal spores can occur through soil disturbance, which can occur during land clearing and site preparation practices for utility-scale energy facilities. Previously, clusters of coccidioidomycosis have occurred in California workers involved in solar installation construction.[41] This exposure can cause coccidioidomycosis, or Valley Fever, if inhaled. Exposed individuals show a range of symptoms. Some exposed individuals may have no symptoms, while others have flu-like symptoms, such as shortness of breath, headache, night sweats, muscle aches, joint pain, rash on upper body or legs.[42] Severe cases, which are not

38 M.M. Aman et al., "A Review of Safety, Health and Environmental (SHE) Issues of Solar Energy System," Renewable and Sustainable Energy Reviews 41 (January 2015): 1190–1204, doi:10.1016/j.rser.2014.08.086.

39 David M. Engelthaler et al., "Local Population Structure and Patterns of Western Hemisphere Dispersal for Coccidioides Spp., the Fungal Cause of Valley Fever," mBio 7, no. 2 (May 4, 2016): e00550-16, doi:10.1128/mBio.00550-16.

40 Anastasia P. Litvintseva et al., "Valley Fever: Finding New Places for an Old Disease: Coccidioides Immitis Found in Washington State Soil Associated With Recent Human Infection," Clinical Infectious Diseases 60, no. 1 (January 1, 2015): e1–3, doi:10.1093/cid/ciu681.

41 Jason A. Wilken et al., "Coccidioidomycosis among Workers Constructing Solar Power Farms, California, USA, 2011–2014," Emerging Infectious Diseases 21, no. 11 (November 2015): 1997–2005, doi:10.3201/eid2111.150129.

42 CDC, "Valley Fever (Coccidioidomycosis)," Government Agency Website, Centers for Disease Control and Prevention, (May 22, 2017), https://www.cdc.gov/fungal/diseases/coccidioidomycosis/index.html.

well understood, can lead to severe and disabling lung or systemic infections and occasionally death.[43] African-Americans, Hispanics and Pacific Islanders are also more susceptible to infection, and elderly, pregnant, and immune-compromised individuals are more likely to have severe infections.[44] The incidence rate of Valley Fever infections in the US has increased, from 5.3 per 100,000 people in the southwestern US in 1998, to 42.6 per 100,000 in 2011.[45]

Table 3. Average Land Use Per Megawatt for Different Electricity Generating Systems

Fuel Type	Average Land Use per Megawatt
Natural Gas	0.08 acres/MW
Nuclear	0.832 acres/MW
Biomass	2.5 acres/MW
Geothermal	6.0 acres/MW
Solar	7.0 acres/MW
Small Hydro	7.5 acres/MW
Large Hydro	29.125 acres/MW
Wind	Ranges from 24.8 to 40 acres/MW

Sources: Adapted from Jim Bartridge et al., "Draft 2016 Environmental Performance Report of California's Electrical Generation System," July 2016. Sources: (1) California Energy Commission staff; (2) NREL Technical Report NREL/TP-6A2-45834 (3) NREL Technical Report NREL/TP-6A20-56290 (4) DRECP Acreage Calculator

To protect facility installation and maintenance workers, as well as communities surrounding new sites, research needs to focus on improving Valley Fever treatments and protection techniques while also developing better *Coccidioides* monitoring technology for air and soil.[46]

43 Gail L. Sondermeyer et al., "Coccidioidomycosis-Associated Deaths in California, 2000–2013," Public Health Reports 131, no. 4 (2016): 531–535.

44 Natalia Castro-Lopez and Chiung-Yu Hung, "Immune Response to Coccidioidomycosis and the Development of a Vaccine," Microorganisms 5, no. 1 (March 16, 2017): 13, doi:10.3390/microorganisms5010013.

45 CDC, "Morbidity and Mortality Weekly Report: Increase in Reported Coccidioidomycosis - United States, 1998-2011," Government Agency Website, Centers for Disease Control and Prevention, (March 29, 2013), https://www.cdc.gov/mmwr/preview/mmwrhtml/mm6212a1.htm.

46 Castro-Lopez and Hung, "Immune Response to Coccidioidomycosis and the Development of a Vaccine"; Engelthaler et al., "Local Population Structure and Patterns of Western Hemisphere Dispersal for Coccidioides Spp., the Fungal Cause of Valley Fever."

LCA.5 Maintenance and Use

Maintenance and use impacts vary based on technology. For instance, utility-scale solar farms have minimal impacts throughout their use, outside of the potential for accidents and extreme weather related damage, while the majority of public health impacts from utility scale biomass facilities will occur during their use phase due to combustion emissions.

LCA.6 Decommissioning and Disposal

As many of these technologies have not been implemented in California long enough to reach the end of their generating life spans, this last phase of their life cycle has the most unknowns. This stage includes hazards present during the decommissioning of utility-scale sites, as well as those involved in the eventual disposal or recycling of the technology's components. For utility-scale sites, decommissioning activities could have similar impacts to those seen during installation, as deconstruction practices could lead to fugitive dust and emissions for workers and surrounding communities.

For many of these technologies, safe disposal or recycling processes have not yet been developed, leading to the potential for hazards when these components reach the end of their life span or when individual units are damaged. There is limited research into the potential hazards related to available and developing disposal methods, which can include landfilling, incineration, and recycling, among others.

Increasingly, industries are recognizing their responsibility - for example through supply chain changes, sub-contractor monitoring, and extended producer responsibility (EPR) - for health and environmental impacts across product life cycles. EPR is a policy initiative that assigns responsibility for the treatment and disposal of a product to manufacturers, with the aim to incentivize waste prevention during product design and manufacture. There is a need for policy and legal research to focus on strategies to promote, or potentially require, EPR to assure that the rapid expansion of EES in California is not associated with significant adverse health and environmental impacts in vulnerable communities across the globe.

With the growth of electronic products that are consumed and disposed of on a short time frame, the world has seen a rise in potentially toxic electronic waste (e-waste). This has become an environmental health concern for communities in developing countries where e-waste is commonly sent for disposal, especially those involved in reclaiming metals and other valuable materials from the debris.[47] By 2025, the UN expects e-waste to grow by 500 percent globally.[48] Similar to e-waste that has been shipped globally from the US, it is possible that some emerging energy technologies (i.e. Li-ion batteries, solar PV cells) will be shipped abroad to be recycled, incinerated, or otherwise disposed, resulting in potential hazards and health impacts on workers and communities from products that were produced for and used in California.

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47 Duncan McCann and Annelaure Wittmann, "E-Waste Prevention, Take-Back System Design and Policy Approaches," Step Green Paper Series (United Nations University, February 13, 2015), http://www.step-initiative.org/publications.html.

48 Ibid.

The following chapters will review each energy technology of focus, highlighting important impacts, exposures, and hazards. Potential risk is noted when possible, though risk is difficult to determine based on the availability of relevant information. These chapters do not include every material used in technology components, as the focus will be on those components that have been highlighted by research as potentially hazardous.

Chapter 2: Solar Photovoltaics

2.1 Solar Photovoltaics in California

The CEC estimated that California generated 16,000 GWh of electricity from solar photovoltaic (PV) in 2016, roughly 6% of the energy mix.[49] To reach the state's ambitious renewable energy goals, models predict that this could grow to 57,000 GWh by 2030, growing to 16% of the state's energy mix.[50] In California from 2010 to 2015, installed utility-scale solar PV grew the most of any utility-scale renewable source, from 100 to 5,500MW.[51] This, in part, has been driven by significant cost declines, from $4.10 per watt in 2010 to $1.80 per watt in 2014 across installed technologies.[52] This drop in price aligns with an increase in efficiency, which further decreases facilities' land-use and emissions footprints. Due to these factors, both utility-scale and distributed solar PV are expected to play an integral role in California's future electricity generation.[53]

2.1.1 Overview of Solar Photovoltaics

Solar photovoltaic cells convert sunlight into direct current (DC) electricity by transporting electrons across layers of semiconducting materials. To do so, the cells absorb sunlight, which is then used to power electron transport between layers producing a direct current according to specific properties of the materials used.[54] Complete solar panels, or modules, are composed of many of these cells interconnected with other components referred to as the balance of system (BOS). These components include wiring to conduct electricity onto the grid, a frame and encasement to protect the PV cells, mounting materials, and an inverter to translate the direct current produced into the alternating current used on the grid. At a utility scale solar PV site, many panels are combined and connected to an electrical transmission system for the grid. In distributed systems, a smaller array of panels is connected to the grid from individual buildings or community installations.

There are many types of PV technologies available on the market that can be used in both utility-scale and distributed systems. Crystalline silicon cells have dominated the solar PV market, though other cell technologies have grown in market capacity. Crystalline silicon cells

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49 CEC, "Renewable Energy – Overview December 2016" (California Energy Commission, December 2016), http://www.energy.ca.gov/renewables/tracking_progress/documents/renewable.pdf.

50 Gregory Brinkman, Jennie Jorgenson, and Marissa Hummon, "California 2030 Low Carbon Grid Study (LCGS): Phase I" (National Renewable Energy Laboratory, 2014), http://lowcarbongrid2030.org/wp-content/uploads/2014/10/LCGS_PhaseI_NRELslides.pdf.

51 Jim Bartridge et al., "Draft 2016 Environmental Performance Report of California's Electrical Generation System," Staff Report (California Energy Commission, July 2016), https://efiling.energy.ca.gov/getdocument.aspx?tn=212338.

52 Ibid.

53 Ibid.

54 Francesca Ferrazza, "Crystalline Silicon: Manufacture and Properties," Practical Handbook of Photovoltaics: Fundamentals and Applications, 2012, 79.

were at a peak amongst all solar technologies in 2005, with 95% of the market share.[55] By 2010, this had dropped to 85%, but has since grown again to just over 95% in 2015.[56] One model of projected market shares for different PV technologies from the International Renewable Energy Agency is shown in Table 4.

Table 4. Modeled Market Share of PV Panel Technologies

Technology		2014	2020	2030
Silicon-Based (c-Si)	Monocrystalline	92%	73.30%	44.80%
	Polycrystalline			
	Ribbon			
	Amorphous			
Thin Films	CIGS	2%	5.20%	6.40%
	CdTe	5%	5.20%	4.70%
Other	Concentrating solar PV (CPV)	1%	1.20%	0.60%
	Organic PV/dye-sensitized cells (OPV)		5.80%	8.70%
	Crystalline silicon (Advanced c-Si)		8.70%	25.60%
	CIGS alternatives, perovskite		0.60%	9.30%

Source: Stephanie Weckend, Andreas Wade, and Garvin Heath, "End-of-Life Management: Solar Photovoltaic Panels," International Renewable Energy Agency, June 2016.

The following section discusses potential health impacts across the life cycle of selected PV technologies. The two types of silicon-based panels included in this report are monocrystalline (mono-Si) and polycrystalline (poly-Si, also known as multicrystalline), which differ based on the number of silicon crystals in each cell – a single crystal for mono-Si and many for poly-Si. This report will also cover cadmium telluride (CdTe) and Copper Indium Gallium Selenide (CIGS) thin films. For third generation PV technologies, common perovskite solar cells (PVCs) will be discussed briefly, though limited information is available on potential exposures and impacts across their life cycles.

55 Edgar G. Hertwich, Jacqueline Aloisi de Larderel, and Sangwon Suh, "Green Energy Choices: The Benefits, Risks, and Trade-Offs of Low-Carbon Technologies for Electricity Production" (United Nations Environmnetal Programme, 2016), http://www.unep.org/resourcepanel/Portals/50244/publications/Summary_for_Policy_Makers_GHG_I.pdf.

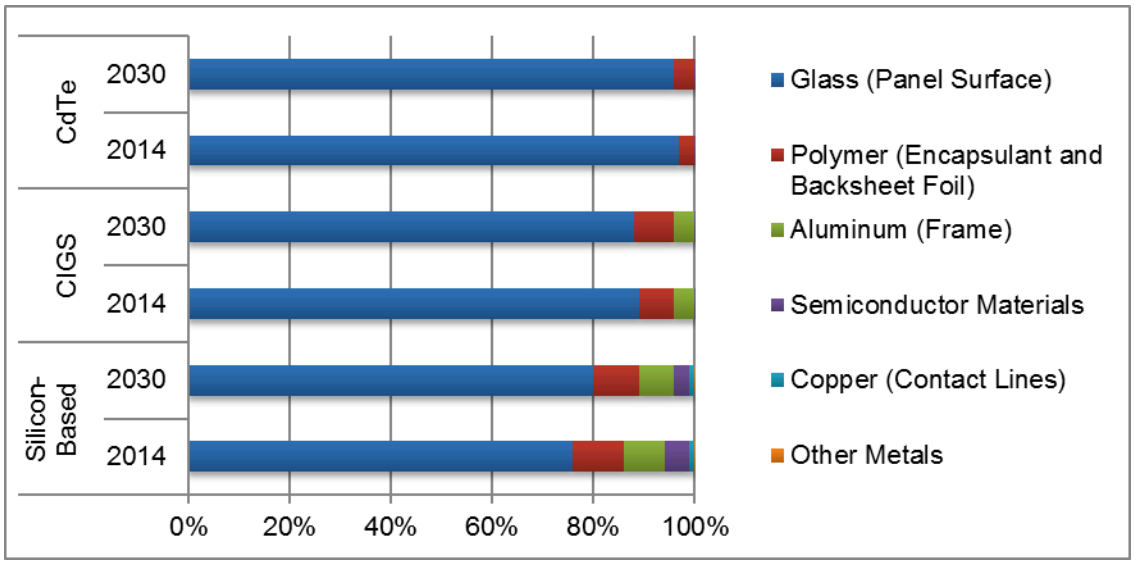
56 Fraunhofer Institute for Solar Energy Systems, ISE, "Photovoltaics Report" (Freiburg, June 6, 2016), https://www.ise.fraunhofer.de/de/downloads/pdf-files/aktuelles/photovoltaics-report-in-englischer-sprache.pdf.

As all of these cells have varying material input and manufacturing processes, these first two life cycle stages will be discussed separately for each cell type. However, hazards and potential risk related to the transport, installation, maintenance and use, and decommissioning and disposal stages will be combined, as major impacts are expected to be similar across technologies, depending on the scale of distribution. Potential hazards and emissions were catalogued from existing resources in which there may be gaps in materials reported or outdated information. As the solar industry is expanding quickly, materials and exposures continue to change, and more recent inventories and hazard assessments of PV materials are necessary to ensure optimal worker and community health.

2.2 Raw Material Extraction and Materials Preparation

A complete PV panel includes many material inputs. Common materials found in silicon-based, CIGS, and CdTe panels are shown in Figure 6. Individual electricity-conducting cells require materials that are capable of absorbing light across the spectrum of solar insolation, while also being good electrical and chemical insulators, with high electrical resistivity and low saturation current density.[57] Table 5 displays common primary materials in PV panels and the top countries producing them in 2014. California is not a primary extractor or producer of any of these materials, and PV manufacturing is not among the leading industries in demand for these materials.[58]

Figure 6. PV Material Inputs by Percent of Panel Weight



Source: Stephanie Weckend, Andreas Wade, and Garvin Heath, "End-of-Life Management: Solar Photovoltaic Panels" International Renewable Energy Agency, June 2016.

57 K. Summers and J. Radde, "Potential Health and Environmental Impacts Associated with the Manufacture and Use of Photovoltaic Cells," PIER Final Project Report (Tetra Tech, Inc., August 2004), http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.439.1726&rep=rep1&type=pdf.

58 Vasilis Fthenakis, Wenming Wang, and Hyung Chul Kim, "Life Cycle Inventory Analysis of the Production of Metals Used in Photovoltaics," Renewable and Sustainable Energy Reviews 13, no. 3 (April 2009): 493–517, doi:10.1016/j.rser.2007.11.012.

Table 5. Top Producers of PV Materials 2014

Raw Material	Top Producing Countries
Silica	China, Russia, United States, Norway, France
Zinc	China, Peru, Australia, United States, India
Copper	Chile, China, Peru, United States, DRC
Cadmium	China, South Korea, Japan, Kazakhstan, Mexico
Tellurium	United States, Russia, Japan, Sweden, Peru
Selenium	China, Japan, Germany, Belgium, Russia
Gallium	China, Ukraine, Japan, Russia, Hungary
Aluminum	China, Russia, Canada, UAE, India
Lead	China, Australia, United States, Peru, Mexico
Nickel	Philippines, Australia, Canada, Indonesia, New Caledonia
Tin	China, Indonesia, Myanmar, Peru, Bolivia
Silver	Mexico, Peru, China, Australia, Chile
Molybdenum	China, United States, Chile, Peru, Mexico
Bauxite	Australia, China, Brazil, India, Guinea

Source: USGS, 2017

The following sections discuss the major occupational and public health concerns related to chemical and mineral exposures during material extraction and processing for silicon-based and thin film PV panels. Only major chemical exposures of specific semiconductor and BOS materials will be discussed. Physical hazards related to mining are summarized in **Section LCA.1**. There is limited publicly available data on extraction statistics for PV manufacturers, so more research is needed into the potential for the PV industry to impact hazards related to metal and mineral mining as it continues to grow.

2.2.1 Common Components Across PV Technologies

Some materials are common across technologies, as glass, plastic, aluminum, and copper are main components of modules and BOS. The most common component of solar PV modules is glass, a material made from silica (see Figure 6). While only a small portion of mined silica is used in PV semiconductor materials, a larger portion is refined for glass components of PV panels. Common health hazards resulting from the production of glass include exposure to

noise and PM.[59] Exposure to silica dust is covered later in **Section 2.2.2.1**, but significant chronic effects such as decreased pulmonary function, lung disease, and silicosis are well known.[60]

Another common material found in PV panels is aluminum, which is produced from bauxite ore. Though this ore is considered chemically inert, the processing stages used to derive aluminum can lead to carcinogenic polycyclic aromatic hydrocarbon (PAH) emissions.[61] There is need for further studies regarding the association of aluminum processing with occupational asthma and lung disease. Releases of benzo[a]pyrene (BaP) present a lung cancer risk to workers and, potentially, surrounding communities.[62] Aluminum mining and smelting practices have led to increased emissions of criteria pollutants in surrounding communities, and increased levels of PM and SO_2 related asthma and bronchiolitis incidence.[63]

Additionally, copper is found throughout PV components, including wiring. Copper mining and processing have well-known environmental and health impacts. Similar to other materials in solar PV, only a small percentage of globally produced copper will be used in solar PV. In considering life cycle toxicities of PV applications, however, copper extraction cannot be ignored. According to the US EPA, the largest processing wastes from metal production in the US results from copper mining, and these tailings can have high acid, metal, and radionuclide concentrations.[64] These can cause environmental damage if uncontained, while also exposing individuals involved in processing to radium, thorium, and uranium, which can lead to cancer and potentially harmful genetic alterations.[65] Copper smelting can release PM and SO_2 into the air, along with trace elements like arsenic, cadmium, and mercury.[66] PM and sulfur oxides are well known criteria pollutants that can lead to coughing, wheezing, and difficulty breathing in acute exposures, with chronic exposure potentially leading to asthma and decreased lung and airway function.[67] Arsenic, cadmium, and mercury exposures through air emissions can lead to

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59 Abdel Rasoul GM, "Some Health Disorders among Workers in a Glass Factory," Occupational Medicine & Health Affairs 1, no. 2 (2013), doi:10.4172/2329-6879.1000106.

60 OSHA, "'Crystalline Silica Exposure:' Health Hazard Information for General Industry Employees," Goverment Ageny Website, United States Department of Labor, Occupational Safety and Health Administration, (2002), https://www.osha.gov/Publications/osha3176.html.

61 James C. Wesdock and Ian M. F. Arnold, "Occupational and Environmental Health in the Aluminum Industry: Key Points for Health Practitioners," Journal of Occupational and Environmental Medicine 56 (May 2014): S5–11, doi:10.1097/JOM.0000000000000071.

62 Stephen Claude Martin and Claude Larivière, "Community Health Risk Assessment of Primary Aluminum Smelter Emissions:," Journal of Occupational and Environmental Medicine 56 (May 2014): S33–39, doi:10.1097/JOM.0000000000000135.

63 Ibid.

64 EPA, "TENORM: Copper Mining and Production Wastes," Goverment Agency Website, US EPA Radiation Protection, (September 14, 2016), https://www.epa.gov/radiation/tenorm-copper-mining-and-production-wastes.

65 EPA, "Radiation Health Impacts," Goverment Agency Website, US EPA Radiation Protection, (July 21, 2016), https://www.epa.gov/radiation/radiation-health-effects.

66 Stanislaw Dudka and Domy C. Adriano, "Environmental Impacts of Metal Ore Mining and Processing: A Review," Journal of Environmental Quality 26 (May 1997): 590–602.

67 EPA, "Criteria Air Pollutants," Goverment Agency Website, US EPA, (April 3, 2017), https://www.epa.gov/criteria-air-pollutants.

cancer, systemic organ damage, and decreased neurological development in children.[68] Cohort studies have found excess mortalities in copper miners resulting from lung cancer.[69]

Zinc is commonly found in small amounts throughout different module types.[70] Globally, it is estimated that between 462 and 1,380 million kg of zinc are released annually into the environment from zinc mining and smelting, with the potential to contaminate local water, soil, and crops with its by-product, cadmium.[71] In the United States, which was the fourth largest global producer of zinc in 2015, major health-related concerns associated with zinc mining and smelting involve the large amount of waste generated and the potential for these wastes to be disposed of on surrounding land.[72] The resulting wastes can include concentrated levels of naturally occurring radioactive materials like uranium, thorium, radium, and radon while also exposing miners and surrounding populations to other toxics like arsenic.[73]

Nickel can also be used in PV applications. This element occurs naturally in laterite or sulphide ores, and can be leached from rock stores at high temperature and pressure. Nickel exposure can lead to dermatitis and respiratory irritation, and nickel compounds are considered human carcinogens.[74] Exposures during the processing phase of nickel have also been found to have respiratory, pulmonary, and neurological impacts on those exposed.[75]

Finally, silver can be found throughout PV applications, and the PV industry uses a significant share of virgin silver.[76] During silver refining, exposure to dust containing high levels of silver compounds (i.e. silver nitrate or silver oxide) can lead to trouble breathing, dermatitis, respiratory tract irritation and stomach pain.[77]

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68 M Hutton, "Human Health Concerns of Lead, Mercury, Cadmium, and Arsenic," in Lead, Mercury, Cadmium, and Arsenic in the Environment (John Wiley & Sons Ltd., 1987), https://dge.carnegiescience.edu/SCOPE/SCOPE_31/SCOPE_31_2.01_Chapter6_53-68.pdf.

69 Ruoling Chen, Li Wei, and Huaming Huang, "Mortality from Lung Cancer among Copper Miners.," British Journal of Industrial Medicine 50, no. 6 (1993): 505–509; Masanori Kuratsune et al., "Occupational Lung Cancer among Copper Smelters," International Journal of Cancer 13, no. 4 (April 15, 1974), doi:10.1002/ijc.2910130415.

70 Stephanie Weckend, Andreas Wade, and Garvin Heath, "End-of-Life Management: Solar Photovoltaic Panels" (International Renewable Energy Agency, June 2016), http://www.irena.org/DocumentDownloads/Publications/IRENA_IEAPVPS_End-of-Life_Solar_PV_Panels_2016.pdf.

71 Xiuwu Zhang et al., "Impacts of Lead/Zinc Mining and Smelting on the Environment and Human Health in China," Environmental Monitoring and Assessment 184, no. 4 (April 2012): 2261–73, doi:10.1007/s10661-011-2115-6.

72 US EPA, "2015 Toxics Release Inventory National Analysis" (U.S. Environmental Protection Agency, January 2017), https://www.epa.gov/sites/production/files/2017-01/documents/tri_na_2015_complete_english.pdf.

73 US EPA, "TENORM: Copper Mining and Production Wastes," US EPA Radiation Protection, 2003, https://www.epa.gov/sites/production/files/2015-04/documents/mineguide.pdf.

74 ATSDR, "Toxicology Profiles: Nickel," Goverment Agency Website, Agency for Toxic Substances and Disease Registry, (August 2005), https://www.atsdr.cdc.gov/phs/phs.asp?id=243&tid=44.

75 M. Cempel and G. Nikel, "Nickel: A Review of Its Sources and Environmental Toxicology," Polish Journal of Environmental Studies 15, no. 3 (2006): 375–382.

76 Dustin Mulvaney, Comments and Edit on Solar PV Chapter, Written, June 9, 2017.

77 ATSDR, "Toxicology Profiles: Silver," Goverment Agency Website, Agency for Toxic Substances and Disease Registry, (December 1990), https://www.atsdr.cdc.gov/PHS/PHS.asp?id=537&tid=97.

2.2.2 Semiconductor Materials

2.2.2.1 Silicon-based Modules

For silicon-based panels, the most significant hazards of the extraction stage are related to silica and lead mining. Poly-Si and mono-Si semiconductors include similar material inputs, a large proportion of which is silicon, which then must be processed to achieve the desired purity-level of silicon for PV.[78] In most cases, silica is extracted through open-pit and dredge mining, often produced as a byproduct of other mining operations.[79] Most silicon-based panels are produced in Asia, but some sand mining, metallurgical silicon, and polysilicon refining occurs in the United States. Open pit and dredging processes can produce high-levels of dust, exposing workers directly to respirable silica. Dust may also travel from mining sites, but the impacts on communities surrounding silica recovery sites are not well defined.[80] Administrative and engineering dust controls are known to be effective, but studies demonstrate that while exposures may be decreased, miners continue to be at risk.[81] The health impacts of such silica exposure are well known, including silicosis, bronchitis, lung cancer, greater susceptibility to tuberculosis, and possible renal failure.[82] Silicosis can manifest as difficulty breathing, chest pain, coughing, and can develop into respiratory failure and death.[83] Silicosis risk can be reduced with protective equipment like respirator masks and dust-reduction practices like surface-wetting and improved ventilation.[84] Despite these controls, Silicosis prevalence in China has been increasing, and a total of 8,095 cases were confirmed in 2013.[85] Only a small portion of mined silica is used in PV semiconductor manufacturing, but a portion is also refined for glass components of PV panels. The risks for miners, therefore, remain significant given the importance of silicon to the PV industry and PV's expected growth in California.[86]

The processing of silica to form silicon used in PV modules can be separated into two steps. First, silica undergoes carbothermic reduction to produce metallurgical silicon, which can expose workers to silica fumes (or amorphous silicon) if furnaces do not have proper protective

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78 Branch of Industrial Minerals, "Crystalline Silica Primer" (U.S. Department of the Interior, US Bureau of Mines, 1992).

79 Thomas P. Dolley and Wallace P. Bolen, "U.S. Geological Survey Minerals Yearbook: Silica" (U.S. Geological Survey, 2000), https://minerals.usgs.gov/minerals/pubs/commodity/silica/780400.pdf.

80 Minnesota Department of Health, "Silica Sand Mining & the Environment" (Minnesota Department of Health, Site Assessment and Consultation Unit, June 2014), http://www.health.state.mn.us/divs/eh/hazardous/topics/silica/ssmenviro.pdf.

81 Weihong Chen et al., "Long-Term Exposure to Silica Dust and Risk of Total and Cause-Specific Mortality in Chinese Workers: A Cohort Study," ed. Naftali Kaminski, PLoS Medicine 9, no. 4 (April 17, 2012): e1001206, doi:10.1371/journal.pmed.1001206.

82 OSHA, "'Crystalline Silica Exposure:' Health Hazard Information for General Industry Employees"; OSHA, "Protect Yourself: Silicosis," Goverment Agency Website, United States Department of Labor, Occupational Safety and Health Administration, (n.d.), https://www.osha.gov/Publications/silicosis.html.

83 OSHA, "OSHA 3267-09N-05."

84 Ibid.

85 Lap Ah Tse et al., "Prediction Models and Risk Assessment for Silicosis Using a Retrospective Cohort Study among Workers Exposed to Silica in China," Scientific Reports 5 (June 19, 2015): 11059, doi:10.1038/srep11059.

86 Dustin Mulvaney et al., "Toward a Just and Sustainable Solar Energy Industry," San Jose: Silicon Valley Toxics Coalition, 2009, http://staging.community-wealth.org/sites/clone.community-wealth.org/files/downloads/paper-mulvaney-et-al.pdf.

hoods and venting.[87] Because it is difficult to separate amorphous silicon inhalation from that of crystalline silica in most occupational settings, there are few epidemiological studies assessing amorphous silica fumes specifically. One review found that further human studies were necessary, though chronic bronchitis, chronic obstructive pulmonary disease, and emphysema were likely occupational outcomes.[88] Other corrosive materials can include acids such as hydrochloric acid, which can cause severe burns and irritation for workers if leaked.[89]

The second step occurs when metallurgical silicon is then further refined to form a high purity polysilicon for wafer production. Depending on whether chemical or metallurgical processes are used for this step, workers can be exposed to different toxic or corrosive materials. For instance, chemical production of polysilicon can expose workers to chlorosilanes, such as trichlorosilane, which can cause severe irritation and burns to skin, eyes, and respiratory tract depending on the type of exposure. Some facilities will also use silane gas during this stage, which can spontaneously combust, leading to fire or explosion hazards for workers and surrounding communities.[90] This stage can also yield silicon tetrachloride, which, if exposed to local water systems, can create hydrochloric acid, acidifying surrounding water and soil.[91]

Lead is a metal found in solder, metallization paste, and frit in most crystalline silicon PV modules. The health impacts of lead exposure from mining and processing practices are well known and include nervous system effects, cognitive dysfunction, and impaired kidney function.[92] In the short term, acute lead exposure can lead to abdominal pain, constipation, tiredness, headaches, memory loss, and irritability. More chronic exposures can lead to forgetfulness, nausea, and depression as well as high blood pressure, heart disease, kidney disease, and reduced fertility.[93] Lead is defined as "probably a human carcinogen" by the International Agency for Research on Cancer (IARC).[94] While only a very small percentage of

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87 B.S. Xakalashe and M. Tangstad, "Silicon Processing: From Quartz to Crystalline Silicon Solar Cells," ed. R.T. Jones and P. den Hoed (Southern African Pyrometallurgy 2011, Johannesburg: Southern African Institute of Mining and Metallurgy, 2011), http://pyrometallurgy.co.za/Pyro2011/Papers/083-Xakalashe.pdf.

88 R. Merget et al., "Health Hazards due to the Inhalation of Amorphous Silica," Archives of Toxicology 75, no. 11–12 (January 2002): 625–34, doi:10.1007/s002040100266.

89 Xakalashe and Tangstad, "Silicon Processing: From Quartz to Crystalline Silicon Solar Cells"; NIOSH, "Occupational Health Guideline for Hydrogen Chloride" (National Institute for Occupational Safety and Health, September 1978), https://www.cdc.gov/niosh/docs/81-123/pdfs/0332.pdf.

90 NIOSH, "Preventing Adverse Health Effects from Exposure to: Dimethylformamide (DMF)," Goverment Agency Website, National Institute for Occupational Safety and Health, (June 6, 2014), https://www.cdc.gov/niosh/docs/90-105/default.html; Tetyana Nychyporuk and Mustapha Lemiti, Silicon-Based Third Generation Photovoltaics. (INTECH Open Access Publisher, 2011).

91 Dustin Mulvaney, "Solar Energy Isn't Always as Green as You Think," IEEE Spectrum, November 13, 2014, http://spectrum.ieee.org/green-tech/solar/solar-energy-isnt-always-as-green-as-you-think.

92 OSHA, "Lead: Health Effects," Goverment Ageny Website, United States Department of Labor, Occupational Safety and Health Administration, (2016), https://www.osha.gov/SLTC/lead/healtheffects.html.

93 NIOSH, "Lead: Information for Workers," Goverment Agency Website, National Institute for Occupational Safety and Health, (April 19, 2017), https://www.cdc.gov/niosh/topics/lead/health.html.

94 Ibid.

mined lead is used in PV systems, it continues to be an important occupational and public health concern throughout manufacturing of PV systems.[95]

2.2.2.2 Thin Films

2.2.2.2.1 Cadmium Telluride (CdTe)

CdTe thin films use copper, zinc, cadmium, sulfur, and tellurium as major components of their semiconductor materials. Zinc and copper are primary source metals for modules. Cadmium is produced from zinc processing, and cadmium leaching from mining activity is a serious global concern.[96] Zinc mines in the United States produce all of the cadmium, germanium, indium, and thorium used in the country, as well as some of the gallium, lead, silver, and gold.[97] These ores are excavated from underground mines or blasted from aboveground quarries and then processed through crushing, screening, and milling. These processes can produce dust, while also releasing cadmium and other materials in tailings, soil, and waste rock.[98]

It is expected that by 2050, 50% of worldwide cadmium production will be for use in PV systems, and cadmium emissions could increase as the industry grows.[99] Cadmium compounds can cause pulmonary edema, nausea, and muscle aches with short-term exposures; chronic exposure is associated with adverse impacts on the respiratory system, kidneys, prostate, and blood.[100] Cadmium compounds are also classified as a human carcinogen by the International Agency for Research on Cancer.[101] US producers of cadmium-containing products generally have waste reduction and management programs. While implementation of management best practices can limit exposures in the production and use of cadmium containing products, on-going monitoring is required to ensure consistent implementation of these practices.

Tellurium is a byproduct from copper refining and is a known eye and skin irritant, and chronic or high exposures can lead to kidney, liver, and nervous system damage.[102] Tellurium

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95 ILA, "Lead Uses - Statistics," International Lead Association, 2012, http://www.ila-lead.org/lead-facts/lead-uses--statistics.

96 Donald I. Bleiwas, "Byproduct Mineral Commodities Used for the Production of Photovoltaic Cells" (U.S. Department of the Interior, U.S. Geological Survey, 2010), http://pubs.usgs.gov/circ/1365/.; Fthenakis, Wang, and Kim, "Life Cycle Inventory Analysis of the Production of Metals Used in Photovoltaics."

97 Vasilis M Fthenakis, "Life Cycle Impact Analysis of Cadmium in CdTe PV Production," Renewable and Sustainable Energy Reviews 8, no. 4 (August 2004): 303–34, doi:10.1016/j.rser.2003.12.001.

98 Vasilis M Fthenakis, "Life Cycle Impact Analysis of Cadmium in CdTe PV Production," Renewable and Sustainable Energy Reviews 8, no. 4 (August 2004): 303–34, doi:10.1016/j.rser.2003.12.001.

99 Coyle, "The Not-So-Green Renewable Energy: Preventing Waste Disposal of Solar Photovoltaic (PV) Panels," Golden Gate University Environmental Law Journal 4, no. 2 Pacific Region Edition (January 2011), http://digitalcommons.law.ggu.edu/cgi/viewcontent.cgi?article=1064&context=gguelj.

100 OSHA, "Cadmium" (U.S. Department of Labor, Occupational Safety and Health Administration, 2004), https://www.osha.gov/Publications/osha3136.pdf.

101 IARC, "Cadmium and Cadmium Compounds," Monograph (International Agency for Research on Cancer, 2012), https://monographs.iarc.fr/ENG/Monographs/vol100C/mono100C-8.pdf.

102 NJ Department of Health, "Hazardous Substance Fact Sheet: Tellurium" (New Jersey Department of Health, April 2009), http://nj.gov/health/eoh/rtkweb/documents/fs/1777.pdf; Fthenakis, "Life Cycle Impact Analysis of Cadmium in CdTe PV Production," August 2004.

processing from copper can also produce selenium, which can lead to hair loss and neurological abnormalities with chronic exposures.[103]

Molybdenum is commonly used to make the back contact for thin films. This element can be mined or produced as a by-product of copper refining.[104] Molybdenum has demonstrated low toxicity in most toxicological and epidemiological studies - though reports from workers involved in molybdenum processing have found exposure to the element can be associated with increased blood uric acid concentrations, gout like symptoms, and pneumoconiosis.[105]

2.2.1.3 Copper Indium Gallium Selenium (CIGS)

Common materials in CIGS cells are zinc, copper, indium, gallium, selenium, cadmium, and molybdenum.[106] The production of CIGS in the US and globally is much smaller than that of CdTe. Hazards related to zinc and copper mining are pertinent to these technologies. Indium is also produced from processing zinc, though it can take the form of trimethylindium, a highly reactive material capable of spontaneous combustion.[107] Selenium is produced as a byproduct during electrolytic refining of copper. Chronic exposure to selenium can cause selenosis, which can lead to hair loss and neurological abnormalities.[108]

Gallium is produced globally by processing bauxite ore to form aluminum, though it can also be recovered during zinc processing. According to the US Geological Survey, gallium is naturally available in high quantities, but is not produced in the US.[109] In elemental form, it has limited toxicity, but more than 95% consumed in the US is in the form of gallium arsenide.[110] GaAs is a chemical included in California's Proposition 65 List of chemicals that cause cancer or reproductive toxicity.[111] The International Agency for Research on Cancer classifies arsenic containing compounds, including GaAs, as carcinogenic to humans.[112]

2.2.2.3 Perovskite Solar Cells

Of the myriad of new PV technologies being researched, perovskite solar cells (PVCs) have had a rapid development, reaching high efficiencies (i.e. 22% for some chemistries being

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103 Mulvaney et al., "Toward a Just and Sustainable Solar Energy Industry."

104 USGS, "Molybdenum: Statistics and Information," Goverment Ageny Website, US Geological Survey Minerals Information, (2017), https://minerals.usgs.gov/minerals/pubs/commodity/gallium/.

105 Adolf Vyskocil and Claude Viau, "Assessment of Molybdenum Toxicity in Humans," Journal of Applied Toxicology 19, no. 3 (1999): 185–192.

106 Fthenakis, Wang, and Kim, "Life Cycle Inventory Analysis of the Production of Metals Used in Photovoltaics."

107 Mulvaney et al., "Toward a Just and Sustainable Solar Energy Industry."

108 Ibid.

109 Bleiwas, "Byproduct Mineral Commodities Used for the Production of Photovoltaic Cells."

110 USGS, "Gallium: Statistics and Information," Goverment Ageny Website, US Geological Survey Minerals Information, (2017), https://minerals.usgs.gov/minerals/pubs/commodity/gallium/.

111 OEHHA, "The Proposition 65 List," California State Government Agency, Office of Environmental Health Hazard Assessment, (January 27, 2017), https://oehha.ca.gov/proposition-65/proposition-65-list.

112 IARC, "Gallium Arsenide"; Bomhard et al., "Evaluation of the Carcinogenicity of Gallium Arsenide."

researched) quickly.[113] Common materials in emerging perovskite solar cells include methylammonium or formamidinium, both halides containing carbon, hydrogen, and nitrogen.[114] These cells are named after a particular crystal structure that these halides components form.

Currently, methylammonium lead halides are common in high-efficiency perovskite cells.[115] Though these cells will use a small percentage of the lead produced globally, the environmental and health concerns of lead processing discussed above in **Section 2.2.2.1** should be considered as risks in the life cycle. Research into lead replacements is ongoing, and some studies have found tin as a promising substitute.[116] Though only a small percentage of global tin would be directed toward perovskite solar cells, tin mines are well known for environmental degradation, landslides, and high injury rates in miners.[117] Exposure to small amounts of tin is not harmful, but ingesting large quantities of the element can lead to stomachaches, anemia, and liver and kidney problems.[118] In some perovskite chemistries, organolead and organotin compounds are used, which have higher fat solubility than their elemental counterparts and, therefore, higher dermal and respiratory absorptions.[119] Additional materials that can be used to form perovskite cells, such as methylamine and hydroiodic acid, are known skin and respiratory irritants.[120]

2.3 Manufacture

As previously mentioned, most PV manufacture occurs outside of California, and the majority occurs in Asia. The US produced less than 3% of solar PV sold globally in 2015.[121] While this means that the majority of occupational and environmental health risks associated with panel manufacture will primarily impact populations outside of the US, the US remains an important manufacturer of PV products, which could increase into the future. In this way, domestic impacts cannot be overlooked.

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113 Shida Yang et al., "Recent Advances in Perovskite Solar Cells: Efficiency, Stability and Lead-Free Perovskite," Journal of Materials Chemistry, February 21, 2017, doi:10.1039/C7TA00366H.

114 Yang Yang and Jingbi You, "Make Perovskite Solar Cells Stable," Nature Comment (April 11, 2017), https://www.nature.com/news/make-perovskite-solar-cells-stable-1.21807.

115 Ibid.

116 Aslihan Babayigit et al., "Assessing the Toxicity of Pb- and Sn-Based Perovskite Solar Cells in Model Organism Danio Rerio," Scientific Reports 6, no. 1 (May 2016), doi:10.1038/srep18721.

117 Kate Hodal, "Death Metal: Tin Mining in Indonesia," The Guardian, November 23, 2012, https://www.theguardian.com/environment/2012/nov/23/tin-mining-indonesia-bangka.

118 ATSDR, "Toxicology Profiles: Tin," Goverment Agency Website, Agency for Toxic Substances and Disease Registry, (August 2005), https://www.atsdr.cdc.gov/phs/phs.asp?id=541&tid=98.

119 Aslihan Babayigit et al., "Toxicity of Organometal Halide Perovskite Solar Cells," Nature Materials 15, no. 3 (2016): 247–251.

120 NIOSH, "Methylamine," Goverment Agency Website, National Institute for Occupational Safety and Health, (December 4, 2014), https://www.cdc.gov/niosh/idlh/74895.html; NJ Department of Health, "Hazardous Substance Fact Sheet: Hydroiodic Acid" (New Jersey Department of Health, June 2001), http://nj.gov/health/eoh/rtkweb/documents/fs/1009.pdf.

121 Fraunhofer Institute for Solar Energy Systems, ISE, "Photovoltaics Report."

This section discusses the potential public and occupational health impacts related to solar PV manufacture of both silicon-based and thin film technologies. As the industry expands, new products are coming online, and manufacturing locations, processes, and materials are changing, creating a need for additional research on the potential health and safety impacts across PV panel manufacture.

A key hazard in manufacturing is the inhalation of potentially toxic fumes, such as the irritant hydrogen selenide in CIGS manufacture. Workers can also come into contact with corrosive liquids or flammable gases from system leaks, which can present chemical burn hazards. With appropriate engineering controls, toxic air emissions should not impact nearby local communities.[122] Most life cycle assessments of solar PV that include a human toxicity measure assume that available safety protocols for manufacturing hazards are in place. However, these protections are not always present or functioning, particularly in developing countries.[123]

Even in domestic manufacturing, these protections are not always adequate, as was the case when the Georgia-based solar company Suniva outsourced some of its manufacturing to inmates in federal prisons.[124] Though there are many potentially hazardous chemicals, gases, and metals throughout the PV manufacturing process, these are mainly a concern for workers in manufacturing facilities and, in cases of leaked effluent or facility fire, communities surrounding these facilities.[125] The final PV product is encased in glass, preventing leaching of materials during its end-use.

2.3.1 Silicon-Based Panels

The process for manufacturing silicon-based panels from polysilicon includes wafer production, cell-component manufacture from wafers and other inputs, and addition to components to complete the module. Workers face physical and mechanical hazards related to noise and heavy machinery use. Injuries from broken glass are also an occupational safety concern. These can be protected against with proper training and safety measures, though the extent to which these are in place globally is unknown. The nature of chemical hazards is process and place dependent, as some countries have better occupational safety regulations than others.

To produce mono-Si and poly-Si modules, the high-purity silicon refined from quartz during the materials preparation stage has to be made into a wafer. This involves crystallization, which can be achieved through several techniques. Czochralski crystallization is commonly used for mono-Si panels, while there are many processes used to form poly-Si

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122 Summers and Radde, “Potential Health and Environmental Impacts Associated with the Manufacture and Use of Photovoltaic Cells.”

123 Mulvaney, “Solar Energy Isn’t Always as Green as You Think.”

124 Nicholas Groom, “Prison Labor Helps U.S. Solar Company Manufacture at Home,” Reuters, June 10, 2015, Online edition, http://www.reuters.com/article/us-solar-prison-suniva-insight-idUSKBN0OQ0DT20150610.

125 Summers and Radde, “Potential Health and Environmental Impacts Associated with the Manufacture and Use of Photovoltaic Cells.”

wafers.[126] The main occupational exposures during this phase result from solvent use, which can expose workers to corrosive substances like nitric acid, sodium hydroxide, and hydrofluoric acid.[127] If leaks occur, these could also pollute areas surrounding manufacturing facilities.[128] In August 2011, a Chinese factory leaked hydrofluoric acid into a nearby river, killing hundreds of fish and polluting waters used by local farmers.[129] When silicon is cut into wafers, workers can be exposed to kerf dust, if the cutting is not done in mineral oil to prevent dust.[130] Inhalation of such dust could lead to potential health outcomes from silica and amorphous silicon inhalation discussed above.

Manufacturing cells from wafers includes etching the wafers to remove damaged areas and to optimize light absorption.[131] Finishing the PV cell includes emitter diffusion, application of non-reflective layers, and metal contact formation and firing.[132] Application of the non-reflective layer can use silane gas, which, as mentioned above, is highly flammable.[133] To complete the module, cells can be soldered together with copper wire, in some cases using lead-containing solders. If this lead is released into the environment, it can pose environmental and human health risks described above. The contact formation and stages can also include screen-printing with silver and aluminum.

2.3.2 Thin Films

2.3.2.1 CdTe

US producer First Solar produces their Series 4 CdTe thin films through an automated, multistep process beginning with a glass layer with a transparent conducting oxide. The transparent conducting oxide used can be indium tin oxide, about which very little information is available regarding its toxicity.[134] A graded absorber layer made up of CdSeTe is then deposited through vapor transport deposition, followed by sputter deposition of the ZnTe back contact. A stepwise process of lasering is then used to insulate individual cells, deposit the back contact (can be made from molybdenum), and isolate the rear cells for application of edge seals, encapsulant, laminate materials, and back glass.[135]

Major health concerns from CdTe manufacturing include occupational exposure to cadmium and cadmium compounds, which are carcinogens and can have other chronic health

126 Ferrazza, “Crystalline Silicon.”

127 Ibid.

128 Mulvaney, “Solar Energy Isn’t Always as Green as You Think.”

129 Ibid.

130 Mulvaney et al., “Toward a Just and Sustainable Solar Energy Industry.”

131 Ferrazza, “Crystalline Silicon.”

132 Xakalashe and Tangstad, “Silicon Processing: From Quartz to Crystalline Silicon Solar Cells.”

133 Ibid.; NIOSH, “Preventing Adverse Health Effects from Exposure to: Dimethylformamide (DMF).”

134 Bomhard, “The Toxicology of Indium Tin”

135 First Solar, First Solar’s Module Manufacturing Process, Video (First Solar, 2016), https://www.youtube.com/watch?v=DksYJqtNcX8.

effects. There is also the potential for cadmium to leach into soil and water, and to be taken up by crops surrounding a manufacturing facility.[136] For instance, cadmium chloride is a potential exposure in CdTe manufacture that is extremely toxic, leading to severe respiratory tract and digestive system irritation with acute exposure, while also being classified as a carcinogen, mutagen, and teratogen.[137] Cadmium chloride is also highly soluble in water, which could allow for ground water pollution and surrounding community impacts.[138] Similar to silicon-based modules, workers face physical and mechanical hazards related to noise, heavy machinery use. Injuries from broken glass are also a major occupational safety concern. There is also the potential for occupational exposures to corrosive substances like sulfuric acid.

CdTe thin film manufacture also uses substances with unknown toxicological profiles, like CdTe and indium tin oxide (ITO). In some studies, it is often assumed that CdTe has similar toxicity to other cadmium compounds. Though studies have determined that CdTe can be less toxic than cadmium, its toxicological properties have not been fully defined.[139] Indium tin oxide also requires more research for potential health impacts.[140]

2.3.2.2 CIGS

To produce CIGS thin films, copper, indium, gallium, and hydrogen selenide are mixed and deposited on a glass substrate. The specific processes involved are varied across producers, but will include the attachment of a back electrode (commonly from molybdenum) and a transparent conductive oxide (often zinc oxide). A buffer layer is also added, which has been made from CdS in the past. The final cell is etched, laminated, and cleaned before adding aluminum encasements.[141]

Occupational health risks occur across these manufacturing stages. For instance, selenium left over as waste product can be inhaled during chamber cleaning, which can cause selenosis, a disorder known for systemic nerve damage, hair loss, and gastrointestinal distress.[142] There is also the potential for occupational exposures to selenium oxide, which is a known mutagen and can cause severe irritation to eyes, skin, and respiratory tract.[143] Higher exposures can lead to pulmonary edema and neurological effects.[144] Cadmium chloride and cadmium sulfide may also be used; both are known carcinogens and can lead to severe irritation of the

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136 Mulvaney et al., "Toward a Just and Sustainable Solar Energy Industry."

137 NJ Department of Health, "Hazardous Substance Fact Sheet: Cadmium Chloride" (New Jersey Department of Health, August 2016), http://nj.gov/health/eoh/rtkweb/documents/fs/0308.pdf.

138 Fthenakis and Zweibel, "CdTe PV."

139 Joseph Zayed and Suzanne Philippe, "Acute Oral and Inhalation Toxicities in Rats With Cadmium Telluride," International Journal of Toxicology 28, no. 4 (2009).

140 Bomhard, "The Toxicology of Indium Tin Oxide."

141 Daniel A. Eisenberg et al., "Comparative Alternative Materials Assessment to Screen Toxicity Hazards in the Life Cycle of CIGS Thin Film Photovoltaics," Journal of Hazardous Materials 260 (September 2013): 534–42, doi:10.1016/j.jhazmat.2013.06.007.

142 Ibid.

143 Ibid.; NJ Department of Health, "Hazardous Substance Fact Sheet: Selenium Oxide" (New Jersey Department of Health, June 2000), http://nj.gov/health/eoh/rtkweb/documents/fs/1651.pdf.

144 NJ Department of Health, "Hazardous Substance Fact Sheet: Selenium Oxide."

respiratory and digestive tracts.[145] In the past, hydrogen selenide was used in manufacturing these films, but it has been phased out in some facilities.[146] This substance is spontaneously combustible and can cause respiratory irritation and nausea if inhaled.[147] Also, ZnO, used as the transparent conducting oxide, can cause the flu-like illness "metal flume fever."[148] The toxicity of the CIGS compound is not well defined; some studies have shown pulmonary toxicity, though further research is needed.[149]

2.3.3 Perovskite Solar Cells

As mentioned above, toxicity concerns of perovskite solar cells include their use of lead and tin compounds. Additionally, the manufacturing of these cells can involve the solvents dimethylformamide (DMF) and dimethylsulfoxide (DMSO).[150] DMF is known to cause damage to the liver when absorbed through the skin, while DMSO absorption through the skin has led to skin irritation and digestive issues in some occupational exposures.[151] These exposures can be prevented with engineering controls, automated processes, and personal protective equipment. Emissions and hazards from perovskite solar cell manufacture will depend on particular cell chemistries and the processes used to create them, and research should prioritize those chemistries with the smallest potential for harmful impacts.

2.4 Transportation

Solar panels need to be transported from manufacturing facilities to their end use site. For the transport of large solar panels, occupational exposures include physical hazards such as load shifts, vehicle rolls, collisions, and potential falls while loading, de-loading, and adjusting solar panels. These can be further amplified with marine transport of panels internationally, as pitching motions from marine vessels can amplify these physical hazards.[152] Apart from physical hazards, solar panel loaders and transporters can also be at risk of chemical exposures if they

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145 NJ Department of Health, "Cadmium Sulfide" (New Jersey Department of Health, February 2017), http://nj.gov/health/eoh/rtkweb/documents/fs/3081.pdf; NJ Department of Health, "Hazardous Substance Fact Sheet: Cadmium Chloride."

146 Eisenberg et al., "Comparative Alternative Materials Assessment to Screen Toxicity Hazards in the Life Cycle of CIGS Thin Film Photovoltaics."

147 Mulvaney et al., "Toward a Just and Sustainable Solar Energy Industry."

148 NJ Department of Health, "Hazardous Substance Fact Sheet: Zinc Oxide" (New Jersey Department of Health, January 2007), http://nj.gov/health/eoh/rtkweb/documents/fs/2037.pdf.

149 Akiyo Tanaka et al., "Pulmonary Toxicity of Indium Tin Oxide and Copper Indium Gallium Diselenide," in Materials Research Society Symposium Proceedings (2012 MRS Spring Meeting, San Francisco, CA, 2012), 125–36.

150 Babayigit et al., "Toxicity of Organometal Halide Perovskite Solar Cells."

151 NIOSH, "Preventing Adverse Health Effects from Exposure to: Dimethylformamide (DMF)"; National Library of Medicine, "Dimethyl Sulfoxide: Human Health Effects," Toxicology Data Network, (April 16, 2015), https://toxnet.nlm.nih.gov/cgi-bin/sis/search/a?dbs+hsdb:@term+@DOCNO+80.

152 EU-OSHA, Occupational Safety and Health in the Wind Energy Sector European Risk Observatory: Report. (Luxembourg: European Agency for Safety and Health at Work, 2013), http://bookshop.europa.eu/uri?target=EUB:NOTICE:TERO13008:EN:HTML.

come in contact with damaged solar cells, as these could potentially leak harmful materials, like cadmium, depending on the damage.[153]

There are also potential public health impacts from transport of solar panels. These include air quality concerns and GHG emissions from transport vehicles. Because PV panels will be shipped from international and domestic manufacturers, emissions related to ship, rail, and truck transport will apply. A fuller discussion of transport related air emissions and hazards can be found in **Section LCA.3**.

2.5 Installation

Solar panels can be used in both utility-scale and distributed installations. For utility-scale projects, a major public health concern results from land clearing and preparation that involves leveling and removal of local vegetation, requiring herbicides and machinery. This can expose workers and fence line communities to potentially toxic herbicides.[154] Another concern specific to Southern California is the potential for occupational and public exposure to the hazardous fungus, *Coccidioides*. Though the actual dispersal of this fungus in Southwestern soils is unknown, exposure can occur through soil disturbance during site preparation involved in utility-scale plant installation. This exposure can cause coccidioidomycosis, or Valley Fever, if inhaled. Exposed individuals show a range of symptoms – ranging from asymptomatic to hospitalization with severe lung or systemic infections.[155] Previously, clusters of coccidioidomycosis have occurred in California workers involved in solar installation construction.[156]

Workers involved in utility-scale solar installations are also exposed to physical hazards related to machinery, falls, and heavy-lifting, and may be exposed to extreme heat since most of these installments are in arid areas with high temperatures.[157,158] There have been conflicting conclusions in studies of the potential for large scale PV installations to generate significant heat island effects. This is an area requiring further research, but may be quite site specific.[159,160]

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153 M.M. Aman et al., "A Review of Safety, Health and Environmental (SHE) Issues of Solar Energy System," Renewable and Sustainable Energy Reviews 41 (January 2015): 1190–1204, doi:10.1016/j.rser.2014.08.086.

154 Ibid.

155 Gail L. Sondermeyer et al., "Coccidioidomycosis-Associated Deaths in California, 2000–2013," Public Health Reports 131, no. 4 (2016): 531–535.

156 Jason A. Wilken et al., "Coccidioidomycosis among Workers Constructing Solar Power Farms, California, USA, 2011–2014," Emerging Infectious Diseases 21, no. 11 (November 2015): 1997–2005, doi:10.3201/eid2111.150129.

157 Aman et al., "A Review of Safety, Health and Environmental (SHE) Issues of Solar Energy System."

158 Teresa Dayrit, "Comparative Analysis of Environmental Impacts of Utility-Scale and Distributed Solar," Research Brief (PSE Healthy Energy, December 2016), http://www.psehealthyenergy.org/data/Solar_Research_Brief_2016_.pdf.

159 Vasilis Fthenakis and Yuanhao Yu, "Analysis of the Potential for a Heat Island Effect in Large Solar Farms," in 2013 IEEE 39th Photovoltaic Specialists Conference (PVSC) (IEEE, 2013), 3362–3366, http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6745171.

160 Greg A. Barron-Gafford et al., "The Photovoltaic Heat Island Effect: Larger Solar Power Plants Increase Local Temperatures," Scientific Reports 6, no. 1 (December 2016), doi:10.1038/srep35070.

Overall, solar PV facilities are expected to use less water across their life cycles than is traditionally used in electricity generation projects.[161] However, water use across utility-scale PV life cycles is highest during the installation stage, and future facilities need to be sited in an informed way, noting potential for water scarcity.[162] As much of this water use is used to control dust and clean modules, changes in common land use decisions and clearing practices could lessen water use.[163]

In distributed solar applications, including rooftop solar, the main hazards are related to occupational exposures. Without proper training and safety mechanisms that resemble general roofing protections, rooftop solar installers can be at risk of falls, lifting injuries, and heat exposure.[164] Anecdotally, there are concerns that solar installers are not receiving the training nor safety protections that are required by state law and are commonly implemented in the roofing industry.[165] Both roofers and solar installation workers are at very high risk of serious and disabling injuries due to falls from heights. In this way, learning from construction and roofing industries needs to be translated to safety measures for distributed solar installation.[166]

2.6 Use and Maintenance

There are limited impacts related to the use and maintenance stage of both distributed and solar PV installations. For utility scale projects, workers and the surrounding public can be exposed to fugitive dusts from on-going land maintenance practices, though this will be far less than similar exposures during installation. Depending on the land maintenance practices used, workers and fence line communities can be exposed to herbicides and *Coccidioides* spores (see **Section LCA.4**. Fugitive dust can also affect air quality, increasing PM and pollutant emissions from diesel vehicles for surrounding communities.

Maintenance workers in both utility scale and distributed solar face similar risks as installation workers, related to machinery, falls from heights, heavy lifting, and extreme heat. Exposures to individual households or first responders if weather or a fire damages solar panels on roofs have been assessed for CdTe films, and results have shown little risk.[167] Similar

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161 Geoffrey T. Klise et al., "Water Use and Supply Concerns for Utility-Scale Solar Projects in the Southwestern United States," SAND2013-5238. Sandia National Laboratories, 2013, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.490.1952&rep=rep1&type=pdf.

162 Ibid.

163 Dustin Mulvaney, Interview with Dustin Mulvaney, Conference Call, August 26, 2016.

164 OSHA, "Green Job Hazards: Solar Energy," Goverment Ageny Website, United States Department of Labor, Occupational Safety and Health Administration, (2009), https://www.osha.gov/dep/greenjobs/solar.html.

165 Deborah Gold, Interview with Deborah Gold, California Division of Occupational Safety and Health, Phone, February 27, 2017.

166 Evan Nadhim et al., "Falls from Height in the Construction Industry: A Critical Review of the Scientific Literature," International Journal of Environmental Research and Public Health 13, no. 7 (June 28, 2016): 638, doi:10.3390/ijerph13070638.

167 Vasilis Fthenakis and Ken Zweibel, "CdTe PV: Real and Perceived EHS Risks," in Prepared for the NCPV and Solar Program Review Meeting, 2003, 5–28, http://www.bollettinoadapt.it/old/files/document/4184paper_05_2003.pdf.

research is needed for other types of panels. For maintenance workers and first responders in cases of emergencies, there will be electric shock risk from installed and operating panels.

Studies have shown that installed solar PV does not increase a building's fire risk but can make fighting fires more difficult for first responders.[168] The California Department of Forestry and Fire Protection offers training materials for firefighters about precautions that should be taken in responding to emergencies in buildings with PV.[169] As PV solar system technology progresses, additional research is needed on this changing technology and best practices in responding to fires and emergencies with PV-equipped buildings.

Unique among other solar PV technologies, perovskite solar cells currently present many challenges during their use. These cells can degrade in uncontrolled conditions (i.e. on a rooftop), which can lead to leakage of toxic chemicals.[170] Depending on cell chemistries, these chemicals could include lead compounds, tin compounds, hydroiodic acid, and methylamine.[171] Research assessing the potential for lead pollution from perovskite degradation has found that resulting lead levels are lower than those from other common industrial emissions, but further research is needed to understand the potential risk in different real world applications.[172] More information is also needed to catalogue total exposures from perovskite degradation and related toxicologies, as well as the potential for fire to cause harmful and toxic emissions from these cells.[173] Research should also focus on producing cells that do not degrade.

2.7 Decommissioning and Disposal

Decommissioning and disposal occurs due to damage or at the end of a panel's lifetime, which can be 20 - 30 years.[174] Decommissioning of utility scale sites will have many of the same hazards to workers and surrounding communities as the installation process, as fugitive dust can expose workers at the site and fenceline communities to potentially hazardous herbicides or *Coccidioides* fungi. Workers also face potential hazards from extreme heat, machinery-use, and heavy lifting.

Disposal of silicon-based and thin films can result in significant exposures from leaching of cell components. For instance, there is the potential for silicon-based panels to leach lead from soldering and inverter applications.[175] Leaching of cadmium has been studied and has

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168 CAL FIRE - Office of the State Marshal, "Fire Operations for Photovoltaic Emergencies" (CAL FIRE - Office of the State Marshal, November 2010), http://osfm.fire.ca.gov/training/pdf/Photovoltaics/Fire%20Ops%20PV%20lo%20resl.pdf.

169 Ibid.; The California Department of Forestry and Fire Protection - Office of the State Fire Marshal, "FINAL DRAFT Solar Photovoltaic Installation Guideline" (The California Department of Forestry and Fire Protection - Office of the State Fire Marshal, 2008), http://osfm.fire.ca.gov/pdf/reports/solarphotovoltaicguideline.pdf.

170 Babayigit et al., "Toxicity of Organometal Halide Perovskite Solar Cells."

171 Ibid.

172 Douglas Fabini, "Quantifying the Potential for Lead Pollution from Halide Perovskite Photovoltaics," The Journal of Physical Chemistry Letters 6, no. 18 (September 17, 2015): 3546–48, doi:10.1021/acs.jpclett.5b01747.

173 Babayigit et al., "Toxicity of Organometal Halide Perovskite Solar Cells."

174 Vasilis M. Fthenakis, Hyung Chul Kim, and Erik Alsema, "Emissions from Photovoltaic Life Cycles," Environmental Science & Technology 42, no. 6 (March 2008): 2168–74, doi:10.1021/es071763q.

175 Mulvaney et al., "Toward a Just and Sustainable Solar Energy Industry."

been found to be limited from CdTe films.[176] Damaged CIGS were found to leach cadmium, molybdenum, and selenium when exposed to acid rain.[177] Leaching of selenium and other material inputs is also possible, however, and needs further study. If cell components are incinerated, there is also the potential for hydrogen chloride, dioxin, cadmium, and PM emissions from incinerated plastic components.[178] More research is needed to understand the potential for toxic leaching during different disposal outcomes.

For disposal in California, the Department of Toxic Substances Control (DTSC) is developing regulations - pursuant to SB 489 - that will designate solar panels as universal waste.[179] As such, the new law requires solar PV disposal in a household hazardous waste facility, through a "Take-it-Back Partner" such as a retailer or manufacturer, or at a collection event.[180] Until the regulations are completed, solar panels deemed hazardous must be managed as general hazardous waste, and determination as to whether panels are hazardous rests with the waste generator, which includes individuals and installers.[181] This leaves open the possibility for individuals who do not know what materials are included in their solar panels to dispose of potentially hazardous materials improperly.

Many researchers promote the need for recycling mechanisms, both to prevent chemical leaching from unsafe disposal, but also to recover valuable materials used in PV that can be re-used in future panels and reduce the need for novel material extraction with its concomitant costs and risks. There are concerns that lessons from e-waste disposal, which some believe could be responsible for 40% of lead and 70% of heavy metals in landfills, have not been sufficiently applied to solar PV waste.[182] Much e-waste has been shipped abroad to be dismantled in unsafe conditions, leading to increased toxic exposures internationally for wastes generated in the US.[183] In order to reduce disposal in US landfills and unsafe conditions abroad, research into recycling processes has begun, and companies like First Solar have programs to recycle key elements of their CdTe panels.[184] Recycling would also reduce the need for increased mining and material extraction as the PV industry continues to expand, confronting the challenge of

176 Fthenakis, "Life Cycle Impact Analysis of Cadmium in CdTe PV Production," August 2004.

177 Yannick-Serge Zimmermann et al., "Thin-Film Photovoltaic Cells: Long-Term Metal(loid) Leaching at Their End-of-Life," Environmental Science & Technology 47, no. 22 (November 19, 2013): 13151–59, doi:10.1021/es402969c.

178 Neeti Rustagi, S.K. Pradhan, and Ritesh Singh, "Public Health Impact of Plastics: An Overview," Indian J Occup Environ Med 15, no. 3 (2011): 100–103.

179 Bill Monning, "Senate Bill No. 489 CHAPTER 419," Pub. L. No. SB 489, § Chapter 6.5, Division 20 Health and Safety Code (2015).

180 DTSC, "Universal Waste Fact Sheet" (Department of Toxic Substances Control, January 2010), https://www.dtsc.ca.gov/HazardousWaste/UniversalWaste/upload/UniversalWfactsheetfinal.pdf.

181 Monning, Senate Bill No. 489 CHAPTER 419.

182 Coyle, "The Not-So-Green Renewable Energy: Preventing Waste Disposal of Solar Photovoltaic (PV) Panels."

183 US EPA, "US EPA International Priorities," US EPA International Cooperation, 2016, https://www.epa.gov/international-cooperation/international-priorities.

184 Lisa Krueger, "Overview of First Solar's Module Collection and Recycling Program," n.d.

resource limits for rarer elements like tellurium while also reducing PV's impacts on miners and material processors.[185]

Because of solar panel's long lifetime, by 2030, there is expected to be a wave of spent panels that require disposal. Though PV waste is expected to be a burden in the coming years as earlier models reach the end of their life span, damage to current solar installations can lead to the need for disposal earlier than planned, as was the case when a small tornado damaged over 100,000 modules at the Desert Sunlight Solar Project.[186] Many of these were disposed of as hazardous waste instead of recycling due to the damage and potential for contamination.[187]

The International Renewable Energy Agency predicted that, globally, there would be 43,500-250,000 tons of PV waste by the end of 2016.[188] This is expected to grow to 5.5-6 million tons of PV waste globally by 2050.[189] Safe and sustainable disposal practices are imperative to prevent both domestic and global emissions of toxic substances from spent PV panels, and to increase the overall sustainability of this industry. Further research into such practices, as well as appropriate policy and regulatory strategies to ensure them, is required. Research into potential health impacts from different disposal and recycling methods is also necessary to understand the hazards and risks present in different processes.

Increasingly, industries are recognizing their responsibility - for example through supply chain changes, sub-contractor monitoring, and extended producer responsibility (EPR) - for health and environmental impacts across product life cycles. EPR is a policy initiative that assigns responsibility for the treatment and disposal of a product to manufacturers, with the aim to incentivize waste prevention during product design and manufacture. There is a need for policy and legal research to focus on strategies to promote, or potentially require, EPR to assure that the rapid expansion of EES in California is not associated with significant adverse health and environmental impacts in vulnerable communities across the globe and in the state.

2.8 Equity Considerations

Solar PV employs a myriad of different workers across its life cycle and creates the most jobs of common renewable energy technologies.[190] According to conservative Bureau for Labor Statistics, solar photovoltaic installation employment is projected to grow 24% in the United

185 Cyrus Wadia, A. Paul Alivisatos, and Daniel M. Kammen, "Materials Availability Expands the Opportunity for Large-Scale Photovoltaics Deployment," Environmental Science & Technology 43, no. 6 (March 15, 2009): 2072–77, doi:10.1021/es8019534.

186 Rich Tarpening, "Solar Farm Damaged by Desert Center Tornado," News Channel 3 ABC (Palm Springs: CBS Local 2, April 22, 2015), http://www.kesq.com/news/solar-farm-damaged-by-desert-center-tornado/62923230.

187 Mulvaney, Comments and Edit on Solar PV Chapter.

188 Weckend, Wade, and Heath, "End-of-Life Management: Solar Photovoltaic Panels."

189 Ibid.

190 Max Wei, Shana Patadia, and Daniel M. Kammen, "Putting Renewables and Energy Efficiency to Work: How Many Jobs Can the Clean Energy Industry Generate in the US?," Energy Policy 38, no. 2 (February 2010): 919–31, doi:10.1016/j.enpol.2009.10.044.

States from 2014 to 2024 – growing from 5,900 to 7,300 jobs.[191] In California from 2002 – 2015, solar PV created a total of 21,724 construction job years.[192] Commercial installations (0.25–1MW) accounted for 88 of the job-years, community scale installations(1-5MW) created 2,405 job-years, and utility-scale (>5MW) created 19,231 job-years.[193]

Some observers suspect a significant difference in job quality between distributed installation workers and utility-scale installers. For utility-scale facilities, investments have been made to form training and apprenticeship programs for solar construction workers – programs associated with improved future lifetime earnings – of which it is estimated that over 1,000 CA workers graduated from between 2002 and 2015.[194] Distributed and rooftop solar installers may not have the same access to broad career training, reducing their earning potential over their careers.[195] Some research suggests that rooftop solar installation offers lower wages, fewer advancement opportunities, inadequate health and safety training, and fewer benefits when compared to utility-scale solar construction.[196] As job quality, career advancement opportunities, and earning a living wage are central to health, more research is needed to assess these differences and identify strategies to ensure that all solar jobs afford living wages, opportunities for job advancement, and adequate on-the-job health and safety protections.

Utility-scale PV development must also account for where new facilities are sited and how facility installation may impact local communities. These facilities may offer opportunities for community economic development and living wage jobs, if development is appropriately implemented. Land clearing for facility installation, continued maintenance, and decommissioning will all result in transport-related emissions and potential fugitive dust for surrounding communities. Utility-scale development will likely continue to occur in areas of Southern California with high solar insolation. However, many of these areas are already suffering from poor air infrastructure build out in the area.[197] These emission impacts could be intensified in lower income or minority communities.

Across the life cycle of solar PV, there are also impacts for communities and workers outside of California. Especially during the material extraction, processing, manufacturing, and disposal stages of solar PV life cycle, products used in California could negatively impact public health in vulnerable communities abroad. This can include toxic exposures, occupational

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191 Bureau of Labor Statistics, "Occupational Outlook Handbook: Solar Photovoltaic Installers," Government Agency Website, United States Department of Labor, Bureau of Labor Statistics, (December 17, 2015), https://www.bls.gov/ooh/construction-and-extraction/solar-photovoltaic-installers.htm.

192 Betony Jones, Peter Philips, and Carol Zabin, "The Link Between Good Jobs and a Low Carbon Future: Evidence from California's Renewables Portfolio Standard, 2002—2015" (DONALD VIAL CENTER ON EMPLOYMENT IN THE GREEN ECONOMY Center for Labor Research and Education University of California, Berkeley, July 2016), http://laborcenter.berkeley.edu/pdf/2016/Link-Between-Good-Jobs-and-a-Low-Carbon-Future.pdf.

193 Ibid.

194 Ibid.

195 Ibid.

196 Betony Jones and Carol Zabin, "Are Solar Energy Jobs Good Jobs?," University, UC Berkeley Labor Center, (July 2, 2015), http://laborcenter.berkeley.edu/are-solar-energy-jobs-good-jobs/.

197 Ricardo American Lung Association, "State of the Air 2016" (American Lung Association, 2016), http://www.lung.org/local-content/california/documents/state-of-the-air/2016/sota-2016-full-report.pdf.

hazards, and pollution from mining, manufacturing, and disposal processes. Future research needs to identify policy responses to address global health impacts of mining for, manufacturing, and disposing of emerging electricity-generating and storing technologies in California. Many workers globally are not afforded the same wage or health and safety protections as US workers, with adverse impacts both on US workers (i.e. loss of higher-paying manufacturing job opportunities) and workers globally.

2.9 Research Needs

1. Update identification and hazard assessment of chemicals used across the life cycle of PV cells and modules, including their environmental and occupational health and safety impacts
    a. Determine potential community health impacts of material extraction, manufacturing, and disposal
    b. Determine occupational risks based on likelihood of exposure, dose, and toxicology of substance
    c. Identify existing and emerging technologies that have relatively lower environmental and occupational risks
    d. Develop green chemistry and safety-by-design manufacturing processes

2. Identify, develop, and evaluate healthy, safe, and sustainable recycling methods for PV cells

Chapter 3: Concentrated Solar Power

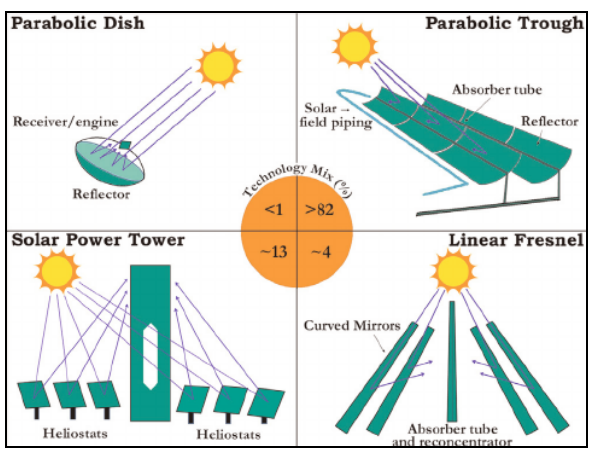
3.1 Concentrated Solar Power in California

The CEC estimated that California generated 2,000 GWh of electricity from concentrated solar power (CSP) in 2016, roughly 1% of the state's energy mix. To reach the state's ambitious renewable energy goals, models predict that this could grow to 8,000 GWh by 2030, expanding to close to 2% of the state's energy mix.[198] Second in growth to solar PV, CSP increased capacity from 400 MW in 2012 to 1,300 MW in 2015.[199] The cost of solar thermal electricity production is dropping, though not as dramatically as solar PV. Solar thermal technologies have the advantage of built in energy storage in certain systems, but due to environmental concerns (e.g. bird fatalities), land use, and production shortfalls in current facilities, growth is expected to lessen.[200]

3.1.1 Overview of Concentrated Solar Power Technologies

Concentrated solar power (CSP) or solar thermal technologies use high temperature heat to drive electricity generation or for cogeneration of electricity and heat. The four main technologies available are parabolic trough, linear fresnel, central tower, and parabolic dish. These technologies are shown in Figure 7 below.

Figure 7. CSP Technologies



Source: Xu et al, 2016. "Prospects and Problems of Concentrating Solar Power Technologies for Power Generation in the Desert Region." Renewable and Sustainable Energy Reviews. January 2016.

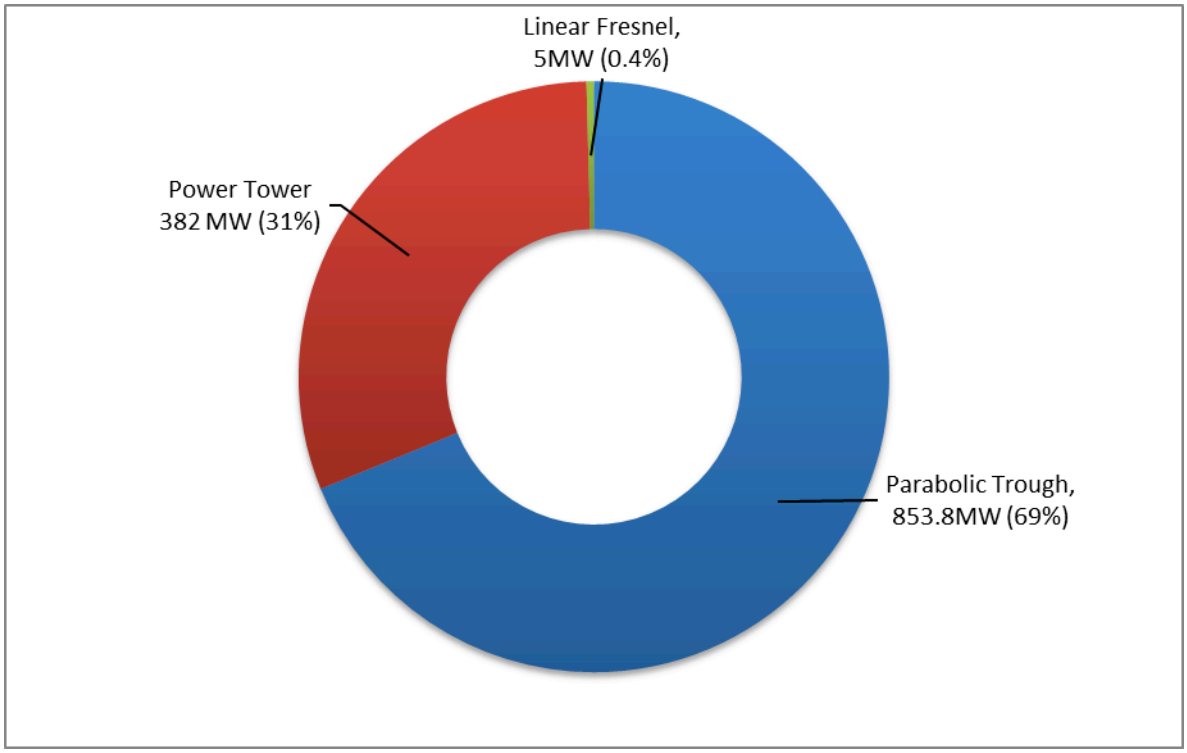
198 Gregory Brinkman, Jennie Jorgenson, and Marissa Hummon, "California 2030 Low Carbon Grid Study (LCGS): Phase I" (National Renewable Energy Laboratory, 2014), http://lowcarbongrid2030.org/wp-content/uploads/2014/10/LCGS_PhaseI_NRELslides.pdf; CEC, "Renewable Energy – Overview December 2016" (California Energy Commission, December 2016), http://www.energy.ca.gov/renewables/tracking_progress/documents/renewable.pdf.

199 Jim Bartridge et al., "Draft 2016 Environmental Performance Report of California's Electrical Generation System," Staff Report (California Energy Commission, July 2016), https://efiling.energy.ca.gov/getdocument.aspx?tn=212338.

200 Ibid.; International Energy Agency, "Technology Roadmap: Solar Thermal Electricity" 2014 Edition (2014), https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapSolarThermalElectricity_2014edition.pdf.

Currently in California, parabolic trough facilities produce over 850 MW of electricity, though central receiving tower generation grew from 5 MW in 2009 to over 380 MW in 2014 with construction of the Ivanpah Solar Power Facility.[201] Parabolic trough is currently the most widely used concentrated solar technology, though central receiving facilities are becoming more popular due to the higher temperatures they can achieve and the higher efficiency produced. Linear fresnel and parabolic dish facilities are also expected to become more popular as the technology advances.[202] Because the materials used throughout these systems are similar and the installation, maintenance, and eventual decommissioning processes will also be comparable, all of these system designs will be assessed together in the following section. Current installed capacity of different CSP technologies is shown in Figure 8.

Figure 8. Installed CSP Capacity in California by Facility Type (2015)



Source: NREL, Concentrating Solar Power Projects in the United States

201 Jane Long and Miriam John, "California's Energy Future: The View to 2050," Summary Report (California Council on Science and Technology, May 2011), http://ccst.us/publications/2011/2011energy.pdf.

202 Edgar G. Hertwich, Jacqueline Aloisi de Larderel, and Sangwon Suh, "Green Energy Choices: The Benefits, Risks, and Trade-Offs of Low-Carbon Technologies for Electricity Production" (United Nations Environmnetal Programme, 2016), http://www.unep.org/resourcepanel/Portals/50244/publications/Summary_for_Policy_Makers_GHG_I.pdf.

3.2 Materials Extraction

Concentrated solar power technologies are mainly composed of steel, glass, and concrete, which are sourced from domestic mining and processing outside of California.[203] Apart from these structural materials, concentrated systems also require wiring and insulation materials, as well as chemicals for pH control, boiler treatments, and lubrication of turbine components.[204]

Throughout parabolic trough, linear fresnel, and central tower systems, the most unique material is the heat transfer fluid (HTF), which central tower technologies can also use for energy storage. Due to their relatively limited toxicity, global availability, and efficiency, nitrate salts are currently promoted as key heat transfer fluid options. These are often sourced from mines in Chile and Peru, and traditional mining hazards discussed in **Section LCA.1** apply to extracting these salts.[205] To reach the 2050 global target of CSP set by the International Energy Agency, mine production of nitrate salts would have to increase by 30 times.[206] Though other salts, like carbonate and chloride based varieties, are being researched as potential supplements to nitrates, no material has been developed yet that is expected to replace nitrates.[207] These salts can also be produced synthetically from natural gas, but this process increases the overall energy intensity of the production process, in some estimates, by almost 52%.[208] Research is also focusing on the potential to include nanoparticles in HTF applications, raising concerns about the potential for unknown hazards related to these materials.[209]

HTF can also be made from diphenyl and diphenyl ether, but these have been found to increase explosion risks and toxic exposures to workers, as diphenyl components cause eye irritation and the potential for systemic toxicity with long-term exposure.[210] Liquid sodium has also been used due to its high thermal conductivity, though it is also hazardous due to its reactivity with water, presenting a potential fire hazard.[211] New HTFs are also being considered,

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203 Craig Turchi et al., "Domestic Material Content in Molten-Salt Concentrating Solar Power Plants," Technical Report (National Renewable Energy Laboratory (NREL), Golden, CO (United States), 2015), http://www.nrel.gov/docs/fy15osti/64429.pdf.

204 Jeffrey D. Bryon, James D. Boyd, and Paul Kramer, "Ivanpah Solar Electric Generating System: Presiding Member's Proposed Decision," DOCKET NUMBER 07-AFC-5 (California Energy Commission, August 2010), http://www.circleofblue.org/wp-content/uploads/2010/09/California-Energy-Commission-Proposed-Ivanpah-Project-DecisionCEC-800-2010-004-PMPD.pdf.

205 Turchi et al., "Domestic Material Content in Molten-Salt Concentrating Solar Power Plants."

206 K. Vignarooban et al., "Heat Transfer Fluids for Concentrating Solar Power Systems – A Review," Applied Energy 146 (May 2015): 383–96, doi:10.1016/j.apenergy.2015.01.125.

207 John J. Burkhardt, Garvin A. Heath, and Craig S. Turchi, "Life Cycle Assessment of a Parabolic Trough Concentrating Solar Power Plant and the Impacts of Key Design Alternatives," Environmental Science & Technology 45, no. 6 (March 15, 2011): 2457–64, doi:10.1021/es1033266.

208 Ibid.

209 Fabrizio Fabrizi, "Concentrated Solar Power: Environmental Impact" (RENEWABLE ENERGY TRAINING PROGRAM MODULE 7, Washington D.C., July 11, 2012).

210 George A. Otieno and Alexander E. Loosen, "An Analysis of Key Environmental and Social Risks in the Development of Concentrated Solar Power Projects," 2016, 160012, doi:10.1063/1.4949253.

211 Y. Tian and C.Y. Zhao, "A Review of Solar Collectors and Thermal Energy Storage in Solar Thermal Applications," Applied Energy 104 (April 2013): 538–53, doi:10.1016/j.apenergy.2012.11.051.

including supercritical CO_2 in falling particle models. $PM_{2.5}$ from fine particle dust created during particle abrasion could be a potential occupational hazard.[212] Depending on particle components, PM exposure can lead to eye irritation, asthma exacerbation, bronchitis, lung damage, and cardiovascular effects.[213] More research is needed on potential health impacts from emerging molten salt, falling particle, and gas-phase pathway technologies for potential supercritical CO_2 pathways.

3.3 Manufacture

The manufacturing process for concentrated solar technologies involves the production of steel and glass components, as well as the connection of these materials with HTF transport tubes and electrical components. Hazards associated with the production of these more common materials are discussed briefly in **Section LCA.2**.

3.4 Transportation

CSP components need to be transported from manufacturing facilities to their end use site. For the transport of large CSP materials that could include hazardous materials, depending on the HTF used, there are hazards that workers involved in this transport are exposed to. These occupational exposures include physical hazards like load shifts, vehicle rolls, collisions, and potential falls while loading, de-loading, and adjusting large equipment.[214] Loaders and transporters can also be at risk of chemical exposures if they come in contact with damaged HTF containers, as these could potentially leak corrosive salt solutions. See **Section LCA.3** for more information on general transportation hazards.

3.5 Installation

CSP systems are mainly used in utility scale facilities with operating capacities over 100 MW, although there is current research to assess the potential efficiency of using CSP in local generation systems.[215] For utility-scale projects, a major public health concern results from land clearing and preparation, related to herbicide and *Coccidioides* fungal spores exposure. For more information, see **Section LCA.4**

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212 Mark Mehos et al., "Concentrating Solar Power Gen3 Demonstration Roadmap," Technical Report (National Renewable Energy Laboratory, January 2017), http://www.nrel.gov/docs/fy17osti/67464.pdf.

213 EPA, "Criteria Air Pollutants," Goverment Agency Website, US EPA, (April 3, 2017), https://www.epa.gov/criteria-air-pollutants.

214 EU-OSHA, Occupational Safety and Health in the Wind Energy Sector European Risk Observatory: Report. (Luxembourg: European Agency for Safety and Health at Work, 2013), http://bookshop.europa.eu/uri?target=EUB:NOTICE:TERO13008:EN:HTML.

215 Zack Norwood and Daniel Kammen, "Life Cycle Analysis of Distributed Concentrating Solar Combined Heat and Power: Economics, Global Warming Potential and Water," Environmental Research Letters 7, no. 4 (December 1, 2012): 44016, doi:10.1088/1748-9326/7/4/044016.

3.6 Maintenance & Use

Public health concerns related to CSP systems involve effects of glare from site equipment and water use. Glint and glare have been studied for different CSP technologies, especially those with moving parts that follow the sun throughout the day. These have occupational impacts for facility workers, but can also affect surrounding communities.[216] Research has also looked into the potential for this glare to impact pilots flying over these systems.[217] Research of specific installations has demonstrated that exposure to these reflected lights does not cause lasting damage to the eye (i.e. retinal burns), though these reflections can cause visual impacts such as afterimages.[218] This could lead to potential hazards for individuals who are operating machinery or vehicles.[219] Research has focused on analytical models to determine distances of reflected light and develop safety metrics to quantify glint and glare.[220][221]

Because these facilities are often sited in areas with potentially scarce water reserves, on-site water use is a concern that could limit the build out of CSP facilities in certain areas of the state into the future.[222] CSP facilities require a cooling system, which can use water or ambient air for wet or dry cooling, respectively. Dry cooling requires less water but can decrease overall plant efficiency.[223] When compared to other electricity generation technologies, CSP using wet cooling was found to be one of the largest water consumers, second to coal, for electricity generating systems.[224] Dry-cooled alternative systems are estimated to reduce lifecycle water consumption by 77% but increase lifecycle GHG emissions and CED by 8%.[225] Because of water use concerns, CSP designs with lower fresh water requirements, such as gas turbine towers and parabolic dishes with Stirling engines, are expected to be the focus of future developments.[226]

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216 C.K. Ho, C.A. Sims, and J.M. Christian, "Evaluation of Glare at the Ivanpah Solar Electric Generating System," Energy Procedia 69 (May 2015): 1296–1305, doi:10.1016/j.egypro.2015.03.150.

217 Ibid.

218 Clifford K. Ho and Siri S. Khalsa, "Hazard Analysis and Web-Based Tool for Evaluating Glint and Glare from Solar Collector Systems" (Solar PACES 2010, Perpignan, France, September 21, 2010), https://share.sandia.gov/phlux/static/references/glint-glare/Glare_SolarPACES2010_v2.pdf.

219 Bryon, Boyd, and Kramer, "Ivanpah Solar Electric Generating System: Presiding Member's Proposed Decision."

220 Clifford K. Ho, Cheryl M. Ghanbari, and Richard B. Diver, "Methodology to Assess Potential Glint and Glare Hazards from Concentrating Solar Power Plants: Analytical Models and Experimental Validation," Journal of Solar Energy Engineering 133, no. 3 (2011): 31021.

221 Ho and Khalsa, "Hazard Analysis and Web-Based Tool for Evaluating Glint and Glare from Solar Collector Systems."

222 Geoffrey T. Klise et al., "Water Use and Supply Concerns for Utility-Scale Solar Projects in the Southwestern United States," SAND2013-5238. Sandia National Laboratories, 2013, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.490.1952&rep=rep1&type=pdf.

223 Michael Hogan, "The Secret to Low-Water-Use, High-Efficiency Concentrating Solar Power," Think Progress, April 29, 2009, http://thinkprogress.org/climate/2009/04/29/204025/csp-concentrating-solar-power-heller-water- use.

224 J Macknick et al., "Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies: A Review of Existing Literature," Environmental Research Letters 7, no. 4 (December 1, 2012): 45802, doi:10.1088/1748-9326/7/4/045802.

225 Burkhardt, Heath, and Turchi, "Life Cycle Assessment of a Parabolic Trough Concentrating Solar Power Plant and the Impacts of Key Design Alternatives."

226 Fabrizi, "Concentrated Solar Power: Environmental Impact."

Other public health considerations for CSP projects include extreme heat exposure for maintenance workers, and those related to dusts from continued land maintenance practices, increasing the potential for hazardous exposures to herbicides and *Coccidioides* fungi (see **Section LCA.4)**. Backup boilers using natural gas are also often installed in cases of low solar insolation or system malfunction, which can also lead to particulate emissions for surrounding areas.[227]

Additional occupational health and safety considerations include the potential for exposure to extremely hot and potentially toxic HTF, as the high pressure at which these systems operate may increase the risk of system leaks. As described above, some potential HTFs like diphenyl or diphenyl ether are irritants to the eyes and respiratory tract.[228] If molten salts are used as HTF, these materials can corrode surrounding tubing or piping, adding to leak potential and putting workers at risk of burns.[229]

Occupational exposures can include loud noises, moving equipment, trenches, and confined spaces. Potential injuries can include falls and burns related to falling equipment or structures, chemical spills, and hazardous waste. Workers are also potentially exposed to fires, explosions, electrical sparks, and electrocution from the flammable and electrical equipment used.[230] According to an environmental impact assessment of the Ivanpah site, hazardous materials stored on site include gasoline, diesel fuel, motor oil, welding gases, lubricants, solvents, paint, and cleaners, although safety mechanisms were in place to prevent potential on and offsite contamination.[231]

3.7 Decommissioning & Disposal

CSP plants have estimated lifetimes of 30 years.[232] Because CSP plants are mainly made of steel, glass, and concrete, recycling of these parts at decommissioning is readily available.[233] Information on HTF disposal standards and practices was not accessible and will be dependent on the particular material used. This could present potential concerns depending on how varied materials will be disposed. For instance, groundwater contamination with nitrate salts from improper disposal could further the state's already contaminated groundwater reserves.[234] As little information is available about this stage of CSP life cycles, there is a need for research on HTF waste streams and potential exposures.

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227 Bryon, Boyd, and Kramer, "Ivanpah Solar Electric Generating System: Presiding Member's Proposed Decision."

228 Otieno and Loosen, "An Analysis of Key Environmental and Social Risks in the Development of Concentrated Solar Power Projects."

229 Tian and Zhao, "A Review of Solar Collectors and Thermal Energy Storage in Solar Thermal Applications."

230 Bryon, Boyd, and Kramer, "Ivanpah Solar Electric Generating System: Presiding Member's Proposed Decision."

231 Ibid.

232 NREL, "Life Cycle Greenhouse Gas Emissions from Concentrating Solar Power," 2013, http://www.nrel.gov/docs/fy13osti/56416.pdf.

233 Fabrizi, "Concentrated Solar Power: Environmental Impact."

234 State Water Resources Control Board, "Recommendations Addressing Nitrate in Groundwater," Report to Legislature, (February 20, 2013), https://www.waterboards.ca.gov/water_issues/programs/nitrate_project/docs/nitrate_rpt.pdf.

3.8 Equity Considerations

Concentrated solar power employs a variety of workers, from construction and maintenance workers, to engineers and site managers.[235] On average, during both construction and operation, CSP provides more direct and indirect employment than fossil fuel generation and utility-scale PV installations, providing more individuals with job opportunities to support their health and quality of life.[236] In California from 2002 – 2015, CSP created a total of 6,014 construction job years.[237] Investments were also made to form training and apprenticeship programs for solar construction workers for utility-scale facilities – programs associated with improved future lifetime earnings.[238]

CSP development must account for where new facilities are sited and how facility installation may impact local communities. Land clearing for facility installation, continued maintenance, and decommissioning will all result in transport-related emissions and potential fugitive dust for surrounding communities. CSP development will likely continue to occur in areas of Southern California with high solar insolation. However, many of these areas are already suffering from poor air quality, so these emissions may increase the cumulative impacts from all infrastructure build out in the area.[239] These emission impacts could be intensified in lower income or minority communities.

3.9 Research Needs

1. Assess potential health impacts of exposure during facility maintenance and end-of-life disposal of heat transfer fluids, including synthetic oils, molten salts, and supercritical CO_2 technologies.

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235 Max Wei, Shana Patadia, and Daniel M. Kammen, "Putting Renewables and Energy Efficiency to Work: How Many Jobs Can the Clean Energy Industry Generate in the US?," Energy Policy 38, no. 2 (February 2010): 919–31, doi:10.1016/j.enpol.2009.10.044.

236 L Stoddard, J. Abiecunas, and R. O'Connell, "Economic, Energy, and Environmental Benefits of Concentrating Solar Power in California," Subcontract Report (National Renewable Energy Laboratory, April 2006), http://www.nrel.gov/docs/fy06osti/39291.pdf; James Hamilton, "Careers in Solar Power," Government Agency Website, United States Department of Labor, Bureau of Labor Statistics, (n.d.), https://www.bls.gov/green/solar_power/.

237 Betony Jones, Peter Philips, and Carol Zabin, "The Link Between Good Jobs and a Low Carbon Future: Evidence from California's Renewables Portfolio Standard, 2002—2015" (DONALD VIAL CENTER ON EMPLOYMENT IN THE GREEN ECONOMY Center for Labor Research and Education University of California, Berkeley, July 2016), http://laborcenter.berkeley.edu/pdf/2016/Link-Between-Good-Jobs-and-a-Low-Carbon-Future.pdf.

238 Ibid.

239 Ricardo American Lung Association, "State of the Air 2016" (American Lung Association, 2016), http://www.lung.org/local-content/california/documents/state-of-the-air/2016/sota-2016-full-report.pdf.

Chapter 4: Wind

4.1 Wind Power in California

The CEC estimated that California generated 27,000 GWh of electricity from wind in 2016, roughly 10% of the state's energy mix.[240] To reach the state's ambitious renewable energy goals, models predict that wind generation could grow to 59,000 GWh by 2030, producing over 16% of the state's energy.[241] Along with solar technologies, wind generation has also grown steadily. In 2001, California's wind energy capacity was approximately 1,500 MW, growing to 4,000 MW in 2011.[242] In 2015, wind generation was measured to be roughly 6,300 MW.[243] In some areas, wind generated electricity is cost competitive with natural gas, as the improvements made to onshore technologies have made them more efficient and cost-effective.[244] Globally, wind generated energy production is expected to grow due to its limited land-use footprint and the prevalence of optimal sites. In the US, the levelized cost of electricity for wind is expected to decrease from an average $70/MWh to $60/MWh by 2020.[245]

Wind turbine technologies are becoming more efficient, and onshore models are becoming larger to more efficiently convert wind power into electricity. Globally, the average size of an installed turbine has grown from 0.85 MW in 2001 to 1.8 MW in 2012 for onshore models.[246] Research has also focused on making smaller models more efficient with higher capacity factors for sites unsuitable for larger turbines.[247]

For California, experts foresee future growth in the development of offshore turbines. Research has focused on the ample wind resources off the northern coast of the state.[248] One such facility has already been proposed off the coast of Morro Bay, and researchers believe that offshore wind could generate between 59-76 GW of power for the state.[249] These projects would

240 CEC, "Renewable Energy – Overview December 2016" (California Energy Commission, December 2016), http://www.energy.ca.gov/renewables/tracking_progress/documents/renewable.pdf.

241 Gregory Brinkman, Jennie Jorgenson, and Marissa Hummon, "California 2030 Low Carbon Grid Study (LCGS): Phase I" (National Renewable Energy Laboratory, 2014), http://lowcarbongrid2030.org/wp-content/uploads/2014/10/LCGS_PhaseI_NRELslides.pdf.

242 Jim Bartridge et al., "Draft 2016 Environmental Performance Report of California's Electrical Generation System," Staff Report (California Energy Commission, July 2016), https://efiling.energy.ca.gov/getdocument.aspx?tn=212338.

243 CEC, "Renewable Energy – Overview December 2016."

244 Matthias Fripp, "Switch: A Planning Tool for Power Systems with Large Shares of Intermittent Renewable Energy," Environmental Science & Technology 46, no. 11 (June 5, 2012): 6371–78, doi:10.1021/es204645c.

245 Ryan Wiser and Mark Bolinger, "2014 Wind Technologies Market Report" (United States Department of Energy, August 2015).

246 Edgar G. Hertwich, Jacqueline Aloisi de Larderel, and Sangwon Suh, "Green Energy Choices: The Benefits, Risks, and Trade-Offs of Low-Carbon Technologies for Electricity Production" (United Nations Environmnetal Programme, 2016), http://www.unep.org/resourcepanel/Portals/50244/publications/Summary_for_Policy_Makers_GHG_I.pdf.

247 Bartridge et al., "Draft 2016 Environmental Performance Report of California's Electrical Generation System."

248 Bethany Speer, David Keyser, and Suzanne Tegen, "Floating Offshore Wind in California: Gross Potential for Jobs and Economic Impacts from Two Future Scenarios," Strategic Partnership Project Report (National Renewable Energy Laboratory, April 2016), http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.515.1211.

249 Bartridge et al., "Draft 2016 Environmental Performance Report of California's Electrical Generation System."

emphasize larger plants in deeper waters further from shore and the development of floating platforms.[250]

4.2 Materials Extraction

Wind turbines are made up mostly of resin, fiberglass, iron, steel, copper and concrete, which have well known extraction and production systems.[251] A main concern as wind turbines continue to develop is with the use of rare earth metals (i.e. neodymium and dysprosium) in certain magnets of specific direct drive turbines.[252] They are mined exclusively in China, whose natural reserves decline as their application in new technologies increases.[253] California has had one rare earth mine located in Mountain Pass that is currently closed, but could potentially re-open depending on future rare earth pricing and the demand for domestic production.[254]

While their scarcity raises concerns for sustainability of these technologies, the mining processes used to extract rare earth elements are highly energy intensive and produce a significant level of waste, which can contain radioactive materials such as thorium.[255] As the demand for rare earths increases dramatically with recent technological innovation and demand for renewable energy, it is important that environmental regulations and enforcement keep up. In China, there have been cases of pollution from mine wastewater and tailings, which have leached acids, heavy metals and radioactive elements into groundwater.[256] The Chinese State Council reported extensive environmental damage from rare earth mining, which affected vegetation, erosion, and acidification.[257] Because of this, there is a need for policy research on preventing this environmental degradation as well on the responsibility of producers to address these concerns through extended producer responsibility and design alternatives.

4.3 Manufacture

Wind turbines are structures that require large material inputs. Occupational hazards during turbine production include physical hazards related to the manual handling of large and heavy materials, use of machinery and equipment, electrical hazards, and noise.[258] Workers involved in blade manufacture and carbon fiber production can be exposed to epoxy-based

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250 Ibid.

251 Hertwich, Aloisi de Larderel, and Suh, "Green Energy Choices: The Benefits, Risks, and Trade-Offs of Low-Carbon Technologies for Electricity Production."

252 Ibid.

253 US DOE, "Critical Materials Strategy" (U.S. Department of Energy, December 2011), https://energy.gov/sites/prod/files/DOE_CMS2011_FINAL_Full.pdf.

254 Cecilia Jamasmie, "Molycorp Shuts down Mountain Pass Rare Earth Plant," Mining.com, August 26, 2015.

255 Nawshad Haque et al., "Rare Earth Elements: Overview of Mining, Mineralogy, Uses, Sustainability and Environmental Impact," Resources 3, no. 4 (October 29, 2014): 614–35, doi:10.3390/resources3040614.

256 Mike Ives, "Boom in Mining Rare Earths Poses Mounting Toxic Risks," University, Yale Environment 360, (January 28, 2013), http://e360.yale.edu/features/boom_in_mining_rare_earths_poses_mounting_toxic_risks.

257 Ibid.

258 EU-OSHA, Occupational Safety and Health in the Wind Energy Sector European Risk Observatory: Report. (Luxembourg: European Agency for Safety and Health at Work, 2013), http://bookshop.europa.eu/uri?target=EUB:NOTICE:TERO13008:EN:HTML.

resins, which can cause dermatitis and potentially damage the reproductive system with chronic exposure.[259] Styrene exposures can also impact workers making glass-reinforced plastics. When inhaled, styrene can cause vision abnormalities, color blindness, lower lung function, and cardiac distress.[260] A summary of prominent chemical exposures and related health outcomes is shown in Table 6 below.[261] Cumulative catalogs of materials and substances used in wind turbine manufacture are not publicly accessible.

Table 6. Health Impacts from Prominent Turbine Manufacturing Exposures

Agent	Acute	Chronic
Epoxies and Resins	Dermatitis	Fertility problems, miscarriage, stillbirth, or birth defects in offspring
Styrene	Eye and respiratory tract irritation; headache; gastrointestinal distress	Dizziness, confusion, weakness, drowsiness, unsteady gait; narcosis; dermatitis; possible damage to liver, kidney, and reproductive systems
Fiberglass	Irritation of eyes, skin, nose, throat; difficulty breathing	Respiratory tract cancers

Source: NIOSH, 2016

4.4 Transportation

Wind turbines are transported from manufacturing facilities to their end use site, usually in piece dues to their immense size. Transport worker risks include physical hazards like load shifts, vehicle rolls, collisions, and potential falls while loading, de-loading, and adjusting turbine parts.[262] Marine transport of turbines for offshore installations may amplify these risks due to the pitching motions of marine vessels. In the EU, as offshore wind becomes more prevalent, turbine manufacturers are increasingly sited at port locations to reduce land-based transport costs.[263]

General transport related emissions and hazards are discussed in **Section LCA.3.** Diesel and other transport-related air emissions can also affect local community air quality. While these will be highest during site prep, turbine installation, and eventual decommissioning, there

259 Ibid.

260 Joshua M. Harney et al., "Evaluation of Styrene and Dust Exposures and Health Effects during Fiberglass-Reinforced Wind Turbine Blade Manufacturing," Health Hazard Evaluation Report (U.S. Department of Health and Human Services Centers for Disease Control and Prevention National Institute for Occupational Safety and Health, August 2016), https://www.cdc.gov/niosh/hhe/reports/pdfs/2013-0056-3256.pdf.

261 EU-OSHA, Occupational Safety and Health in the Wind Energy Sector European Risk Observatory.

262 Ibid.

263 Ibid.

will be some emissions related to transporting workers and machinery for turbine maintenance. Although transport emissions from wind energy are likely to be minimal relative to all transport emissions, they may add to the cumulative impact of multiple air emission exposure sources, particularly in areas with poor air quality and high concentration of wind farms (i.e. Kern County, which ranked highest in number of people at risk from poor air quality in CA).[264]

4.5 Installation

4.5.1 Onshore Wind

Land clearing and preparation for utility-scale wind projects may require clearing of local vegetation with herbicides and/or machinery, although generally less so than for utility scale solar installations.[265] Models of wind energy's land use impacts often assume limited impacts, as the land between turbines can be left untouched.[266] However, even limited clearing can expose workers and fenceline communities to potentially toxic herbicide chemicals if they are used.[267] Depending on the location of these installations, workers and nearby communities may also be at risk of *Coccidioides* fungi spores exposure. With soil disturbance, these spores can be released into the air, leading to the potential for Valley Fever infection.[268] More information on *Coccidioides* and herbicide exposure can be found in **LCA.4.** Workers should be trained on Valley Fever prevention and symptom recognition if new onshore wind sites fall within suspected *Coccidioides*-endemic areas.

Wind farm construction also entails exposure to physical hazards related to machinery, falls, and heavy lifting. Key concerns related to this life cycle stage are those resulting from working at heights and in confined spaces.[269] As large-scale wind facilities are often sited based on the power and regularity of strong winds, workers will also likely be exposed to potentially hazardous wind speeds, which can amplify routine construction risks. Many of these hazards could be addressed through turbine design, and turbine designs that best protect workers should be prioritized as researchers continue.[270]

4.5.2 Offshore Wind

In offshore installations, hazards such as working at heights, in confined spaces, and with high wind speeds, can be amplified by the marine environment. The floating turbines off

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264 Ricardo American Lung Association, "State of the Air 2016" (American Lung Association, 2016), http://www.lung.org/local-content/california/documents/state-of-the-air/2016/sota-2016-full-report.pdf.

265 Hertwich, Aloisi de Larderel, and Suh, "Green Energy Choices: The Benefits, Risks, and Trade-Offs of Low-Carbon Technologies for Electricity Production."

266 Ibid.

267 M.M. Aman et al., "A Review of Safety, Health and Environmental (SHE) Issues of Solar Energy System," Renewable and Sustainable Energy Reviews 41 (January 2015): 1190–1204, doi:10.1016/j.rser.2014.08.086.

268 Gail L. Sondermeyer et al., "Coccidioidomycosis-Associated Deaths in California, 2000–2013," Public Health Reports 131, no. 4 (2016): 531–535.

269 EU-OSHA, Occupational Safety and Health in the Wind Energy Sector European Risk Observatory.

270 Committee on Offshore Wind Farm Worker Safety, Worker Health and Safety on Offshore Wind Farms, vol. 297, 2013016731 (Transportation Research Board, 2013).

the coast may also have unexpected pitching and rolling that could put installation workers at risk, as these would be new devices that have not been implemented before. Lifting mechanisms and cranes used also need to be equipped for marine conditions, and weather should be considered in determining installation schedules and timing. Researchers note that hazards from offshore oil and gas platforms may inform those from offshore wind systems.[271]

4.6 Maintenance and Use

4.6.1 Onshore Wind

While hundreds of workers can be involved in wind farm installation, a typical maintenance crew will consist of two workers for every 30 turbines, and regional crews may be in charge of oversight of many smaller wind farms.[272] Similar to installation, maintenance works requires working from heights and confined spaces. Due to metal fatigue, improper installation, and general wear and tear from extreme wind exposure, blade failures, generator malfunctions, and even tower collapse may occur with aging turbines.[273] In a German study assessing wind turbine failures in 1,500 turbines, researchers observed a 4% failure rate for structural parts and gearbox components and a 7% failure rate for rotor blades over 15 years.[274] Therefore, turbines need to be assessed regularly for related hazards to workers. Adverse weather is also a potential contributor to occupational injuries in turbine maintenance due to lightning, heavy winds, and rain. Fires can also be generated if lightning strikes the turbine's power pack.[275]

Some people living in close proximity to wind turbines have expressed concerns about a set of reported symptoms termed "wind turbine syndrome." In different situations these symptoms have included sleep disturbance, headache, dizziness, vertigo, tinnitus ear pressure or pain, trouble with memory and concentration, irritability, fatigue, and loss of motivation.[276] In different reports, these symptoms were linked with noise, low-frequency noise (infrasound), vibration, shadow flicker, and aesthetic effects of living near a wind farm installation. Shadow flicker, or the effect of blades passing between an observer and the sun, has been linked with annoyance if an individual is exposed for more than 30-minutes per day, but can often be mitigated through planning and computer control mechanisms.[277]

A number of studies have been done to assess the relationship between these factors and reported symptoms, and the evidence was considered inadequate to support a causal

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271 EU-OSHA, Occupational Safety and Health in the Wind Energy Sector European Risk Observatory.

272 Ibid.

273 Chia Chen Ciang, Jung-Ryul Lee, and Hyung-Joon Bang, "Structural Health Monitoring for a Wind Turbine System: A Review of Damage Detection Methods," Measurement Science and Technology 19, no. 12 (December 1, 2008): 122001, doi:10.1088/0957-0233/19/12/122001.

274 Berthold Hahn, Michael Durstewitz, and Kurt Rohrig, "Reliability of Wind Turbines," Wind Energy, 2007, 329–332.

275 EU-OSHA, Occupational Safety and Health in the Wind Energy Sector European Risk Observatory.

276 A Farboud, R Crunkhorn, and A Trinidade, "'Wind Turbine Syndrome': Fact or Fiction?," The Journal of Laryngology & Otology 127, no. 3 (March 2013): 222–26, doi:10.1017/S0022215112002964.

277 Jeffrey M. Ellenbogen et al., "Wind Turbine Health Impact Study: Report of Independent Expert Panel," January 2012, http://www.mass.gov/eea/docs/dep/energy/wind/turbine-impact-study.pdf.

relationship between wind turbine noise, infrasound, and vibration and many of the symptoms common to "wind turbine syndrome" reports.[278] However, evidence did support that chronic exposure to wind turbine noise and infrasound may lead to annoyance and sleep disruption.[279] Extensive sleep disruption can impact metabolism, increasing potential risks of diabetes and obesity, while also leading to potential cardiovascular outcomes.[280] Researchers note, however, that there is difficulty with confounding, as it is difficult to determine how factors like visual impact and personal attitudes affect the relationship between noise, annoyance, and sleep disruption.[281] More research is needed to understand infrasound exposures and their potential relationship to sleep disruption and annoyance outcomes.

4.6.2 Offshore Wind

Marine movements like pitching and rolling for offshore turbine structures exacerbate hazards related to maintenance of onshore turbines. Because California offshore will likely operate from floating platforms due to deep coastal waters, these will need to be assessed for potential occupational hazards and safety mechanisms to prevent injury. Maintenance workers will also have to be transported to the turbine structures, presenting additional hazards of marine transport and personnel transfers.[282] Because of the hazards related to turbine maintenance, safety protocols and training must include emergency response protocols accounting for marine conditions. Maintenance should also be scheduled seasonally to ensure worker protection from adverse weather conditions.

4.7 Decommissioning and Disposal

Because wind turbine life spans can be 20-30 years, hazards related to decommissioning and disposal have not been well documented. It is likely that these processes will be different for onshore and offshore facilities, as the location of offshore turbines presents additional hazards. Also, there is the potential for long-term exposure to high winds and general wear and tear may affect the stability of spent turbine, presenting additional hazards of tower failures.[283] These can be amplified by corrosive marine waters in offshore installations.[284]

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278 CCA, Understanding the Evidence: Wind Turbine Noise (Council of Canadian Academies, 2015), http://www.deslibris.ca/ID/246309.

279 Ellenbogen et al., "Wind Turbine Health Impact Study: Report of Independent Expert Panel."

280 O. M. Buxton et al., "Adverse Metabolic Consequences in Humans of Prolonged Sleep Restriction Combined with Circadian Disruption," Science Translational Medicine 4, no. 129 (April 11, 2012): 129ra43-129ra43, doi:10.1126/scitranslmed.3003200; Peter Meerlo, Andrea Sgoifo, and Deborah Suchecki, "Restricted and Disrupted Sleep: Effects on Autonomic Function, Neuroendocrine Stress Systems and Stress Responsivity," Sleep Medicine Reviews 12, no. 3 (June 2008): 197–210, doi:10.1016/j.smrv.2007.07.007.

281 CCA, Understanding the Evidence; Ellenbogen et al., "Wind Turbine Health Impact Study: Report of Independent Expert Panel"; Jesper Hvass Schmidt and Mads Klokker, "Health Effects Related to Wind Turbine Noise Exposure: A Systematic Review," ed. Shilu Tong, PLoS ONE 9, no. 12 (December 4, 2014): e114183, doi:10.1371/journal.pone.0114183.

282 Committee on Offshore Wind Farm Worker Safety, Worker Health and Safety on Offshore Wind Farms.

283 Ciang, Lee, and Bang, "Structural Health Monitoring for a Wind Turbine System."

284 Committee on Offshore Wind Farm Worker Safety, Worker Health and Safety on Offshore Wind Farms.

Because so few large-scale wind facilities have reached the end of their life cycles, disposal techniques are not well known. As the main components of wind turbines are resin, fiberglass, iron, steel, copper and concrete, it is expected that large portions of these structures will be recycled.[285] However, processes like mechanical separation and melting in a foundry, may present hazards for workers, including chemical exposures.[286] Blades, made up of reinforced or carbon fibers may either be landfilled, recycling, or incinerated. Incineration can lead to the creation of toxic fumes and pollutant ash, while recycling strategies are not well defined.[287]

More research is needed into wind turbine recycling, specifically in designing components for eventual recycling or refurbishing, and for the recycling of rare earth materials.

4.8 Equity Considerations

According to the Bureau for Labor Statistics, wind turbine technician employment is projected to grow 108% in the United States from 2014 to 2024 – growing from 4,400 to 9,200 jobs.[288] This does not include any of the indirect jobs produced through turbine manufacture and design. Wind energy employs a variety of workers, from construction and maintenance workers, to engineers and site managers.[289] On average, wind energy provides more direct employment than fossil fuel generation, providing more individuals with jobs opportunities to support their health and quality of life.[290] In California from 2002 – 2015, wind energy created a total of 2,754 construction job years, with a large percentage of job openings in Kern County, an area with high unemployment.[291] Investments were also made to form training and apprenticeship programs for wind farm construction – programs associated with improved future lifetime earnings.[292] More information is needed to assess the training, safety, and job quality for wind turbine technicians involved in maintenance.

Wind energy development must account for where new facilities are sited and how turbine installation may impact local communities. Turbine installation, continued maintenance, and decommissioning will all result in transport-related emissions and the

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285 Hertwich, Aloisi de Larderel, and Suh, "Green Energy Choices: The Benefits, Risks, and Trade-Offs of Low-Carbon Technologies for Electricity Production."

286 Per Dannemand Andersen et al., "Recycling of Wind Turbines," in Dtu International Energy Report 2014 (Technical University of Denmark, 2014), http://orbit.dtu.dk/fedora/objects/orbit:135159/datastreams/file_e2eb410f-0fa1-4704-8157-05f8cf683691/content.

287 EU-OSHA, Occupational Safety and Health in the Wind Energy Sector European Risk Observatory.

288 Bureau of Labor Statistics, "Occupational Outlook Handbook: Wind Turbine Technicians," Goverment Agency Website, United States Department of Labor, Bureau of Labor Statistics, (December 17, 2015), https://www.bls.gov/ooh/installation-maintenance-and-repair/wind-turbine-technicians.htm.

289 Max Wei, Shana Patadia, and Daniel M. Kammen, "Putting Renewables and Energy Efficiency to Work: How Many Jobs Can the Clean Energy Industry Generate in the US?," Energy Policy 38, no. 2 (February 2010): 919–31, doi:10.1016/j.enpol.2009.10.044.

290 Ibid.

291 Betony Jones, Peter Philips, and Carol Zabin, "The Link Between Good Jobs and a Low Carbon Future: Evidence from California's Renewables Portfolio Standard, 2002—2015" (DONALD VIAL CENTER ON EMPLOYMENT IN THE GREEN ECONOMY Center for Labor Research and Education University of California, Berkeley, July 2016), http://laborcenter.berkeley.edu/pdf/2016/Link-Between-Good-Jobs-and-a-Low-Carbon-Future.pdf.

292 Ibid.

potential for fugitive dust from wind farm sites during land preparation. In areas already suffering from poor air quality – such as Kern County where most of California's wind turbines are located – these emissions may increase the cumulative impacts from all infrastructure build out in the area. These emission impacts could be intensified in lower income or minority communities.

4.9 Research Needs

1. Conduct life cycle hazard assessment of turbine technologies including rare-earth magnets

2. Improve infrasound exposure and impact assessment
   a. Exposure assessment at various turbine-receptor distances
   b. Epidemiological research on sleep disruption and annoyance from larger turbine design, controlling when possible for known confounders

Chapter 5: Biomass

Biomass energy resources come from a diverse set of organic materials – mostly forest trees, agricultural, livestock, and urban waste streams – and can be used to generate electricity, heat, or biofuels for transportation. Because this report focuses on electricity generation, the following section only discusses biomass electricity production. The impacts of biofuel production cannot be extrapolated from those related to electricity production. A fuller assessment of the health impacts associated with various future bioenergy development scenarios – including the mix of electricity and biofuel production – is necessary.[293]

5.1 Biomass Electricity Production in California: Current Context

5.1.1 Current and Projected Electricity Generation from Biomass Resources

The CEC estimated that California generated 8,000GWh of electricity from biomass in 2016, roughly 3% of the state's energy. To reach the state's ambitious renewable energy goals, models predict that this could grow to 12,000GWh by 2030, increasing net electricity production slightly.[294] According to a 2015 report for the Air Resources Board, the state has an installed generation capacity of 550 MW for woody biomass solid fuel combustion, 280 MW for landfill gas, and 75 MW for wastewater treatment biogas.[295]

California Senate Bill 1122 from 2013 required the California Public Utilities Commission (CPUC) to direct electrical corporations in procuring 250 MW of new small biopower (less than 3 MW per project). Of the 250MW, 110 MW is set aside for wastewater treatment and urban organic waste biogas, 90 MW for dairy and other agricultural bioenergy, and 50MW for forest biomass.[296] Governor Schwarzenegger's executive order S-06-06 also required 20% of renewable electricity in CA to be generated from biopower resources through 2020.[297]

The future of biomass electricity production in California is unclear, as biomass system build out will require public financial support to develop and commercialize more sustainable

293 Marc Carreras-Sospedra et al., "Assessment of the Emissions and Energy Impacts of Biomass and Biogas Use in California," Contract 11 (2015): 307.

294 Gregory Brinkman, Jennie Jorgenson, and Marissa Hummon, "California 2030 Low Carbon Grid Study (LCGS): Phase I" (National Renewable Energy Laboratory, 2014), http://lowcarbongrid2030.org/wp-content/uploads/2014/10/LCGS_PhaseI_NRELslides.pdf; CEC, "Renewable Energy – Overview December 2016" (California Energy Commission, December 2016), http://www.energy.ca.gov/renewables/tracking_progress/documents/renewable.pdf.

295 Carreras-Sospedra et al., "Assessment of the Emissions and Energy Impacts of Biomass and Biogas Use in California."

296 Adam Schultz, "Overview of SB 1122 Staff Proposal Rulemaking (R.) 11-05-005" (California Public Utilities Commission, December 3, 2013).

297 Arnold Scwarzenegger, "Executive Order S-06-06" (Executive Department, State of California, April 2006), http://www.dot.ca.gov/hq/energy/Exec%20Order%20S-06-06.pdf.

technologies.[298] Modelers suggest that biofuel production may garner greater interest than biomass electricity generation in light of potentially greater air quality benefits when biofuels replace gasoline or diesel in comparison to biomass electricity generation replacing fossil fuel generation.[299]

5.1.2 Biomass and California's Forests

Wood for energy production has historically been procured primarily through waste streams from timber and construction industry activities and from state and federal forest management projects.[300] Recently there has been resurgent interest in biomass energy due to the role it might play in managing forest waste resulting from the state's large tree die-off.[301] In recent years, California's forests suffered an immense tree die-off due to drought, warmer temperatures, and beetle infestations that resulted in more than 100 million dead trees.[302] As part of a statewide response, Governor Brown signed SB 859 requiring electric utilities to collectively procure 125MW of biomass energy generation from forest biomass sources by December 2016.[303]

In a 2017 report, the state's Tree Mortality Task Force estimated that there are 14.53 million dead trees statewide that present a "potential direct threat to people, buildings and infrastructure from falling trees" that should be prioritized in removal efforts.[304] By some estimates, 500,000 dead trees have already been collected statewide through a joint effort by Forest Service, the California Department of Forestry and Fire Protection, the California Department of Transportation and private utilities.[305] The question of where the resulting logs will go has become a waste management concern. In response, the state has prioritized deployment of smart development and distribution of biomass energy systems to process at least a fraction of the expected waste.[306]

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298 "California Forest Carbon Plan: Managing Our Forest Landscapes in a Changing Climate," Draft for Public Review (CalFire, California Natural Resources Agency, CalEPA, January 20, 2017).

299 Geoffrey M. Morrison et al., "Comparison of Low-Carbon Pathways for California," Climatic Change 131, no. 4 (August 2015): 545–57, doi:10.1007/s10584-015-1403-5.

300 Peter Tittmann, Interview with Peter Tittmann, UC Forest Products Laboratory, Phone, January 18, 2017.

301 Jacques Leslie, "Op-Ed A Beneficial Way to Dispose of the Sierra's Lost Trees: Use Them for Energy," LA Times, March 17, 2017.

302 Matt Stevens, "102 Million Dead California Trees 'Unprecedented in Our Modern History,' Officials Say," LA Times, November 18, 2016, Web edition, sec. Local, http://www.latimes.com/local/lanow/la-me-dead-trees-20161118-story.html.

303 Committee on Budget and Fiscal Review, "Senate Bill No. 859, Chapter 368," Pub. L. No. SB 859 (2016), https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB859.

304 Tree Mortality Task Force, "Tree Mortality: Facts and Figures" (California Tree Mortality Task Force, April 2017), http://www.fire.ca.gov/treetaskforce/downloads/TMTFMaterials/Facts_and_Figures_April_2017.pdf.

305 Kurtis Alexander, "California's Huge Tree Die-off Expected to Slow after Wet Winter," San Francisco Chronicle, April 8, 2017, Web edition, sec. Local, http://www.sfchronicle.com/bayarea/article/California-s-huge-tree-die-off-expected-to-slow-11059513.php.

306 Kurtis Alexander, "California Has 66 Million Dead Trees but Nowhere to Put the Wood," San Francisco Chronicle, July 1, 2016, Local edition, http://www.sfchronicle.com/bayarea/article/California-has-66-million-dead-trees-and-nowhere-8337745.php; Edmund G. Brown, "Proclamation of a State of Emergency" (Executive Department, State of California, October 30, 2015), https://www.gov.ca.gov/docs/10.30.15_Tree_Mortality_State_of_Emergency.pdf.

Once trees are removed from forests, the wood can be repurposed, landfilled, converted into energy, or burned in controlled fires. All of these outcomes will have vastly different community health impacts, which are summarized in Table 2 for all solid biomass feedstocks. Biomass energy conversion systems could assist in managing forest waste to prevent or reduce open burning practices near population centers. One study found that, compared with open burning practices, utilization of forest waste from the Sierra Nevada foothills for electricity production in a stoker boiler and steam turbine resulted in over 96% reduction in PM, CO, and methane emissions, as well as a 14% and 54% reduction in CO_2 and NOx emissions respectively (including emissions from transporting the materials 96km to the biomass facility).[307]

Similarly, the gasification system is expecting a reduction in emissions from waste displaced from open burns. A health impact assessment (HIA) of a 2MW gasification plant in Placer County found an overall reduction in air pollutant emissions. The authors estimated that if the facility is running at capacity, 17,000 bone dry tons of forest sourced biomass per year would be displaced from open-pile burns. This would result in an annual decrease of 78 tons of NO_x, 102 tons of reactive organic gases (ROGs), 167 tons of PM_{10}, and 142 tons of $PM_{2.5}$.[308]

There is additional concern that the state's tree die-off will lead to worsening wildfires. Wildfires have increased in recent years as a result of changing seasonal patterns and rising temperatures.[309] There is not scientific agreement on what impact the millions of dead trees in Western forests have on the potential severity and spread of wildfires in these areas.[310] The relationship of biomass energy resources to wildfire reduction is also unknown as 1) it is not clear what impact the reduction of already collected wood waste will have on wildfires and 2) biomass energy resources have yet to achieve the needed distribution and funding to respond to the state's vast forest waste. Because of this, future research needs to model the potential for biomass distribution in relation to prioritized forest waste removal sites, as well as assess the impact that bioenergy deployment might have on wildfire risk reduction.

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307 Bruce Springsteen et al., "Emission Reductions from Woody Biomass Waste for Energy as an Alternative to Open Burning," Journal of the Air & Waste Management Association 61, no. 1 (January 2011): 63–68, doi:10.3155/1047-3289.61.1.63.

308 Sequoia Foundation, "A Health Impact Assessment of the Proposed Cabin Creek Biomass Energy Facility in Placer County, California," Health Impact Assessment (Sequoia Foundation, 2007), www.placer.ca.gov/~/media/cdr/.../Biomass/.../HIAReport.as.

309 A. L. Westerling and B. P. Bryant, "Climate Change and Wildfire in California," Climatic Change 87, no. S1 (March 2008): 231–49, doi:10.1007/s10584-007-9363-z.

310 Jeffrey A. Hicke et al., "Effects of Bark Beetle-Caused Tree Mortality on Wildfire," Forest Ecology and Management 271 (May 2012): 81–90, doi:10.1016/j.foreco.2012.02.005; Garrett W Meigs et al., "Do Insect Outbreaks Reduce the Severity of Subsequent Forest Fires?," Environmental Research Letters 11, no. 4 (April 1, 2016): 45008, doi:10.1088/1748-9326/11/4/045008; Sarah J. Hart et al., "Area Burned in the Western United States Is Unaffected by Recent Mountain Pine Beetle Outbreaks," Proceedings of the National Academy of Sciences 112, no. 14 (April 7, 2015): 4375–80, doi:10.1073/pnas.1424037112.

Table 7. Potential Fates of Forest Waste and Related Impacts

Source	Potential Disposal	Exposure	Health Impacts
Forest Waste	**Wildfire**	Dangerous and uncontrolled fire, Polluted smoke (PM, CO, O3, mercury, VOCs, and other air toxics, etc.), watershed pollution, short lived climate pollutants (i.e. methane and black carbon), CO2	Asthma exacerbation, chronic obstructive pulmonary disease, bronchitis, pneumonia, eye irritation, sore throat, wheeze, cough, and chest pain, cardiovascular outcomes, increased mortality, toxic emissions from burned transmission lines and other electrical or chemical equipment, mental health outcomes, climate change
	Open Burn	Emission of criteria pollutants, short lived climate pollutants (i.e. methane and black carbon), CO2, ash, dioxins, furans,	Susceptibility to respiratory infections, irritation of lung and respiratory symptoms (e.g., cough, chest pain, difficulty breathing), eye and throat irritation, asthma exacerbation, bronchitis, lung damage, cardiovascular effects, cancer, heavy metal poisoning (will depend on specific components), impaired fetal development, climate change
	Landfill	Land use issue, methane emissions, potential for toxic leaching into surrounding water or soil	Climate change, leachates into local water systems, eye irritation, upper respiratory irritation and illness, odor impacts
	Bioenergy	Emission of criteria pollutants, CO2	*Depending on conversion technology and emissions mitigation used*: Susceptibility to respiratory infections, irritation of lung and respiratory symptoms (e.g., cough, chest pain, difficulty breathing), eye and throat irritation, asthma exacerbation, bronchitis, lung damage, cardiovascular effects, cancer, heavy metal poisoning (will depend on specific components), impaired fetal development, climate change

Colors are used to compare the severity of emissions and potential impacts (Red – high impact, Orange – Medium impact, Yellow – Moderate impact)

Source: Liu et al. "A systematic review of the physical health impacts from non-occupational exposure to wildfire smoke." 2015. Springsteen et al., "Emission Reductions from Woody Biomass Waste for Energy as an Alternative to Open Burning," January 2011; CDC, "Criteria Air Pollutants;" EPA, "Landfills"

Healthy forests provide important ecosystem benefits, including carbon sequestration and watershed protection. These dynamics are impacted by a myriad of factors including droughts, wildfires, and climate change, in addition to forest management and fire prevention practices. More research is needed on the impacts of management and fire prevention practices on forest ecosystem dynamics.[311] Research also needs to focus on how these effects are further impacted by climate change.[312] Energy production from forest biomass will be tied to forest management practices into the future. A better understanding of how to promote healthy forests, considering changing temperatures and climates, will aid in planning sustainable biomass energy resources.

5.2 Overview of Biomass Electricity Production and Related Impacts

Biomass power plants convert organic matter from forest, agriculture, and urban waste streams into electricity. The siting, distribution, and scale of biomass facilities and technologies, as well as differences in emissions associated with various biomass development scenarios, all dramatically affect potential health impacts. It is thus difficult to draw conclusions about the health impacts of biomass electricity absent further research and modeling on the likely characteristics of various biomass development scenarios and the emissions expected from each.

For solid biomass, feedstocks are combusted in direct fire or gasification plants to drive a turbine for electricity production. Potential impacts will also vary based on the conversion technology used. For instance, developing gasification systems have lower projected air emissions than traditional combustion systems, but costs have limited the commercial application of these technologies.[313] For biogas feedstocks, gases produced naturally through anaerobic digestion are used to generate electricity. Future statewide biomass scenarios must account for changes in technology mixes to better model potential impacts.

This section discusses size and distribution of facilities (5.2.1), conversion technology used (5.2.2), and feedstock life cycle (5.2.3) as they apply to future biomass deployment in the state. The following sections (5.3 – 5.5) discuss the life cycles of biomass and biogas feedstocks, noting potential hazards and impacts.

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311 Tara W. Hudiburg et al., "Regional Carbon Dioxide Implications of Forest Bioenergy Production," Nature Climate Change 1, no. 8 (October 23, 2011): 419–23, doi:10.1038/nclimate1264; Morgan L. Wiechmann et al., "The Carbon Balance of Reducing Wildfire Risk and Restoring Process: An Analysis of 10-Year Post-Treatment Carbon Dynamics in a Mixed-Conifer Forest," Climatic Change 132, no. 4 (October 2015): 709–19, doi:10.1007/s10584-015-1450-y; Sabina Dore et al., "Management Impacts on Carbon Dynamics in a Sierra Nevada Mixed Conifer Forest," PloS One 11, no. 2 (2016): e0150256; Matthew Hurteau and Malcolm North, "Fuel Treatment Effects on Tree-Based Forest Carbon Storage and Emissions under Modeled Wildfire Scenarios," Frontiers in Ecology and the Environment 7, no. 8 (October 2009): 409–14, doi:10.1890/080049; Kevin C. Grady and Stephen C. Hart, "Influences of Thinning, Prescribed Burning, and Wildfire on Soil Processes and Properties in Southwestern Ponderosa Pine Forests: A Retrospective Study," Forest Ecology and Management 234, no. 1–3 (October 2006): 123–35, doi:10.1016/j.foreco.2006.06.031.

312 Kristina J. Anderson-Teixeira et al., "Altered Dynamics of Forest Recovery under a Changing Climate," Global Change Biology 19, no. 7 (July 2013): 2001–21, doi:10.1111/gcb.12194.

313 "California Forest Carbon Plan: Managing Our Forest Landscapes in a Changing Climate."

5.2.1 Size, Distribution, and Transportation Hazards

Differences in facility size and siting throughout the state will influence the potential health impacts of biomass deployment. Historically, biomass energy production had been linked with large timber-processing facilities, and feedstocks were transported to these utility-scale installations to be converted into energy.[314] However, more emphasis is currently being placed on smaller, distributed systems closer to feedstock sources, thus reducing impacts related to feedstock transport and storage.[315] These distributed systems, if sited appropriately, could potentially improve grid resiliency in more remote areas.[316] The feasibility, likelihood, and scale of building out smaller, distributed biomass electricity systems is currently unclear, and determination of potential health impacts will thus require further study based on better modeling of how these systems will grow in use throughout the state.

Biomass facility location and siting will affect its cumulative impacts. For instance, some advocacy groups are concerned that unless new biomass facilities are built near forest waste resources, expanding bioenergy production could result in significant shipment of forest waste to facilities in the Central Valley. The Central Valley already endures poor air quality. The added transport and conversion emissions would create more negative impacts on regional air quality, with the potential to boost open agricultural burning if facilities reach maximum capacity from forest wastes.[317] While distributed, transportable systems will still require transport of machinery to feedstock sites, they will remove the impacts on surrounding communities from emissions of continuous feedstock transport to a utility-scale facility. As a result, transport related hazards for communities depends on the scale and siting of biomass facilities.

5.2.2 Conversion Technology

Conversion is the process via which biomass feedstocks are converted into thermal energy that can then be converted to electricity, heat, or fuel. This report focuses on conversion systems for electricity production. For solid biomass, these technologies include direct-fire/combustion and evolving gasification technologies. The main health impacts associated with conversion and electricity generation are related to emissions of particulate matter and other criteria pollutants from the combustion system, though emerging gasification technologies appear to have limited these emissions in their initial small-scale development.[318]

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314 Arne Jacobson, Interview with Arne Jacobson, Humboldt State University, Phone, October 17, 2016.

315 Julia Levin, Interview with Julia Levin, Bioenergy Association of California, In Person, September 9, 2016; Schultz, "Overview of SB 1122 Staff Proposal Rulemaking (R.) 11-05-005."

316 Jacobson, Interview with Arne Jacobson, Humboldt State University.

317 Dolores Weller et al., "Comments on Draft Forest Carbon Action Plan" (Central Valley Air Quality Coalition, Central California Environmental Justice Network, Central California Asthma Collaborative, Medical Advocates for Healthy Air, Association of Irritated Residents, March 17, 2017), http://www.fire.ca.gov/fcat/downloads/FCAT_PublicComment/Genevieve%20Gale-FCAPComments-CentralValley.pdf; Ricardo American Lung Association, "State of the Air 2016" (American Lung Association, 2016), http://www.lung.org/local-content/california/documents/state-of-the-air/2016/sota-2016-full-report.pdf.

318 Robert B. Williams and Stephen Kafka, "Biomass Gasification DRAFT," Draft Interim Project Report (California Biomass Collaborative / California Renewable Energy Collaborative, University of California, Davis, January 2015), http://biomass.ucdavis.edu/files/2015/10/Task7-Report_Biomass-Gasification_DRAFT.pdf.

5.2.2.1 Direct-Fired Plants

Conventional biomass energy systems use direct-fired or combustion plants. These plants burn feedstock in a boiler to produce steam, which drives a turbine for power generation. The most common combustion systems in use today are stoker boilers and fluidized bed boilers. For direct-fired plants, more than 90% of NOx, CO, PM, and SOx emissions and 98% of GHG emissions occur during the combustion phase.[319]

Table 8 compares emissions from a direct fire biomass boiler to those from facilities using emerging gasification systems.[320] These air emissions should be compared to reductions in similar emissions from offsetting open burning practices. However, they have the potential to cause health impacts in facility workers and surrounding populations. These are summarized in Table 9 below.

There is a need to improve understanding of the emissions and ambient air impacts of air toxics associated with biomass combustion at varying scales (large, utility-scale and distributed systems).[321] Better data is needed to characterize emissions under different fuel compositions and from emerging combustion technologies. To ensure the protection of surrounding community health, health impact assessments (HIAs) – like the one completed for the Placer County gasification facility – could be an important tool during site planning.[322] Because emissions will depend on many variables, including location and type of facility, the ability of a site-specific HIA to account for these considerations would be useful. For smaller, distributed systems, there is a need for more information on air dispersion analyses, especially for combustion units that may fall below regulatory thresholds requiring impact analyses.[323] On the other hand, site-specific assessments may not adequately address the cumulative impacts associated with siting in areas with multiple other emissions sources, or of build out of multiple facilities in an already polluted air basin.

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319 Carreras-Sospedra et al., "Assessment of the Emissions and Energy Impacts of Biomass and Biogas Use in California."

320 D. Schuetzle, G. Tamblyn, and F. Tornatore, "Appendix 10: Power Plant Analysis for Conversion of Forest Remediation Biomass to Renewable Fuels and Electricity. Report to the Biomass to Energy Project (B2E)" (California Energy Commission, January 2010).

321 Polly Hoppin and Molly Jacobs, "Wood Biomass for Heat & Power: Addressing Public Health Impacts, Summary of a 2011 Symposium" (Wood Biomass for Heat and Power: Addressing Public Health Impacts, Massachusetts Medical Society in Waltham, Massachusetts: Lowell Center for Sustainable Production University of Massachusetts Lowell, 2012), http://www.sustainableproduction.org/downloads/WoodBiomassSymposium-Full-Final.pdf.

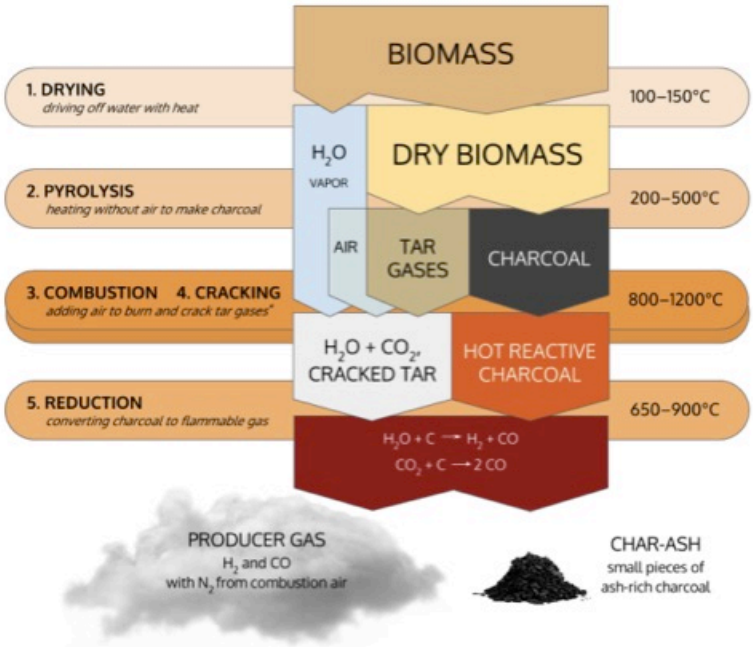
322 Sequoia Foundation, "A Health Impact Assessment of the Proposed Cabin Creek Biomass Energy Facility in Placer County, California"; Hoppin and Jacobs, "Wood Biomass for Heat & Power: Addressing Public Health Impacts, Summary of a 2011 Symposium."

323 Hoppin and Jacobs, "Wood Biomass for Heat & Power: Addressing Public Health Impacts, Summary of a 2011 Symposium."

5.2.2.2 Gasification

Gasification systems are highly efficient, developing technologies that allow for far more effective pollutant removal. They significantly reduce emissions of particulate matter and criteria pollutants like SO_x and NO_x relative to direct-fired systems or open burn practices.[324] The gasification process produces a gas, or syngas, through drying the feedstock followed by heating of the feedstock in anaerobic conditions. These processes can then be followed by combustion with "cracking" to break down larger molecules, like tar, in the presence of oxygen, before this oxygen is removed through a production process. This process is shown in more detail in Figure 9 for All Power Lab's gasification technologies.[325] This syngas can then be used to generate electricity through firing in reciprocating engines, microturbines, Stirling engines, or fuel cells.[326] Gasification technologies have demonstrated greater flexibility when compared to direct combustion mechanisms, as they can handle a diverse set of feedstocks. Additionally, they can be used in versatile applications, from boilers, engines, and fuel cells, to pipeline distribution or in combination with natural gas and other fuel gases.[327] However, these technologies - while promising - are not yet widely commercially available.[328]

Figure 9. Gasification Process for All Power Labs Gasification Systems



324 Williams and Kafka, "Biomass Gasification DRAFT."

325 All Power Labs, "How Gasification Works," All Power Labs, 2017, http://www.allpowerlabs.com/gasification-explained.

326 EPA, "Chapter 5. Biomass Conversion Technologies," Biomass CHP Catalog (U.S. Environmental Protection Agency Combined Heat and Power Partnership, September 2007), https://www.epa.gov/sites/production/files/2015-07/documents/biomass_combined_heat_and_power_catalog_of_technologies_5._biomass_conversion_technologies.pdf.

327 Ibid.

328 Jaquelyn Birdsall et al., "Repowering Solid Fuel Biomass Electricity Generation," Final Project Report (California Biomass Collaborative / California Renewable Energy Collaborative, University of California, Davis, April 2012).

Source: All Power Labs, 2016 (http://www.allpowerlabs.com/gasification-explained)

In 2011, the Sequoia Foundation completed an HIA for a 2MW gasification facility planned for Placer County. From the facility's Environmental Impact Report, it was found that emissions of NO_x, PM, and reactive organic agents (ROGs) would fall below the California Environmental Quality Act's significance thresholds for the Placer County Air Pollution Control District. Based on the facility's planned location, emissions related to the plant's life cycle were considered insignificant, even for potentially vulnerable populations, as residences were located at least 1000ft from the site.[329] A health risks assessment (HRA) of modeled air toxic emissions (i.e. benzene, formaldehyde, acrolein, nickel, etc.) found that cancer and non-cancer related health risks were non-significant for surrounding populations based on the facility's siting.[330] This HRA over-estimated emissions as emissions data for the planned gasification system were not available.[331] In total, the facility is expected to reduce overall emissions by displacing wood waste from open burning practices.[332]

Current research is focused on how syngas can be more efficiently cleaned, especially at high temperatures, to reduce energy loss throughout the process.[333] The cleaning process used depends on the composition of the feedstock as well as the end use product (i.e. electricity, fuel, or heat). For smaller electricity generation systems, cleaning is typically limited to particulate and tar removal.[334] For gas turbine applications, sulfur compounds must be removed, and current cleaning techniques have achieved 95-99.9% efficiency.[335]

Syngas can contain contaminants, such as tars, PM, alkali compounds, and ammonia, which need to be removed before this gas can be used in engine, microturbine, or fuel cell applications.[336] These are illustrated in Figure 10. These ultimate applications will impact the ultimate emissions of the biomass conversion process, as advanced technologies like fuel cells are expected to significantly lower related air emissions from the electricity conversion process. One example modeling ozone emissions is shown in

A byproduct of these gasification systems is a condensed solid waste, or biochar, which can be used as soil additive. Recent studies have assessed the role of biochar in promoting soil nutrients and reducing pollutant transport, and some have assessed the potential for toxics like metals, metalloids and polycyclic aromatic hydrocarbons (PAHs) to be present and leach from biochar application. This potential for contamination will depend on the feedstock source and

329 Sequoia Foundation, "A Health Impact Assessment of the Proposed Cabin Creek Biomass Energy Facility in Placer County, California."

330 Air Permitting Specialists, "Final Report: Analysis of Public Health Risks Associated with Operation of a Biomass Power Plant," Phase II Report, U.S. Department of Energy/Placer County Biomass Utilization Pilot Project (Auburn, CA: Placer County Planning Services Division, September 7, 2011).

331 Ibid.

332 Sequoia Foundation, "A Health Impact Assessment of the Proposed Cabin Creek Biomass Energy Facility in Placer County, California."

333 EPA, "Chapter 5. Biomass Conversion Technologies."

334 Kevin J. Whitty, Hongzhi R. Zhang, and Eric G. Eddings, "Emissions from Syngas Combustion," Combustion Science and Technology 180, no. 6 (May 15, 2008): 1117–36, doi:10.1080/00102200801963326.

335 Ibid.

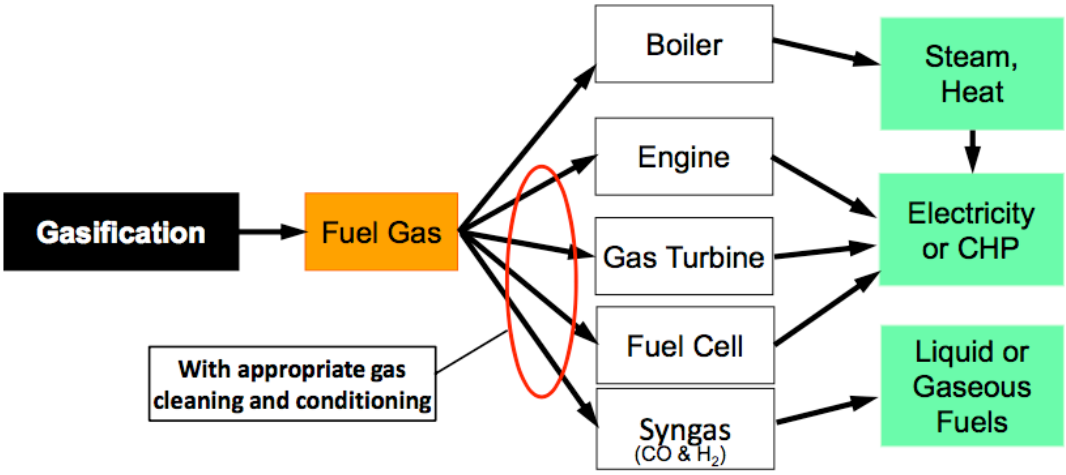
336 EPA, "Chapter 5. Biomass Conversion Technologies."

electricity generating technology and more research is needed to produce informed policy for safe biochar agricultural applications.

To date, there are no long-term studies of health impacts from biomass gasification plants, and emissions data from these emerging technologies are limited. More research is needed as to actual emissions from gasification biomass systems in real world applications as they continue to develop. There is also a need for more comprehensive deployment scenarios for biomass generation in California, so the future siting of gasification systems, and the potential for related health impacts, can be assessed.

Figure 11.[337] This figure shows high levels of ozone from maximum deployment of current biomass facilities; however, ozone levels drop severely when enhanced technologies like gasification and fuel cells were implemented. Further ozone depletion is shown for biofuel development. A comparison of emissions from engine and fuel cell power generation is found in Table 12 (**Section 5.6.5**). More data is needed to model how and where these technologies are likely to develop in California and what the expected air emissions – both GHG and pollutants – would be from such real world applications.

Figure 10. Gasification Applications



Source: Robert B. Williams and Stephen Kafka, "Biomass Gasification DRAFT," Draft Interim Project Report (California Biomass Collaborative / California Renewable Energy Collaborative, University of California, Davis, January 2015), http://biomass.ucdavis.edu/files/2015/10/Task7-Report_Biomass-Gasification_DRAFT.pdf.

337 Carreras-Sospedra et al., "Assessment of the Emissions and Energy Impacts of Biomass and Biogas Use in California."

A byproduct of these gasification systems is a condensed solid waste, or biochar, which can be used as soil additive.[338] Recent studies have assessed the role of biochar in promoting soil nutrients and reducing pollutant transport, and some have assessed the potential for toxics like metals, metalloids and polycyclic aromatic hydrocarbons (PAHs) to be present and leach from biochar application.[339] This potential for contamination will depend on the feedstock source and electricity generating technology and more research is needed to produce informed policy for safe biochar agricultural applications.[340]

To date, there are no long-term studies of health impacts from biomass gasification plants, and emissions data from these emerging technologies are limited.[341] More research is needed as to actual emissions from gasification biomass systems in real world applications as they continue to develop. There is also a need for more comprehensive deployment scenarios for biomass generation in California, so the future siting of gasification systems, and the potential for related health impacts, can be assessed.

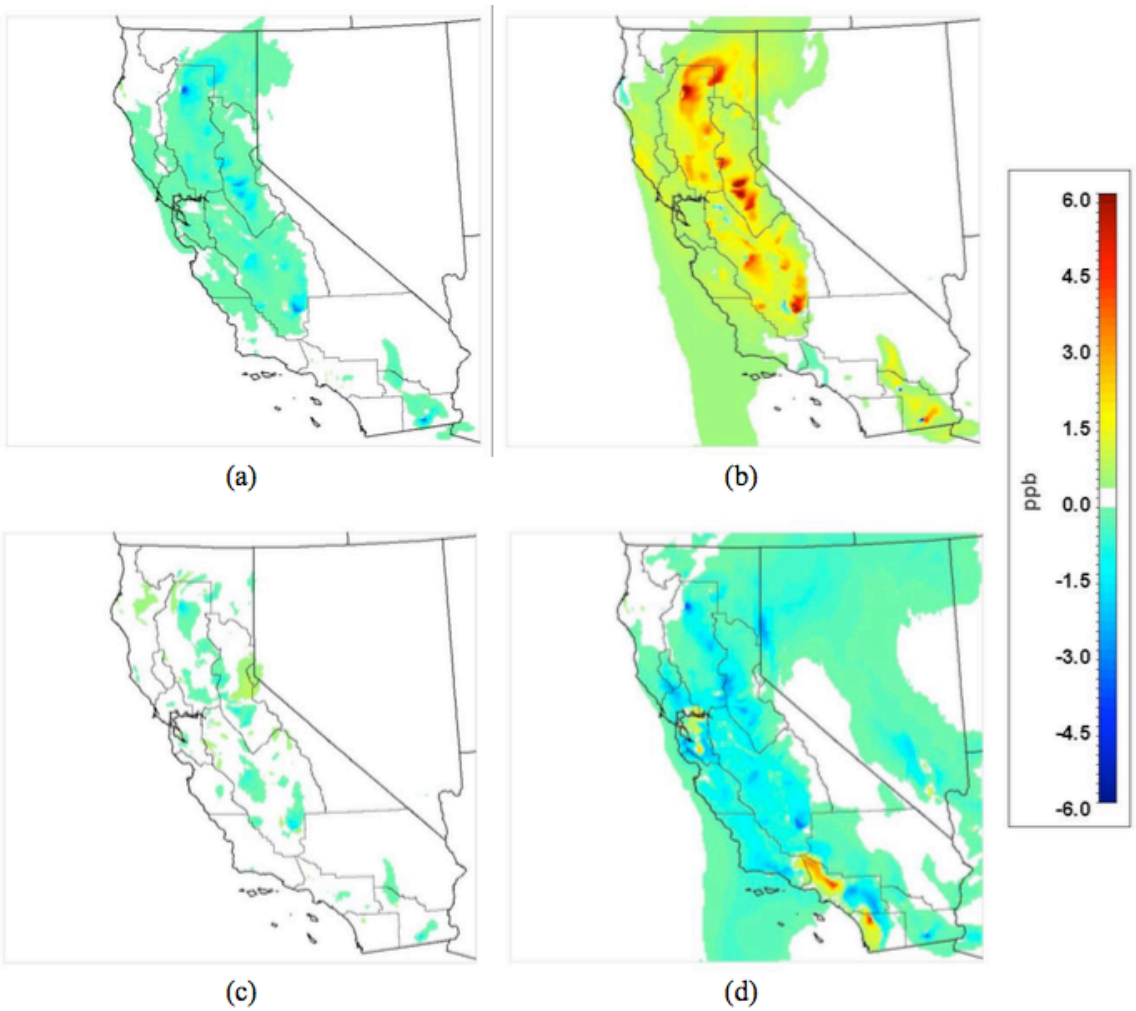
Figure 11. Change in Peak Summer Ozone Concentrations with Different Biomass Deployment by 2020 Using the Community Multiscale Air Quality Model

338 "California Forest Carbon Plan: Managing Our Forest Landscapes in a Changing Climate."

339 Alessia Freddo, Chao Cai, and Brian J. Reid, "Environmental Contextualisation of Potential Toxic Elements and Polycyclic Aromatic Hydrocarbons in Biochar," Environmental Pollution 171 (December 2012): 18–24, doi:10.1016/j.envpol.2012.07.009; Michał Kołtowski and Patryk Oleszczuk, "Toxicity of Biochars after Polycyclic Aromatic Hydrocarbons Removal by Thermal Treatment," Ecological Engineering 75 (February 2015): 79–85, doi:10.1016/j.ecoleng.2014.11.004.

340 Freddo, Cai, and Reid, "Environmental Contextualisation of Potential Toxic Elements and Polycyclic Aromatic Hydrocarbons in Biochar."

341 Sequoia Foundation, "A Health Impact Assessment of the Proposed Cabin Creek Biomass Energy Facility in Placer County, California."



Compared to a baseline scenario of emissions from biomass facilities operating in 2014, the four scenarios modeled include (a) No biomass to evaluate impact of current system on air quality (b) Maximum biopower production (4.66GW) where facilities were located in 2014 using current technologies, (c) Maximum biopower production (4.66GW) where facilities were located in 2014 using enhanced technology like gasification and fuel cell systems, (d) Maximum production of compressed natural gas (CNG) from biomass for vehicle consumption (16% of gasoline vehicles are converted to CNG vehicles) assuming same emissions from petroleum refining. (This does not model new or likely biomass energy systems in the state.)

Source: Marc Carreras-Sospedra et al., "Assessment of the Emissions and Energy Impacts of Biomass and Biogas Use in California," *Contract* 11 (2015): 307.

Table 8. Direct Emissions from Biomass Combustion and Gasification Systems

Pollutants	Direct Emissions (lbs/MMBtu output)	
	Average Biomass Combustion Boiler	Integrated Gasification and Combustion Power Plant
Volatile Organic Compounds (VOCs)	0.085	0.018
Carbon Monoxide (CO)	0.897	0.07
Nitrous Oxides (NO_x)	0.329	0.067
Particulate Matter (PM)	0.269	0.03
Sulfur Oxides (SO_x)	0.125	0.01
Carbon Dioxide (CO_2)	890	884

(The biomass boiler emissions are based on CA-GREET 1.8b values, which the author notes is in the range of emissions of biomass boilers inventoried by the California Biomass Collaborative)

Source: Scheutzle et al. 2010[342]

Table 9. Criteria Pollutants Health Impacts

Emission	Related Health Impacts (EPA, 2017)
SOx	Irritation of respiratory system, asthma exacerbation and development, difficulty breathing (also forms particulate matter through secondary reactions)
NOx	Irritation of respiratory system, asthma exacerbation and development, difficulty breathing (also forms ozone and particulate matter through secondary reactions)
PM	Exacerbated asthma, difficulty breathing, irritation of the airways, coughing, irregular heartbeat, decreased lung function, and premature death in people with heart or lung disease
CO	Headaches, fatigue, exacerbation of heart disease and angina (higher concentrations unlikely outdoors, but can lead to confusion and death)
VOCs	Eye and skin irritation, nausea, headaches (depending on specific composition, certain compositions are known carcinogens)

Source: EPA, “Criteria Air Pollutants"

342 Schuetzle, Tamblyn, and Tornatore, “Appendix 10: Power Plant Analysis for Conversion of Forest Remediation Biomass to Renewable Fuels and Electricity. Report to the Biomass to Energy Project (B2E).”

5.2.3 Feedstock

The feedstocks used as fuel for electricity production in biomass facilities are diverse and, therefore, have different impacts on workers, surrounding communities, and ecosystems. Biomass resources can be categorized as:

- Solid biomass (from forest, agricultural, and urban wood waste)
- Biogas (from landfills, wastewater treatment systems, diverted organic waste such as food and food processing waste, and manure digesters)

The life cycle of biomass electricity production follows a different life cycle process than other technologies included in this report, as shown in Figure 12.

Figure 12. Biomass Electricity Generation Life Cycle Stages

1. Feedstock Sourcing
2. Feedstock Transport
3. Site Development
4. Feedstock Processing and Storage
5. Conversion and Electricity Generation
6. Decommissioning

Life cycle GHG emissions from biomass electricity production will depend on a myriad of facility characteristics (i.e. feedstock, feedstock processing, conversion technology, site location). Comparison of these emissions to those from other generation systems also requires assessment of how the feedstock would have otherwise been managed and of GHG emissions from alternative energy mixes.[343] These complexities have made modeling life cycle GHG emissions difficult and controversial. Research is currently focused on producing a tool that can account for these intricacies.[344]

5.3 Potential Health Impacts of Electricity Production from Forest Waste

5.3.1 Sourcing

Procuring forest waste will involve occupational hazards found throughout timber and tree-removal industries. The following hazards pertain to all logging and forest industries, through whose waste streams, biomass energy production will obtain feedstock. However, as OSHA credits logging as one of the most hazardous occupations in the US, these hazards are included as part of the life cycle occupational health impacts of forest products used in energy production.[345] Workers are exposed to hazards of working with heavy loads, with chainsaws, at

343 Birdsall et al., "Repowering Solid Fuel Biomass Electricity Generation."

344 USDA Forest Service, "Biomass to Energy: Forest Management for Wildfire Reduction, Energy Production, and Other Benefits" (California Energy Commission, 2009); Thomas Buchholz et al., "A Global Meta-Analysis of Forest Bioenergy Greenhouse Gas Emission Accounting Studies," GCB Bioenergy 8, no. 2 (March 2016): 281–89, doi:10.1111/gcbb.12245.

345 OSHA, "Logging," Goverment Agency Website, United States Department of Labor, Occupational Safety and Health Administration, (n.d.), https://www.osha.gov/SLTC/logging/.

heights, and on potentially unstable surfaces and trees.[346] In mechanical operations, loggers will also be exposed to physical hazards of working with heavy equipment. These hazards can be amplified based on landscape; many of the dead and fallen trees are located in remote, mountainous, currently roadless terrain. These trees are expected to be a major source of woody biomass in the coming decade. The isolated terrain may impact the effectiveness and applicability of known safety protocols for loggers.[347]

5.3.2 Transportation

General transportation related hazards and air emissions are discussed in **Section LCA.3**. However, transport-related hazards from biomass energy production are unique among the other technologies discussed in this report. Transport hazards will differ based on the scale, placement, and distribution of the system implemented. Larger, utility-scale applications will require feedstocks to be continuously transported to the facility to maintain its operation. In order to account for life cycle air emissions from these facilities, diesel and criteria pollutant emissions from feedstock transport should be included.

Transportation of forest biomass from the harvest site to a biomass facility in larger, utility-scale systems can occur before or after processing, and hazards will differ based on the amount of biomass being transported. During transportation of forest waste, workers can be exposed to particulate matter made up of bioaerosols and dusts during loading and unloading of transported materials.[348] These bioaerosols can include molds, fungi, bacteria, and endotoxins, which can be harmful if workers are unprotected or chronically exposed.[349] The direct impacts of these exposures depends on particular bioaerosol components, as various molds and fungi will have varying health effects that are difficult to determine.[350] Other hazards include the potential for buildup of carbon monoxide and volatile organics in contained transport spaces (i.e. covered truck beds).[351] The make-up of these potential emissions differs by fuel source and moisture content.[352] Gaseous buildup can be hazardous for site management and transport workers, especially in instances when feedstocks are stored and transported in confined spaces.[353] These

346 OSHA, "Logging E-Tool," Goverment Agency Website, United States Department of Labor, Occupational Safety and Health Administration, (2000), https://www.osha.gov/SLTC/etools/logging/manual/limbing_bucking.html.

347 Peter A. Angwin et al., "Hazard Tree Guidelines for Forest Service Facilities and Roads in the Pacific Southwest Region," USDA Forest Service, Pacific Southwest Region, Report# RO 12, no. 1 (2012).

348 Annette Rohr et al., "Potential Occupational Exposures and Health Risks Associated with Biomass-Based Power Generation," International Journal of Environmental Research and Public Health 12, no. 7 (July 22, 2015): 8542–8605, doi:10.3390/ijerph120708542.

349 Ibid.

350 J. Douwes et al., "Bioaerosol Health Effects and Exposure Assessment: Progress and Prospects," The Annals of Occupational Hygiene 47, no. 3 (April 2003): 187–200, doi:10.1093/annhyg/meg032.

351 Urban R. Svedberg et al., "Emission of Hexanal and Carbon Monoxide from Storage of Wood Pellets, a Potential Occupational and Domestic Health Hazard," The Annals of Occupational Hygiene 48, no. 4 (June 2004): 339–49, doi:10.1093/annhyg/meh015; Rohr et al., "Potential Occupational Exposures and Health Risks Associated with Biomass-Based Power Generation."

352 Jaya Tumuluru et al., "Analysis on Storage Off-Gas Emissions from Woody, Herbaceous, and Torrefied Biomass," Energies 8, no. 3 (March 2, 2015): 1745–59, doi:10.3390/en8031745.

353 Rohr et al., "Potential Occupational Exposures and Health Risks Associated with Biomass-Based Power Generation."

hazards do not apply to smaller, distributed systems where feedstock resources are not transported.

The high cost and related emissions of transporting feedstocks to utility-scale facilities is a challenge for the state's current biomass system. While distributed, gasification systems are considered a possible reply to this challenge, these will require public financial support to develop and commercialize.[354]

5.3.3 Site Development

Construction of biomass facilities can have negative impacts on local air quality and water quality, depending on where facilities are located. These impacts range from site preparation and land clearing practices, to subsequent increased traffic impacts. Related emissions and hazards are discussed in **Section LCA.4**. The risk of potential exposure to *Coccidioides* fungal spores and resulting Valley Fever risk is a potential outcome from large-scale biomass development, and these concerns are also covered in LCA.4. These impacts may be cumulative in communities experiencing build-out of multiple facilities.

5.3.4 Materials Processing and Storage

For energy conversion technologies and facilities, forest waste products must be prepared before they can be used to generate electricity. In distributed biomass generating systems, forest waste can be chipped or processed at the harvest site to produce usable feedstock for both gasification and combustion systems. Further processing, such as torrefication – anaerobic roasting of chipped wood into briquettes with greater energy densities – will need larger facility capacity.[355] Torrefication is not always necessary for bioenergy production, and other processing stages at utility-scale facilities could include drying, sizing, and grinding.

In larger facilities, the processed feedstock then has to be stored until it is loaded into the boiler, gasifier, or digester. In smaller, distributed systems, feedstocks can be used more immediately without need for storage.

5.3.4.1 Processing

Forest wastes are often sent through chipping, pelleting, or mulching machinery to produce correctly sized feedstocks for biomass conversion machinery. In distributed systems, this can be done at the harvest site. The major exposure of concern for workers and surrounding communities is the creation of particulate matter, which can include bioaerosols and volatile organic compounds, such as aldehydes.[356] The direct impacts of these exposures depends on particular bioaerosol components.[357] Exposures will also depend on the proximity of

354 "California Forest Carbon Plan: Managing Our Forest Landscapes in a Changing Climate."

355 Jacobson, Interview with Arne Jacobson, Humboldt State University.

356 Rohr et al., "Potential Occupational Exposures and Health Risks Associated with Biomass-Based Power Generation."

357 Douwes et al., "Bioaerosol Health Effects and Exposure Assessment."

chipping or pelleting takes place relative to population centers, and the protective equipment used by workers to prevent emissions and inhalation.

Processing of forest waste at both distributed and utility-scale biomass facilities produces wood dust. The US National Toxicology Program and the International Agency for Research on Cancer classify wood dust as a known human carcinogen, as epidemiological studies have shown strong associations between wood dust exposure and nasal cavity cancers, specifically adenocarcinoma.[358] Wood dust exposure is also associated with occupational asthma and can cause skin and eye irritation.[359] Airborne wood dust also poses a potential fire hazard if an ignition source is present. Wood dust exposures can be controlled with proper protective equipment and engineering controls. Further, workers exposed to high wood dust levels can wear respirators to prevent inhalation.[360]

Additional processing of wood to create products with higher energy densities, such as torrefication, is being explored as a means of improving the cost-effectiveness of biomass energy production. The costs of transporting and processing materials for energy production would be offset by the increase in energy produced per unit volume of feedstock.[361] This processing would likely require larger facilities and larger energy inputs and could involve the repurposing of abandoned mills throughout the state, a consideration that should be included in modeling of biomass development processing in future biomass energy systems.[362]

For gasification systems, moisture content of the feedstock must be limited. As increasing wood moisture content causes reduction in the resulting syngas' net energy available. While up to 60% of typical harvested plant material's weight can be water, some gasification systems require moisture content as low as 20%.[363] Freshly harvested biomass will need to be heated to remove water, which can increase the costs of these systems, though distributed technologies have developed drying mechanisms.[364] The potential for PM exposures during this process depends on the drying mechanism used and containment mechanisms in place to prevent exposure.

5.3.4.2 Storage

Storage of feedstocks in tanks and silos at large, utility-scale facilities before and after processing poses potential risks of PM inhalation (See **Sections 5.2.2** and **5.3.3.1**). Design and automation of storage facilities reduces risks relative to more manual systems. These controls

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358 NTP, "Report on Carcinogens, Fourteenth Edition: Wood Dust" (U.S. Department of Health and Human Services, National Toxicology Program, November 3, 2016).

359 Gene Darling and Kate Oliver, "Wood Dust and Occupational Asthma" (Occupational Health Surveillance and Evaluation Program (OHSEP), Occupational Health Branch, California Department of Health Services, Labor Occupational Health Program (LOHP), Center for Occupational and Environmental Health, School of Public Health, University of California, Berkeley, January 2004), https://archive.cdph.ca.gov/programs/ohsep/Documents/wooddust.pdf.

360 Ibid.

361 Jacobson, Interview with Arne Jacobson, Humboldt State University.

362 Ibid.

363 EPA, "Chapter 5. Biomass Conversion Technologies."

364 Ibid.; All Power Labs, "How Gasification Works."

also depend on the facility's capacity and the type of fuel stored, as seasonal feedstocks can require storage for much longer periods.[365]

Utility scale feedstock storage poses a risk for store collapse or fire due to faulty design, change in fuel composition, or storage overload.[366] Other potential occupational hazards include those from slips, falls, and ladder-use.

5.3.5 Conversion

Workers may be exposed to ash residues from combustion of biomass through dermal contact or inhalation, depending on the ash containment system used.[367] Ash residues from burning solid biomass in direct fire plants may contain metals (i.e. mercury, nickel, arsenic, cobalt, and chromium), polycyclic aromatic hydrocarbons (PAHs), and in some cases silica.[368] Additionally, biomass ash may contain radionuclides, but this has not been studied extensively.[369] Risk of exposure to these hazards depends on the facility type and disposal process, as well feedstock material and the extent to which workers handle ash. The occupational risks of biomass ash residue exposure - as well as administrative and engineering controls to protect workers - are likely to be similar to those of coal ash handling, though this will depend on ash composition.[370] However the variable composition of biomass feedstocks and resulting ash suggests that further evaluation of worker risk and effectiveness of protective mechanisms is warranted.

5.3.6 Decommissioning

Impacts from general electricity facility decommissioning can be found in **Section LCA.6** and pertain to larger, utility-scale biomass facilities. These impacts will vary based on the facility location and scale. Smaller, distributed systems will have less of an impact than larger systems.

5.4 Potential Health Impacts of Electricity Production from Agricultural Waste

5.4.1 Sourcing

Agricultural residues include prunings from orchards and vineyards, crop residues, and food processing residues (rice hulls, shells, and pits). Electricity and fuel can also be generated

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365 Martina Poeschl, Shane Ward, and Philip Owende, "Environmental Impacts of Biogas Deployment – Part I: Life Cycle Inventory for Evaluation of Production Process Emissions to Air," Journal of Cleaner Production 24 (March 2012): 168–83, doi:10.1016/j.jclepro.2011.10.039.

366 Rohr et al., "Potential Occupational Exposures and Health Risks Associated with Biomass-Based Power Generation."

367 Ibid.

368 Ibid.

369 C. Organo et al., "Investigation of Occupational Radiation Exposures to NORM at an Irish Peat-Fired Power Station and Potential Use of Peat Fly Ash by the Construction Industry," Journal of Radiological Protection 25, no. 4 (December 6, 2005); Rohr et al., "Potential Occupational Exposures and Health Risks Associated with Biomass-Based Power Generation."

370 Rohr et al., "Potential Occupational Exposures and Health Risks Associated with Biomass-Based Power Generation."

from dedicated crops, or those grown specifically for biomass conversion. In California, most agricultural biomass resources used are residues from crops and wastes from orchards and vineyards, and there is little current use of dedicated crops for electricity production due to concerns such as land use and water consumption.[371] This report will thus focus on converting agricultural waste streams. These resources are mainly located in the Central Valley of the state.[372]

Assessment of the potential hazards or health impacts related to sourcing agricultural wastes for biomass electricity production should be considered in the context of alternative fates for these resources. As with forest waste, use of agricultural wastes as feedstock for biomass energy production facilities may displace these resources from open burning practices. Reductions in related emissions are discussed above in **Section 5.1.2**. Agricultural wastes may also be transported to landfills, requiring additional land use for these facilities and increased methane emissions associated with anaerobic organics decomposition.[373]

Workers involved in collecting and moving crop wastes for biomass energy production are exposed to similar hazards as those present in traditional agricultural work. California farmworkers experience hazards including pesticide exposure and extreme heat exposure, along with injuries related to agriculture machinery use. Agricultural workers may be exposed to high concentrations of inhalable dust, often containing pesticide and insecticide residues.[374]

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371 Navigant, "Recommendations for a Bioenergy Plan for California" (California Energy Commission, April 2006), https://mail.google.com/mail/u/0/#inbox/15bb52ff092e9609.

372 Carreras-Sospedra et al., "Assessment of the Emissions and Energy Impacts of Biomass and Biogas Use in California"; CDFA, "California Agricultural Statistics Review 2015-2016" (California Department of Food & Agriculture, 2016), https://www.cdfa.ca.gov/statistics/PDFs/2016Report.pdf.

373 CalRecycle, "State of Recycling in California: Updated 2016" (CalRecycle, February 2016), http://www.calrecycle.ca.gov/Publications/Documents/1554/201601554.pdf.

374 M. B. Schenker et al., "Improving the Health of Agricultural Workers and Their Families in California: Current Status and Policy Recommendations" (UC Global Health Institute, 2015), http://www.ucghi.universityofcalifornia.edu/docs/ucghi-ag-work-paper-2015.pdf.

Table 10. Potential Fates of Agricultural Waste and Related Impacts

Source	Potential Disposal	Exposure	Health Impacts
Agricultural Waste *NOTE: health impacts will be amplified in areas of the state with poor air quality where the majority of this feedstock is located*	**Open Burn**	Emission of criteria pollutants, short lived climate pollutants (i.e. methane and black carbon), CO2	Susceptibility to respiratory infections, irritation of lung and respiratory symptoms (e.g., cough, chest pain, difficulty breathing), eye and throat irritation, asthma exacerbation, bronchitis, lung damage, cardiovascular effects, cancer, heavy metal poisoning (will depend on specific components), impaired fetal development, climate change
	Landfill	Land use issue, methane emissions, potential for toxic leaching into surrounding water or soil	Climate change, leachates into local water systems, eye irritation, upper respiratory irritation and illness, odor impacts
	Bioenergy	Emission of criteria pollutants, CO2	Depending on conversion technology and emissions mitigation used: Susceptibility to respiratory infections, irritation of lung and respiratory symptoms (e.g., cough, chest pain, difficulty breathing), eye and throat irritation, asthma exacerbation, bronchitis, lung damage, cardiovascular effects, cancer, heavy metal poisoning (will depend on specific components), impaired fetal development, climate change

Colors are used to compare the severity of emissions and potential impacts (Dark Orange – higher impact, Orange – Medium impact, Yellow – Moderate impact)

Source: Springsteen et al., "Emission Reductions from Woody Biomass Waste for Energy as an Alternative to Open Burning," January 2011; CDC, "Criteria Air Pollutants;" EPA, "Landfills"

5.4.2 Transportation

Transportation of agricultural wastes includes the same hazards as described in **Section 5.3.2** and **Section LCA.3**. Increased traffic related to transport of feedstock to biomass facilities may contribute to cumulative exposures in areas of California already burdened by poor air quality (e.g. San Joaquin Valley, Coachella Valley), where agricultural waste resources are

concentrated in.[375] Onsite biomass conversion at agricultural sites could reduce these transport related emissions. However, the challenge of connecting these new converting facilities to the grid would then include additional transmission build-out, which would also result in emissions from construction vehicles. Use of these resources for biofuel production instead of electricity generation is an option to limit these impacts, since biofuel production can result in lower emissions and the resulting fuels could be used in vehicles onsite.[376] In order to assess the comparative benefits and challenges of these systems, there is a need for research approaches that allow for on-going comparison of the full lifecycle impacts of alternative technologies.

5.4.3 Site Development

Depending on where facilities are located, construction of biomass facilities can have negative impacts on local air quality and water quality beginning with site preparation, land clearing practices, and subsequent increased traffic impacts. Related emissions and hazards are discussed in **Section LCA.4**. The risk of potential exposure to *Coccidioides* fungal spores and resulting Valley Fever risk is a potential outcome from large-scale biomass development, and these concerns are also covered in LCA.4. These impacts may be cumulative in communities experiencing build-out of multiple facilities. These emissions are of particular concern in areas of the Central Valley where most agricultural-related facilities would be sited that already have many air quality issues.[377]

5.4.4 Material Processing and Storage

The hazards related to agricultural processing and storage are comparable to those related to forest waste feedstocks. These are described in **Section 5.3.4** above.

5.4.5 Conversion

Emissions from combustion and gasification technologies are discussed in **Section 5.2.2**. Unlike with forest wastes, the concentration of agricultural resources in the Central Valley of California is important to note. Because of the poor air quality due to geography and industry emissions, emissions from the conversion process at biomass facilities can exacerbate existing air quality challenges in this region.[378] However, in areas where biomass facilities divert agriculture wastes from open pile/burn disposal in these areas, these facilities can improve air quality in these regions.[379]

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375 CDFA, "California Agricultural Statistics Review 2015-2016"; Carreras-Sospedra et al., "Assessment of the Emissions and Energy Impacts of Biomass and Biogas Use in California"; American Lung Association, "State of the Air 2016."

376 Scott Samuelsen et al., "Air Quality and Greenhouse Gas Emissions Impact Assessment from Biomass and Biogas Derived Transportation Fuels and Electricity and Heat Generation" (California Energy Commission, March 2015), http://www.energy.ca.gov/2016publications/CEC-500-2016-022/CEC-500-2016-022.pdf.

377 Ibid.

378 CDFA, "California Agricultural Statistics Review 2015-2016"; Carreras-Sospedra et al., "Assessment of the Emissions and Energy Impacts of Biomass and Biogas Use in California"; American Lung Association, "State of the Air 2016"; Samuelsen et al., "Air Quality and Greenhouse Gas Emissions Impact Assessment from Biomass and Biogas Derived Transportation Fuels and Electricity and Heat Generation"; ARB, "Short-Lived Climate Pollutant Reduction Strategy" (California Air Resources Board, March 2017), https://www.arb.ca.gov/cc/shortlived/meetings/03142017/final_slcp_report.pdf.

379 Springsteen et al., "Emission Reductions from Woody Biomass Waste for Energy as an Alternative to Open Burning."

In California, agricultural and livestock wastes are concentrated in the Central Valley, and biomass generation from these resources (and other feedstocks that may be transported in) will further affect local air quality concerns. In the southern San Joaquin Valley is known to have the worst levels of $PM_{2.5}$ pollution in the United States, and cities like Bakersfield, Fresno, Visalia, and Modesto have the highest number of unhealthy air days annually.[380] Advocacy groups have noted that 11 of the 13 utility scale biomass combustion facilities located near the southern Sierras are sited in the top 25% of census tracts most burdened by air pollution (using data from CalEnviroScreen).[381] This is also a health equity concern, as areas of the San Joaquin Valley are known to have large health inequities based on demographic considerations like race and income that are both exacerbated and driven by poor air quality.[382]

5.4.6 Decommissioning

The hazards related to decommissioning and disposal of agricultural biomass sites are comparable to those related to forest wastes. These are described in **Section LCA.6**.

5.5 Potential Health Impacts of Electricity Production from Urban Waste

Urban wood waste is an additional solid biomass feedstock for the state of California. This feedstock includes clean construction waste, paper and cardboard, urban tree trimmings.[383] As state regulators strive to reduce waste production and landfilling, there is the potential for woody biomass disposed of in urban centers to be diverted for biomass conversion.

5.5.1 Sourcing

The source of urban wood waste will determine related potential occupational and community hazards. These impacts could be quite variable. For instances, workers could be exposed to physical hazards related to demolition work, or, if the woody biomass is removed from municipal solid waste streams, there is potential for toxic emissions from the handling of treated wood. These emissions could include bioaerosols, dioxins, heavy metals, furans, H2S, CO, and flammable gases.[384] Impacts of landfilling urban wood waste is compared to bioenergy outcomes in Table 11.

Table 11. Potential Fates of Urban Wood Waste and Related Impacts

380 American Lung Association, "State of the Air 2016."

381 Weller et al., "Comments on Draft Forest Carbon Action Plan."

382 Joint Center for Political and Economic Studies et al., "Place Matters for Health in the San Joaquin Valley: Ensuring Opportunities for Good Health for All, A Report on Health Inequities in the San Joaquin Valley" (Washington, DC: Joint Center for Political and Economic Studies, March 2012), https://www.fresnostate.edu/chhs/cvhpi/documents/cvhpi-jointcenter-sanjoaquin.pdf.

383 Navigant, "Recommendations for a Bioenergy Plan for California."

384 Sherri Berger et al., "Landfill Gas Primer - An Overview for Environmental Health Professionals" (Department of Health and Human Services Agency for Toxic Substances and Disease Registry Division of Health Assessment and Consultation, November 2001), https://www.atsdr.cdc.gov/HAC/landfill/html/intro.html.

Source	Potential Disposal	Exposure	Health Impacts
Urban Waste	**Landfill**	Land use issue, methane emissions, potential for toxic leaching into surrounding water or soil	Climate change, leachates into local water systems, eye irritation, upper respiratory irritation and illness, odor impacts
	Bioenergy	Emission of criteria pollutants, CO2	Depending on conversion technology and emissions mitigation used: Susceptibility to respiratory infections, irritation of lung and respiratory symptoms (e.g., cough, chest pain, difficulty breathing), eye and throat irritation, asthma exacerbation, bronchitis, lung damage, cardiovascular effects, cancer, heavy metal poisoning (will depend on specific components), impaired fetal development, climate change

Colors are used to compare the severity of emissions and potential impacts (Orange – Higher impact, Yellow – Moderate impact)

Source: CDC, "Criteria Air Pollutants" EPA, "Landfills"

5.5.2 Transportation

Transportation of urban wastes includes the same hazards as described in **Section LCA.3** and **Section 5.3.2** above. Because urban waste collection and transport is already occurring throughout municipalities, the magnitude of emissions related specifically to the transport of diverted wood matter for biomass generation depends on the location of conversion facilities. If these facilities are sites near common disposal areas, then there will be limited increase in health impacts related to transport emissions specifically for biomass conversion. If, however, new facilities are built, transport emissions to these facilities will increase for workers and surrounding communities.

5.5.3 Site Development

Depending on where facilities are located, construction of biomass facilities can have negative impacts on local air quality and water quality beginning with site preparation, land clearing practices, and subsequent increased traffic impacts. Related emissions and hazards are discussed in **Section LCA.4**.

5.5.4 Material Processing and Storage

Hazards related to urban wood processing and storage for biomass electricity production are similar to those related to forest waste feedstocks, but will be impacted by the source of the wood and potential exposures from any paint or chemicals treatments applied, which will vary. These are described in **Section 5.3.4** above.

5.5.5 Conversion

Emissions from combustion and gasification systems for solid biomass sources are discussed **Section 5.2.2** above.

5.5.6 Decommissioning

General decommissioning hazards are discussed in **Section LCA.6**, though these will vary based on site location and the resulting waste from the site.

5.6 Biogas Feedstocks

Apart from solid biomass resources from forest, agriculture, and urban waste residues, electricity can also be generated from biogases generated in landfills, diverted organic wastes, wastewater treatment, and animal waste storing facilities. According to a 2015 CEC report, 20% of California's landfills and 12.5% of the state's waste water treatment plants power waste-to-energy projects through biogas.[385]

When stored at high concentrations in contained areas, organic wastes naturally undergo anaerobic digestion, creating gas with high methane, carbon monoxide, and carbon dioxide content.[386] This can be used to generate electricity, transport fuels, or heat. According to the Air Resources Board, California can cut methane emissions by 40 percent below current levels by 2030 by capturing and avoiding emissions of methane from dairies, landfills, and other sources.[387]

As this report focuses on electricity generation, the potential hazards and co-benefits related to fuel and heat applications will not be discussed. However, it is important to note that using these resources for fuel and heat production on site could decrease emissions related to transport, transmission build out, and conversion seen in electricity production.[388] A comparative assessment with a focus on health impacts would be helpful in building a sustainable and healthy bioenergy system.

The following sections describe potential hazards and health impacts throughout the life cycle of biogas feedstocks. Overall, biogas energy developments are expected to have positive impacts on air quality and emissions because they will capture gaseous emissions from landfill, wastewater treatment, and dairy facilities.[389] There is little information currently available on health impacts across biogas feedstock life cycles. Additional work is needed to understand the potential for occupational and public hazards.

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385 Samuelsen et al., "Air Quality and Greenhouse Gas Emissions Impact Assessment from Biomass and Biogas Derived Transportation Fuels and Electricity and Heat Generation."

386 Ibid.

387 ARB, "Short-Lived Climate Pollutant Reduction Strategy."

388 Samuelsen et al., "Air Quality and Greenhouse Gas Emissions Impact Assessment from Biomass and Biogas Derived Transportation Fuels and Electricity and Heat Generation."

389 California Integrated Waste Management Board, "New and Emerging Conversion Technologies Report to the Legislature," Staff Report (California Environmental Protection Agency, Integrated Waste Management Board, June 2007), http://www.calrecycle.ca.gov/Publications/Documents/Organics/44205016.pdf.

5.6.1 Biogas Sourcing

5.6.1.1 Landfill Gas Sourcing

Assembly Bill 341 (AB 341) passed in 2011 established a goal of 75 percent recycling statewide by 2020 of all solid waste, including organics, which will significantly impact landfill operations and related biogas availability. Assembly Bill 1826 (AB 1826) passed in 2014, sets a 50 percent reduction in organic waste by 2020. In order to reach this goal, AB 1826 includes a mandate for local jurisdictions to implement organics recycling programs beginning in January 2016, further limiting landfill gas by diverting this waste to recycling operations. Because the state is attempting to divert organic waste away from landfills, it is unclear how biomass electricity generation in landfill applications will be affected by these changes.

Landfill gas is normally collected through vertical wells or horizontal trenches.[390] Potential exposures from MSW in landfills include bioaerosols, dioxins, heavy metals, furans, and more. If uncontrolled, buildups of hydrogen sulfide, carbon monoxide, and flammable gases in sites with stored organic wastes can result in toxic or fatal exposures for workers, who also face traditional hazards related to confined spaces, ladders, noise, machinery, and liquid tanks.[391] Leaks in the collection system can increase fire risks and expose surrounding communities to potentially hazardous gases.

5.6.1.2 Diverted Organic Waste Sourcing

For organic waste, Senate Bill 1383 requires that 75% of all organic waste currently being landfilled must be diverted by 2025.[392] Diverting organic waste for energy generation can reduce methane emissions and land-use challenges associated with landfills, while also producing energy. According to the EPA, if 50% of US food scraps disposed annually were anaerobically digested, enough electricity would be produced to power over 2.5 million homes for one year.[393]

The expected role biomass energy could play is reducing landfilled organic waste has not been determined, though this diversion would also reduce potential health impacts related to odor and PM emissions on surrounding communities. These include eye and upper respiratory system irritation, as well as odor impacts on general quality of life and activity levels.[394]

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390 Energy and Environmental Analysis, Inc, "Biomass Combined Heat and Power Catalog of Technologies" (U.S. Environmental Protection Agency Combined Heat and Power Partnership, September 2007), https://www.epa.gov/sites/production/files/2015-07/documents/biomass_combined_heat_and_power_catalog_of_technologies_v.1.1.pdf.

391 Berger et al., "Landfill Gas Primer - An Overview for Environmental Health Professionals"; Penn State College of Agricultural Sciences, "Biogas Safety" (The Pennsylvania State University, 2017), http://extension.psu.edu/natural-resources/energy/waste-to-energy/resources/biogas/biogas-safety.

392 Ricardo Lara, "Senate Bill 1383- Short-Lived Climate Pollutants: Methane Emissions: Dairy and Livestock: Organic Waste: Landfills," Pub. L. No. SB 1383 (2016).

393 EPA Pacific Southwest, Region 9, "Waste to Biogas Mapping Tool," Goverment Agency Website, United States Environmental Protection Agency, (February 22, 2016), https://www3.epa.gov/region9/biogas/purpose.html.

394 Christopher D. Heaney et al., "Relation between Malodor, Ambient Hydrogen Sulfide, and Health in a Community Bordering a Landfill," Environmental Research 111, no. 6 (August 2011): 847–52, doi:10.1016/j.envres.2011.05.021.

5.6.1.3 Wastewater Treatment Biogas Sourcing

Containment of human and animal waste within closed spaces can produce anoxic conditions that can lead to asphyxiation if workers are not informed and protected, though systems are built to avoid human contact with enclosed areas.[395] Storage and collection of biogas also present fire and toxicity hazards associated with methane, hydrogen sulfide, and ammonia.

5.6.1.4 Dairy Digester Gas Sourcing

Dairy facilities are often found in California's Central Valley of the state, impacting the Valley's poor air quality with increased odor and methane emissions.[396] Dairies can also be a source of leached wastes, leaching nitrate and phosphorous into surrounding communities and waterways.[397] This is of particular concern due to the state's high levels of ground water nitrate contamination.[398]

Dairy digesters collect some of the facility's methane emissions by allowing for anaerobic digestion of manure and, in the case of co-digesters, diverted organic waste in a contained environment. These materials can be processed on site in an individual dairy or at a centralized facility serving multiple dairies.[399] Collecting these emissions will reduce methane emissions into the atmosphere, while reducing related odors for surrounding communities. While dairy digesters may be able to kill off some manure-borne pathogens, they do not provide direct protection against water quality concerns related to nitrate and phosphate leaching.[400]

5.6.2 Biogas Transport

Onsite conversion of landfill, wastewater treatment, and dairy digester biogases is not associated with additional transportation hazards or emissions. However, transporting manure or biogas from dairies to centralized facilities will produce air emissions for surrounding communities, which is of particular concern in areas like the Central Valley.[401] Diverted organic waste used for biogas energy production will also need to be transported to conversion sites, which will increase related transport emissions in communities surrounding these facilities.

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395 Penn State College of Agricultural Sciences, "Biogas Safety."

396 Carreras-Sospedra et al., "Assessment of the Emissions and Energy Impacts of Biomass and Biogas Use in California"; American Lung Association, "State of the Air 2016."

397 F. Battini et al., "Mitigating the Environmental Impacts of Milk Production via Anaerobic Digestion of Manure: Case Study of a Dairy Farm in the Po Valley," Science of The Total Environment 481 (May 2014): 196–208, doi:10.1016/j.scitotenv.2014.02.038.

398 State Water Resources Control Board, "Recommendations Addressing Nitrate in Groundwater," Report to Legislature, (February 20, 2013), https://www.waterboards.ca.gov/water_issues/programs/nitrate_project/docs/nitrate_rpt.pdf.

399 ESA, "DAIRY MANURE DIGESTER AND CO-DIGESTER FACILITIES," Draft Environmental Impact Report (California Regional Water Quality Control Board, Central Valley Region, July 2010), http://www.calrecycle.ca.gov/swfacilities/compostables/anaerobicdig/DairyDigDEIR.pdf.

400 Mark Borchardt et al., "Inactivation of Dairy Manure-Borne Pathogens by Anaerobic Digestion" (University of Wisconsin, Madison, 2013), https://www.documentcloud.org/documents/3227503-Inactivation-of-Dairy-Manure-Borne-Pathogens-by.html; Scott Gordon, "What Manure Digesters Can and Can't Do," WisContext, November 30, 2016, https://www.wiscontext.org/what-manure-digesters-can-and-cant-do; Senay Boztas, "Poo Power: Dutch Dairy Industry Launches €150m Biogas Project," The Guardian, November 2, 2016, https://www.theguardian.com/sustainable-business/2016/nov/02/netherlands-europe-dairy-industry-agriculture-biogas-cows-manure-poo-power.

401 ESA, "DAIRY MANURE DIGESTER AND CO-DIGESTER FACILITIES."

5.6.3 Site Development

Impacts of site development will depend on where facilities are located. This is especially the case for dairy digestion facilities, resulting from the cumulative impact of all development in areas already suffering from poor air quality. For instance, in an environmental impact report on dairy digester and co-digesters, it was noted that criteria air pollutant emissions from the cumulative development of 200 dairy manure digester and co-digester facilities in the Central Valley exceeded the significance thresholds of the San Joaquin Valley Air Pollution Control District for both annual construction emissions and operational emissions.[402] While digester facilities also benefit the region by reducing overall GHG emissions from dairy facilities, these emissions from site development, along with emissions from biogas conversion discussed later could lead to negative air quality impacts.[403]

5.6.4 Biogas Storage

To protect from errant methane emissions, biogas feedstocks are often kept in covered landfills, wastewater treatment plants, and manure lagoons. Landfill, wastewater treatment, and dairy facilities are associated with air and water quality concerns for surrounding communities. As a result, bioenergy has been proposed as a possible mitigation technique for some of these emissions (i.e. methane) through recovering some of the gases emitted.[404]

5.6.5 Biogas Conversion Technologies

The main source of air emissions from biogas electricity production results from the combustion of these biogases to generate electricity; however, these can be limited by substituting fuel cell and microturbine technologies for higher emitting engines.[405] Emissions from conventional engine conversion are compared to estimated fuel cell emissions in Table 12. These newer technologies are at varying levels of development, and it is unclear how they will scale and distribute in California by 2030. Data on cumulative emissions from the application of these technologies is also limited.

Table 12. Emission Comparisons from Engine and Fuel Cell Power Generation from Biogas

402 Ibid.

403 Ibid.

404 UMass Extension, "Air Quality Issues for Dairy Operations," 2011, https://ag.umass.edu/sites/ag.umass.edu/files/fact-sheets/pdf/AirQualityIssuesforDairy%20Operations%2811-44%29.pdf.

405 Carreras-Sospedra et al., "Assessment of the Emissions and Energy Impacts of Biomass and Biogas Use in California."

Pollutants	Emissions (lb/MWh)	
	Engine	Fuel Cell
Volatile Organic Compounds (VOCs)	2.23	--
Carbon Monoxide (CO)	6.96	--
Nitrous Oxides (NOX)	1.67	0.01
Sulfur Oxides (SOX)	0.07	0.0001
Particulate Matter (PM)	0.14	0.00002
Carbon Dioxide (CO2)	1441	940

Source: Carreras-Sospedra et al., "Assessment of the Emissions and Energy Impacts of Biomass and Biogas Use in California," 2015

Despite reducing overall GHG emissions by converting methane into energy, biogas conversion can result in criteria pollutant emissions, especially for technologies in use today. In a national assessment of dairy digester emissions, the facilities monitored emitted hydrogen sulfide, acrolein, acetaldehyde, formaldehyde, NOx, SOx, and CO.406 In a study of six dairy digesters operating in California, emissions of NOx, SOx, and CO were found to be comparable to or slightly better than those from fossil fuel combustion.407 Though these digester facilities will have an impact reducing GHG emissions, more work is necessary to improve overall emissions from these facilities to prevent negative air quality impacts.

At larger facilities, the gases can be cleaned to remove potentially harmful components like hydrogen sulfide, corrosive gases, particulates, pollutants, and sioxanes. Smaller farm systems often do not clean the gas beyond moisture removal. This treatment can also differ based on conversion technology used, as boilers and reciprocating engines can require less clean up than gas turbines.[408]

Due to the potential for further methane emissions, the digestate produced as a byproduct of anaerobic digestion must be stored in covered tanks or lagoons.[409] Similarly, with development of digestate in municipal solid waste, landfill, and wastewater treatment, proper

406 Department of Ecology, State of Washington, "Technical Support Document for Dairy Manure Anaerobic Digester Systems with Digester Gas Fueled Engine Generators," General Order of Approval (State of Washington, Department of Ecology, March 2012), http://www.ecy.wa.gov/programs/air/AOP_Permits/Boiler/TTODD/PDFs/FINAL_TSD_12AQ-GO-01_Digesters.pdf.

407 Summers Consulting, Inc., "ENERGY AND ENVIRONMENTAL PERFORMANCE OF SIX DAIRY DIGESTER SYSTEMS IN CALIFORNIA: Volume 1" (California Energy Commission, March 2013), http://www.energy.ca.gov/2014publications/CEC-500-2014-001/CEC-500-2014-001-V1.pdf.

408 Energy and Environmental Analysis, Inc, "Biomass Combined Heat and Power Catalog of Technologies."

409 Alessandra Fusi et al., "Life Cycle Environmental Impacts of Electricity from Biogas Produced by Anaerobic Digestion," Frontiers in Bioengineering and Biotechnology 4 (March 11, 2016), doi:10.3389/fbioe.2016.00026.

storage and handling can prevent additional emissions, and suitable digestate can be diverted into compost. Digestate may also need to be treated further at wastewater treatment facilities.[410]

The location of conversion facilities will impact related hazards from facility emissions. This is a key concern for dairy digester facilities specifically, as agricultural and livestock wastes are concentrated in the Central Valley of California. The southern San Joaquin Valley is known to have the worst levels of $PM_{2.5}$ pollution in the United States, and cities like Bakersfield, Fresno, Visalia, and Modesto have the highest number of unhealthy air days annually.[411] Therefore, a build out of dairy digesters using engine technologies for conversion could increase this pollution. This is also a health equity concern, as areas of the San Joaquin Valley are known to have large health inequities based on demographic considerations like race and income that are both exacerbated and driven by poor air quality.[412]

5.6.6 Decommissioning

Limited information is available on potential hazards and emissions from biogas electricity conversion facilities. General hazards related to decommissioning and disposal in utility-scale facilities are discussed in **Section LCA.6**.

5.7 Equity Considerations

In California from 2002 – 2015, biomass energy generation created a total of 1,346 construction job years.[413] As noted earlier, workplace exposures across biomass facility and feedstock life cycles are not well define. Further work is needed to ensure that biomass employment is safe, while also providing quality jobs with living wages and proper training and benefits. This is necessary for both utility-scale facilities and emerging distributed systems.

Biomass development must also account for where new facilities are sited and how facility installation may impact local communities. These facilities may offer opportunities for community economic development and living wage jobs, if development is appropriately implemented. For utility-scale sites, land clearing for facility installation, continued maintenance, and decommissioning will all result in transport-related emissions and potential dust emissions for surrounding communities. Utility-scale facilities will likely continue to operate in areas of the Central Valley due to proximity to agricultural and livestock feedstocks. However, many communities in this Valley currently suffer from poor air quality due to their

410 Ken Decio, "Statewide Anaerobic Digester Facilities for the Treatment of Municipal Organic Solid Waste," Final Program Environmental Impact Report (California Department of Resources, Recycling, and Recovery, June 2011).

411 American Lung Association, "State of the Air 2016."

412 Joint Center for Political and Economic Studies et al., "Place Matters for Health in the San Joaquin Valley: Ensuring Opportunities for Good Health for All, A Report on Health Inequities in the San Joaquin Valley."

413 Betony Jones, Peter Philips, and Carol Zabin, "The Link Between Good Jobs and a Low Carbon Future: Evidence from California's Renewables Portfolio Standard, 2002—2015" (DONALD VIAL CENTER ON EMPLOYMENT IN THE GREEN ECONOMY Center for Labor Research and Education University of California, Berkeley, July 2016), http://laborcenter.berkeley.edu/pdf/2016/Link-Between-Good-Jobs-and-a-Low-Carbon-Future.pdf.

geography and continued infrastructure build out in the area.[414] These emission impacts will also be intensified in lower income and minority communities.

In order to assess potential health outcomes in vulnerable communities, more information is necessary on the expected distribution of biomass technologies – accounting for the scalability of newer, lower emitting systems (i.e. gasification paired with fuel cells). Modeled deployment scenarios should consider location not only based on feedstock availability, but also on the potential for adverse health impacts on low income and minority communities already burdened by poor air quality.

5.8 Research Needs

1. Monitor emissions from different gasification technology deployment scenarios, noting differences in electricity generating technologies (i.e. engines, microturbines, fuel cells)

2. Monitor emissions from operating biomass facilities, noting effectiveness of applied air emission mitigation technologies and workplace exposures, and develop improved mitigation systems

3. Model life cycle air emissions from different biomass energy deployment scenarios, noting baseline regional air quality and possible changes in conversion technology

414 American Lung Association, "State of the Air 2016."

Chapter 6: Geothermal Electricity Production

6.1 Geothermal Electricity Production in California

The CEC estimated that California generated 13,000 GWh of energy from geothermal resources in 2016, roughly 5% of the energy mix.[415] To reach the state's ambitious renewable energy goals, models predict that this could grow to 34,000 GWh by 2030, almost 10% of the state's energy production.[416] According to the CEC, there are a total of 44 operating geothermal power plants in California with an installed capacity of 2,716 MW, the largest of which is the Geysers Geothermal Resource Area in Anderson Springs, which has been in operation since 1960. Other sites include Salton Sea area in Imperial County, the Coso Hot Springs area in Inyo County, and the Mammoth Lakes area in Mono County.

California has a wealth of promising geological sites for geothermal energy production due to its location within the Pacific's "ring of fire." With new technological developments – e.g. Enhanced Geothermal Systems (EGS) – as much as 67,600 MW of potential generation may be accessible from sites that were previously untapped due to decreased permeability or fluid presence.[417] Geothermal electricity production is reliable and facilities usually have a high generating capacity with a lower land use footprint than other generating technologies. However, these systems remain costly and can consume a lot of water.[418] The potential for well failures and low efficiency has also limited geothermal growth in the past, though EGS could potentially address these challenges.[419] In some cases, recovery of highly valued mineral resources (such as lithium) from geothermal brine can be an added benefit of geothermal production. Currently, California's geothermal facilities mainly use binary generation, though there are untapped resources for flash or direct steam turbine facilities.[420]

Development of new Salton Sea geothermal production is currently of particular interest. This site is expected to produce upwards of 1.18 GW of energy by 2030, and it is estimated that the site could also produce 51,000 to 122,000 metric tons of lithium.[421] This

415 CEC, "Renewable Energy – Overview December 2016" (California Energy Commission, December 2016), http://www.energy.ca.gov/renewables/tracking_progress/documents/renewable.pdf.

416 Gregory Brinkman, Jennie Jorgenson, and Marissa Hummon, "California 2030 Low Carbon Grid Study (LCGS): Phase I" (National Renewable Energy Laboratory, 2014), http://lowcarbongrid2030.org/wp-content/uploads/2014/10/LCGS_PhaseI_NRELslides.pdf.

417 USGS, "Assessment of Moderate- and High-Temperature Geothermal Resources of the United States" (U.S. Department of the Interior, U.S. Geological Survey, 2008).

418 Jim Bartridge et al., "Draft 2016 Environmental Performance Report of California's Electrical Generation System," Staff Report (California Energy Commission, July 2016), https://efiling.energy.ca.gov/getdocument.aspx?tn=212338.

419 USGS, "Assessment of Moderate- and High-Temperature Geothermal Resources of the United States."

420 William Glassley, Interview with William Glassley of the California Geothermal Energy Alliance, Conference Call, December 12, 2016.

421 Bartridge et al., "Draft 2016 Environmental Performance Report of California's Electrical Generation System."

project is part of the statewide effort to rehabilitate the Salton Sea region, though concerns have been raised regarding adverse effects of development on local habitats and populations.[422]

6.1.1 Geothermal Electricity Production

Geothermal electricity production accesses thermal energy in rock, trapped steam, or liquid water in the earth's crust. This thermal energy, when brought to the surface, can be used to generate electricity or as a heating source for facilities and homes. To produce high conversion efficiencies from thermal to electric energy, large temperature gradients are ideal, and these are often found in young, geologically active regions where hot resources are within a few kilometers of the earth's surface. Older sites that are not tectonically active have hot zones but they are at much deeper depths in the earth's crust, making it much more expensive and difficult to access them to produce electricity. Ideal conditions for traditional geothermal electricity production involve active sites with large geothermal fluid – or hydrothermal – reserves hundreds to thousands of meters below the surface.

However, sites with hot, dry rock formations and limited fluid reserves – or petrothermal resources – are currently becoming more accessible through enhanced or engineered geothermal systems (EGS). These systems use mechanical stimulation to increase fluid permeability, allowing injection and circulation of water to recover thermal energy from these deeper sites. Such systems are the focus of active research.[423] One EGS project has been used to increase efficiency at one geothermal site in Desert Peak, NV. EGS is being considered for various sites across California, including previously failed traditional geothermal wells.[424]

In California, the Geysers uses a direct steam system, accessing one of only two known global reserves of dry steam below the earth's surface. The steam is transmitted through a series of pipes to a powerhouse, where it is used to drive a turbine generator. Along with water vapor, the steam carries non-condensable gases (NCG) with variable concentration of CO_2 and hydrogen sulfide (H_2S).

The majority of geothermal electricity production globally occurs at single and double flash steam plants. After separating geothermal fluids from vapor, the hot fluid can then be used to drive turbines for power generation, and then collected and re-injected to recharge the subsurface hot water or steam reservoir. Once used for power generation, the fluid may also be utilized for co-generation of heat, before being re-injected. Facilities that only use the primary, high-pressure steam are called single flash systems, while those that use both primary and secondary, high and low pressure, steam are called double flash plants.[425] According to the

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422 Little Hoover Commission, "Salton Sea Action Report," Little Hoover Commission Letter Report (Little Hoover Commission, September 2015).

423 Edgar G. Hertwich, Jacqueline Aloisi de Larderel, and Sangwon Suh, "Green Energy Choices: The Benefits, Risks, and Trade-Offs of Low-Carbon Technologies for Electricity Production" (United Nations Environmnetal Programme, 2016), http://www.unep.org/resourcepanel/Portals/50244/publications/Summary_for_Policy_Makers_GHG_I.pdf.

424 Ethan Chabora and Ezra Zemach, "Desert Peak EGS Project," April 22, 2013, https://energy.gov/sites/prod/files/2014/02/f7/desert_peak_egs_peer2013.pdf.

425 Hertwich, Aloisi de Larderel, and Suh, "Green Energy Choices: The Benefits, Risks, and Trade-Offs of Low-Carbon Technologies for Electricity Production."

Geothermal Energy Association, California had 700 MW of installed capacity from flash steam facilities in 2011.[426]

Binary plants are closed systems, in which geothermal fluid is piped into the system to transfer its thermal energy to a secondary fluid with a low boiling point. This second fluid, used only within the facility in a closed loop, then produces a high-temperature vapor to drive a Rankine cycle turbine for electricity production. The geothermal fluid pumped from below the surface is re-injected, resulting in zero emissions. The secondary fluid is then cooled by either wet or dry cooling mechanisms to be reheated to continue the process. This secondary fluid can be made up of isobutane, isopentane, propane, CO_2 or any of a host of other volatile fluids with low boiling points.[427]

Because geothermal plants use thermal resources below the earth's surface to generate electricity directly, it is difficult to describe the life cycle in separate material extraction, manufacturing and installation stages. Processes for geothermal electricity generation include direct/dry steam, flash steam, and binary plant types, which largely have similar health impacts and will thus be addressed together.

6.2 Material Extraction

Steel, cement, concrete, and aluminum are used for piping, turbine components, and other system elements in geothermal plants.[428] The amount of material required differs based on well depths, rock/geological formation, geofluid temperature, and other facility-specific factors. As with other systems, the climate and health impacts of cement and concrete creation and steel and aluminum production are well known, but are outside the scope of this report.[429]

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426 GEA, "Online California Geothermal Power Plants" (Geothermal Energy Association, 2011), http://www.geo-energy.org/pdf/CAplants_all3.11.pdf.

427 Andriy REDKO et al., "Efficiency of Geothermal Power Plant Cycles with Different Heat-Carriers" (PROCEEDINGS, 41st Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, 2016), https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2016/Redko.pdf.

428 J.L. Sullivan, C.E. Clark, and M. Wang, "Life Cycle Analysis Results of Geothermal Systems in Comparison to Other Power Systems" (Argonne, Energy Systems Division, August 2010).

429 Lisa J. Hanle, Kamala R. Jayaraman, and Joshua S. Smith, "CO2 Emissions Profile of the U.S. Cement Industry" (13th International Emission Inventory Conference "Working for Clean Air in Clearwater, Clearwater, Fl: U.S. Environmental Protection Agency, 2004), https://www3.epa.gov/ttnchie1/conference/ei13/ghg/hanle.pdf; IARC, "Chemical Agents and Related Occupations: A Review of Human Carcinogens" (Lyon, France: International Agency for Research on Cancer, 2012), https://www.ncbi.nlm.nih.gov/books/NBK304416/pdf/Bookshelf_NBK304416.pdf; OSHA, "Worker Safety Series: Cement Manufacturing," Goverment Ageny Website, United States Department of Labor, Occupational Safety and Health Administration, (2004), https://www.osha.gov/Publications/concrete_manufacturing.html; OSHA, "Basic Steel Products," Goverment Ageny Website, United States Department of Labor, Occupational Safety and Health Administration, (2014), https://www.osha.gov/SLTC/basicsteel/standards.html; Radian, "Health Hazard Assessment Summary: Steel Mill Emissions" (U.S. Environmental Protection Agency, September 29, 1989), https://nepis.epa.gov/Exe/ZyNET.exe/9100JSM3.txt?ZyActionD=ZyDocument&Client=EPA&Index=1986%20Thru%201990&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&UseQField=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5CZYFILES%5CINDEX%20DATA%5C86THRU90%5CTXT%5C00000022%5C9100JSM3.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=3; Michael Turner, "Mitigating Iron and Steel Emissions," ed. Nico Tjabil (Columbia Climate Center, The Global Network for Climate Solutions, 2012), http://climate.columbia.edu/files/2012/04/GNCS-Iron-Steel.pdf.

6.3 Transportation

A summary of transportation related emissions and hazards can be found in **Section LCA.3**. For geothermal sites, transportation related emissions and hazards will mainly result from machinery used in installation and transport of workers for facility operation.

6.4 Installation

Like any other utility-scale power plant, the land use footprint of geothermal facilities can be significant, though usually less than that needed for generating systems such as utility-scale solar PV and concentrated solar installations.[430] While operations are primarily below the surface, land is also used for holding ponds, the facility, cooling towers, and transmission infrastructure. Disposal of waste fluids in holding ponds could leach chemicals or hazardous materials into surrounding waterways if sufficient protections are not taken as the site is being developed and throughout operation. These include petroleum, oil, lubricants, paints, solvents, and herbicides.[431] There is also the potential for occupational exposure to *Coccidioides* fungi during land clearing and maintenance, particularly in the Salton Sea installations, which can lead to Valley Fever infection. More information on this and emissions related to utility-scale installations is included in **Section LCA.4**.

Drilling during installation requires the use of heavy equipment such as drill rigs, which use fuel and water to drive materials from below the surface upward. Drilling releases hydrogen sulfide contained in geothermal fluids or steam, an occasional emission of geothermal systems, which can cause respiratory and gastrointestinal irritation at lower concentrations but can be fatal at high concentration.[432] H_2S monitoring and control are thus critical in installation and operation of geothermal facilities located in regions where H_2S is likely present, such as the Geysers region.[433]

6.5 Use and Maintenance

Geothermal electricity generating facilities are located on land that is geothermally active, which can result in landslides, subsidence, and ground deformations, especially with fluid withdrawal.[434] In cases of extreme accidents or system failures, a hydrothermal explosion can occur if well steam builds up below a groundwater reserve or an earthquake causes an unexpected buildup of pressure.[435] Seismic activity is common at geothermal sites, and facility processes like drilling, injection, and stimulation can impact these natural characteristics.

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430 Bartridge et al., "Draft 2016 Environmental Performance Report of California's Electrical Generation System."

431 Peter Bayer et al., "Review on Life Cycle Environmental Effects of Geothermal Power Generation," Renewable and Sustainable Energy Reviews 26 (October 2013): 446–63, doi:10.1016/j.rser.2013.05.039.

432 ASTDR, "Medical Management Guidelines for Hydrogen Sulfide," Agency for Toxic Substances and Disease Registry, October 21, 2014, https://www.atsdr.cdc.gov/mmg/mmg.asp?id=385&tid=67.

433 Glassley, Interview with William Glassley of the California Geothermal Energy Alliance.

434 NREL, "Renewable Electricity Futures Study: Volume One, Exploration of High-Penetration Renewable Electricity Futures" (Golden, CO: National Renewable Energy Laboratory, 2012), http://www.nrel.gov/docs/fy12osti/52409-1.pdf.

435 Hertwich, Aloisi de Larderel, and Suh, "Green Energy Choices: The Benefits, Risks, and Trade-Offs of Low-Carbon Technologies for Electricity Production."

"Microseismic" events are common with injection, and facilities are required to monitor seismic changes to ensure safety.[436]

Waste generated from geothermal electricity production includes heat, non-condensable gases (NCGs), fluids, and solid residues. Heat can be used for on-site heat cogeneration or released into the atmosphere, holding ponds, or natural water bodies. NCGs commonly contain hydrogen sulfide, CO_2, benzene, methane, and may contain mercury, ammonia, radon, and boron, although at levels an order of magnitude below those in emissions from coal-fired plants.[437] Health impacts related to potential emissions are shown in Table 8.

Systems to mitigate emissions are available. Older technologies that used cooling towers to oxidize H_2S into elemental sulfur caused potentially dangerous occupational exposures to resulting sludge, which included concentrated mixtures of sulfur with hydrogen peroxide, caustic soda, and catalytic compounds of nickel and iron.[438] Binary systems are closed, and thus produce minimal air emissions, but there is a potential for isopentane, a GHG, to leak from system pipelines.[439]

If the water used as geothermal fluid is not fully contained or recycled (in the case of binary systems), water can absorb harmful substances such as arsenic, boron, mercury, and fluoride. In some cases, radioactive elements may also be concentrated in wastewater.[440] If contaminated waters are not re-injected properly, there is the potential to contaminate surface and ground waters, possibly impacting drinking and irrigation water.[441] Though protections are in place to prevent leaching in facility and piping design, environmental impact assessments should identify potential contaminants based on a proposed site's geology in order to facilitate an informed response to malfunctions.

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436 Sullivan, Clark, and Wang, "Life Cycle Analysis Results of Geothermal Systems in Comparison to Other Power Systems."

437 Ibid.

438 L.R. Anspaugh and J.L. Hahn, "Human Health Implications of Geothermal Energy" (Health implications of the new energy technologies, Park City, Utah, 1979), https://www.osti.gov/geothermal/servlets/purl/5946550.

439 Bayer et al., "Review on Life Cycle Environmental Effects of Geothermal Power Generation."

440 National Geographic, "Geothermal Energy," National Geographic, 2013, https://www.nationalgeographic.org/encyclopedia/geothermal-energy/.

441 Jochen Bundschuh and Jyoti Prakash Maity, "Geothermal Arsenic: Occurrence, Mobility and Environmental Implications," Renewable and Sustainable Energy Reviews 42 (February 2015): 1214–22, doi:10.1016/j.rser.2014.10.092.

Table 13. Known Health Impacts of Potential Geothermal Facility Emissions

Emission	Acute	Chronic
Hydrogen Sulfide (H_2S)	Respiratory and gastrointestinal irritation at lower concentrations but can be fatal at high concentration	Low blood pressure, headache, nausea, loss of appetite, weight loss, eye-membrane inflammation, and chronic cough, neurologic symptoms
Benzene	Drowsiness, dizziness, rapid/irregular heartbeat, headache, tremors, confusion, unconsciousness, (very high levels can be fatal)	Anemia, excessive bleeding, decreased immune system efficiency, (long-term exposure to high levels can lead to leukemia)
Mercury	Shortness of breath, cough, sore throat, metallic taste, nausea, vomiting, diarrhea, abdominal pain, headache, weakness, and visual disturbances, enteritis, and renal damage, chronic CNS effects	Permanent damage to the nervous system and kidneys shown through tremors, anxiety, emotional lability, forgetfulness, insomnia, anorexia, abnormal irritation, sensitivity, or excitement, fatigue, and cognitive and motor dysfunction, neuromuscular changes, polyneuropathy
Ammonia	High levels in air - skin, eyes, throat, and lung irritation	Severe irritation of respiratory tract
Radon	Lung cancer	Lung cancer
Boron	Irritation of the nose, throat, and eye	Irritation of respiratory tract, potential reproductive system damage (especially in males)

Source: ASTDR, Toxic Substances Portal

Solid waste from drilling can be disposed of as cuttings, cement residues, and muds, and may include concentrated amounts of mercury, arsenic, or heavy metals; occupational or community exposure to these wastes is hazardous.[442] Mineral resources, however, can also be extracted from geothermal fluids. Silica is being extracted at geothermal facilities in Mammoth Lake and Coso, and the feasibility of lithium and zinc extraction is being researched at the Salton Sea site.[443] Extraction processes include separation with acid and biochemical leaching, sorption with resins or bacteria, and precipitation with hydrogen sulfide.[444] More research is

442 Sullivan, Clark, and Wang, "Life Cycle Analysis Results of Geothermal Systems in Comparison to Other Power Systems."

443 Piyush A. Bakane, "Overview of Extraction of Mineral/Metals with the Help of Geothermal Fluids" (PROCEEDINGS, Thirty-Eighth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, 2013), http://large.stanford.edu/courses/2016/ph240/makalinao2/docs/bakane.pdf.

444 W. L. Bourcier, M. Lin, and G. Nix, Recovery of Minerals and Metals from Geothermal Fluids (United States. Department of Energy, 2005), https://e-reports-ext.llnl.gov/pdf/324646.pdf.

needed to understand potential hazards, occupational exposures, and contaminated waste streams from these processes.

Specific to EGS wells, stimulation is necessary to access geofluids, so water is pumped into the wells at pressure to open spaces in the rock using a process related to hydraulic fracturing. While natural gas fracking involves injecting water with additives into tight rock formations, EGS systems stimulate the release of heated geothermal fluids by injecting water in formations that are already semipermeable. There is limited information on how much fluid is actually used.[445] Unlike hydraulic fracturing, well stimulation in EGS systems does not result in wastewater.[446] Impacts will differ based on location and depth of the well. Further assessments of the potential for occupational and public exposures, including leaks that contaminate water resources or soil, are needed.

Injection and re-injection of fluids at high pressures activities may precipitate seismic activity if regional faults are not well mapped or appropriate caution is not taken in areas with active faults. Induced seismicity can occur when a previously drilled site is stimulated to enhance production. For example, at a geothermal plant in Basel, Switzerland that was located along a major fault, plant installation activities for an EGS stimulated a 3.4 magnitude earthquake.[447] Seismic activity impact is a particular concern for EGS, which requires injecting fluids at higher pressure deeper into the crust, reducing the friction along fault surfaces and allowing slips to occur.[448] Seismicity induced by the use of dry steam production at the Geysers is constantly monitored, but there is a risk of unknown seismic activity following new stimulation, especially in EGS, depending on site location.

Major occupational considerations across geothermal technologies include exposure to geothermal fluid or steam if system components leak, exposure to hydrogen sulfide, petroleum, oils, lubricants, paints, solvents, and herbicides, and the potential for well blowouts in extreme cases.

6.6 Decommissioning and Disposal

Geothermal plants have an expected lifetime of 20 or more years, and the impacts of decommissioning are not well established.[449] Certain plants within the Geysers complex have been decommissioned, but little information is available about this process or potential related

445 Sullivan, Clark, and Wang, "Life Cycle Analysis Results of Geothermal Systems in Comparison to Other Power Systems."

446 Kevin Bullis, "Fracking for Geothermal Heat Instead of Gas," MIT Technology Review, October 21, 2013.

447 Adam Gabbatt, "Swiss Geothermal Power Plan Abandoned after Quakes Hit Basel," The Guardian, December 15, 2009, Switzerland edition, https://www.theguardian.com/world/2009/dec/15/swiss-geothermal-power-earthquakes-basel.

448 James Glanz, "Geothermal Project in California Is Shut Down," New York Times, December 11, 2009, sec. Environment.

449 Edward D Frank, John L Sullivan, and Michael Q Wang, "Life Cycle Analysis of Geothermal Power Generation with Supercritical Carbon Dioxide," Environmental Research Letters 7, no. 3 (September 1, 2012): 34030, doi:10.1088/1748-9326/7/3/034030; Sullivan, Clark, and Wang, "Life Cycle Analysis Results of Geothermal Systems in Comparison to Other Power Systems."

hazards.[450] Physical hazards related to heavy machinery use and land-clearing hazards that were present during installation will also be present in this stage.

6.7 Equity Considerations

A 2006 report found that if Western US states installed 5600MW of new geothermal power capacity, this would create nearly 10,000 jobs and 36,000 person years of construction and manufacturing business. Geothermal facilities create a variety of jobs across their life cycles, including in engineering, drilling, and construction fields. In California from 2002 – 2015, wind energy created a total of 457 construction job years.[451] Investments were also made to apprenticeship programs for geothermal construction – programs associated with improved future lifetime earnings.[452]

Geothermal development must account for where new facilities are sited and how facility installation may impact local communities. Facility installation, continued maintenance, and decommissioning will all result in transport-related emissions and the potential for fugitive dust from geothermal facility sites during land preparation. In areas already suffering from poor air quality – such as around the Salton Sea where the Sea's rapid evaporation has led to toxic dust and PM exposure – geothermal facility construction and operation may increase the cumulative impacts from all infrastructure build out in the area. These emission impacts could be intensified for lower income or minority communities who live nearest to likely geothermal development sites.[453] The Salton Sea is already posing significant public health hazards, and some see geothermal development as a mechanism to reduce risk for surrounding communities (i.e. covering the "playa" that is currently generating large blooms of toxic dust). However, there are also concerns about the cumulative impacts of installation and transportation on surrounding area that already has very high levels of asthma. Before any substantial new development, a health impact assessment should be done.

6.8 Research Needs

Although geothermal energy has been producing electricity in California for over forty years, new developments in these systems require further assessment for potential health impacts, particularly with regard to Enhanced Geothermal Systems, which have not yet been successfully implemented in California. These impacts can be classified as those resulting from seismic activity, emissions from facilities, occupational health risks, and contamination of surrounding water resources.

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450 GRC, "The Geysers Geothermal Field: Update 1990-2010," Special Report (Geothermal Resources Council, 2010).

451 Betony Jones, Peter Philips, and Carol Zabin, "The Link Between Good Jobs and a Low Carbon Future: Evidence from California's Renewables Portfolio Standard, 2002—2015" (DONALD VIAL CENTER ON EMPLOYMENT IN THE GREEN ECONOMY Center for Labor Research and Education University of California, Berkeley, July 2016), http://laborcenter.berkeley.edu/pdf/2016/Link-Between-Good-Jobs-and-a-Low-Carbon-Future.pdf.

452 Ibid.

453 Little Hoover Commission, "Salton Sea Action Report."

1. Technology development to reduce hydrogen sulfide emissions from potential sites for flash facility build out in Geysers region, especially in regions where local geology has high hydrogen sulfide concentrations

2. Perform a health impact assessment of major geothermal development plans at Salton Sea, noting the potential for emissions across facility life cycle on surrounding communities

3. Assess potential occupational, public health and environmental consequences of materials recovery (e.g. sulfur, lithium, zinc) from geothermal fluids under different systems
    a. What is the impact on emissions, waste disposal, and occupational exposures across all phases of material recovery

Chapter 7: Small Hydroelectric Power and Marine Energy

7.1 Small Hydroelectric Power

Compared to other renewable generation technologies, small hydropower facilities have an uncertain future. In 2002, SB 1078 restricted the eligibility of small hydro facilities under the state's RPS to those that do not require "new or increased appropriation or diversion of water" and have a running capacity of 30 MW or less.[454] Currently, small hydro facilities generate around 3,000 GWh of electricity for California's grid. This makes up around 1% of the state's energy mix.[455] Considering the state's renewable generation goals, some models predict that this will increase to 6,000 GWh by 2030, growing to almost 2% of the estimated electricity mix.[456] Large capital costs relative to existing electricity-generating infrastructure and the need for lengthy transmission build out to reach new sites – often remote – of small hydro generation are considered key challenges for this industry moving forward.

The technologies of focus in statewide small hydro include "run-of-river" and in-conduit systems. In "run-of-river" systems, turbines are placed in streams or rivers that can maintain a minimum flow, often with the assistance of a small dam system to ensure ample water supply. The facilities use the natural flow of these river or streams to directly generate electricity. In-conduit systems retrofit existing man-made tunnels, canals, aqueducts, and irrigation systems that carry water with electricity generating equipment. While both of these require minimal structural preparation outside of transmission line connections to the grid, there are high capital costs associated with building and installing the electricity generating components in these systems.[457]

There is very limited information available on the potential health impacts, though these systems are championed as "environmentally friendlier" hydropower. These impacts are likely to differ based on the specifics of the technology implemented. For instance, some "run-of-river" facility can involve building a small dam, but some systems do not. This will dramatically impact the potential environmental and health impacts from these systems. Additional, the specifics of the location where these technologies are sited will also determine what their ultimate impact will be. Without this context, it is difficult to determine how these systems can impact health of workers and surrounding communities.

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454 Byron Sher, "Renewable Energy: California Renewables Portfolio Standard Program," Pub. L. No. 1078, Public Utilities (2002), http://www.energy.ca.gov/portfolio/documents/documents/SB1078.PDF.

455 CEC, "Renewable Energy – Overview December 2016" (California Energy Commission, December 2016), http://www.energy.ca.gov/renewables/tracking_progress/documents/renewable.pdf.

456 Gregory Brinkman, Jennie Jorgenson, and Marissa Hummon, "California 2030 Low Carbon Grid Study (LCGS): Phase I" (National Renewable Energy Laboratory, 2014), http://lowcarbongrid2030.org/wp-content/uploads/2014/10/LCGS_PhaseI_NRELslides.pdf.

457 Mike Kane and Elaine Sison-Lebrilla, "Statewide Small Hydropower Resource Assessment," PIER Final Project Report (Navigant Consulting, Inc., June 2006).

7.1.1 Run-of-River Systems

Though they are often championed as the environmentally friendly hydroelectric power, there is limited research on the ecological impacts of run-of-river systems, and the few studies that have been done focus on impacts to local fish and invertebrate communities.[458] In terms of impacts to surrounding human populations, there is a need for further research on the impacts of building a complex of these systems along one river or stream system. Though each installation may not have a large impact on the river's flow and potential for flooding, many generating system placed along one river or stream could lead to cumulative impacts and flooding risks for communities living nearby. It could also change the river's flow, impacting the river or stream's ecosystem.[459] This was seen in Uttarakhand, India where monsoon rains overwhelmed recently built run-of-river systems, flooding nearby regions.[460]

The potential risk of water contamination from generator materials is also unknown. In a study of a run-of-river system in the Karai River in Indonesia, the substance used to prevent corrosion of the pipeline and generator system construction – nickel ion – was found to leach into the surrounding water, accumulating in phytoplankton and plants.[461] Materials used throughout these systems must be assessed for their potential environmental and health impacts before installation.

When these systems include a small dam, there are additional hazards related to still water storage. There is the potential for a dam system to create anoxic conditions, which can release mercury contained in the sediment. If this mercury is then methylated, the resulting methylmercury can bioaccumulate throughout the river's ecosystem, with the potential to affect humans if local fishing occurs downstream. The resulting methylmercury can then enter aquatic food chains and lead to systemic toxic effects on the nervous, digestive and immune systems, and on lungs, kidneys, skin and eyes.[462] There is also the potential for still water to impact the incidence of vector borne disease in surrounding areas. Though this is mainly a concern for tropical regions where malaria, river blindness, dengue or yellow fever can be endemic, there placement of sites within California must also consider relevant vectors in the area and how the system could potentially impact them.[463]

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458 Gary S. Bilotta et al., "The Effects of Run-of-River Hydroelectric Power Schemes on Invertebrate Community Composition in Temperate Streams and Rivers," ed. Louis-Felix Bersier, PLOS ONE 12, no. 2 (February 3, 2017): e0171634, doi:10.1371/journal.pone.0171634.

459 Kelly M. Kibler and Desiree D. Tullos, "Cumulative Biophysical Impact of Small and Large Hydropower Development in Nu River, China: Biophysical Impact of Small and Large Hydropower," Water Resources Research 49, no. 6 (June 2013): 3104–18, doi:10.1002/wrcr.20243.

460 Dave Levitan, "As Small Hydropower Expands, So Does Caution on Its Impacts," Yale Environment 360, August 4, 2014, http://e360.yale.edu/features/as_small_hydropower_expands_so_does_caution_on_its_impacts.

461 Jessica Hanafi and Anthony Riman, "Life Cycle Assessment of a Mini Hydro Power Plant in Indonesia: A Case Study in Karai River," Procedia CIRP 29 (2015): 444–49, doi:10.1016/j.procir.2015.02.160.

462 Charles T. Driscoll et al., "Mercury as a Global Pollutant: Sources, Pathways, and Effects," Environmental Science & Technology 47, no. 10 (May 21, 2013): 4967–83, doi:10.1021/es305071v.

463 Edgar G. Hertwich, Jacqueline Aloisi de Larderel, and Sangwon Suh, "Green Energy Choices: The Benefits, Risks, and Trade-Offs of Low-Carbon Technologies for Electricity Production" (United Nations Environmnetal Programme, 2016), http://www.unep.org/resourcepanel/Portals/50244/publications/Summary_for_Policy_Makers_GHG_I.pdf.

Small hydro installations will also have indirect impacts, especially if new transmission lines will be needed to carry the generated electricity. With the construction phase, this will involve additional diesel emissions in surrounding areas from transport of workers and materials and from the heavy machinery used for installation and transmission build-out.

7.1.2 In-Conduit Systems

Little research has been done on the health and environmental impacts of In-Conduit small hydro systems. Because these systems involve building electricity-generating systems in already existing canals and aqueducts, there is the potential for these water systems to be interrupted by problems that arise during installation, impacting downstream populations. Because of this, installation could interrupt this water supply for populations. Additionally, materials and chemicals used in the generating systems would need to be evaluated for their potential to leach into the water, leading to exposures in drinking water sources.

Like run-of-river systems, in-conduit projects are often praised for their limited impact on local environments as compared to larger hydroelectric dams. However, there has been limited research on their potential to impact water quality and availability if added to systems that are collecting water for human use.

7.2 Marine Energy

Though there are potential wave energy resources off the coast of California marine energy using wave and tidal currents to generate electricity is still in the research and development phase. Although some wave energy may be implemented off the California coast in the next 10-15 years, these technologies are not yet considered as competitive as other emerging technologies. Tidal energy resources in the state are limited to the San Francisco Bay and could be used to generate electricity for San Francisco, although it is unlikely these systems will be implemented by 2030. There has been limited research into potential environmental and health costs of these generation systems.[464]

In order to prevent impacts on local marine ecosystems and coastline communities, the materials selected for these systems must be selected for their environmental safety. This includes for anti-fouling components used to prevent organisms from attaching to the machinery or moving parts. Traditionally, on large-scale vessels, anti-fouling materials contained copper and tin, which presented the environmental hazard of leaching metals into the surrounding water for uptake by aquatic animals. More and more, slimes and slippery substances are replacing these metal-based varieties, though these substances will also need to ensure limited environmental impact.[465]

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464 Sam Blakeslee and Bill Toman, "CalWave Update" (Offshore Renewable Energy Workshop, California Energy Commission, May 25, 2016).

465 Brian Polagye et al., "Environmental Effects of Tidal Energy Development," in Tech Memo F/SPO-116 (US Dept of Commerce, NOAA, 2011), 181, https://depts.washington.edu/nnmrec/workshop/docs/workshop_report_low_res.pdf; Kenneth Schiff, Dario Diehl, and Aldis Valkirs, "Copper Emissions from Anti-Fouling Paint on Recreational Vessels," Marine Pollution Bulletin 48, no. 3–4 (February 2004): 371–77.

Workers involved in installing and maintaining these systems will also be exposed to physical hazards of working in marine environments. Work is being done to automate these processes, so workers would not need to be on the water, but these have not been developed yet.[466]

There is also the potential for marine energy systems to impact aquatic ecosystems, with could then affect coastline livelihoods and resources for communities reliant on these resources. Siting of new marine energy operations will have to take this into account, and more research should be done to understand how different energy producing designs and materials will affect local fish communities and the human populations.

7.3 Equity Considerations

In California from 2002 – 2015, small hydro created a total of 341 construction job years.[467] Investments were also made to form training and apprenticeship programs for solar construction workers for utility-scale facilities – programs associated with improved future lifetime earnings.[468]

Small-hydro development must account for where new facilities are sited and how facility installation may impact local communities. Construction, continued maintenance, and decommissioning will all result in transport-related emissions for surrounding communities. These impacts will depend on site location, as areas already suffering from poor air quality may enhanced due to the cumulative impacts from all infrastructure build out in the area.[469] These emission impacts could be intensified in lower income or minority communities.

7.4 Research Needs

Although small hydroelectric systems have been rolled out throughout the state and marine energy is still in development, there is a need for research into the health and environmental impacts of these systems.

1. Assessment of potential health and environmental impacts of ocean wave energy technologies, including a life cycle assessment of the various parts and materials used and how these will interact with the marine environment
    a. Assessment of planned or projected ocean and tidal systems on local fishery and coastal community economies

466 Brian Polagye, Marine Energy Meeting with Brian Polagye, March 28, 2017.

467 Betony Jones, Peter Philips, and Carol Zabin, "The Link Between Good Jobs and a Low Carbon Future: Evidence from California's Renewables Portfolio Standard, 2002—2015" (DONALD VIAL CENTER ON EMPLOYMENT IN THE GREEN ECONOMY Center for Labor Research and Education University of California, Berkeley, July 2016), http://laborcenter.berkeley.edu/pdf/2016/Link-Between-Good-Jobs-and-a-Low-Carbon-Future.pdf.

468 Ibid.

469 Ricardo American Lung Association, "State of the Air 2016" (American Lung Association, 2016), http://www.lung.org/local-content/california/documents/state-of-the-air/2016/sota-2016-full-report.pdf.

Chapter 8: Storage Technologies

Storage technologies are likely to play an increasingly important role in California's electricity grid. Paired with the rise in renewable sources that have intermittent generation – like wind and solar technologies – storage technologies will be able to store excess electricity produced during the day outside of peak energy demand times, maintaining it until peak hours for release onto the grid. These technologies will also assist with load leveling, reducing strain on the grid during peak use times, and smoothing variability in solar and wind generation. Build out of electricity storage systems is considered a key piece of establishing grid resiliency while achieving California's renewable energy goals.[470]

Storage technologies currently being considered for grid deployment in the next 10 to 15 years include mechanical, electrochemical, chemical, and thermal systems. Mechanical storage systems in the form of pumped hydro facilities are already used across the state; compressed air energy storage and flywheel are also being researched and considered. Electrochemical storage includes many common batteries in use today – lead acid and lithium ion – as well as newer technologies such as redox flow and high temperature sodium sulfur batteries. Chemical storage in the form of fuel cells is also being researched for grid deployment, especially polymer electrolyte membrane fuel cells. Thermal storage materials are discussed more fully in **Chapter 3**, as they are currently used in CSP applications.

Assembly Bill 2514 established an energy storage goal of 1.3GW by 2020. As of July 2016, battery storage projects have already been approved and implemented, and additional funding for compressed air storage and flywheel research has been allocated.[471] Currently, the majority of storage capacity on the grid comes from pumped hydro facilities, however batteries and other forms of storage are increasingly common for new installations.[472] Researchers contacted for this report agreed that ultracapacitor and most fuel cell chemistries will have limited commercial viability for grid storage over the 10-15 year timeframe on which this report is focused.[473]

The following section describes the major storage categories and technologies across their life cycles, highlighting the potential for occupational and public health impacts.

470 Sonia Yeh et al., "A Modeling Comparison of Deep Greenhouse Gas Emissions Reduction Scenarios by 2030 in California," Energy Strategy Reviews 13–14 (November 2016): 169–80, doi:10.1016/j.esr.2016.10.001.

471 Collin Doughty, Linda Kelly, and John Mathias, "Bulk Energy Storage in California," Staff Paper (Supply Analysis Office Energy Assessments Division California Energy Commission, July 2016), http://www.energy.ca.gov/2016publications/CEC-200-2016-006/CEC-200-2016-006.pdf.

472 Jim Bartridge et al., "Draft 2016 Environmental Performance Report of California's Electrical Generation System," Staff Report (California Energy Commission, July 2016), https://efiling.energy.ca.gov/getdocument.aspx?tn=212338.

473 Katharina Snyder, Interview with Katharina Snyder of the California Energy Commission, Conference Call, August 4, 2016.

8.1 Mechanical Storage

Currently, mechanical, pumped hydroelectric storage (pumped hydro) facilities are the only grid storage technology in large-scale commercial use throughout California. Additional mechanical systems – compressed air and flywheels – are being researched for future use in the state.

8.1.1 Pumped Hydro

Pumped hydroelectric storage systems operate by pumping and releasing water between two reservoirs depending on grid electricity availability. In times of high generation and lower demand, a pumped hydro facility uses energy to pump water to an upper reservoir, storing it as potential energy. When there is higher energy demand, water is released from the upper reservoir through a generator to produce electricity. Older pumped hydro systems have around 60% efficiency, while newer systems can reach 80% efficiency.[474] Pumped hydro storage systems can operate through two reservoirs that are closed off from other water bodies or through one or two reservoirs built into existing river systems. The environmental impacts will differ based on the system, as newer, closed loop systems relying on two artificial or modified reservoirs unattached to other water systems will have a lower overall impact than those established in a river system.

According to a 2016 report from the CEC, pumped hydro energy storage has been deployed in California since the late 1800s and currently provides 98% of the state's energy storage. Currently, California has three operational facilities, including projects in Lake Hodges, Castaic Lake, Helms, as well as built infrastructure in San Luis Reservoir, O'Neill Forebay, Big Creek, and Oroville.[475] Last year, a pumped hydro project at Iowa Hill was canceled due to high start-up costs. Additionally, Eagle Mountain Pumped Storage – located in a spent iron mine – is expected to come online in 2023 to provide 1300MW of output storage. Future pumped hydro deployment is challenging due to limited site availability, long lead times, and high installation costs.

8.1.1.1 Transportation

Impacts related to increased traffic to the site and emissions from off-road vehicles will largely be determined by the siting of pumped-hydro facilities and will primarily be related to constructing new systems. A summary of transportation-related emissions and hazards can be found in **Section LCA.3**.

8.1.1.2 Siting and Construction

Land use is a central issue in life-cycle assessment of the environmental impacts of pumped hydro storage facilities. For example, proximity to Joshua Tree National Park was of particular concern during the siting of the Eagle Mountain project. Depending on whether a

474 Doughty, Kelly, and Mathias, "Bulk Energy Storage in California."

475 Ibid.

system uses above or belowground reservoirs, land use impacts will vary.[476] There is limited land available in California for new, large-scale pumped hydro storage facilities. However, hazards related to traditional reservoirs – including land flooding – apply to these storage facilities and any potential new sites.[477] If not controlled for, these can put local populations at risk of flooding, and produce a potent GHG that will contribute to climate change and its associated health impacts. These impacts will depend on the type of system implemented, and whether it connects with an existing river system to operate. If these systems are constructed to use reservoirs that are built into existing river systems, the scheduled draining and flooding of the reservoirs for storage purposes can impact local ecosystems and fish populations.[478]

Construction activities may cause seismic activity, subsidence, or soil erosion depending on the geology and structural stability of the site. If regional faults are not well mapped and local seismic activity is not well understood, there is a risk of unintended seismic activity during construction. However, sites are often chosen that are not along major fault lines.[479]

Impacts related to land clearing activities will also be based on where these facilities are located. **Section LCA.4** provides a summary of these hazards, though modeling these impacts for specific technologies or sites is outside the scope of this report.

8.1.1.3 Use and Maintenance

Depending on the system implemented, flooding can be a concern with pumped hydro systems, especially if the project uses one or both reservoirs built into an existing river system. Similar to hydroelectric dam facilities, severe weather, infrastructure damage, or system malfunction can lead to the release of overflow into surrounding areas. Flooding can cause traumatic injuries as well as damage to homes and buildings that could impact surrounding populations.

Due to the siting of projects and the need for underground construction, landslides, subsistence, and ground deformation can be physical hazards of pumped hydro sites, which can result in traumatic injuries from earth movement or instability. Seismic activity must be monitored throughout facility use, as reservoir-triggered seismicity can also be a potential effect of these facilities. Research shows that reservoir-triggered seismicity has only increased localized and existing seismic activity when placed along active fault lines; proper planning of pumped hydro facilities can often mitigate these effects.[480]

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476 Chi-Jen Yang and Robert B. Jackson, "Opportunities and Barriers to Pumped-Hydro Energy Storage in the United States," Renewable and Sustainable Energy Reviews 15, no. 1 (January 2011): 839–44, doi:10.1016/j.rser.2010.09.020.

477 Edgar G. Hertwich, Jacqueline Aloisi de Larderel, and Sangwon Suh, "Green Energy Choices: The Benefits, Risks, and Trade-Offs of Low-Carbon Technologies for Electricity Production" (United Nations Environmnetal Programme, 2016), http://www.unep.org/resourcepanel/Portals/50244/publications/Summary_for_Policy_Makers_GHG_I.pdf.

478 John Roach, "For Storing Electricity, Utilities Are Turning to Pumped Hydro," University, Yale Environment 360, (November 24, 2015), http://e360.yale.edu/features/for_storing_electricity_utilities_are_turning_to_pumped_hydro.

479 GEI Consultants, "Eagle Mountain Pumped Storage Project Draft Environmental Impact Report Volume I" (State Water Resources Control Board, July 2010), http://www.waterboards.ca.gov/waterrights/water_issues/programs/water_quality_cert/docs/eagle_mountain_pumped_ferc13123/2_eagltmtn_deir_vol1_2.pdf.

480 Ibid.

Additionally, methane emissions can be a concern for surface reservoirs. As microorganisms in the water breakdown organic nutrients in anaerobic conditions, methane can be produced and emitted from the surface.[481] This is a problem for reservoirs because they are often created by flooding areas that previously contained a variety of organic material, providing ample food for microorganisms.[482] This process is amplified by nitrogen and phosphorous pollution from agricultural and waste streams, as the resulting algal blooms provide additional food for microorganisms.[483] As methane is a potent GHG, new reservoirs should be carefully sited (i.e. away from potential agricultural waste streams) and existing reservoirs should be managed to reduce these potential emissions.

Throughout facility operation, hazardous chemicals like cleaning agents, water treatment chemicals, welding gasses, oils, and activated carbon could be present in small amounts and represent limited hazards to communities surrounding facilities because of their small quantities, low volatility, and/or low toxicity.[484] These materials can be contained with adequate implementation of federal and state standards for safe use and storage. Fire risk due to mechanical systems failure can be reduced with proper engineering controls and training.

8.1.1.4 Decommissioning and Disposal

There is little information on hazards present for workers or surrounding communities during decommissioning of pumped hydro facilities, as these facilities have a long lifetime and older systems are still in use throughout the state.

8.1.2 Compressed Air

Compressed Air Energy Storage (CAES) facilities store energy by actively compressing air in underground mines or reservoirs during times when there is lower demand on the grid. When this energy is then needed during peak hours, the gas can be expanded or released from its storage, driving a turbine to produce electricity.[485] Typically, natural gas is combusted to heat the air during the expansion phase in order to increase pressure and drive the system's turbine. Ongoing research focuses on reducing this external heat input by using adiabatic systems, which store heat released during the compression process and return this heat to the system during expansion.[486] Additional research is needed into thermal energy storage systems that could store this heat to reduce natural gas reliance.[487]

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481 Bridget R. Deemer et al., "Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis," BioScience 66, no. 11 (November 1, 2016): 949–64, doi:10.1093/biosci/biw117.

482 Ibid.

483 Ibid.

484 GEI Consultants, "Eagle Mountain Pumped Storage Project Draft Environmental Impact Report Volume I."

485 PG&E, "Compressed Air Energy Storage (CAES): Request for Offers," PG&E, 2017, https://www.pge.com/en_US/for-our-business-partners/energy-supply/electric-rfo/wholesale-electric-power-procurement/compressed-air-energy-storage-request-for-offers.page.

486 André Sternberg and André Bardow, "Power-to-What? – Environmental Assessment of Energy Storage Systems," Energy Environ. Sci. 8, no. 2 (2015): 389–400, doi:10.1039/C4EE03051F.

487 Ethan Elkind et al., "2020 Stratetic Analysis of Energy Storage in California," PIER Final Project Report (University of California, November 2011), http://www.energy.ca.gov/2011publications/CEC-500-2011-047/CEC-500-2011-047.pdf.

As of 2015, there were only two CAES facilities in use globally – in Germany and Alabama operating at 290MW and 110MW capacity respectively.[488] A statewide study of CAES potential in the state identified a depleted natural gas reservoir in San Joaquin County as a potential compressed air site, and PG&E is currently developing plans for this site, which is expected to have a storage capacity of 100-350MW.[489] CAES may potentially be sited in salt mines, such as a project in a salt deposit in Utah that may feed into the California grid. [490,491] CAES still has to overcome many barriers before achieving large-scale deployment, as the technology is expensive to develop, limited sites are available, and the ultimate project approval process is lengthy.[492]

There is very limited information available about the safety and health impacts of compressed air storage systems.

8.1.2.1 Transportation

Because these sites may be located in salt mines or spent natural gas fields, construction will likely increase traffic into these areas. A summary of transportation related emissions and hazards can be found in **Section LCA.3**. Currently, the only site under consideration for CAES development is located in San Joaquin County, an area with poor air quality. Both facility specific and cumulative impacts related to proximity of multiple and varied facilities must thus be considered during project planning and siting.

8.1.2.2 Construction

Siting of CAES in spent natural gas fields may present a risk of occupational exposure to residual hydrocarbons. This siting may also present a fire hazard, as hydrocarbons – depending on their concentration – could act as a fuel that, when mixed with oxygen from the compressed air and an ignition source, could cause an explosion. The heat released during compression of the air or friction during air charging or discharging could be potential ignition sources.[493] In order for detonation or combustion to occur, a very specific relationship of oxygen to hydrocarbon would have to exist, but sites should be analyzed and purged of natural gas remnants if possible, and gas leaks should be closed to avoid conflagrations reaching the surface. Continual monitoring will also be necessary to ensure natural gas residues do not reach a critical concentration. Sites must also be monitored for the cavity's stability and the mineral content of the underground reservoir.

Construction activities may cause seismic activity, subsidence, or soil erosion depending on the geology and structural stability of the land sited. If regional faults are not well mapped

488 Doughty, Kelly, and Mathias, "Bulk Energy Storage in California."

489 PG&E, "Compressed Air Energy Storage (CAES): Request for Offers."

490 Sternberg and Bardow, "Power-to-What?"

491 Bartridge et al., "Draft 2016 Environmental Performance Report of California's Electrical Generation System."

492 Doughty, Kelly, and Mathias, "Bulk Energy Storage in California."

493 Mark C. Grubelich, Stephen J. Bauer, and Paul W. Cooper, "Potential Hazards of Compressed Air Energy Storage in Depleted Natural Gas Reservoirs" (Sandia National Laboratories, September 2011), http://prod.sandia.gov/techlib/access-control.cgi/2011/115930.pdf.

and local seismic activity is not well understood, there is a risk of unintended seismic activity when a CAES site is located near a fault.[494]

8.1.2.3 Maintenance and Use

CAES systems involve above and below-ground facilities equipped with compressors, expanders, and turbines. In case of emergencies for systems already in use, safety relief and pressure relief valves are built-in.[495] In order to ensure reservoir stability, the water content, temperature of injected air, pressure, and humidity must be carefully monitored.[496] With proper monitoring, occupational and public health impacts related to explosions or leaked gases can be controlled. As air will be compressed and expanded in these systems, this component is innocuous, but emissions of remnant natural gas and other potential exposures should be contained and monitored.

8.1.2.4 Decommissioning and Disposal

Because of the limited roll out of these systems, little is known about potential hazards for workers or the public during decommissioning of sites, nor about site stability for future use. It is likely these will be related to sites of natural gas development.

8.1.3 Flywheel

Grid scale flywheels store energy by spinning a rotor up to tens of thousands of revolutions per minute (RPM), which stores energy through rotational kinetic energy and elastic energy from deformation of the rotor.[497] Deceleration of the flywheel can then produce electricity. PG&E is currently contracting with developers to test a small, 20MW flywheel system for the CA grid.[498]

The 2020 Strategic Analysis of Energy Storage in California recommended research into improved safety for large-scale development of flywheel storage.[499] The major occupational and public health impact of concern related to flywheels are the risk of explosion if a flywheel system fails, though additional details related to other hazards across the life cycle are limited in current literature.

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494 M.A. Beckwith and D.W. Boehm, "Compressed Air Energy Storage (CAES) Environmental Control Concerns and Program Plan" (U.S. Department of Energy, June 1980), https://www.osti.gov/scitech/servlets/purl/5106163.

495 Vasilis Fthenakis, "Integrating Wind-Solar-CAES" (2nd Compressed Air Energy Storage (CAES) Conference & Workshop, Columbia University, 2010), http://www.clca.columbia.edu/CAES2workshop_proceedings.pdf.

496 Beckwith and Boehm, "Compressed Air Energy Storage (CAES) Environmental Control Concerns and Program Plan."

497 DOE, "Energy Storage Safety Strategic Plan" (U.S. Department of Energy Office of Electricity Delivery and Energy Reliability, December 2014), https://energy.gov/sites/prod/files/2014/12/f19/OE%20Safety%20Strategic%20Plan%20December%202014.pdf.

498 PG&E, "PG&E Presents Innovative Energy Storage Agreements," PG&E, December 20, 2015, https://www.pge.com/en/about/newsroom/newsdetails/index.page?title=20151202_pge_presents_innovative_energy_storage_agreements_.

499 Elkind et al., "2020 Stratetic Analysis of Energy Storage in California."

8.1.3.1 Materials Extraction

Flywheels can be composed of advanced composite materials like carbon fibers or graphite, with large strength and weight ratios, or more traditional materials like steel.[500] Hazards related to the extraction and processing of carbon fibers and graphite are discussed later in **Sections 8.2.1.1** and **8.2.3.1.**

8.1.3.2 Manufacture

Carbon felt and graphite are often used as electrodes in VRB.[501] Exposure to carbon fibers in producing the carbon felt electrode is a potential hazard, as preliminary toxicology research has found increases in lung cancer in mice following exposure to these fibers.[502]

Very little information is publicly available on flywheel manufacturing and associated risks. However, occupational standards upheld across manufacturing fields should apply, as well as workers protections against system failures and related fire-hazards during system testing.

8.1.3.3 Transportation

A summary of transportation related emissions and hazards can be found in **Section LCA.3**.

8.1.3.4 Installation

Because of the variation in flywheel size and structures, it is difficult to assess potential hazards related to system installation. Occupational exposures could include physical hazards of heavy machinery use and working from heights and within confined spaces, depending on where the flywheel is located.

8.1.3.5 Maintenance and Use

Safety concerns with flywheel storage mainly derive from system failures. When a flywheel builds up too much speed or a component or structure fails, the entire system can explode.[503] With proper encasing, fragmentation can be contained, though this containment can also fail.[504] Such explosions can damage buildings and put workers at risk of serious injuries due to projectiles, as was the case of the test-flywheel explosions at Quantum Energy Storage

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500 Haichang Liu and Jihai Jiang, "Flywheel Energy storage—An Upswing Technology for Energy Sustainability," Energy and Buildings 39, no. 5 (May 2007): 599–604, doi:10.1016/j.enbuild.2006.10.001.

501 Aishwarya Parasuraman et al., "Review of Material Research and Development for Vanadium Redox Flow Battery Applications," Electrochimica Acta 101 (July 2013): 27–40, doi:10.1016/j.electacta.2012.09.067.

502 Yann Grosse et al., "Carcinogenicity of Fluoro-Edenite, Silicon Carbide Fibres and Whiskers, and Carbon Nanotubes," Lancet Oncology 15, no. 13 (2014): 1427.

503 Liu and Jiang, "Flywheel Energy storage—An Upswing Technology for Energy Sustainability."

504 Donald Bender, "Recommended Practices for the Safe Design and Operation of Flywheels" (Sandia National Laboratories (SNL-CA), Livermore, CA (United States), 2015), http://www.sandia.gov/ess/publications/SAND2015-10759.pdf.

Corporation in California.[505] If these flywheel-equipped facilities are sited in areas with high population densities or surrounding communities at close proximity, these system failures could pose a fire and explosion hazard for local populations.

Research is currently centered on safe design mechanisms to prevent system failures. Current safety mechanisms of focus include burst simulations to determine containment integrity, speed testing, and monitoring the rate of fatigue of different material inputs.[506]

8.1.3.6 Decommissioning and Disposal

Depending on the supplier, most flywheel components will be recyclable, although little information is available on safe recycling practices.[507]

8.2 Electrochemical Storage

Batteries, the most common form of electrochemical storage, have long been used to power cars and electronic applications. A battery works through the build-up and transfer of electrons. Battery components can include a positive electrode (anode), a negative electrode (cathode), an electrolyte to separate these electrodes, a membranous separator to facilitate this separation, and contacts and wiring to facilitate charging and discharging. In traditional batteries, when charging, electrons build up in the battery's anode through chemical reaction of battery components, but are prevented from moving to the cathode directly by the electrolyte and/or separator. Instead, they pass through contacts and wiring, to the cathode. The process is opposite for battery discharge, as electrons move from cathode to anode, and are shared to exterior applications (electronics, cars, etc.) through wiring.

Batteries are growing in use across grid applications, although 2030 forecasts of storage technology prevalence vary significantly by model. Some assume greater battery storage, while other models rely more on existing and new pumped hydro facilities and compressed air technologies. Battery storage is expected to be dominated by lithium-ion chemistries in the near term, although new developments may encourage use of lead-acid batteries in grid storage. Flow batteries and sodium-sulfur batteries are also expected to grow in commercial viability by 2030.

The following hazard assessment across battery life cycles was completed based on available information. However, as many of these technologies are developing rapidly with a variety of different chemistries, updated inventories of materials used throughout processing are needed. These would assist in producing more informed hazard assessments for occupational and community health impacts, while also allowing for informed development of particular chemistries with the least negative impact. Lessons learned from lead acid batteries,

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505 Safety BLR, "Flywheel Explosion Teaches Lessons in Machine Safety," Safety BLR, February 25, 2016, http://safety.blr.com/workplace-safety-news/equipment-and-process-safety/machine-safety/Machine-safety-Flywheel-explosion-teaches-lessons-/.

506 DOE, "Energy Storage Safety Strategic Plan."

507 John Baffa and Mark Hinrichs, "Flywheel Energy Storage System" (San Diego Gas & Electric, October 2016), file:///Users/loxfordbuck/Downloads/sdge_flywheel_energy_storage_report_033017_final.pdf.

their vast health impacts, and related environmental pollution can also inform protective measures for developing technologies.

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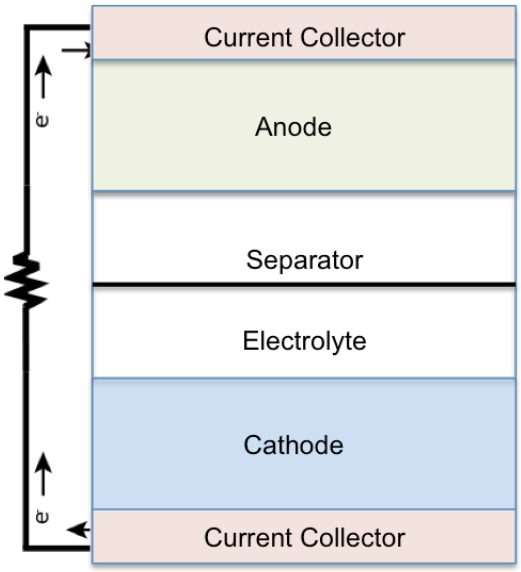
508 Yeh et al., "A Modeling Comparison of Deep Greenhouse Gas Emissions Reduction Scenarios by 2030 in California."

509 Chris Warren, "Ensuring a Clean Grid—Batteries Not Excluded," EPRI Journal, February 2016, http://eprijournal.com/wp-content/uploads/2016/01/Ensuring-a-Clean-Grid.pdf.

Figure 13. Generic Battery Component Diagram (Charging)



Source: Center for Climate Change and Health (2017)

8.2.1 Lithium-Ion

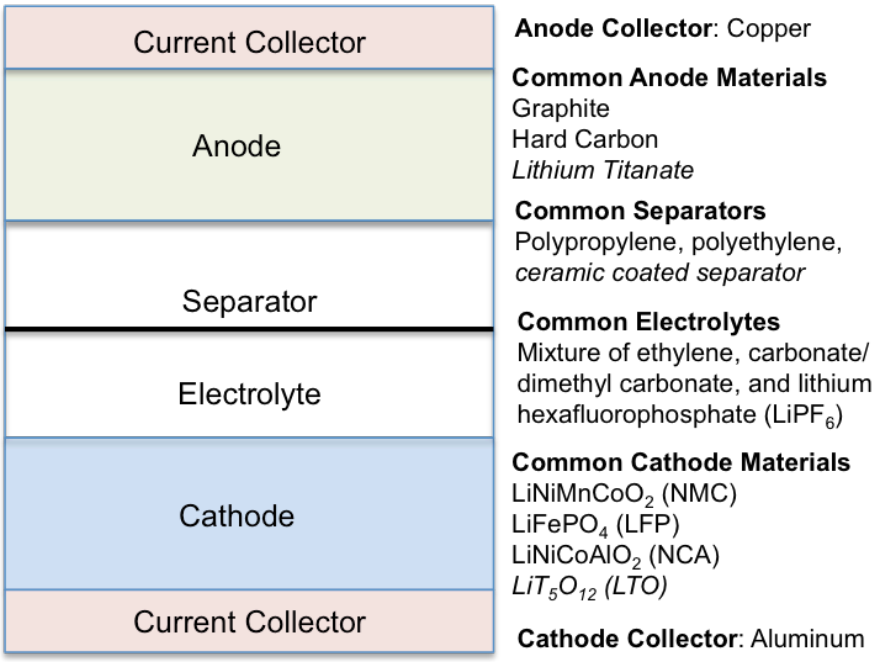
Lithium-ion (Li-ion) batteries are currently considered the most promising battery for grid storage application due to their commercial viability and widespread use in other applications. Li-ion batteries used in electric vehicles, electronics, and stationary storage have high energy densities, as they are capable of storing 130-170 Wh of energy per unit kg. They also have thousands of cycles within their lifetime.[510] US production of Li-ion battery packs is expected to increase substantially with Tesla's Gigafactory in Nevada, and large projects have been contracted to AES and Tesla to build grid-capacity Li-ion storage facilities in San Diego and Los Angeles counties.[511]

Commercial Li-ion batteries are typically composed of a graphite anode, an electrolyte containing lithium salts in an organic solvent, and a variety of lithium-based cathode materials, depending on the application. Lithium nickel cobalt aluminum oxide (NCA) and lithium manganese oxide (LMO) cathodes are all commonly used in electric vehicles, while lithium cobalt oxide (LCO) cathodes are common in electronics and cell phones. Cathodes made of lithium nickel manganese cobalt oxide (NMC) are used in Tesla's Powerwall battery, marketed for household electricity storage. Lithium iron phosphate (LFP) batteries are increasingly common in grid applications due to their high cycle life and thermal stability. Common materials used in Li-ion batteries researched for grid applications are illustrated in Figure 14.

510 J.L. Sullivan and L. Gaines, "A Review of Battery Life-Cycle Analysis: State of Knowledge and Critical Needs" (Argonne, Energy Systems Division, October 1, 2010), https://greet.es.anl.gov/publication-batteries_lca.

511 Diane Cardwell and Clifford Krauss, "A Big Test for Big Batteries.pdf," The New York Times, January 14, 2017, sec. Energy & Environment.

Figure 14. Materials in Potential Lithium-Ion Batteries for Grid Storage



Source: Center for Climate Change and Health (2017)

Chemical hazards related to Li-ion batteries will be highly dependent on the specific chemistry of the battery being manufactured or used. Because there are many varieties of lithium-ion batteries and very little publicly accessible information on material inputs throughout the industry, it is difficult to assess hazards and risk without further study into the specific materials used in California's grid batteries and their occupational and environmental impacts.

8.2.1.1 Materials Extraction

Global lithium production increased by 12% in 2016, and this upward trend is expected to continue as the Li-ion market grows. In the US, lithium production occurs from brine recovery at a plant in Nevada. Two other US companies produce lithium compounds from domestic or imported lithium carbonate, lithium chloride, and lithium hydroxide. Globally, 39% of lithium produced was used in battery manufacture.[512] While only a small proportion of batteries are currently used for grid storage, significant expansion of EES will increase that proportion. The USGS estimates significant lithium resources – around 6.9 million tons – in the US, from continental brines, geothermal brines, hectorite, oilfield brines, and pegmatites; lithium resources in other countries are estimated at 40 million tons.[513] The largest producers of lithium are Australia, Chile, and Argentina.[514] Compared to mining of other raw materials,

512 USGS, "Lithium," Goverment Ageny Website, US Geological Survey Minerals Information, (2017), https://minerals.usgs.gov/minerals/pubs/commodity/lithium/mcs-2017-lithi.pdf.

513 Ibid.

514 Ibid.

extraction of lithium is considered to have fewer environmental impacts.[515] However, lithium exposure may be linked with neurotoxicity, developmental toxicity, and immunotoxicity, therefore more research is needed to fully characterize these risks.[516]

The recovery process of lithium from brines can include evaporation, filtering of other minerals and metals, and precipitation with soda ash to produce lithium carbonate, a stable compound that can be further processed through electrolysis to form elemental lithium. Little data is available regarding the mineral makeup of these brines, so it is difficult to categorize potential hazards related to brine exposure.[517]

There are also risks with the extraction and processing of nickel and cobalt components of some Li-ion cathodes. These elements occur naturally together in laterite or sulphide ores, and can be leached from rock stores at high temperature and pressure. This produces slurry, which can be flash-cooled and further purified to produce nickel and cobalt. Nickel exposure can lead to dermatitis and respiratory irritation, and nickel compounds are considered a human carcinogen.[518] Exposure to high cobalt levels can also lead to respiratory irritation and difficulty breathing. Exposures during the processing phase of these metals have also been found to have respiratory, pulmonary, and neurological impacts on those exposed. A 2013 report from the US EPA found that Li-Ion batteries containing cobalt and nickel have the largest environmental impact of common chemistries in use today.[519] This is due to their role in resource depletion and their contribution to ecological toxicity and human health impacts, including respiratory, pulmonary, and neurological effects in those exposed.[520]

Additional environmental and health impacts result from the extraction of aluminum and copper for collector and wiring components. Aluminum, used as a cathode charge collector and cooling system, is produced from bauxite ore. Though this ore is considered chemically inert, the processing stages used to derive aluminum can lead to carcinogenic polycyclic aromatic hydrocarbon (PAH) emissions.[521] There is need for further studies of the association of aluminum processing with occupational asthma and lung disease. Releases of benzo[a]pyrene (BaP) present a lung cancer risk to workers and, potentially, surrounding communities.[522]Aluminum mining and smelting practices have led to increased emissions of

515 Dominic A. Notter et al., "Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles," Environmental Science & Technology 44, no. 17 (September 2010): 6550–56, doi:10.1021/es903729a.

516 Shanika Amarakoon, Jay Smith, and Brian Segal, "Application of Life-Cycle Assessment to Nanoscale Technology: Lithium-Ion Batteries for Electric Vehicles," DfE/ORD Li-Ion Batteries and Nanotechnology for Electric Vehicles Partnership (United States Environmental Protection Agency, April 24, 2013), https://www.epa.gov/sites/production/files/2014-01/documents/lithium_batteries_lca.pdf.

517 Ibid.

518 Ibid.

519 Ibid.

520 Ibid.

521 James C. Wesdock and Ian M. F. Arnold, "Occupational and Environmental Health in the Aluminum Industry: Key Points for Health Practitioners," Journal of Occupational and Environmental Medicine 56 (May 2014): S5–11, doi:10.1097/JOM.0000000000000071.

522 Stephen Claude Martin and Claude Larivière, "Community Health Risk Assessment of Primary Aluminum Smelter Emissions:," Journal of Occupational and Environmental Medicine 56 (May 2014): S33–39, doi:10.1097/JOM.0000000000000135.

criteria pollutants in surrounding communities, as well as related asthma and bronchiolitis incidence.[523]

Copper mining and processing has well known environmental and health impacts. In the US, copper is mainly mined and produced in Arizona, New Mexico, Utah, Nevada, Montana, and Michigan. 19% of copper mined in the US was used for electric appliances in 2016.[524] According to the US EPA, copper mining results in the largest processing wastes from metal production in the US, though associated hazards to miners, processors, and surrounding populations depend on regional geology. Tailings can have high acid, metal, and radionuclide concentrations.[525] These can cause environmental damage if uncontained, while also exposing individuals involved in processing to radium, thorium, and uranium, which can lead to cancer and potentially harmful genetic alterations.[526] Copper smelting can release PM and SO_2 into the air, along with trace elements like arsenic, cadmium, and mercury.[527] PM and sulfur oxides are well known criteria pollutants. Acute exposures to SO_2 can lead to coughing, wheezing, and difficulty breathing, while chronic exposure can potentially lead to asthma and decreased lung and airway function.[528] PM exposures can lead to bronchitis, lung damage, cardiovascular effects, cancer, heavy metal poisoning, and potential reproductive impacts.[529] Arsenic, cadmium, and mercury exposures through air emissions can lead to cancer, systemic organ damage, and decreased neurological development in children.[530] Cohort studies have found excess mortalities in copper miners resulting from lung cancer.[531]

Li-ion batteries also contain graphite, a natural form of carbon found largely in China. Mining and processing stages of this material are known for emitting large amounts of PM, impacting local air quality and increasing risk of asthma and lung disease in local populations. Graphite production can also pollute local water systems due to inadequate controls of waste products.[532] Acute graphite exposure is associated with respiratory infections and irritation,

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523 Ibid.

524 USGS, "Copper," Goverment Agency Website, US Geological Survey Minerals Information, (2017), https://minerals.usgs.gov/minerals/pubs/commodity/copper/mcs-2017-coppe.pdf.

525 EPA, "TENORM: Copper Mining and Production Wastes," Goverment Agency Website, US EPA Radiation Protection, (September 14, 2016), https://www.epa.gov/radiation/tenorm-copper-mining-and-production-wastes.

526 EPA, "Radiation Health Impacts," Goverment Agency Website, US EPA Radiation Protection, (July 21, 2016), https://www.epa.gov/radiation/radiation-health-effects.

527 Stanislaw Dudka and Domy C. Adriano, "Environmental Impacts of Metal Ore Mining and Processing: A Review," Journal of Environmental Quality 26 (May 1997): 590–602.

528 EPA, "Criteria Air Pollutants," Goverment Agency Website, US EPA, (April 3, 2017), https://www.epa.gov/criteria-air-pollutants.

529 Ibid.

530 M Hutton, "Human Health Concerns of Lead, Mercury, Cadmium, and Arsenic," in Lead, Mercury, Cadmium, and Arsenic in the Environment (John Wiley & Sons Ltd., 1987), https://dge.carnegiescience.edu/SCOPE/SCOPE_31/SCOPE_31_2.01_Chapter6_53-68.pdf.

531 Ruoling Chen, Li Wei, and Huaming Huang, "Mortality from Lung Cancer among Copper Miners.," British Journal of Industrial Medicine 50, no. 6 (1993): 505–509; Masanori Kuratsune et al., "Occupational Lung Cancer among Copper Smelters," International Journal of Cancer 13, no. 4 (April 15, 1974), doi:10.1002/ijc.2910130415.

532 Peter Whoriskey, "In Your Phone, In Their Air," Washington Post, October 2, 2016, Web edition, https://www.washingtonpost.com/graphics/business/batteries/graphite-mining-pollution-in-china/.

while chronic exposure to high levels can lead to lung tumors and respiratory disease.[533] Graphite processing also uses heavy metals and solvents that may contaminate waste streams. High levels of exposure are more common for workers in mining and processing facilities, though surrounding populations can also be exposed to dangerous heavy metals or solvents in waste streams. Additionally, exposure to carbon fibers in producing other carbon-based anode materials is a potential hazard, as preliminary toxicology research has found increases in lung cancer in mice following exposure to these fibers.[534]

8.2.1.2 Manufacture

Individual components of Li-ion batteries can present chemical hazards for manufacturers. The production processes for graphite electrode present the potential for occupational inhalation of silica dust, graphite dust, polyaromatic hydrocarbons, and asbestos. These can lead to lung disorders like silicosis, as well as lung cancer in workers exposed over time throughout the production process.[535] The use of fluoride salt, $LiPF_6$ as a common electrolyte also presents a chemical hazard. Depending on the battery's chemistry, there is the potential for this salt to create toxic and reactive byproducts like fluroethanol ether, fluoroethylene, and hydrofluoric acid when mixed with other components.[536]

Workers are potentially exposed to a number of other chemicals during materials processing and manufacturing of Li-ion battery packs. Exposures to isocyanate from paints are possible, leading to eye, skin, and respiratory tract irritation and allergic sensitization.[537] Exposures to styrene, polyvinyl chloride, and polyethylene in plastics are also possible. When inhaled, styrene can cause vision abnormalities, color blindness, lower lung function, and cardiac distress.[538] Polyvinyl chloride and polyethylene are also highly reactive and can decompose to form toxic and reactive gases such as hydrogen gas.[539]

Specific process and material inputs are not publicly available for Li-ion batteries, so additional research is needed to more comprehensively assess hazards and potential risks.

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533 NIOSH, "Occupational Health Guideline for Natural Graphite," Goverment Ageny Website, United States Department of Labor, Occupational Safety and Health Administration, (1978), https://www.cdc.gov/niosh/docs/81-123/pdfs/0306.pdf.

534 Grosse et al., "Carcinogenicity of Fluoro-Edenite, Silicon Carbide Fibres and Whiskers, and Carbon Nanotubes."

535 D. F. Merlo et al., "A Mortality Cohort Study among Workers in a Graphite Electrode Production Plant in Italy," Occupational and Environmental Medicine 61, no. 2 (2004): e9–e9.

536 Jean-Marie Tarascon, "Towards Sustainable and Renewable Systems for Electrochemical Energy Storage," ChemSusChem 1, no. 8–9 (September 1, 2008): 777–79, doi:10.1002/cssc.200800143.

537 NIOSH, "Isocyanates," Goverment Agency Website, Workplace Safety and Health Topics, (November 10, 2014), https://www.cdc.gov/niosh/topics/isocyanates/; C. Korepp et al., "Isocyanate Compounds as Electrolyte Additives for Lithium-Ion Batteries," Journal of Power Sources 174, no. 2 (December 6, 2007): 387–93.

538 Joshua M. Harney et al., "Evaluation of Styrene and Dust Exposures and Health Effects during Fiberglass-Reinforced Wind Turbine Blade Manufacturing," Health Hazard Evaluation Report (U.S. Department of Health and Human Services Centers for Disease Control and Prevention National Institute for Occupational Safety and Health, August 2016), https://www.cdc.gov/niosh/hhe/reports/pdfs/2013-0056-3256.pdf.

539 NIOSH, "Polyethylene," National Institute for Occupational Safety and Health, July 1, 2014, https://www.cdc.gov/niosh/ipcsneng/neng1488.html; NIOSH, "Polyvinyl Chloride," Goverment Agency Website, National Institute for Occupational Safety and Health, (July 1, 2014), https://www.cdc.gov/niosh/ipcsneng/neng1487.html.

8.2.1.3 Transportation

A summary of transportation related emissions and hazards can be found in **Section LCA.3**. Specific to Li-ion batteries, transportation-related hazards relate to the combustibility of battery packs due to damage, mechanical stress, or temperature shifts. Though most transport-related fires have been caused by small Li-ion batteries in cell phone and electronic applications, precautions need to be taken in transporting grid-scale models due to this potential fire hazard.[540] Due to this fire risk, the UN's Recommendations on the Transport of Dangerous Goods addresses transport of lithium ion batteries, with strict standards regarding international transport.[541]

8.2.1.4 Installation

The installation of large, grid-scale Li-ion installations is a new practice, so there is limited information available on the potential hazards for workers or surrounding populations. Because it is known that damaged cells can lead to venting of potentially toxic gases and risk of fire, installation workers should be trained to understand and appropriately handle signs of damage. Given that there have been cases of smaller Li-ion batteries igniting due to mechanical shock and mechanical damage, there is the potential for accidents during installation resulting in venting of contained gases and, potentially, fire.[542]

Though land-use for grid-scale Li-ion storage facilities will be much less than for utility-scale generation facilities (e.g. a large CSP site), there will still be installation impacts related to land clearing activities. These will largely be determined by the siting of these facilities. **Section LCA.4** provides a summary of these hazards.

8.2.1.5 Maintenance and Use

A public health concern regarding large-scale Li-ion use is the potential for a battery failure in one cell to cause a fire in a storage facility. If Li-ion batteries are damaged, exposed to strong vibration or mechanical shock, or kept in high temperatures, the lithium electrolyte can decompose, leading to vaporization and venting from the cell.

This can also lead to "thermal runaway," where venting within one unit can cause the overheating of neighboring units. The resulting vapors released from the battery packs would be flammable, creating a fire hazard, while also potentially exposing workers to hazardous gases. These gases are summarized in

Table 14 below. An additional concern is the venting of hydrofluoric acid, which can cause severe irritation, pulmonary edema, and irregular heartbeat.[543] This could also be a concern

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540 Celina Mikolajczak et al., Lithium-Ion Batteries Hazard and Use Assessment (Springer New York, 2011).

541 Mark Anderson, "Potential Hazards at Both Ends of the Lithium-Ion Life Cycle," IEEE Spectrum, March 1, 2013, http://spectrum.ieee.org/green-tech/fuel-cells/potential-hazards-at-both-ends-of-the-lithiumion-life-cycle.

542 Mikolajczak et al., Lithium-Ion Batteries Hazard and Use Assessment.

543 Anderson, "Potential Hazards at Both Ends of the Lithium-Ion Life Cycle"; CDC, "Hydroflouric Acid," Government Agency Website, Centers for Disease Control and Prevention, (April 22, 2013), https://emergency.cdc.gov/agent/hydrofluoricacid/basics/facts.asp.

for first responders to a Li-ion module fire or fire of a building containing a Li-ion battery pack, as they would also be exposed to potentially hazardous gases. While Li-ion related fires have been successfully put out by water, there is the potential for the runoff water to contain chemicals and elements like chlorine and fluorine, which could impact local water systems.[544]

8.2.1.6 Decommissioning and Disposal

The process of decommissioning and disposal of grid-scale Li-ion battery sites is capital intensive and will include similar physical hazards to the installation phase. Because battery materials may have degraded through use, there is the potential for failures that could result in fire hazards or gas emissions. Especially if these sites are located in areas of high temperature, decommissioning workers need to be protected from the potential for vented gases.

Table 14. Potential Vented Gases from Li-Ion Battery Damage

Emitted Gases	Hazards According to SDS-Praxa
Acrolein	Acute toxicity, aquatic acute toxicity, aquatic chronic toxicity, carcinogenicity, corrosive to the respiratory tract, eye damage, flammable liquid, germ cell mutagenicity, skin corrosion, skin sensitization
Biphenyl	Aquatic acute toxicity, aquatic chronic toxicity, eye irritation
Benzene	Carcinogen, eye irritation, germ cell mutagenecity, aspiration hazard
Carbon Monoxide (CO)	Acute toxicity, flammable, reproductive toxicity, specific target organ toxicity with repeated exposure
Carbonyl Sulfide	Acute toxicity, eye irritation, flammable gases
Diethyl Carbonate	Eye irritation, skin irritation, specific target organ toxicity with repeated exposure
Ethylene Carbonate	Eye irritation, skin irritation, specific target organ toxicity with repeated exposure
Ethyl Methyl Cabonate	Eye irritation, flammable liquid, skin irritation, specific target organ toxicity-repeated exposure
Styrene	Acute toxicity, eye irritation, flammable liquid, skin irritation, specific target organ toxicity-repeated exposure
Toluene	Aspiration hazard, flammable liquid, reproductive toxicity, skin irritation, specific target organ toxicity with repeated exposure

544 Mikolajczak et al., Lithium-Ion Batteries Hazard and Use Assessment.

Hydrogen (H_2)	Capable of sudden release of pressure, suffocation, flammable *(Hydrogen SDS, 2016).*
Carbon Dioxide (CO_2)	CO_2 may explode if heated, cause suffocation, increase respiration and heart rate.
Methane (CH_4)	Extremely flammable gas, may explode if heated, cause rapid suffocation, may form explosive mixture with air.
Ethylene (C_2H_4)	Contains gas under pressure, may explode if heated, causes drowsiness or dizziness, may displace oxygen and cause rapid suffocation, may form explosive mixtures with air *(Ethylene SDS, 2016).*
Propane (C_3H_8)	Explosion hazard, suffocation
Hydrogen Flouride (HF)	Acute toxicity; corrosive to the respiratory tract, skin corrosion

Source: Antonio Nedjalkov et al., "Toxic Gas Emissions from Damaged Lithium Ion Batteries—Analysis and Safety Enhancement Solution," *Batteries* 2, no. 1 (March 7, 2016): 5, doi:10.3390/batteries2010005. Prepared by: John Fodairo

California currently does not have regulations requiring recycling of large Li-ion batteries. As Li-ion use has grown to include electric vehicles (EV), electronic, and now grid applications, there is a need to assess how waste streams from these industries can be safely and sustainably handled in the state. Because Li-ion batteries continue to evolve in their chemistries and technology, there is a need for recycling processes capable of adapting with these technologies.[545] While there are recycling systems available for Li-ion battery components, potential dumping of parts in landfills in the state and abroad poses a risk of chemical leaching, especially of heavy metals such as copper, cobalt, nickel, and thallium.[546] The future of in-state Li-ion recycling will depend on the economies of material availability and the costs and environmental impacts of different disposal solutions and regulatory requirements.

Li-ion battery components can be recycled through mechanical, hydrometallurgical, and pyrometallurgical processes. In mechanical separation, battery components are sorted based on material and physical characteristics to prepare for crushing and shredding. These components are often then transported to a recycling facility to be refined for use in future batteries.[547] Hydrometallurgical processes involve dissolving component metals in acid or base solutions. The metals can then be leached from these solutions and purified for further use. Pyrometallurgical processes use high temperatures, pyrolysis, smelting, distillation, and refining to recover reusable metals. Mechanical separation usually has the highest recovery rate

545 Thomas P Hendrickson et al., "Life-Cycle Implications and Supply Chain Logistics of Electric Vehicle Battery Recycling in California," Environmental Research Letters 10, no. 1 (January 1, 2015): 14011, doi:10.1088/1748-9326/10/1/014011.

546 Daniel Hsing Po Kang, Mengjun Chen, and Oladele A. Ogunseitan, "Potential Environmental and Human Health Impacts of Rechargeable Lithium Batteries in Electronic Waste," Environmental Science & Technology 47, no. 10 (May 21, 2013): 5495–5503, doi:10.1021/es400614y.

547 J.B. Dunn et al., "Material and Energy Flows in the Materials Production, Assembly, and End-of-Life Stages of the Automotive Lithium-Ion Battery Life Cycle" (Argonne, Energy Systems Division, September 2014), https://greet.es.anl.gov/publication-lib-lca.

for metals, while pyrometallurgical has the lowest.[548] Hydrometallurgical disposal has also demonstrated lower toxicity measures in LCAs when compared to pyrometallurgical processing, though little information is presented about the specific toxic exposures. Pyrometallurgical processing involves higher energy inputs and the potential to emit VOCs from battery components at high temperatures.[549]

Li-ion recycling infrastructure poses similar hazards to battery pack installation and transportation, with the potential for added leaching of chemicals from recycling processes. Siting of recycling facilities requires careful consideration due to the potential for waste products to impact local ecosystems and communities.[550] Without administrative and engineering controls, recycling workers may be exposed to hazards related to heavy machinery, high temperatures, crushing mechanisms, and to chemical hazards associated with crushing or melting materials that produce toxic fumes or dust, including heavy metals and polyvinyl chloride.

Because EV Li-ion waste is expected to grow in the coming years, it is possible that Li-ion batteries may be re-used directly or repurposed from EV applications for grid storage. Research shows that this repurposing could have a modest effect on grid electricity availability.[551] There is a need to understand the potential for battery degradation following prolonged use, which could impact the safety and efficiency if its secondary use on the grid. This is especially a concern if Li-ion batteries are repurposed behind the meter or in uncontrolled settings. More research is needed on the potential for battery failures and hazards if EV batteries are repurposed for grid storage use.

8.2.2 Lead Acid

Lead acid (Pb-acid) batteries are well known for their vehicle applications but may also be used for larger scale grid storage applications. Some research has indicated that the cycle life of lead acid batteries may be too low for grid applications, although research into advanced lead acid battery technologies are reestablishing these batteries as a potential grid storage option.[552] From previous applications, it is known that the life cycle of lead acid batteries – from lead smelting through recycling – have been associated with significant adverse health impacts in workers, their families, and surrounding communities. If these batteries are applied for grid

548 Linda Gaines, "Lifecycle Analysis of Li-Ion Batteries an End-of-Life Issues" (ENV-Vision, Washington, D.C., May 10, 2016), http://www.epri.com/Documents/ENV-Vision/EMERGING%20AND%20CROSS-CUTTING%20ISSUES/Environmental%20Considerations%20of%20Grid%20Scale%20Battery%20Storage/Linda%20Gaines_Argonne%20Laboratory.pdf.

549 Hendrickson et al., "Life-Cycle Implications and Supply Chain Logistics of Electric Vehicle Battery Recycling in California."

550 Ibid.

551 Roger Sathre et al., "Energy and Climate Effects of Second-Life Use of Electric Vehicle Batteries in California through 2050," Journal of Power Sources 288 (August 2015): 82–91, doi:10.1016/j.jpowsour.2015.04.097.

552 Brian B. McKeon, Jun Furukawa, and Scott Fenstermacher, "Advanced Lead Acid Batteries and the Development of Grid-Scale Energy Storage Systems," Proceedings of the IEEE 102, no. 6 (June 2014): 951–63, doi:10.1109/JPROC.2014.2316823.

storage, proper enforcement of existing relevant regulations is imperative, along with consideration of new control technologies to minimize worker and community risks.

Pb-acid batteries are typically composed of a lead anode, which can be doped with other metals including antimony and graphite. The liquid electrolyte is usually composed of sulfuric acid, which can have additional components in valve regulated lead acid batteries (VRLA). These batteries reduce the water used in more traditional lead acid battery varieties as contacts, allowing for different chemical reactions to charge and discharge the battery. The anode of these batteries is often composed of lead oxide, and the separator is often polypropylene and glass. The main components of lead acid batteries are shown in Figure 15.

8.2.2.1 Materials Extraction

Lead acid batteries are composed of lead, lead oxides, polypropylene, sulfuric acid, water, glass, and antimony as shown in Figure 15. Lead mining and smelting are known environmental hazards, as it is estimated that between 357 and 857 million kg of lead are released annually into the global environment by these activities, with the potential to contaminate local water, soil, and crops.[553] In 2012, 85% of lead was mined globally for lead-acid battery production, so this industry is a main contributor to these occupational and public health hazards.[554] In the US, 99% of lead-acid batteries were recycled in 2014, so more US batteries are produced from these recycled materials.[555]

The health impacts of lead exposure are well known and include nervous system effects, cognitive dysfunction, and impaired kidney function.[556] In the short term, acute lead exposure can lead to abdominal pain, constipation, tiredness, headaches, memory loss, and irritability. More chronic exposures can lead to forgetfulness, nausea, and depression as well as high blood pressure, heart disease, kidney disease, and reduced fertility. Lead is defined as probably a human carcinogen by the International Agency for Research on Cancer (IARC).[557] Lead overexposure and toxicity has been well-documented in the US and globally in workers, their families and communities in association with lead smelting, lead battery manufacture, and battery recycling.[558]

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553 Xiuwu Zhang et al., "Impacts of Lead/Zinc Mining and Smelting on the Environment and Human Health in China," Environmental Monitoring and Assessment 184, no. 4 (April 2012): 2261–73, doi:10.1007/s10661-011-2115-6.

554 ILA, "Lead Uses - Statistics," International Lead Association, 2012, http://www.ila-lead.org/lead-facts/lead-uses--statistics.

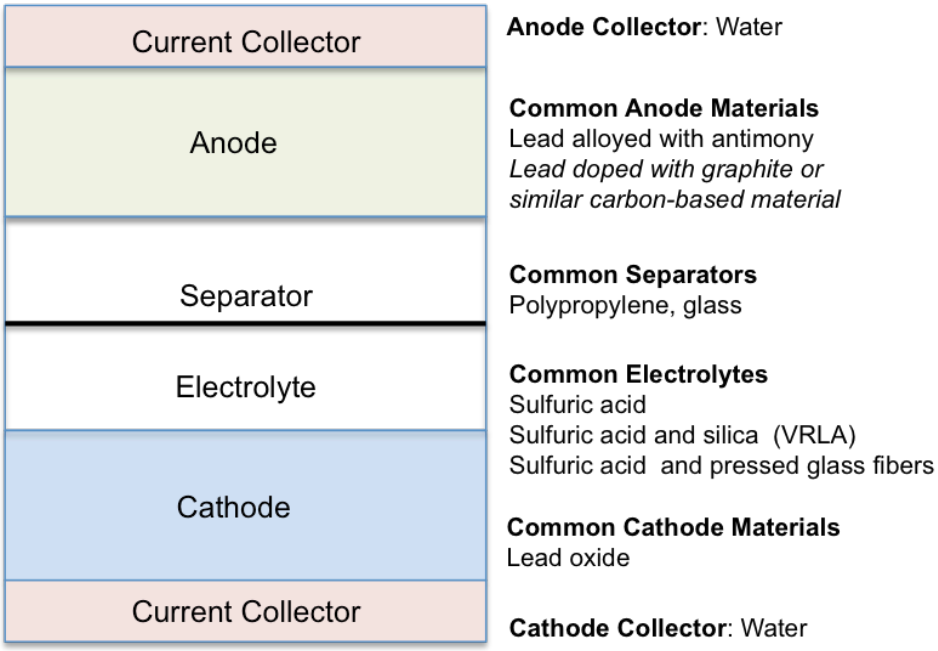
555 EPA, "Advancing Sustainable Materials Management: 2014 Fact Sheet Assessing Trends in Material Generation, Recycling, Composting, Combustion with Energy Recovery and Landfilling in the United States" (U.S. Environmental Protection Agency, November 2016), https://www.epa.gov/sites/production/files/2016-11/documents/2014_smmfactsheet_508.pdf.

556 OSHA, "Lead: Health Effects," Goverment Ageny Website, United States Department of Labor, Occupational Safety and Health Administration, (2016), https://www.osha.gov/SLTC/lead/healtheffects.html.

557 NIOSH, "Lead: Information for Workers," Goverment Agency Website, National Institute for Occupational Safety and Health, (April 19, 2017), https://www.cdc.gov/niosh/topics/lead/health.html.

558 P Meyer, M Brown, and H Falk, "Global Approach to Reducing Lead Exposure and Poisoning," Mutation Research/Reviews in Mutation Research 659, no. 1–2 (July 2008): 166–75, doi:10.1016/j.mrrev.2008.03.003; OSHA, "Lead: Battery Manufacturing eTool," Goverment Ageny Website, United States Department of Labor, Occupational Safety and Health Administration, (2010), https://www.osha.gov/SLTC/etools/battery_manufacturing/.

Figure 15. Materials in Potential Lead Acid Batteries for Grid Storage



Source: Center for Climate Change and Health (2017)

Without proper protections, communities living around lead smelting facilities are at risk of these dangerous exposures. Apart from these air emissions, lead processing can also produce liquid slag wastes containing zinc, silica, iron, arsenic, sulfate, copper, other heavy metals, and waste acids and bases used in processing.[559] Pollution from lead smelting sites is a global concern, and since lead acid batteries consume the majority of lead produced globally, this pollution is a concern the industry needs to address through informed and sustainable supply chain management.

Antimony is one of many metals that can cause metal fume fever, which results in respiratory tract irritation, decreased lung capacity, and gastrointestinal effects. The risks of chronic exposure to antimony are poorly understood. Preliminary research suggests reproductive damage and potential carcinogenicity, although antimony has not been classified by IARC as a carcinogen and further research is necessary.[560]

Advanced lead acid batteries also involve a carbon doping agent, which usually includes graphite. Mining and processing stages of this material are known for emitting large amounts of PM, impacting local air quality and increasing risk of asthma and lung disease in local

559 EPA, "Profile of the Nonferrous Metals Industry" (U.S. Environmental Protection Agency, September 1995), https://nepis.epa.gov/Exe/ZyNET.exe/50000FOZ.TXT?ZyActionD=ZyDocument&Client=EPA&Index=1995+Thru+1999&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5Czyfiles%5CIndex%20Data%5C95thru99%5CTxt%5C00000003%5C50000FOZ.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=1&SeekPage=x&ZyPURL.

560 Shyam Sundar and Jaya Chakravarty, "Antimony Toxicity," International Journal of Environmental Research and Public Health 7, no. 12 (December 20, 2010): 4267–77, doi:10.3390/ijerph7124267.

populations. Graphite production can also pollute local water systems due to inadequate controls of waste products.[561] Acute graphite exposure is associated with respiratory infections and irritation, while chronic exposure to high levels can lead to lung tumors and respiratory disease.[562] Graphite processing also uses heavy metals and solvents that may contaminate waste streams. Elevated levels of exposure are more common for workers in mining and processing facilities, though surrounding populations can also be exposed to dangerous heavy metals or solvents in waste streams. Additionally, exposure to carbon fibers in producing other carbon-based electrode materials is a potential hazard, as preliminary toxicology research has found increases in lung cancer in mice following exposure to these fibers.[563]

8.2.2.2 Manufacture

Emissions from lead processing for battery manufacture include SO_2, PM, cadmium and lead. The health impacts of lead exposure are discussed above in **Section 8.2.2.1**. Occupational exposure to cadmium can lead to pulmonary edema, breathing difficulty, chest tightness, headache, chills, muscle aches, nausea, vomiting, diarrhea, anosmia, emphysema, proteinuria, and anemia. Cadmium is also classified as a carcinogen, and occupational exposures have been associated with lung and prostate cancers.[564] These exposures can also spread to surrounding communities, as there is the potential for cadmium and lead to leach into soil and water, and to be taken up by crops surrounding a manufacturing facility.[565]

Health hazard evaluations of US based manufacturing sites have found that all employees except those working in enclosed, controlled rooms and water treatment were overexposed to lead. High levels of exposure were found in breaker, foundry, and maintenance workers.[566] In 2014, 109 adults in California were found to have blood lead levels higher than 25μg/dL from occupational exposures, and 38.9% of workers with blood lead levels above 25μg/dL in the United States were employed in battery manufacturing.[567] Lead oxide can also potentially leak from conveying and receiving machinery, further exposing workers.[568]

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561 Whoriskey, "In Your Phone, In Their Air."

562 NIOSH, "Occupational Health Guideline for Natural Graphite."

563 Grosse et al., "Carcinogenicity of Fluoro-Edenite, Silicon Carbide Fibres and Whiskers, and Carbon Nanotubes."

564 NIOSH, "Cadmium Dust (as Cd)," Goverment Agency Website, National Institute for Occupational Safety and Health, (April 11, 2016), https://www.cdc.gov/niosh/npg/npgd0087.html.

565 Zhang et al., "Impacts of Lead/Zinc Mining and Smelting on the Environment and Human Health in China"; OSHA, "Cadmium" (U.S. Department of Labor, Occupational Safety and Health Administration, 2004), https://www.osha.gov/Publications/osha3136.pdf.

566 Bradley S. King et al., "Evaluation of Employees' Exposure to Lead, Noise, and Heat at an Automotive Lead-Acid Battery Recycling Center," Health Hazard Evaluation Report (U.S. Department of Health and Human Services Centers for Disease Control and Prevention National Institute for Occupational Safety and Health, October 2014), https://www.cdc.gov/niosh/hhe/reports/pdfs/2012-0071-3224.pdf.

567 NIOSH, "Adult Blood Lead Epidemiology & Surveillance (ABLES): ABLES Data," Goverment Agency Website, National Institute for Occupational Safety and Health, (January 30, 2017), https://www.cdc.gov/niosh/topics/ables/data.html.

568 OSHA, "Lead: Battery Manufacturing eTool."

Sulfuric acid is highly corrosive and can cause burns and irritation to exposed skin and eyes. If inhaled, sulfuric acid can burn the respiratory tract and cause pulmonary edema, bronchitis, and emphysema.[569]

8.2.2.3 Transportation

Lead acid batteries need to be transported from their manufacturing site for installation in grid-level applications. A summary of transportation related emissions and hazards can be found in **Section LCA.3**. Apart from these general hazards, there is also the potential for transport workers to be exposed to corrosive acid if the battery system is damaged or leaks during transport, so workers should be trained on how to handle these potential concerns.

8.2.2.4 Installation

As noted before for Li-ion batteries, land-use for grid-scale storage facilities will be much less than for utility-scale generation facilities. However, there will still be installation impacts related to increased traffic and land clearing activities will largely be determined by the siting of these facilities. **Section LCA.4** provides a summary of these hazards.

8.2.2.5 Maintenance and Use

Leakage of sulfuric acid from a battery packs may occur due to physical damage to the battery. This leakage can lead to eye, respiratory, and skin irritation and burns in on-site maintenance and facility workers. Under certain extreme conditions, lead acid batteries can explode, leading to fire hazards for site workers and surrounding communities considering the expected large size of these facilities.[570] On August 1st, 2012, a fire broke out at the wind farm at Kahuku, Oahu, Hawaii, on a 15 MW Pb-acid battery from Xtreme Power, a Texas based energy storage start-up.[571]

8.2.2.6 Decommissioning and Disposal

By some estimates, a lead acid battery will have 500-1000 cycles in battery life, though this can reduce based on how completely the battery is discharged.[572] In the US, 99% of lead-acid batteries were recycled in 2014.[573] Lead acid battery smelting for reuse can lead to occupational exposures and to toxic air emissions from smelting facilities. There are existing regulations covering the management of spent lead acid batteries. Because lead acid batteries contain lead and sulfuric acid, disposal is regulated through hazardous waste management. Recycling lead

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569 NIOSH, "Sulfuric Acid," Goverment Agency Website, National Institute for Occupational Safety and Health, (April 11, 2016), https://www.cdc.gov/niosh/npg/npgd0577.html.

570 University of Wisconsin, Environment, Health and Safety, "Lead-Acid Battery Safety," University, (n.d.), https://www.wisconsin.edu/ehs/osh/battery-safety/.

571 Eric Wesoff, "Battery Room Fire at Kahuku Wind-Energy Storage Farm," Green Tech Media, August 3, 2012, https://www.greentechmedia.com/articles/read/Battery-Room-Fire-at-Kahuku-Wind-Energy-Storage-Farm.

572 Sullivan and Gaines, "A Review of Battery Life-Cycle Analysis: State of Knowledge and Critical Needs."

573 EPA, "Advancing Sustainable Materials Management: 2014 Fact Sheet Assessing Trends in Material Generation, Recycling, Composting, Combustion with Energy Recovery and Landfilling in the United States."

acid batteries is also regulated under hazardous waste management, and recycling facilities are required to have a hazardous waste treatment permit.[574]

At the Exide lead acid battery smelter in Vernon, CA, melting down used car batteries to refurbish into new battery sets resulted in significant toxic lead and arsenic exposures in the surrounding community. Though the site was issued many citations for lead and arsenic emissions, acid leaks, and hazardous waste management in unprotected ponds, it took many years and a federal investigation to finally shut the plant down in 2015 and clean up in surrounding homes continues. The lack of emissions control in this facility contaminated soil in the communities of Boyle Heights, East Los Angeles, Commerce, Bell, Huntington Park and Maywood, potentially exposing thousands of people [575]

Because arsenic is a known carcinogen and lead is a potent neurotoxin and affects neurodevelopment in children, emissions from this plant may have a vast impact on health in affected communities for many years. This site is an example of how recycling practices may create significant health risks for workers and communities surrounding recycling facilities, and there is need for additional research into how these batteries can be more safely recycled, protecting occupational and public health. For instance, Aqua Metals, an Oakland, CA based company, claims to be developing an electrochemical lead recycling method which is less energy intensive, eliminates toxic waste, reduces permitting and is less expensive to build than conventional smelting.[576]

8.2.3 Vanadium Redox Batteries

Though Li-ion batteries are considered the most likely to scale for widespread grid storage in the near future, due to their commercial viability, many researchers have claimed that redox flow batteries are better suited for grid storage purposes. Researchers champion these technologies for their high number of life cycles and limited safety concerns, though there is a dearth of information on life cycle hazards for these technologies.[577] Currently redox flow batteries are hindered by expense, and most chemistries have lower energy densities in comparison to Li-ion varieties, though this is more important for application in portable technologies and less so for grid storage. [578]

Functioning as a cross between a traditional battery and a fuel cell, flow batteries operate by pumping charged, liquid electrolyte through positive and negative electrodes separated by a membrane. The ion exchange that occurs between the positive and negative

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574 Department of Toxic Substances Control, "Management of Spent Lead Acid Batteries" (California Department of Toxic Substances Control, December 2006), https://www.dtsc.ca.gov/HazardousWaste/upload/FS_DutyOfficer_LeadAcidBatteries1.pdf.

575 Tony Barboza, "How a Battery Recycler Contaminated L.A.-Area Homes for Decades," LA Times, December 21, 2015, sec. Local, http://www.latimes.com/local/lanow/la-me-exide-cleanup-story-so-far-20151121-story.html.

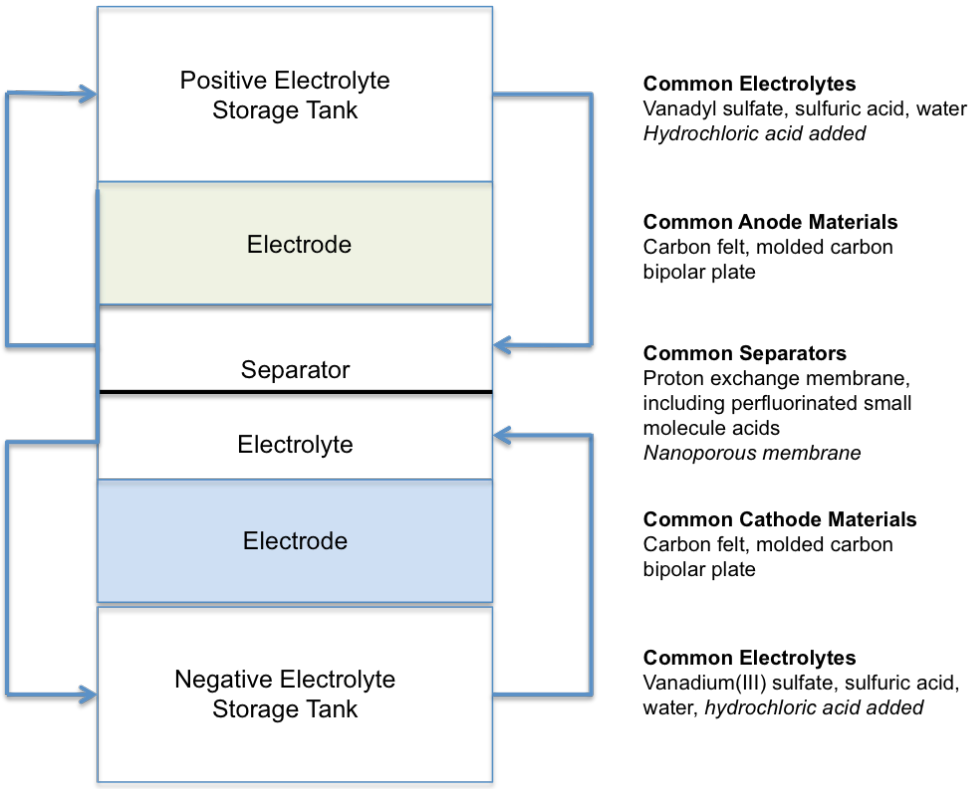
576 "Aqua Metals," Business, Aqua Metals, (2017), http://www.aquametals.com/.

577 Mitavachan Hiremath, Karen Derendorf, and Thomas Vogt, "Comparative Life Cycle Assessment of Battery Storage Systems for Stationary Applications," Environmental Science & Technology 49, no. 8 (April 21, 2015): 4825–33, doi:10.1021/es504572q.

578 Ibid.

electrodes produces electricity.[579] Vanadium flow redox batteries (VRB) are currently the most commercially viable, although other chemistries are being researched.[580] VRB technologies use vanadium compounds for both positive and negative electrolytes, and carbon-based materials for electrodes. A diagram of common VRB materials is shown in Figure 16.

Figure 16. Diagram of VRB Battery and Common Materials



Source: Center for Climate Change and Health (2017)

8.2.3.1 Materials Extraction

Because VRB batteries use large electrolyte stores, these technologies require a large amount of vanadium for wider deployment. This element is extracted through mining and recovery from petroleum. General mining hazards are described in **Section LCA.1**. 60% of the world's vanadium supply comes from vanadiferous magnetite deposits, a byproduct of iron. Vanadium is also present in coal and oil tailings, and vanadium is commonly recovered from petroleum boilers, though there is no production in the United States.[581] Exposure to vanadium through inhalation, ingestion, or dermal contact can lead to respiratory and skin irritation and asthma, and chronic exposures may lead to kidney damage. While mining and refining activities

579 Piergiorgio Alotto, Massimo Guarnieri, and Federico Moro, "Redox Flow Batteries for the Storage of Renewable Energy: A Review," Renewable and Sustainable Energy Reviews 29 (January 2014): 325–35, doi:10.1016/j.rser.2013.08.001.

580 Ibid.

581 USGS, "Vanadium," Goverment Agency Website, US Geological Survey Minerals Information, (2017), https://minerals.usgs.gov/minerals/pubs/commodity/vanadium/mcs-2017-vanad.pdf.pdf.

are the most well known routes of occupational and public exposure, there is limited data on actual exposures throughout these industries.[582]

Carbon felt and graphite are often used as electrodes in VRB.[583] Exposure to carbon fibers in producing carbon felt electrode is a potential hazard; preliminary toxicology research has found increases in lung cancer in mice following exposure to these fibers.[584] Graphite production can also pollute local water systems due to inadequate controls of waste products.[585] Graphite exposure is associated acutely with respiratory infections and irritation, while chronic exposure to high levels can lead to lung tumors and respiratory disease.[586] Graphite processing also uses heavy metals and solvents that may contaminate waste streams. Elevated levels of exposure are more common for workers in mining and processing facilities, though surrounding populations can also be exposed to dangerous heavy metals or solvents in waste streams.

8.2.3.2 Manufacture

The perfluorinated small molecule acids used for separator membranes pose potentially severe toxicity concerns. These compounds are known to be acutely toxic and capable of bioaccumulation. A commonly used variety is perfluorooctanoic acid, which has been associated with testicular and kidney cancer, as well as high cholesterol, ulcerative colitis, thyroid diseases, and preeclampsia in pregnant women.[587]

The degree to which these compounds break down to form more toxic small molecule perfluorinated acids and the extent to which toxic perfluorinated intermediates are used/disposed of in the manufacture of these polymers should be further researched.

Additional chemical exposures during manufacturing of VRB include phenol formaldehyde resin, which, in one case report of a spill, led to necrotic skin lesions, fever, hypertension, and adult respiratory distress syndrome.[588] Depending on exposures, phenol exposures can lead to skin and gastrointestinal damage and, potentially, cardiovascular disease.[589] Formaldehyde is a known human carcinogen.[590] Acute exposure to formaldehyde can

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582 Carl Johan Rydh, "Environmental Assessment of Vanadium Redox and Lead-Acid Batteries for Stationary Energy Storage," Journal of Power Sources 80, no. 1 (1999): 21–29.

583 Parasuraman et al., "Review of Material Research and Development for Vanadium Redox Flow Battery Applications."

584 Grosse et al., "Carcinogenicity of Fluoro-Edenite, Silicon Carbide Fibres and Whiskers, and Carbon Nanotubes."

585 Whoriskey, "In Your Phone, In Their Air."

586 NIOSH, "Occupational Health Guideline for Natural Graphite."

587 OECD, "OECD/UNEP Global PFC Group Synthesis Paper on per- and Polyfluorinated Chemicals (PFCs)" (United National Environmental Program, Environment, Health and Safety, Environment Directorate, OECD., 2013), https://www.oecd.org/env/ehs/risk-management/PFC_FINAL-Web.pdf.

588 N Cohen et al., "Acute Resin Phenol-Formaldehyde Intoxication: A Life Threatening Occupational Hazard," Human Toxicology 8, no. 3 (May 1989): 247–50.

589 ATSDR, "Toxic Substances Portal: Phenol," Goverment Agency Website, Agency for Toxic Substances and Disease Registry, (September 2008), https://www.atsdr.cdc.gov/phs/phs.asp?id=146&tid=27.

590 ATSDR, "Toxic Substances Portal: Formaldehyde," Goverment Agency Website, Agency for Toxic Substances and Disease Registry, (October 21, 2014), https://www.atsdr.cdc.gov/mmg/mmg.asp?id=216&tid=39.

lead to headache and trouble breathing, while higher doses may cause severe mucous membrane irritation, burning, bronchitis, pulmonary edema, or pneumonia.[591]

During electrolyte synthesis or a cell breech during assembly, exposure to high levels of vanadium could have toxic effects on workers, which are described above in **Section 8.2.3.1**.[592] The electrolyte is synthesized by reaction of vanadium with water and corrosive solutions of sulfuric acid and hydrochloric acid, which have the potential to cause severe burns if not used and stored properly. If inhaled, sulfuric acid can burn the respiratory tract and cause pulmonary edema, bronchitis, and emphysema.[593]

Nanoparticles of platinum can also be used in VRB applications. Though nanoparticles are still being researched for VRB applications, there are many health unknowns related to occupational exposure to these materials. This is due to lack of measurement tools, exposure measurements, and relevant toxicological and epidemiological studies.[594] As these chemicals continue to grow in use throughout emerging energy systems, more research is needed into the potential for occupational and public health hazards.

8.2.3.3 Transportation

VRB units are larger than traditional batteries due to the need for large electrolyte storage tanks. This will increase hazards for transport workers who will lift and load these heavy systems. A summary of transportation related emissions and hazards can be found in **Section LCA.3**.

8.2.3.4 Installation

An individual VRB unit for utility-scale grid storage applications will be larger in size than other battery units (i.e. one Li-ion unit), but grid-level storage facilities will still use less land in comparison to electricity generating facilities. **Section LCA.4** provides a summary of these hazards. VRB technologies could also be used in distributed applications in buildings, which would negate any land-use and most installation hazards.

8.2.3.5 Maintenance and Use

With large-scale VRB installations, there is the potential for liquid electrolyte to leak from breaches in the battery, including sites like the pump, tank, piping, and the battery stack. The positive electrolyte is highly oxidative, and the negative electrolyte is highly reductive, and both are very acidic due to the sulfuric acid solutions used. If leached, this electrolyte could contaminate nearby water and react with other materials. It could also cause severe burns if workers are exposed. This could be avoided by daily checks to ensure the plumbing system is

591 Ibid.

592 DOE, "Energy Storage Safety Strategic Plan."

593 NIOSH, "Sulfuric Acid."

594 A. Seaton et al., "Nanoparticles, Human Health Hazard and Regulation," Journal of The Royal Society Interface 7, no. Suppl_1 (February 6, 2010): S119–29, doi:10.1098/rsif.2009.0252.focus.

maintained and the use of a secondary encasement to hold any leached material in case of system breach.[595]

8.1.2.5 Decommissioning and Disposal

Because of the limited roll out of these systems, little is known about potential hazards for workers or the public during decommissioning of sites. These technologies are expected to have an operating lifetime of around 20 years.[596] Research into safe recycling and building for recycling is also needed. In 2004, 44% of vanadium used in the US was from recycled sources. The recycling process includes leaching with acids and bases, salt roasting, or carbon reduction. Safety mechanisms need to protect against the potential for occupational exposures to corrosive substances and potential toxic solvents involved.[597] Research into the recyclability of perfluorosulfonic membrane components has also begun.[598]

8.2.4 Sodium Sulfur Batteries

The final battery discussed in this report is one that has already been applied in some global grid applications. Sodium sulfur (Na/S) batteries have been used for load leveling in global applications from Japan and Dubai to Texas. They have a high specific energy and can be made from naturally abundant materials, unlike other battery varieties. These batteries operate at very high temperatures (300˚C or higher), so some energy input is needed to maintain these high operating temperatures, unlike other battery varieties.

Commercial Na/S batteries are typically composed of a sodium metal anode, an elemental sulfur cathode, and a solid electrolyte composed of beta-alumina ceramic. Charge collectors can be composed of graphite and copper. A diagram of common and emerging Na/S materials is shown in Figure 17.

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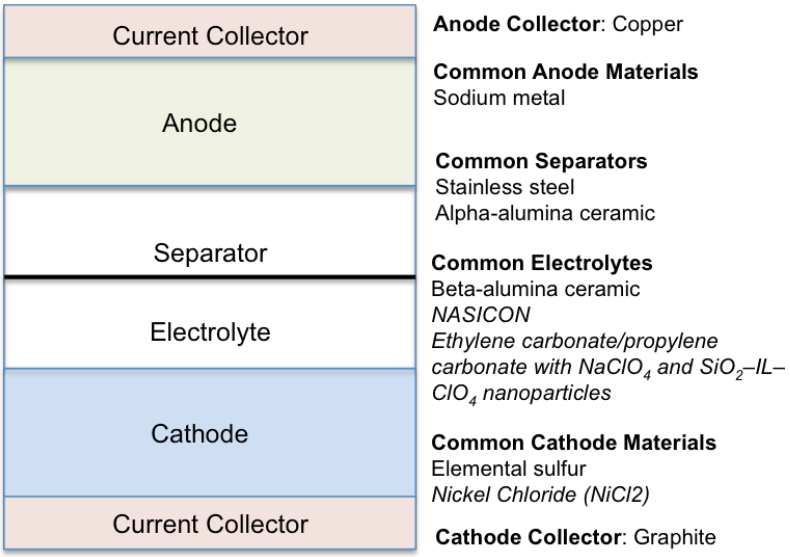
595 Chaokang Gu, Chaokang Gu on Vanadium Redox Flow Batteries, English, May 9, 2017.

596 Maryam Arbabzadeh et al., "Vanadium Redox Flow Batteries to Reach Greenhouse Gas Emissions Targets in an off-Grid Configuration," Applied Energy 146 (May 2015): 397–408, doi:10.1016/j.apenergy.2015.02.005.

597 Thomas G. Goonan, "Vanadium Recycling in the United States in 2004," U.S. GEOLOGICAL SURVEY CIRCULAR (U.S. Department of the Interior, U.S. Geological Survey, 2004), https://pubs.usgs.gov/circ/circ1196-S/pdf/FINAL4WEB_CIRC1196-S_Ver1_1.pdf.

598 H.F. Xu et al., "Recycling and Regeneration of Used Perfluorosulfonic Membranes for Polymer Electrolyte Fuel Cells," Journal of Applied Electrochemistry 32, no. 12 (2002): 1337–40.

Figure 17. Diagram of Common Na/S Materials



Source: Center for Climate Change and Health (2017)

8.2.4.1 Materials Extraction

The active components of Na/S batteries are sulfur and sodium. Sulfur is recovered from petroleum refineries, natural-gas-processing plants, and coking plants. In 2016, the US was the largest producer of sulfur, followed by China, Canada, Russia, and the UAE. However, because sulfur can be refined from fossil fuel reserves, the country of production is not always the country where the original fuel source was retrieved.[599] Sulfur recovery can assist in mitigating SOx pollution from these facilities.[600] This processing has many potential hazards, including risk of explosion from sulfur dust particles in natural gas refining.[601] Sulfur dust is a known irritant, and workers exposed to both sulfur residues and hydrogen sulfide could be at risk of respiratory irritation, chest pain, and gastrointestinal distress following inhalation or ingestion. Chronic exposure can lead to respiratory disease.[602] Waste sulfur can also mix with water resources to create sulfuric acid, which can lead to the leaching of arsenic, copper, nickel, zinc, chromium along with aluminum and iron from surrounding land.[603]

Sodium, like sulfur, is abundant in the earth's crust, and is mined as sodium carbonate, also called soda ash or trona. The United States produces most of this resource globally, with

599 USGS, "Sulfur," Goverment Ageny Website, US Geological Survey Minerals Information, (2017), https://minerals.usgs.gov/minerals/pubs/commodity/sulfur/mcs-2017-sulfu.pdf.

600 Joyce A. Ober, "Materials Flow of Sulfur" (Reston, VA: U.S. Department of the Interior, U.S. Geological Survey, 2002), https://pubs.usgs.gov/of/2002/of02-298/of02-298.pdf.

601 Yu Yanqiu and Fan Jianchun, "Research on Explosion Characteristics of Sulfur Dust and Risk Control of the Explosion," Procedia Engineering 84 (2014): 449–59, doi:10.1016/j.proeng.2014.10.455.

602 Hovensa, "Material Safety Data Sheet: Sulfur," Materials Safety Data Sheet, (2012), http://westliberty.edu/health-and-safety/files/2012/08/Sulfur.pdf.

603 US EPA, "Leviathan Mine," Goverment Ageny Website, Superfund Sites, (April 17, 2017), https://yosemite.epa.gov/r9/sfund/r9sfdocw.nsf/ViewByEPAID/CAD980673685.

four operations in Wyoming and one in California.[604] An epidemiological study of trona miners demonstrated that miners have significantly lower forced expiratory volume, a characteristic common to obstructive lung diseases like asthma and chronic obstructive pulmonary disease (COPD). Short-term exposure to trona dust was also found to increase incidence of irritation of the eyes, skin, and respiratory tract for miners.[605] Outside of early studies in 1980s, little has been done to assess potential health impacts from chronic exposure to trona.

Na/S batteries also include beta-alumina, alpha alumina, steel, aluminum, graphite, copper, polypropylene, glass, and sand components. Hazards and potential health impacts from aluminum, graphite, and copper extraction are described above in **Section 8.2.1.1**. Hazards related to general mining hazards are included in **Section LCA.1**.

8.2.4.2 Manufacture

Elemental sodium is used for the negative electrode. Sodium is a highly reactive element, presenting a fire hazard if containment systems are breached. The sulfur and sodium electrodes are separated by a solid beta alumina ceramic electrolyte, which facilitates the proton transfer from the molten sodium to the molten sulfur compartments during operation. This ceramic can be produced through solid state reactions, sol-gel process, co-precipitation, or spray-freeze-drying methods. Dopants such as Li_2O, MgO, ZrO_2 may be used, with potential risks of irritation and metal flume fever with acute exposures. Production of beta alumina ceramic materials may involve milling of components, shaping materials under high pressure, and sintering in high heat. These processes present the potential for respiratory related hazards involved with inhaling milled powders and fugitive dust, as well as those stemming from high temperatures. More research is needed on health risks associated with these processes.

8.2.4.3 Transportation

As Na/S batteries need to be transported to their installation site, communities surrounding this site and transport workers may be exposed to potential hazards. For a discussion of general transport hazards, see **Section LCA.3**.

8.2.4.4 Installation

Like other potential battery facilities for grid storage, Na/S batteries will have a small land-use footprint but can still lead to increased traffic and land clearing activities in utility-scale projects. **Section LCA.4** provides a summary of these hazards.

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604 USGS, "Soda Ash," Goverment Ageny Website, US Geological Survey Minerals Information, (2017), https://minerals.usgs.gov/minerals/pubs/commodity/soda_ash/mcs-2017-sodaa.pdf.

605 WN Rom et al., "An Epidemiologic Study of the Respiratory Effects of Trona Dust," Arch Environ Health 38, no. 2 (1983): 86–92.

8.2.4.5 Maintenance and Use

During the operation of Na/S batteries, sodium polysulfide is produced within the cell. This compound is highly corrosive, and can lead to acute skin and eye toxicity if exposure occurs, for example due to a containment breach.[606]

Fire is an inherent risk with any containment failure. In 2011, a fire broke out at a Na/S battery plant in Japan, which was determined to result from leakage of molten material from one cell, causing shorts and failure in other cells within a module. The resulting fire and molten material leakage caused more of the module to ignite, leading to a system failure.[607] Since then, the manufacturers have implemented new safety mechanisms to further separate cells in the hopes of isolating any breaches from causing larger module failures.

8.2.4.6 Decommissioning and Disposal

It is estimated that a Na/S battery will have a battery lifetime of 10-15 years.[608] Because of limited global deployment, decommissioning of these batteries will involve treatment of the sodium and polysulfide components. The polysulfide produced can also be reacted with acid to form hydrogen sulfide, a toxic gas that can cause respiratory and gastrointestinal irritation at lower concentrations and can be fatal at high concentration.[609] The economics of recycling are questionable due to the wide availability of sulfur.[610]

8.3 Chemical Storage

This report considers one hydrogen fuel cell technology for grid storage. These technologies currently have an unclear future in grid storage applications in California, and some experts predict these will have limited development by 2030. Fuel cells operate by running hydrogen or natural gas through a membrane to produce hydrogen along with secondary products like heat and water depending on cell chemistries. The hydrogen then passes through a second membrane, generating electrons. Polymer electrolyte membrane fuel cells (PEMFCs) are the primary hydrogen fuel cell technology currently under exploration for grid deployment. This report covers these technologies, as it is unclear if the will scale in the coming 10-15 years. Because of this and limited industry information on materials and hazards present, only key hazards are presented here and more research is needed to fully understand fuel cell safety impacts.

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606 D Corbus, "Environmental, Health, and Safety Issues of Sodium-Sulfur Batteries for Electric and Hybrid Vehicles: Volume II: Battery Recycling and Disposal" (National Renewable Energy Laboratory, September 1992), http://www.nrel.gov/docs/legosti/old/4680.pdf.

607 NGK, "Cause of NAS Battery Fire Incident, Safety Enhancement Measures and Resumption of Operations," NGK, June 7, 2012, http://www.ngk.co.jp/english/news/2012/0607.html.

608 Sullivan and Gaines, "A Review of Battery Life-Cycle Analysis: State of Knowledge and Critical Needs."

609 ASTDR, "Medical Management Guidelines for Hydrogen Sulfide," Agency for Toxic Substances and Disease Registry, October 21, 2014, https://www.atsdr.cdc.gov/mmg/mmg.asp?id=385&tid=67.

610 D. Corbus, "Environmental, Health, and Safety Issues of Sodium-Sulfur Batteries for Electric and Hgybrid Vehicles, Volume II: Batter Ecycling and Disposal" (National Renewable Energy Laboratory, 1992), http://www.afdc.energy.gov/pdfs/2966.pdf.

8.3.1 Materials Extraction

PEMFCs require a small amount of platinum. Though this metal makes up less than 1% of material, it leads to 89.5% of related environmental impacts due to energy and environmental demands of mining and refining.[611] Platinum is mainly sourced from South Africa, where mine-related wastes have led to local water contamination with heavy metals and particulate emissions in surrounding communities.[612] PEMFCs utilize nanoparticle platinum species. There are many health unknowns related to occupational and community exposure to these materials, due to poor measurement tools, lack of exposure measurements, and lack of relevant toxicological and epidemiological studies.[613] Further research is warranted prior to wider deployment of this technology. For general information on mining hazards, see **Section LCA.1**.

8.3.2 Manufacture

PEMFCs, like VRB technologies, can have perfluorinated small molecule acids as components of their membranes. These compounds are known to be acutely toxic and capable of bioaccumulation. Perfluorooctanoic acid is a well studied example, which has been associated with testicular and kidney cancer, as well as high cholesterol, ulcerative colitis, thyroid diseases, and preeclampsia in pregnant women.[614] The degree to which similar compounds in PEMFC membranes break down to form more toxic small molecule perfluorinated acids and the extent to which toxic perfluorinated intermediates are used/disposed of in the manufacture of these polymers should be further researched.

Hazards related to platinum and platinum nanoparticle exposures are also possible. Though nanoparticles are still being researched for chemical storage systems like PEMFCs, there are many health unknowns related to occupational exposure to these materials. This is due to lack of measurement tools, exposure measurements, and relevant toxicological and epidemiological studies.[615]

8.3.3 Transportation

As fuel cells need to be transported to their end use site, hazards for transport workers should be applied in life cycle health considerations. A discussion of general transportation related emissions and hazards can be found in **Section LCA.3**. Because damage to fuel cell encasings can lead to hydrogen gas leaks, presenting a fire hazard, workers need to be trained to respond safely to damaged fuel cells and hydrogen venting.

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611 Dominic A. Notter et al., "Life Cycle Assessment of PEM FC Applications: Electric Mobility and μ-CHP," Energy Environ. Sci. 8, no. 7 (2015): 1969–85, doi:10.1039/C5EE01082A; Wolf Vielstich, Arnold Lamm, and Hubert A. Gasteiger, eds., Handbook of Fuel Cells: Fundamentals, Technology, and Applications (Chichester, England ; Hoboken, N.J: Wiley, 2003).

612 Garvin M. Mudd and Bonnie J. Glaister, "The Environmental Costs of Platinum-PGM Mining: An Excellent Case Study In Sustainable Mining" (48th Annual Conference of Metallurgists, Canadian Metallurgical Society, Sudbury, Ontario, Canada, 2009), http://users.monash.edu.au/~gmudd/files/2009-CMS-02-Platinum-PGMs-v-Sust.pdf.

613 Seaton et al., "Nanoparticles, Human Health Hazard and Regulation."

614 OECD, "OECD/UNEP Global PFC Group Synthesis Paper on per- and Polyfluorinated Chemicals (PFCs)."

615 Seaton et al., "Nanoparticles, Human Health Hazard and Regulation."

8.3.4 Installation

Fuel cell technologies, even in utility-scale application containing many units, will have fewer impacts related to increased traffic and land clearing activities because of their small size in comparison to other energy systems. These impacts will also largely be determined by the siting of these facilities. **Section LCA.3** provides a summary of these hazards, though it is important to note that the size of storage facilities will likely decrease these impacts.

8.3.5 Maintenance and Use

Hydrogen gas produced in fuel cells is a flammable gas and can cause fires if it is not contained. Hydrogen leaks can be hard to detect because hydrogen is a colorless, odorless, and tasteless gas. Hydrogen fires are similarly difficult to detect and may begin invisibly in daylight. Workers must be trained on how to recognize signs and protect themselves against flames. Risk of fire can affect surrounding communities too. Exposure to liquid hydrogen leaks from cells may result in freeze burns, avoidable by encasing the fuel cell within protective materials while in operation.[616] More research is needed to determine the potential for perfluorinated small molecule acid membrane to emit potentially toxic gases, exposing workers and first responders to inhalation hazards if fuel cells overheat or are damaged.

8.3.6 Decommissioning and Disposal

Because fuel cells have not been used for grid-level storage, the only work done on recycling needs relates to those in vehicle applications. These fuel cells have an estimated life span of 10 years, though it is not clear how larger, grid-scale versions of these technologies will differ in life span. Fuel cell recycling is an active area of research, considering the high-value of certain components like platinum. Though certain components have known recycling mechanisms (e.g. platinum is recycled at 95% efficiency), a system has not been created for safe separation and recycling of all fuel cell materials.[617] Research into the recyclability of the perfluorosulfonic membranes used is also being done.[618] Health impacts and worker safety should be a component of researched methods.

8.4 Equity Considerations

As emerging storage technologies continue to develop, there is a need to ensure that all communities have access to these technologies and their expected benefits. Especially for new technologies being developed for home energy storage, access to these technologies should not be limited to higher-income households. Similar to policy efforts to promote solar installation

616 OSHA, "Green Job Hazards: Hydrogen Fuel Cells," Goverment Agency Website, United States Department of Labor, Occupational Safety and Health Administration, (2010), https://www.osha.gov/dep/greenjobs/hydrogen.html.

617 Rikka Wittstock, Alexandra Pehlken, and Michael Wark, "Challenges in Automotive Fuel Cells Recycling," Recycling 1, no. 3 (December 1, 2016): 343–64, doi:10.3390/recycling1030343.

618 Xu et al., "Recycling and Regeneration of Used Perfluorosulfonic Membranes for Polymer Electrolyte Fuel Cells."

and electric vehicle deployment, more work needs to be done to assure equitable access to emerging storage technologies as they continue to develop.[619]

Grid energy storage employs a variety of different workers across technology life cycles as newer technologies continue to progress towards deployment. Currently, there is no assessment of employment in energy storage. This should be added to studies of renewable energy, noting the types of jobs created, their quality, and related health and safety trainings.

For large storage facilities, development must account for where new facilities are sited and how facility installation may impact local communities. These facilities may offer opportunities for community economic development and living wage jobs, if development is appropriately implemented. Where applicable, land clearing for facility installation and decommissioning will result in transport-related emissions and potential fugitive dust for surrounding communities. Resulting impacts will depend on existing air quality concerns in sited areas and the facility type (i.e. digging for underground compressed air storage vs. slight land clearing for battery pack facility). These emission impacts could be intensified in lower income or minority communities.

Across the life cycle of emerging electrochemical and chemical storage technologies, there are also impacts for communities and workers outside of California. Especially during the material extraction, processing, manufacturing, and disposal stages for certain battery types, products used in California could negatively impact public health in vulnerable communities abroad. This can include toxic exposures, occupational hazards, and pollution from mining, manufacturing, and disposal processes. Future research needs to identify policy responses to address global health impacts of mining for, manufacturing, and disposing of emerging storage technologies in California. Many workers globally are not afforded the same wage or health and safety protections as US workers, with adverse impacts both on US workers (i.e. loss of higher-paying manufacturing job opportunities) and workers globally.

8.5 Research Needs

1. Update identification and hazard assessment of chemicals used throughout the life cycle of electrochemical storage technologies, including their environmental and occupational health and safety impacts
    a. Determine potential community health impacts of material extraction, manufacturing, and disposal
    b. Determine occupational risks based on likelihood of exposure, dose, and toxicology of substance
    c. Identify existing and emerging technologies that have relatively lower environmental risks
    d. Further develop green chemistry and safety-by-design mechanisms

2. Identify, develop, and evaluate healthy, safe, and sustainable recycling methods for electrochemical storage technologies and promote research into varieties designed for recycling

619 Dana Rubin and Evelyne St-Louis, "Evaluating the Economic and Social Implications of Participation in Clean Vehicle Rebate Programs," Transportation Research Record: Journal of the Transportation Research Board 2598 (2016), doi:10.3141/2598-08.

Chapter 9: Distribution

Adding renewable resources to the electric grid poses challenges related to intermittent generation and reliability. In cases where added generation sources are located in remote and difficult to access areas, there is also the challenge of planning and constructing new transmission lines. Microgrid applications are being championed as a means of addressing reliability concerns for certain communities while diminishing the need for larger transmission projects throughout the state. Microgrid development will allow smaller communities to produce and distribute their own electricity, in some cases even totally off the grid. Similarly, smart meters provide information and data to assist utilities and planners in better siting facilities and transmission, allowing for a smoother transition to renewable generation across the state. As smart meters and microgrid applications are currently considered essential to the creation of smarter distributed systems throughout California, this report identifies concerns related to these technological developments.

In considering the future of electricity distribution, there is the potential for technological developments to introduce new hazards "behind the meter" or at the household level outside of known safety regulations. With home battery storage, there is the potential for individuals storing electricity to share with others in a community that may not use utility company distribution lines. This could present hazards related to faulty wiring and other potential safety hazards. While these considerations are outside the scope of this report, technology development and related regulation should address these potential unintended health impacts through safe designs and grid implementation.

9.1 Smart Meters

Utility companies use smart meters to measure how much electricity, natural gas, or water a particular home or building uses. These systems are replacing traditional analog meters, and can transmit information to utility companies in real-time.[620] To do so, smart meters produce radiofrequency radiation (RFR) emissions, a form of non-ionizing radiation. This RFR is not unique to smart meters – most household electronic devices emit RFR – and smart meters, depending on the type, can emit similar RFR frequencies to garage door openers, wireless speakers, and some lower-emitting cell phones (300-928 MHz).[621] RFR can be emitted at different intensities and can be intermittent, as smart meter units often operate in short bursts.

Research looking into RFR emissions from smart meters have found that meters radiate outward, with most radiation coming from the meter's face, directed away from home and buildings.[622] Readings at the meter, therefore, may not reflect accurate exposures for building occupants. Research has looked into the level of RFR emitted from smart meters in California,

620 Rollin Richmond et al., "Health Impacts of Radio Frequency Exposure from Smart Meters" (California Council on Science and Technology, April 2011), https://ccst.us/publications/2011/2011smart-final.pdf.

621 Chuck Goldman, Roger Levy, and Janie Page, "Smart Meters: Health and Safetyy Issues," March 12, 2011.

622 Ibid.

though there is some concern that these estimates overlook the potential for increased RFR exposure in particular cases. An 2011 report measured RFR emissions from 47,000 meters in southern California, 99.5% of which emitted RFR for a maximum of 3 minutes and 10 seconds a day.[623] In certain readings, the radiation levels found were less than .8% of the federal maximum permissible exposure limit.[624] However, to send information to utility companies, as subset of smart meters act as relay meters. Relay meters, which can be located on individual homes, act as collectors for information sent from other meters in a designated area. Because this meter collects a large quantity of information as it is sent from other meters, it will be in operation mode for longer than other meters. There is limited information on how these relay meters are placed within a community and whether individual homes or buildings are potentially exposed to increased hours and levels of RFR because of them.

It is known that RFR causes both thermal and non-thermal impacts on human populations. Thermal impacts result in the warming sensation caused when a person comes into contact with a device in use and emitting radiofrequencies (i.e. a cell phone emits heat on one's face when it is in use against one's cheek). These impacts are regulated under FCC exposure standards, to which all smart meters must adhere.[625] Through these policies and due to the placement of smart meters outside of homes, these thermal impacts are considered non-threatening and easily controlled.[626]

Non-thermal impacts of RFR are not well characterized, and even less is known about RFR resulting from smart meters specifically. Studies of these impacts have almost exclusively focused on cell phone RFR, and none have looked at impacts from smart meters. However, despite limited evidence, the International Agency for Research on Cancer (IARC) classified RFR as possibly carcinogenic to humans (Group 2B). Though some studies of cell phone RFR have found positive associations between cell phone radiofrequency exposure and gliomas and acoustic neuromas, the IARC decision was made based on limited evidence from all toxicology and epidemiological studies of RFR exposure.[627]

In 2016, the National Toxicology Program (NTP) released partial findings from the Carcinogenesis Studies of Cell Phone Radiofrequency Radiation in Sprague Dawley Rats project. Because of the increased incidence of cardiac schwannoma tumors and brain glioma tumors in exposed male rats in comparison to a non-exposed group, the NTP released their findings early to the public.[628] There is concern that these findings provide new information about the potential

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623 EPRI, "Radio-Frequency Exposure Levels from Smart Meters: A Case Study of One Mode" (Electric Power Research Institute, February 2011), file:///Users/loxfordbuck/Downloads/000000000001022270.pdf.

624 Goldman, Levy, and Page, "Smart Meters: Health and Safetyy Issues."

625 Ibid.

626 Richmond et al., "Health Impacts of Radio Frequency Exposure from Smart Meters."

627 IARC, "Non-Ionizing Radiation Part II: Radiofrequency Electromagnetic Fields," IARC Monographs (Lyon, France, 2013), https://monographs.iarc.fr/ENG/Monographs/vol102/mono102.pdf.

628 Michael Wyde et al., "Report of Partial Findings from the National Toxicology Program Carcinogenesis Studies of Cell Phone Radiofrequency Radiation in Hsd: Sprague Dawley® SD Rats (Whole Body Exposure)," May 26, 2016, http://biorxiv.org/lookup/doi/10.1101/055699.

carcinogenicity of RFR, and further research is needed to clarify the relationship between RFR exposure and tumor development.

Additional research has looked at associations of RFR exposure with DNA breaks, enhanced glucose production in brain, and sleep disturbances. A review of these studies found limited applicability to smart meter exposures. While DNA breaks were found following exposure to 2450 MHz and 60 Hz RFR extra mag frequencies, these frequencies are outside the range of typical smart meters. Studies assessing glucose production in brain used RFR levels far higher and at very small distances that are not seen with typical smart meter placement and use. Finally, sleep disturbance research is inconclusive in terms of its applicability to smart meter exposures.[629]

As noted above, the levels of RFR exposure are different between cell phones and smart meters, so it is difficult to extrapolate conclusions from cell phone studies to smart meters. Compounding this further, data on actual RFR exposure associated with smart meters under a variety of operating conditions, including relay meters - for example in multiunit housing - is currently insufficient. While exposure assessments have been made from different smart meter applications, there have not been studies specifically assessing health impacts from these exposures.[630] No epidemiological studies have looked at smart meter emissions specifically. More research is needed to assess the potential for increased RFR exposure in households using smart meters and the potential for this radiation to lead to health outcomes like increased tumor development and sleep disturbance.

9.2 Microgrids

In 2016, the CEC sought to better define microgrid applications in order to better implement and integrate these systems throughout the state. As these grids interconnect loads and energy production on a smaller scale that can operate alone or connect to the larger grid when needed, they promote grid resiliency while also easing the transition to renewable sources of electricity for particular communities.[631] Grid resiliency is protected as these smaller microgrid units can maintain their own electricity production and use, allowing for the potential to "island" off the grid, especially when the grid may be down. The self-balancing ability positions microgrid development as an important tool in the state's future energy system.

Overall, when used to promote renewable generation sources, microgrids are seen as environmentally beneficial, as they assist in limiting the production of GHG and criteria pollutants from fossil fuel generation sources.[632]Apart from the reduction of these air emissions,

629 Goldman, Levy, and Page, "Smart Meters: Health and Safetyy Issues."

630 Jerrold T. Bushberg et al., "IEEE Committee on Man And Radiation—COMAR Technical Information Statement Radiofrequency Safety and Utility Smart Meters:," Health Physics 108, no. 3 (March 2015): 388–91, doi:10.1097/HP.0000000000000217.

631 Jim Bartridge et al., "Draft 2016 Environmental Performance Report of California's Electrical Generation System," Staff Report (California Energy Commission, July 2016), https://efiling.energy.ca.gov/getdocument.aspx?tn=212338.

632 Su Youli, "Economic and Environmental Impact Assessment of Micro Grid" (International MultiConference of Engineers and Computer Scientists, IMECS 2015, Hong Kong: IAENG, 2015).

microgrids can also improve health through increased grid resiliency in communities. In studies of power reliability, the social cost of unreliable power has been estimated to be $80-120 billion per year in the United States.[633] Because communities rely so much on power for every day needs – from food preparation and storage to medical equipment operation – an unreliable grid increases the vulnerability of affected populations. Promoting reliable electricity will protect certain vulnerable populations, especially those who rely on electricity for medical equipment in their homes. As they continue to be researched and implemented throughout the state, microgrids are expected to increase overall grid reliability, and promote health through better, more reliable electricity access.

There is limited information on the potential for negative environmental and health impacts from microgrids. These could result from building out transmission lines to support the microgrid infrastructure, as the related traffic and construction emissions could impact the health of individuals living near these systems. This will need to be considered in planning of microgrid systems.

9.3 Equity Considerations

In order to maximize the health benefits of emerging energy systems and innovations in electricity distribution, all communities in California should have access to these healthier technologies as they come online. In this way, if microgrids are expected to increase grid resiliency and reduce air emissions through increasing the feasibility of renewable generation, these systems should be prioritized in areas impacted by poor air quality. Lower income and minority communities should also be prioritized considering the potential for air quality health impacts to be exacerbated in these areas.

9.4 Research Needs

Regarding new distribution technologies, the main research need is ensuring that smart meter RFR emissions are well understood throughout their different uses in California.

1. Monitor exposures to extra-low-frequency electromagnetic radiation under a range of real-world conditions (e.g. multi-unit housing, relay units)
    a. Continue research into the potential from health impacts from RFR, specifically from smart meter applications and related frequencies

633 NY SERDA, "Microgrids: An Assessment of the Value, Opportunities, and Barriers to Deployment in New York State" (New York State Energy Research and Development Authority, September 2010), http://web.mit.edu/cron/project/EESP-Cambridge/microgrid/NYS-Microgrids-Roadmap.pdf.

Chapter 10: Conclusion and Research Roadmap

To date, there is a paucity of data and information on the health impacts of EES across technology life cycles. **But based on – albeit incomplete – information, the life cycle health impacts of EES have been determined to be significantly smaller than those of fossil fuel electricity production**. This is based on the magnitude and severity of potential hazards, as well as the size and vulnerability of populations exposed.

For those technologies that have had previous life cycle hazard assessments, there is a need for updated analyses as these technologies evolve. Currently, there are no mechanisms to ensure these assessments remain up-to-date, which is a problem considering how quickly some technologies are developing and changing. There are also few standardized methodologies that allow for comparison of health impacts across technology mixes and potential deployment scenarios, making it difficult to plan for future developments with a robust understanding of potential hazards or relative risk.

Across the life cycle of technologies in this report, there is the potential for health impacts on workers and the public through a range of different hazards (i.e. chemical, physical, electrical, etc.). However, there is a dearth of information available on the specific chemicals and processes used in many of these technologies and on the nature of protection for workers and fenceline communities, making a full characterization of these hazards difficult.

Moreover, climate change is the greatest health challenge of this century; strategies to reduce greenhouse gas emissions and slow climate change are thus of significant health benefit. **The health benefits of climate change mitigation and GHG emission reduction through shifting from fossil fuels to these emerging energy systems must thus be emphasized in any overall assessment of strategies to attain a healthy energy system**.

With this knowledge, the research agenda shown in Table 15 has been identified.

Table 15. Priority Research Needs

	High Priority Research Topics
	• Comparative health and health equity risk assessment across the life cycle of energy technology mixes projected for California in 2050 • Update identification and hazard assessment of materials used across technology life cycles, including environmental health, occupational safety, and community health impacts • Conduct routine life cycle hazard assessments of energy technologies • Identify, develop, and evaluate healthy, safe, and sustainable recycling methods for PV cells, wind turbine components, and electrochemical and chemical storage technologies • Expand research on safety-by-design in manufacturing processes • Develop strategies to reduce the risk of *Coccidioides* exposure associated with construction, maintenance, and operation of utility-scale energy

	facilities • Develop methods to test for presence of *Coccidioides* to facilitate risk-informed site selection • Conduct occupational and community exposure assessment across energy systems

Solar Photovoltaics	• Update identification and hazard assessment of chemicals used across the life cycle of PV cells and modules, including their environmental and occupational health and safety impacts
	  o Determine potential community health impacts of material extraction, manufacturing, and disposal
	  o Determine occupational risks based on likelihood of exposure, dose, and toxicology of substance
	  o Identify existing and emerging technologies that have relatively lower environmental and occupational risks
	  o Develop green chemistry and safety-by-design manufacturing processes
	• Identify, develop, and evaluate healthy, safe, and sustainable recycling methods for PV cells

Biomass	• Monitor emissions from different gasification technology deployment scenarios, noting differences in electricity generating technologies (i.e. engines, microturbines, fuel cells) • Monitor emissions from operating biomass facilities, noting effectiveness of applied air emission mitigation technologies and workplace exposures, and develop improved mitigation systems • Model life cycle air emissions from different biomass energy deployment scenarios, noting baseline regional air quality and possible changes in conversion technology
Geothermal	• Develop technology to reduce hydrogen sulfide emissions from geothermal facilities • Perform a health impact assessment of proposed geothermal developments and facilities in Salton Sea region, including risks associated with fugitive dust creation and other impacts on surrounding communities

Storage	• Update identification and hazard assessment of chemicals used across the life cycle of electrochemical storage technologies, including their environmental and occupational health and safety impacts
	  o Determine potential community health impacts of material extraction, manufacturing, and disposal
	  o Determine occupational risks based on likelihood of exposure, dose, and toxicology of substance
	• Identify existing and emerging technologies that have relatively lower environmental risks
	• Further develop green chemistry and safety-by-design mechanisms
	• Identify, develop, and evaluate healthy, safe, and sustainable recycling methods for electrochemical storage technologies

Occupational Health	• Assess need for occupational health and safety regulations for emerging electricity generating system implementation in California
	  o Worker and employer knowledge of hazards and related risk
	  o Health and safety training practices
	  o Implementation and enforcement of existing safety and health regulations

Equity	• Assess the *quality* of employment created throughout emerging energy system life cycles and identify strategies to incentivize access to high quality jobs that are safe and healthy with living wages and career opportunities in EES • Explore mechanisms to improve community engagement and participation

	in siting and planning of facilities
	• Develop mechanisms to promote equitable access to the benefits of EES
	• Analyze global health impacts of emerging energy systems and potential strategies to address them:
	  ○ Examine the global health impacts of emerging energy systems
	  ○ Assess best practices for addressing global impacts and the possible strategies to minimize/mitigate global impacts of emerging energy systems
	  ○ Analyze whether and how California laws, regulations, and incentives address global impacts, or could be used to address global impacts of emerging energy systems
	  ○ Identify changes needed to laws or regulations, or new initiatives needed for California to adequately address global impacts

	Medium Priority Research
Smart Meters	• Monitor exposures to extra-low-frequency electromagnetic radiation under a range of real-world conditions (e.g. multi-unit housing, relay units)
Concentrated Solar	• Assess potential health impacts of exposure during facility maintenance and end-of-life disposal of heat transfer fluids, including synthetic oils, molten salts, and supercritical CO_2 technologies

Wind Energy	• Improve infrasound exposure and impact assessment
	  ○ Exposure assessment at various turbine-receptor distances
	  ○ Epidemiological research on sleep disruption and annoyance from larger turbine design, controlling when possible for known confounders

Geothermal	• Identify health and environmental impacts of materials recovery (e.g. sulfur, lithium) from brine in California's geothermal plants
	Low Priority Research
Storage	• Assess occupational and public hazards during construction and maintenance of compressed air and flywheel facilities
Marine Energy	• Identify marine energy and offshore wind turbines impacts on California coastal fishing communities

10.1 Criteria for Prioritization

To determine the most important gaps for the Energy Commission, a criteria for prioritization was developed based on literature review and, expert interviews, and public input.[634] The outlined criteria are presented in Figure 18.

Figure 18. Criteria for Prioritization

1. Number of people exposed
   a. CA specific
   b. Global estimates
2. Likelihood of Exposures
3. Likelihood of Impact with Exposure
4. Severity of Impact
5. Available Control Technologies
6. Equity Implications
7. Feasibility of Research

634 Staff, Scientific Opportunities and Public Needs; Dandoy, "A Priority Rating System for Public Health Programs."

With available data, these criteria would prioritize research based on impacts to California residents and global populations. However, the application of these criteria was limited by lack of available data. Verified data on the number of people employed in each phase of the life cycle of EES technologies is not readily available, especially for stages occurring outside the US (i.e. miners in developing nations). Additionally, details of manufacturing processes for these technologies remains proprietary, and without access to industry inventories of chemicals used, nor to more information about the processes themselves and the safety protocols implemented, it is difficult to quantify the likelihood of exposure. Likelihood of impact with exposure and severity of impact can be determined from known toxicological understandings, though these can be limited for newer or poorly researched materials (i.e. indium tin oxide, used throughout electronics and in solar PV applications, has not been thoroughly studied in toxicological or epidemiological studies). While available control technologies and methodologies could be identified, it cannot be assumed that these are adhered to throughout EES life cycles.[635]

The lack of information made it very difficult to apply the criteria to prioritize research needs. Ultimately, research needs were prioritized based on broad estimates of the number of people exposed and levels of exposure, and knowledge about the severity of health impacts known to be associated with known exposures, with input from experts and technical advisory committee members. Because of the statutory mandates of the EPIC research program, exposures and hazards occurring in California were weighted more heavily than those occurring abroad.

The following section summarizes high, medium, and low priority research needs to explain why these research priorities were selected and to give a brief overview of how the research could be conducted.

10.2 High Priority Research

The high priority research identified in Table can be re-organized to reflect similarities in research needs across technologies. This reorganization is shown in Table 16. The research agendas for solar PV and the growing battery industry have been combined as both require research into recycling systems and updated manufacturing inventories and hazard assessment.

Table 16. High Priority Research Organized by Research Agenda

	High Priority Research Topics
Across Technologies	• Comparative health and health equity risk assessment across the life cycle of energy technology mixes projected for California in 2050 • Update identification and hazard assessment of materials used across the life cycle, including environmental health, occupational safety, and community health impacts • Conduct routine life cycle hazard assessments of energy technologies

635 Brun and European Agency for Safety and Health at Work, Green Jobs and Occupational Safety and Health; Mulloy et al., "Renewable Energy and Occupational Health and Safety Research Directions."

	○ Determine potential community health impacts of material extraction, manufacturing, and disposal ○ Determine occupational risks based on likelihood of exposure, dose, and toxicology of substance ○ Identify existing and emerging technologies that have relatively lower environmental risks compared to other cell types • Expand research on safety-by-design in manufacturing processes • Develop strategies to reduce the risk of *Coccidioides* exposure associated with construction, maintenance, and operation of utility-scale energy facilities • Develop methods to test for presence of *Coccidioides* to facilitate risk-informed site selection • Conduct occupational and community exposure assessment across energy systems
Technology Recycling	• Identify, develop, and evaluate healthy, safe, and sustainable recycling methods ○ Solar PV ○ Wind Turbine Components ○ Electrochemical Storage ○ Chemical Storage
Biomass	• Monitor emissions from different gasification technology deployment scenarios, noting differences in electricity generating technologies (i.e. engines, microturbines, fuel cells) • Monitor emissions from operating biomass facilities, noting effectiveness of applied air emission mitigation technologies and workplace exposures, and develop improved mitigation systems • Model life cycle air emissions from different biomass energy deployment scenarios, noting baseline regional air quality and possible changes in conversion technology
Geothermal	• Develop technology to reduce hydrogen sulfide emissions from geothermal facilities • Perform a health impact assessment of proposed geothermal developments and facilities in Salton Sea region, including risks associated with fugitive dust creation and other impacts on surrounding communities
Occupational Health	• Assess occupational health and safety regulations for emerging electricity generating system implementation in California ○ Worker and employer knowledge of hazards and related risk ○ Health and safety training practices ○ Implementation and enforcement of existing safety and health regulations
Equity	• Assess the *quality* of employment created throughout emerging energy system life cycles and identify strategies to incentivize access to high quality jobs that are safe and healthy with living wages and career opportunities in EES • Explore mechanisms to improve community engagement and participation in siting and planning of facilities • Develop mechanisms to promote equitable access to the benefits of EES • Analyze global health impacts of emerging energy systems and potential strategies to address them: ○ Examine the global impacts of emerging energy systems ○ Assess best practices for addressing global impacts and the possible strategies to minimize/mitigate global impacts of emerging energy systems ○ Analyze whether and how California laws, regulations, and incentives address global impacts, or could be used to address global impacts of emerging energy systems

	○ Identify changes needed to laws or regulations, or new initiatives needed for California to adequately address global impacts

10.2.1 Across Technologies

10.2.1.1 Comparative health and health equity risk assessment across the life cycle of energy technology mixes projected for California in 2050

This report focuses on the potential health impacts, and related research gaps, of various EES that will together comprise California's electricity system over the next several decades. However, no single energy technology will operate alone, and there are many options for prioritizing or subsidizing the development of one energy mix scenario over another. Ideally, these decisions should incorporate an understanding of the resulting health impacts. To plan the healthiest energy mix in California, there is a need for models and methodologies that can account for health impacts across the life cycles of multiple emerging technologies and to assess how various energy mixes effect the cumulative health and health equity impacts of California's energy system overall. These methodologies must also be able to assess how future energy scenarios compare to current energy mix relative to potential health and health equity impacts.

Little is known about the potential for health impacts across energy scenarios. Many of the subject matter experts and stakeholders interviewed for this project mentioned the need to understand how health impacts differ based on the mix of technologies in use together, rather than the health impacts of individual technologies. It is important to note, the global population health benefits associated with reducing the impacts of climate change are great. Climate mitigation is thus a public health priority. Switching from fossil-fuel electricity to EES is a key climate mitigation strategy. **Any health impacts of EES must be weighed against the significant health benefits of climate mitigation.** Ideally, methodologies will be developed that support the routine assessment of health impacts of different energy scenarios, similar to how efficiency and cost impacts are currently assessed.[636] Of course any cross-technology assessment would be limited by research and data gaps regarding the health impacts of individual technologies.

Comparative risk assessment (CRA) is an example of one methodology that, in principle, can be used to quantify the change in the burden of disease and injury due to different energy scenarios, including comparison to a business-as-usual scenario.[637] CRA has already been used to assess air pollution and other public health risks and co-benefits in scenarios based on California's strategies (AB32, SB375) to mitigate greenhouse gases.[638] The health outcomes are

636 Dale, "A Comparative Analysis of Energy Costs of Photovoltaic, Solar Thermal, and Wind Electricity Generation Technologies."

637 Ezzati et al., "Comparative Quantification of Health Risks: Global and Regional Burden of Disease Attributable to Selected Major Risk Factors."

638 Zapata, Muller, and Kleeman, "PM2.5 Co-Benefits of Climate Change Legislation Part 1: California's AB 32."; Maizlish, Linesch, and Woodcock, "Health and Greenhouse Gas Mitigation Benefits of Ambitious Expansion of Cycling, Walking, and Transit in California."

usually expressed as deaths or measures of premature mortality and morbidity such as disability adjusted life years (DALYs), which can be monetized. This approach can account for exposures and health pathways in each segment of the EES life cycle (where sufficient information is available) and in each population affected. CRA using existing databases for the burden of disease would be most sensitive to the health impacts of chronic disease and fatal and serious injuries, rather than non-disabling illness.[639]

The key data needed to conduct population-based CRA include: (1) the health risks associated with a particular chemical, material, or process; (2) the dose response relationship between that risk and the health outcomes of concern; (3) the magnitude and duration of exposure; and (4) the percentage of the population that is exposed to the life cycle specific risk (where population might be a workforce, a specific community, the population of California, etc.). Sources of this data may include toxicology and epidemiology studies, administrative data, industrial hygiene and environmental monitoring data, and population surveys. Additionally, assessment of the health impacts of various energy scenarios requires the availability of scenario models that incorporate not only specific technologies but also likely geographic distribution of implementation of these technologies.

However, as noted throughout this report, much of the data required for CRA of California's energy mix scenarios in currently unavailable. A full inventory of the chemicals and materials used in various EES is not available because much of the information remains proprietary. Very little population or environmental exposure data (workplace or community) is available, and this is particularly true for mining, manufacturing, and recycling/disposal processes occurring outside of the U.S. For some chemicals/materials and processes, there is little toxicological or epidemiological data currently available on the risks and health impacts.

10.2.1.2 Update identification and hazard assessment of materials used across the life cycle, including environmental health, occupational safety, and community health impacts

There is an important need for methodologies that allow for the routine assessment of the life cycle health impacts of energy technologies proposed for development, similar to how technology efficiency and cost impacts are considered currently.[640] Hazard assessment is one important component in the evaluation of these impacts that could be relatively easily integrated with existing tools and data available to the industry.

New processes and technologies are being researched, developed, and implemented constantly throughout the renewables industry. For example, the CEC completed an inventory of solar PV materials in 2004, looking across cell and module life cycles to understand potential environmental risks from the materials used. However, PV technology has changed, and an updated PV material inventory is needed. Moreover, most extant assessments of PV materials are already outdated and do not account for potential occupational health and safety considerations (versus environmental impacts).

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639 IHME, "Global Burden of Disease (GBD)."

640 Dale, "A Comparative Analysis of Energy Costs of Photovoltaic, Solar Thermal, and Wind Electricity Generation Technologies."

Therefore, there is a need for updated inventories *and* hazard assessments for materials used across the life cycle in EES, including those proposed for future applications. There are existing tools, such as GreenScreen, that can be used to screen for potential hazards.[641] This would allow developers to seek less hazardous materials for use in technologies under development, manufacturers to implement better-informed procurement procedures, and employers to improve health and safety in worksites across the life cycle.

Given the importance of and likely very rapid expansion of existing and new grid storage technologies (e.g. Li-ion and redox flow batteries), these deserve priority in terms of materials inventory, hazard assessment, and understanding of mechanisms to ensure worker and community protection. As solar PV systems continue to develop and evolve, updating related material inventories and hazard assessments would also be important.

Such assessments, where applicable, should also include hazards and pollution related to material extraction processes. For instance, Li-ion batteries for smaller electronic applications have led to an increase in dangerous fugitive emissions from mining practices across the world, including in the Democratic Republic of the Congo and China.[642] Similarly for wind turbines, direct drive, magnetized technologies increase the need for rare-earth elements like neodymium and dysprosium. This leads to pollution in communities surrounding these mining communities, mostly in Asia.[643] These hazards have not yet been added to many life cycle assessments of the environmental impacts from these technologies, but must be considered to understand the full life cycle impact of these technologies.[644]

10.2.1.3 Conduct routine life cycle hazard assessments of energy technologies

Conduct more routine life cycle hazard assessments to augment and update understanding of the health risks and impacts of specific energy technologies, particularly as the specific processes and materials used in current technologies evolve, and as new technologies emerge. While emissions data may not be available for California for all of these systems, data can be extrapolated from global assessments.[645] More recent inventories and hazard assessments of emerging energy system materials would promote optimal worker and community health by identifying where greater protections are needed and to ensure technologies are safe across their life cycles.

10.2.1.4 Expand research on safety-by-design in manufacturing processes

With more information from updated, routine hazard assessments, more information would be available regarding where potential health impacts could result from energy system production, use, and disposal. There are existing tools, such as GreenScreen, that can be used to

641 GreenScreen, "GreenScreen for Safer Chemicals."

642 Frankel, "The Cobalt Pipeline."

643 Ives, "Boom in Mining Rare Earths Poses Mounting Toxic Risks."

644 Hertwich, Aloisi de Larderel, and Suh, "Green Energy Choices: The Benefits, Risks, and Trade-Offs of Low-Carbon Technologies for Electricity Production."

645 Ibid.

screen for potential hazards across technology life cycles, while also identifying potential substitutes.[646] This would allow developers to seek less hazardous materials for use in technologies under development, manufacturers to implement better-informed procurement procedures, and employers to improve health and safety in worksites across the life cycle. By incorporating safety-by-design methodologies across energy technology life cycles, hazards related to their manufacture, use, and disposal could be controlled for before a product enters the market.

10.2.1.5 Develop strategies to reduce the risk of *Coccidioides* exposure associated with construction, maintenance, and operation of utility-scale energy facilities

New large-scale renewable electricity generating facilities will be necessary to reach California's renewable energy goals. Land clearing and maintenance practices during the construction and use stages of these technologies can result in soil disturbance, releasing *Coccidioides* fungal spores into the air. When exposed, workers on site and populations breathing in fugitive dust from the facility can develop Valley Fever (coccidioidomycosis), or a severe lung infection that can be fatal. This is a known hazard, and the California Department of Public Health has identified workers that were exposed during construction of solar facilities in San Luis Obispo County.[647] The exact dispersal of this fungus in California's soil is not accurately known, nor is it known how far spores can travel in air. Without this information, it will be difficult to safely site facilities and prevent worker and community exposures.

Apart from the risk of exposing populations to *Coccidioides* spores, land-clearing and maintenance practices for utility-scale facilities can also result in environmental degradation, due to the removal of native vegetation and use of potentially toxic herbicide chemicals. When vegetation is removed, soil can become more vulnerable to erosion and surrounding populations can be exposed to greater amounts of fugitive dust from the site.

To promote safe facility installations and maintenance, there is a need to develop alternatives to land-clearing practices. This would also reduce the environmental impact of utility-scale facilities. Currently, practices like soil moistening and reduction of off-road vehicle use can be implemented to reduce dust on site and fugitive dust in surrounding communities. However, the California Occupational Safety and Health Administration (CalOSHA) investigated one site and found that these protective measures were not being taken.[648] The previously mentioned CDPH study also noted that the permitting process for the solar site included coccidioidomycosis safety training for all employees. However, these practices did not fully prevent exposure. While alternatives to land clearing are developed, the effectiveness of different mitigation practices should be studied, so that workers and surrounding populations can be given the best tools to prevent infection. Current safety practices and training also need to be implemented and enforced across new energy system installations.

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646 GreenScreen, "GreenScreen for Safer Chemicals."

647 Wilken et al., "Coccidioidomycosis among Workers Constructing Solar Power Farms, California, USA, 2011–2014."

648 Gold, Interview with Deborah Gold, California Division of Occupational Safety and Health.

10.2.1.6 Develop methods to test for presence of *Coccidioides* to facilitate risk-informed site selection

Institutions like the Centers for Disease Control and Prevention have voiced interest in developing sensors and monitors that could detect the presence of *Coccidioides* in soil and air.[649] With this technical ability, facilities could be sited with more information, further protecting workers and surrounding communities. Developing these technologies could facilitate implementation of measures to prevent infection in many communities of California workers and fenceline populations as these facilities are built in the future.

10.2.1.7 Conduct occupational and community exposure assessment across energy systems

Occupational health and safety in worksites across all stages of EES technology life cycles should be assessed. There is currently very little information available as to the industry-wide implementation of best practices (e.g. engineering and administrative controls, personal protective equipment, training) to protect workers from occupational health and safety risks. While this is particularly true in facilities abroad, it remains a significant concern in California and the U.S.

Similarly, exposures in fenceline communities (e.g. fugitive dust from land clearing for utility-scale solar PV sites) and implementation of best practices to minimize them are poorly characterized. This is especially the case for *Coccidioides* fungal exposures, as more information is needed about where these spores are found in California soils, distances traveled in fugitive dust, and how this spread can be mitigated most effectively.

10.2.2 Technology Recycling

Identify, develop, and evaluate healthy, safe, and sustainable recycling methods for solar PV cells, wind turbine components, and electrochemical and chemical storage technologies

As California's installed solar and wind capacity continues to age and growth in renewable energy sources and storage technologies increases in the coming years, there is an urgent need for the state to invest in research for eventual recycling of these systems' components. In comparison to other disposal methods, safe recycling would create more sustainable technologies, in that repurposing spent materials may reduce the need for extracting new materials, some of which may be limited in supply. Reducing extraction will also reduce risks related to mining and processing of primary materials. Though some solar PV modules are currently being re-classified as universal waste and certain battery technologies are already counted in this category, investment in recycling processes would prevent the growth of hazardous and universal waste facilities throughout the state and of less regulated waste disposal facilities abroad.

Certain PV companies like First Solar have recycling methods for their products. Additionally, certain batteries have known recycling mechanisms. However, these processes have historically been associated with significant environmental and community health risks, as

649 Materna et al., Interview with CDPH RE: Coccidioidomycosis.

was seen at the Exide Technologies plant in Los Angeles, which polluted local communities with lead and arsenic during lead battery smelting and repurposing.[650] Considering the vast environmental and health implications of the global e-waste crisis, it is imperative that better systems are developed to process and repurpose spent energy technologies. Therefore, it is critical to identify and develop healthy recycling systems. This would protect workers and communities from potentially toxic emissions, facility waste, and environmental contamination potentially associated with less healthy recycling practices.

10.2.3 Biomass

10.2.3.1 Monitor emissions from different gasification technology deployment scenarios, noting differences in electricity generating technologies (i.e. engines, microturbines, fuel cells)

Gasification of solid biomass is considered a cleaner conversion technology to conventional combustion boilers as it results in fewer air emissions. However, there is limited data available on emissions from these technologies, and many environmental and health impact assessments of proposed gasification facilities use data from older, combustion technologies.[651] There is a need to monitor emissions from the small-scale systems being deployed in the state, accounting for the differences in technology and conversion systems and for local air quality considerations. Though outside of the scope of this report, emissions from gasification for biofuel production should also be considered.

With gasification developments, researchers believe that biomass-related emissions should decrease further with the use of cleaner technologies like fuel cells and microturbines to convert syngas into electricity. It has not been determined how these technologies are likely to scale considering economic and technological advancements. Emission monitoring should account for the wide scope of different biomass electricity producing technologies available, which would help in prioritizing those with fewer emissions for future development.

10.2.3.2 Monitor emissions from operating biomass facilities, noting effectiveness of applied air emission mitigation technologies and workplace exposures, and develop improved mitigation systems

Though gasification systems are being promoted for biomass energy generation in the future, some of the state's combustion systems will remain in place. A number of community advocates have suggested that existing emission mitigation for combustion facilities is inadequate to protect the health of nearby communities.[652] Better knowledge of existing biomass facility emissions is necessary, coupled with assessment of the effectiveness of emerging emissions mitigation technologies in real-world applications. This information could also be

650 Barboza, "How a Battery Recycler Contaminated L.A.-Area Homes for Decades."

651 Air Permitting Specialists, "Final Report: Analysis of Public Health Risks Associated with Operation of a Biomass Power Plant"; Ascent Environmental, Inc., "Cabin Creek Biomass Facility Project: Final Environmental Impact Report"; Sequoia Foundation, "A Health Impact Assessment of the Proposed Cabin Creek Biomass Energy Facility in Placer County, California."

652 Weller et al., "Comments on Draft Forest Carbon Action Plan."

used to inform prioritization of newer mitigation technologies, and enforcement of air quality standards.

This is especially important in areas of the state where emissions from existing biomass could exacerbate existing poor air quality concerns. In the case of biomass energy production from agriculture waste and dairy digesters, energy production is expected to reduce emissions related to open burning and open manure lagoon emissions in areas of the state already suffering from poor air quality. However, these systems will have associated emissions, especially if combustion systems continue to be prevalent. Because of this, effective emission controls are essential. Current systems should be assessed for effectiveness, while also prioritizing research and development into better emission controls and lower-emitting technologies.

Occupational exposures throughout biomass facility operation are not well characterized. Personal exposure monitors, dust monitors, and filters for fungal and bacteria sampling can be used to assess workers' potential inhalation exposures.[653] These methods should be applied to different stages of the life cycle of plants, providing a better understanding of occupational exposures and the potential need for exposure controls throughout sourcing, processing, and facility use.

10.2.3.3 Model life cycle air emissions from different biomass energy deployment scenarios, noting baseline regional air quality and possible changes in conversion technology

Current air quality assessments from biomass facilities may overlook emissions related to feedstock transport and site installation and maintenance. Emissions across the life cycle of biomass energy production should be included in assessments of potential environmental and health impacts. This is especially important for biomass energy generation in regions of the state with poor air quality (i.e. San Joaquin Valley), where cumulative emissions from transportation, installation, and facility use can have pronounced effects on the health of surrounding communities.

Both the location of biomass facilities in relation to their feedstocks and the conversion technologies used will affect potential health impacts. Specific, localized impact assessment models of likely biomass energy developments should account for these considerations, complemented by more comprehensive air emission assessments that consider cumulative impacts from multiple facilities and sources. For instance, if forest waste is trucked into multiple biomass facilities in the Central Valley, this will have negative impacts from both transportation and biomass facilities in an area with baseline poor air quality. However, if this feedstock can be realistically processed with emerging, distributed gasification systems, transport and facility-related emissions would be lessened and located in areas of the state with better air quality overall.

Biomass energy generation has been proposed as an important component of the state's response to statewide tree death from drought, pest infestation, and wildfires. However, there

653 Rohr et al., "Potential Occupational Exposures and Health Risks Associated with Biomass-Based Power Generation."

is as yet insufficient research to determine the extent to which processing biomass energy may reduce wildfires, or how many facilities would be required to process forest waste (currently and not-yet collected). More comprehensive modeling of potential biomass generation scenarios coupled with comparative health risk assessment of these scenarios (vs. other management options, such as more open burning of forest waste) could inform strategies to minimize health impacts while increasing biomass energy, managing forest wastes, and reducing wildfire risks.

10.2.4 Geothermal

10.2.4.1 Develop technology to reduce hydrogen sulfide emissions from geothermal facilities

Researchers have noted that there are sites located throughout California that are ideal for geothermal energy production that have not yet been tapped. Some researchers think that site development is limited in part by inadequate hydrogen sulfide emission abatement technologies (though primarily by cost considerations). Hydrogen sulfide emissions will differ based on the specific geology of facility sites. For sites with higher emissions, current mitigation technologies may not be adequate. Research on developing technologies that better prevent hydrogen sulfide emissions within facilities for workers and surrounding communities is thus important for further safe development of potential geothermal energy sites, especially for potential sites for flash facility build out in Geysers region and other regions with high hydrogen sulfide emissions. Collection of sulfur from these abatement technologies could potentially be used as a component of agricultural fertilizer, producing a possible profit from emission reduction technology and reducing net cost of emission mitigation.

10.2.4.2 Perform a health impact assessment of proposed geothermal developments and facilities in Salton Sea region, including risks associated with fugitive dust creation and other impacts on surrounding communities

Special attention is required to geothermal energy development in the Salton Sea region, because dust samples from dried areas of the Salton Sea have shown pesticide and heavy metal contamination, increasing the risk of health impacts when inhaled.[654] In order to prevent adverse health outcomes from geothermal development in this area, a health impact assessment should be undertaken to identify potential hazards and emissions for surrounding communities so that mitigation efforts can be better formalized. There will be a need for continuous monitoring of dust formation and fugitive dust spread to local communities, particularly during site preparation and development. Research on effective strategies to reduce toxic dust exposures is needed, as well as emergency planning to reduce exposures if monitoring demonstrates high dust levels. A better assessment of the risk of toxic dust exposure - and strategies to reduce any related risk – should be conducted before development of a large project.

10.2.5 Occupational Health

654 Iovenko, "Toxic Dust From a Dying California Lake"; Olmedo, Interview with Luis Olmedo, Comite Civico del Valle.

10.2.5.1 Assess occupational health and safety regulations for emerging electricity generating system implementation in California

Many informants have expressed concerns that required and recommended occupational health and safety practices are not being adequately implemented in emerging energy fields. For instance, installation of distributed rooftop solar on rooftops includes significant risks found throughout roofing occupations. However, occupational health experts provide anecdotal evidence that common safety protocols (i.e. personal fall arrest systems) have not been routinely implemented in solar panel installations.[655] Similarly, for wind turbine maintenance, workers often have to climb up a narrow, tall ladder to access the turbine's nacelle. Some CalOSHA inspections have found that these ladders did not meet the California Occupational Safety and Health Administration (CalOSHA) standards for ladders, as they did not include cages or landings to prevent falling injuries. While wind companies initially argued that wind turbine ladders did not fall under ladder standards, the federal Occupational Safety and Health Administration eventually required compliance with federal ladder standards.[656] Similarly, current known mitigation strategies to reduce the risks of coccidioidomycosis in jobsites with land clearing (i.e. soil moistening) are not always implemented. Some have raised concerns as to whether marine and offshore wind energy workers will receive the same training and protections currently required for offshore oil workers facing harsh marine environments.

California's ambitious renewable energy goals into 2050 will require construction of large-scale facilities and build out of smaller distributed systems throughout the state. While this will employ a high number of Californians in construction and maintenance of these facilities and installation of distributed systems, the state must ensure that these jobs are safe and protected under related regulations. As new technologies come online, workers involved throughout their life cycle need to be protected. An assessment of current health and safety practices in EES would inform workers, employers, and regulators as to the need to improve efforts to implement and enforce best practices to protect worker health and safety.

10.2.6 Equity Concerns

10.2.6.1 Assess the *quality* of employment created throughout emerging energy system life cycles and identify strategies to incentivize access to high quality jobs that are safe and healthy with living wages and career opportunities in EES

Access to quality jobs (i.e. a living wage compensation, safe and healthy, opportunities for advancement, health and other benefits) is a fundamental determinant of health. While ample work has been done on the number of jobs expected from renewable development, few studies have focused on the quality of these positions. However, research suggests that some renewable energy jobs are of higher quality than others. For instance, one assessment found that employment in utility-scale facility installation (often unionized) offered more skills

655 Stock and El-Askari, Interview with Laura Stock and Nazima El-Askari, Labor and Occupational Health Program, UC Berkeley.

656 Gold, Interview with Deborah Gold, California Division of Occupational Safety and Health.

development, advancement opportunities, safety training, and higher wages than distributed solar installation.[657]

More information about the pay scale, benefits, skills development and advancement opportunities, health and safety training and conditions, and unionization would help to identify the need for and strategies to improve the quality of EES jobs (i.e. apprenticeship programs that provide broad skills development to diversify future career options). In addition, data on the demographics of EES employment - particularly regarding employment of people of color and those from disadvantaged communities - could facilitate strategies to increase opportunities for all segments of California's working population to benefit from high quality jobs in EES.

10.2.6.2 Explore mechanisms to improve community engagement and participation in siting and planning of facilities

Concerns still abound that community needs are overlooked in the siting of new energy facilities. Hazards such as exposure to *Coccidioides* fungi in fugitive dust from facility construction or emissions from diesel trucks during transport and installation impact communities surrounding these new facilities. While there are fewer emissions during the maintenance and use phase of most renewable sources when compared to fossil fuel combustion, communities may still be impacted negatively, particularly when EES facilities may add to the cumulative impacts of multiple emissions sources in regions with poor air quality and high disease burden.

Community attitudes about the siting of EES facilities are likely to vary substantially, given variables such as community exposures, concerns, and economic status. For instance, as referenced in **Section 10.2.3.3,** some low-income communities are facing an increased wildfire risk due to tree die-off. The potential health risks of wildfire emissions relative to any potential emissions from expansion or construction of new biomass promote implementing this system in some of these areas, despite the technology's emissions. Other communities are more hesitant toward new energy system developments, for example, around the Salton Sea. In this region, communities fear that toxic dust, containing pesticide and heavy metals like arsenic, will be further disturbed when building geothermal systems in the area, exposing local communities. To better respond to these concerns, an evaluation of previous strategies used to engage communities on siting issues could provide a basis for further exploration of how community engagement in project siting and planning can be improved.

10.2.6.3 Develop mechanisms to promote equitable access to the benefits of EES

The California Energy Commission has conducted some assessment of current barriers for access to the benefits of EES among low-income households and disadvantaged communities.[658] This work has focused on access to renewable energy systems (especially solar

657 Jones and Zabin, "Are Solar Energy Jobs Good Jobs?"

658 Scavo et al., "A Study of Barriers and Solutions to Energy Efficiency, Renewables, and Contracting Opportunities Among Low-Income Customers and Disadvantaged Communities."

PV) and energy efficiency improvements in lower income communities. Research has shown that access to emerging technologies is not equitable across all communities, as lower income populations are often left behind.[659]

Mechanisms to improve access to these technologies in all communities (i.e. forums to share best practices on current projects located in disadvantaged communities) should be further explored, and energy developments should be analyzed for the potential action points to promote equitable access. While outside the scope of this report, research is needed to identify effective strategies to fully assure benefit to disadvantaged communities from decarbonization across sectors (i.e. in transportation electrification).

10.2.6.4 Analyze global health impacts of emerging energy systems and potential strategies to address them

Energy systems used in California may have health impacts globally. These impacts can occur at a variety of stages of the energy system's life cycle beginning at the initial stage of raw material extraction, and extending all the way through the end-of-life disposal of the energy system.

To understand how to respond to these global challenges, an assessment of best practices for addressing global impacts across industries should be conducted, along with an analysis of possible strategies to minimize and mitigate global impacts of emerging energy systems. There are a number of existing efforts that address global health impacts (e.g. Framework for Responsible Mining, Basel Convention, etc.). These and other public or private efforts, tools, and resources, should be considered for assessing best practices and possible strategies to minimize and mitigate global impacts of emerging energy systems.

Some components of emerging energy systems may fall under California's existing regulations or incentives, but others may not. As a result, it is important that an analysis be undertaken of current policies, regulations, and incentives to determine how global impacts of emerging energy systems are, or are not accounted for in current policies and regulations. Recognizing and accounting for the global impacts of products used in California is not a new concept for California state government. California was the first state to legislate on electronic waste - "e-waste". Senate Bill 20 (1993) set out a framework for regulating e-waste and notes:

> *"Electronic waste recovered for recycling, including devices from California public agencies, has been found to have been illegally handled and discarded in developing countries, posing a significant threat to public health, worker safety, and the environment in those countries."* [SB 20 (1993), Section 1(g)].

In addition, AB 1879 (2008) required the Department of Toxic Substances Control to adopt regulations to identify and prioritize chemicals in consumer products, which has led to regulations that provide for life cycle analysis of products and the consideration of potential exposures of the chemicals over a product's life cycle, including the "manufacturing, use,

659 Ibid.

storage, transportation, waste, and end-of-life management *and the location of these practices*." [22 CCR §69503.3(b)(4)(A)].

These legislative and regulatory efforts, as well as other state government efforts such as CalRecycle's Extended Producer Responsibility Framework should be assessed for their implications for addressing offshore impacts of emerging energy systems.[660] Addressing global impacts may require changes to laws or regulations or entirely new initiatives. Identifying these items early on will position California well to address global impacts.

10.3 Medium Priority Research

Table 17. Medium Priority Research

	Medium Priority Research
Smart Meters	• Monitor exposures to extra-low-frequency electromagnetic radiation under a range of real-world conditions (e.g. multi-unit housing, relay units) and assess potential for related health impacts
Concentrated Solar	• Assess potential health impacts of exposure during facility maintenance and end-of-life disposal of heat transfer fluids, including synthetic oils, molten salts, and supercritical CO_2 technologies

Wind Energy	• Improve infrasound exposure and impact assessment
	  ○ Exposure assessment at various turbine-receptor distances
	  ○ Epidemiological research on sleep disruption and annoyance from larger turbine design, controlling when possible for known confounders

Geothermal	• Identify health and environmental impacts of materials recovery (e.g. sulfur, lithium) from brine in California's geothermal plants

10.3.1 Smart Meters

Monitor exposures to extra-low-frequency electromagnetic radiation under a range of real-world conditions (e.g. multi-unit housing, relay units)

Smart meters are used throughout California to inform utility companies of how electricity is being used throughout the state. To transmit this information, smart meters produce radiofrequency radiation (RFR) – sending a pulse into the surrounding environment whenever actively transmitting or receiving information. The California Council on Science and Technology produced an extensive report on smart meter emissions and the potential for related impacts, which determined that smart meters result in lower RFR emissions than other household electronics and that studies to date have not assessed potential impacts from RFR of smart meters.[661] However, the report also concluded that there is currently not enough information available on potential impacts to suggest major changes to current standards.[662]

660 CalRecycle, "Attachment 1: Overall Framework for an Extended Producer Responsibility System in California."

661 Richmond et al., "Health Impacts of Radio Frequency Exposure from Smart Meters."

662 Ibid.

However, the National Toxicology Program recently released results from a study on the impacts of cell phone RFR exposure in rats that found a higher rate of brain schwannomas and cardiac glioma tumors in exposed rats. This study raises significant concerns about RFR especially because of the potentially ubiquitous exposures from multiple sources.[663]

Cell phones emit higher levels of RFR than smart meters. One assessment of RFR exposure from smart meters suggests limited exposure only while the smart meter is active.[664] However, experts have expressed concern that these assessments inadequately address settings where RFR exposure could be greater. For instance, multi-unit buildings including more than one smart meter may produce a higher cumulative RFR exposure for residents. Houses or buildings with relay meters –meters used to collect information from other meters in a specific area – may also produce higher and more prolonged RFR exposures. Real-world exposure assessment, for example including multi-unit housing and relay meters, would provide greater certainty regarding RFR exposure levels associated with smart meters.

10.3.2 Concentrated Solar

Assess potential health impacts of exposure during facility maintenance and end-of-life disposal of heat transfer fluids, including synthetic oils, molten salts, and supercritical CO_2 technologies

In life cycle assessments of concentrated solar systems (CSP), the main health hazard presented is that of occupational exposure to heat transfer fluids.[665] The type of heat transfer fluid used will determine the risk to workers and surrounding communities. As systems reduce the use of synthetic oils in favor of molten salts, the potential toxicity hazard is reduced. However, how these salts are ultimately disposed of or repurposed after facility decommissioning will impact local communities. Due to concerns about nitrate contamination of groundwater, these salts must be disposed of in a way that protects water resources and more information is needed on end-of-life practices for these substances. This is also true for potentially hazardous mixtures of liquid metals that are being developed for CSP HTF applications, as well as supercritical CO_2 technologies, which would improve efficiency while also potentially increasing risk of hazard exposures with system leaks.[666]

In order to prevent occupational health outcomes related to HTF exposure, more research is needed to determine how often workers are exposed, the nature of these exposure determined by different HTF materials, and the potential for toxic effects following continued exposure across an individual's employment. Because many of California's facilities use a combination of solar salt and steam as HTF, the potential for toxic hazards is limited. However,

663 Wyde et al., "Report of Partial Findings from the National Toxicology Program Carcinogenesis Studies of Cell Phone Radiofrequency Radiation in Hsd."

664 EPRI, "Radio-Frequency Exposure Levels from Smart Meters: A Case Study of One Mode."

665 Hertwich, Aloisi de Larderel, and Suh, "Green Energy Choices: The Benefits, Risks, and Trade-Offs of Low-Carbon Technologies for Electricity Production."

666 Vignarooban et al., "Heat Transfer Fluids for Concentrating Solar Power Systems – A Review."

as new HTF are developed, the potential for chronic, occupational exposures in maintenance workers should be considered prior to implementation.

10.3.3 Wind Energy

Improve infrasound exposure and impact assessment

There is insufficient data to support a causal relationship between wind turbine noise, infrasound, and vibration and many of the symptoms common to reports of "wind turbine syndrome" (i.e. headache, dizziness, vertigo, tinnitus ear pressure or pain, trouble with memory and concentration, irritability, fatigue, and loss of motivation).[667] However, there is emerging evidence that chronic exposure to wind turbine noise and infrasound may lead to annoyance and sleep disruption.[668] Researchers note, however, that there is difficulty with confounders, as it is difficult to determine how factors like visual impact and personal attitudes affect these noise-annoyance and sleep disruption relationships.[669] Further studies of infrasound exposure and sleep disruption and annoyance may be useful to determine if there is a causal relationship, if designed to control for participant attitudes and other confounders. Additionally, little information is available about infrasound exposure levels at various turbine-receptor distances. This information - in conjunction with greater understanding of any impact of infrasound on sleep - could inform siting of wind facilities.

10.3.4 Geothermal

Identify health and environmental impacts of materials recovery (e.g. sulfur, lithium) from brine in California's geothermal plants

Mineral resources can be extracted from geothermal fluids. Silica is being extracted at geothermal facilities in Mammoth Lake and Coso, and the feasibility of lithium and zinc extraction is being researched at the Salton Sea site. Extraction processes include separation with acid and biochemical leaching, sorption with resins or bacteria, and precipitation with hydrogen sulfide.[670] Each of these processes poses potential risks of worker exposure and contaminated waste streams, though little is known about occupational and community exposures from these processes.

An assessment should include identification of the chemicals used during separation and how and where these are disposed. This assessment should also include the potential for occupational exposure to chemicals, corrosives, or heavy metals throughout the process.

As the cost and technical feasibility of new mineral recovery from geothermal brines may inhibit the growth of these systems by 2030, this research need was not considered a high

667 Farboud, Crunkhorn, and Trinidade, "'Wind Turbine Syndrome.'"

668 Ellenbogen et al., "Wind Turbine Health Impact Study: Report of Independent Expert Panel."

669 CCA, Understanding the Evidence; Ellenbogen et al., "Wind Turbine Health Impact Study: Report of Independent Expert Panel"; Schmidt and Klokker, "Health Effects Related to Wind Turbine Noise Exposure."

670 Bourcier, Lin, and Nix, Recovery of Minerals and Metals from Geothermal Fluids.

priority. However, because of the high value of materials such as lithium and silica for future energy technologies, it is likely that these recovery systems will be implemented by 2050.

10.4 Low Priority Research

Table 18. Low Priority Research

	Low Priority Research
Storage	• Assess occupational and public hazards during construction and maintenance of compressed air and flywheel facilities
Marine Energy	• Identify marine energy and offshore wind turbines impacts on California coastal fishing communities

10.4.1 Storage

Assess occupational and public hazards during construction and maintenance of compressed air and flywheel facilities

Compressed air energy storage (CAES) and flywheels are currently being considered for storage applications on California's grid. These projects are in early stages of development, and it is unlikely that these systems will have a large impact on California energy storage by 2030. However, because projects are being considered for CAES application in San Joaquin Valley and flywheel research has been funded, they were included in this report.

For CAES systems, research needs to identify best practices for safe installation and use of these systems, monitoring for known hazards (i.e. moisture, ignitable dust, etc.). Because the site under consideration is a spent natural gas facility, the planning phase should include assessment of the potential for natural gas remnants to increase fire hazards.

Little information is available on flywheel manufacture and installation. Because of this, it is difficult to perform a qualitative life cycle assessment of potential risks and hazards. Though research has noted that flywheels can present a fire risk when installed or operated incorrectly, there needs to be more information available on how these mistakes can be prevented in both design and implementation before grid deployment.

As these systems are still in early stages of development and likely to be surpassed by other storage technologies in grid deployment, these research needs were given low priority.[671]

10.4.2 Marine Energy

Identify marine energy and offshore wind turbines impacts on California coastal fishing communities

Marine energy is expected to have very limited deployment by 2030. Because of this, research into the potential for marine technologies to affect marine ecosystems and, related,

671 Burwen, Interview with Jason Burwen, Energy Storage Association.

coastal populations who rely on fishing and other seafood harvesting for food and employment, are considered a low priority.

GLOSSARY

Term	Definition
a-Si	Amorphous silicon thin film solar cell
ASTDR	Agency for Toxic Substances and Disease Registry
BaP	Benzo[*a*]pyrene
BOS	Balance of system, or components of a solar panel outside of the semiconductor cell (frame, mounting system, etc.)
CAES	Compressed air energy storage
CDC	Centers for Disease Control and Prevention
CEC	California Energy Commission
CdTe	Cadmium telluride thin film solar module
CIGS	Copper Indium Gallium Selenium thin film solar module
CRA	Comparative Risk Assessment
CSP	Concentrated solar power
EPA	Environmental Protection Agency
EPIC	Electric Program Investment Charge
EES	Emerging Electricity [Generating] Systems
GaAs	Gallium Arsenide or Gallium Arsenide thin film solar cell
HIA	Health Impact Assessment
HTF	Heat Transfer Fluid
IARC	International Agency for Research on Cancer
ITO	Indium Tin Oxide
LCA	Life cycle assessment
Li-Ion	Lithium ion batteries
Mono-Si	Monocrystalline silicon solar modules
Na/S	Sodium sulfur batteries

NIOSH	National Institute for Occupational Health and Safety
NCG	Non-condensable gases
NO_x	Nitrogen oxides, a criteria pollutant
OSH	Occupational safety and health
OSHA	US Department of Labor, Occupational Safety and Health Association
PAHs	Polycyclic aromatic hydrocarbons
Pb-Acid	Lead acid batteries
PM	Particulate matter ($PM_{2.5}$ – particulate matter with a diameter of 2.5 micrometers or less, PM_{10} – particulate matter with a diameter of 10 micrometers or less)
PV	Solar photovoltaics
Poly-Si	Polycrystalline silicon solar modules
RPM	Revolutions per minute
RPS	Renewable Portfolio Standard
SO_x	Sulfur oxides
USGS	United States Geological Survey
VOCs	Volatile organic compounds
VRB	Vanadium redox flow batteries

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