Environmental and Circular Economy Implications of Solar Energy in a Decarbonized U.S. Grid

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The *Solar Futures Study* and Supporting Reports

The *Solar Futures Study*, initiated by the U.S. Department of Energy (DOE) Solar Energy Technologies Office and led by the National Renewable Energy Laboratory (NREL), envisions how, over the next few decades, solar could come to power 40% or more of U.S. electricity demand, dramatically accelerating the decarbonization of buildings, transportation, and industry.

Through state-of-the-art modeling, the *Solar Futures Study* is the most comprehensive review to date of the potential role of solar in decarbonizing the U.S. electric grid and broader energy system. However, not all the detailed analysis that informed the *Solar Futures Study* could be included within its pages. This further analysis is collected in additional NREL reports, each dedicated to a different technology or socioeconomic concern.

This report, *Environmental and Circular Economy Implications of Solar Energy in a Decarbonized U.S. Grid*, focuses on a particular set of environmental, economic, and social considerations related to the decarbonization of the U.S. energy system.

The *Solar Futures Study* Reports

- *Solar Futures Study* (main report published by DOE)
- *Research and Development Priorities to Advance Solar Photovoltaic Lifecycle Costs and Performance*
- *The Role of Concentrating Solar-Thermal Technologies in a Decarbonized U.S. Grid*
- *The Demand-Side Opportunity: The Roles of Distributed Solar and Building Energy Systems in a Decarbonized Grid*
- *Maximizing Solar and Transportation Synergies*
- *The Potential for Electrons to Molecules Using Solar Energy*
- *Affordable and Accessible Solar for All: Barriers, Solutions, and On-Site Adoption Potential*
- *Environmental and Circular Economy Implications of Solar Energy in a Decarbonized U.S. Grid*

You can learn more about the project and reports on the NREL website at https://www.nrel.gov/analysis/solar-futures.html.

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Finally, several of the graphics from this report have been previously published as part of the *Solar Futures Study*, for which we thank Eric O'Shaughnessy (Clean Kilowatts).

List of Acronyms and Abbreviations

ac	acres
AI	artificial intelligence
ANSI	American National Standards Institute
bgal	billion gallons
BC	black carbon
BoS	balance of system
Btu	British thermal unit
CdTe	cadmium telluride
CE	circular economy
CO_2	carbon dioxide
c-Si	crystalline silicon
CSP	concentrating solar power
DOE	U.S. Department of Energy
DUPV	distributed utility-scale photovoltaic
EOL	end of life
EPA	U.S. Environmental Protection Agency
EVA	ethylene vinyl acetate
GHG	greenhouse gas
GW_{AC}	gigawatts alternating current
GW_{DC}	gigawatts direct current
ha	hectares
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
IRENA	International Renewable Energy Agency
ITRPV	International Technology Roadmap for Photovoltaic
kg	kilograms
LCA	life cycle assessment
ML	machine learning
MOVES	MOtor Vehicle Emission Simulator
MW_{DC}	megawatts direct current
NO_x	nitrogen oxides
NREL	National Renewable Energy Laboratory
PM	particulate matter
$PM_{2.5}$	fine particulate matter
PSS	product service system
PV	photovoltaic(s)
PViCE	PV in the Circular Economy model
QA	quality assurance
R&D	research and development
ReEDS	Regional Energy Deployment System
reV	Renewable Energy Potential
RFID	radio frequency identification
SO_2	sulfur dioxide
TCLP	toxicity characteristic leaching procedure
TES	thermal energy storage

TW	terawatts
TW_{DC}	terawatts direct current
UPV	utility-scale photovoltaic
USGS	U.S. Geological Survey
USDA	U.S. Department of Agriculture
VOC	volatile organic compound
W_{DC}	watts direct current

Executive Summary

The U.S. Department of Energy's (DOE's) *Solar Futures Study* projects deployment of solar technologies—including photovoltaics (PV) and concentrating solar power (CSP)—of up to nearly 1.6 terawatts by 2050. These technologies account for far lower levels of greenhouse gas (GHG) emissions than conventional power generation technologies based on fossil fuels, both during their operation and across their full life cycles. They also reduce emissions of non-GHG air pollutants. However, expanded PV and CSP deployment has spurred environmental and resource concerns related to issues including material requirements, land use, water use (primarily for CSP), and plans for managing system components that reach end of life (EOL).

This report addresses environmental and circular economy (CE) considerations related to solar technologies via novel analysis of the three *Solar Futures* core scenarios as well as synthesis of published research. We organize these issues into the three basic life cycle phases of a solar technology: manufacturing, operation (including site selection and construction), and EOL. Related environmental justice issues are also explored. Finally, we recommend research and development (R&D) activities that could help clarify challenges and identify solutions. Because PV deployment is projected to be much larger than CSP deployment, we offer a more detailed analysis of PV-related issues.

Manufacturing

We use the PV in the Circular Economy (PViCE) tool to calculate material demands for PV module manufacturing during 2010–2050 based on deployment in the *Solar Futures* scenarios, assuming a completely linear economy (no recycling, repair, etc.).[i] Our estimates are gross material demands and may overestimate material requirements if some manufacturers use secondary materials, although this does not appear to be a prevalent practice today. We only examine crystalline silicon (c-Si) modules, which are assumed to represent a constant 85% of new capacity in the *Solar Futures* scenarios.

Figure ES-1 compares cumulative virgin material demands for c-Si PV during 2020–2050 by scenario. Glass accounts for most of the mass in each scenario, which corresponds to typical PV module design. The Decarb+E scenario has the greatest cumulative material demand through 2050. Although silver is barely visible within the scale of the chart, it is the material demanded at the highest fraction of global supply. While U.S. demand for silver is less than 5% of global supply in the Decarb+E scenario, when considered on a global scale in a global decarbonization scenario, silver demand from PV could reach almost 40% of 2020 global production. Overall, our analysis of U.S. solar material demands under the *Solar Futures* scenarios suggests material supplies likely will not limit solar deployment growth, especially if EOL materials are recovered and used to offset virgin material demand.

A broad range of CE methods can be incorporated in the PV manufacturing stage to improve the economic and environmental performance of PV systems. These include reducing the material intensity of manufacturing, using EOL PV materials in PV manufacturing (closed-loop recycling), using materials recovered from non-PV systems in PV manufacturing (open-loop

[i] See the introduction for descriptions of the *Solar Futures* scenarios.

recycling), powering PV manufacturing processes with renewable electricity, and using novel PV module designs and materials in the manufacturing stage to enhance recyclability, transition away from supply-constrained materials to abundant materials, and decrease risks to human health and the environment over the PV life cycle (design for circularity).

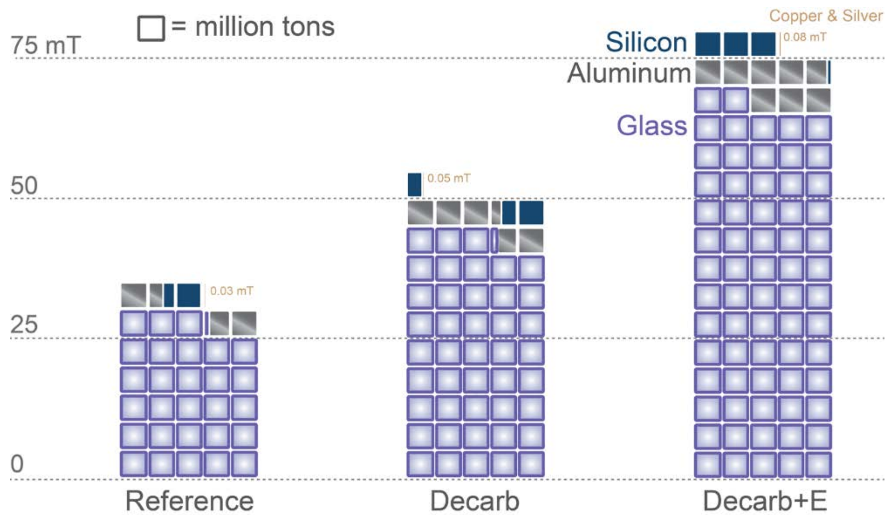

Figure ES-1. Comparison of virgin material demands for each silicon-based PV material cumulatively (2020–2050) across the three *Solar Futures* scenarios

Site Selection, Construction, and Operation

We evaluate solar land requirements under the *Solar Futures* scenarios from 2010 to 2050. In the scenario with the largest land requirement (Decarb+E), the total aggregated solar deployment area across the contiguous United States is approximately 10.3 million ac (41,683 km^2) by 2050—roughly equivalent to the combined surface area of Connecticut, Massachusetts, and Rhode Island. The maximum amount of land required among the three scenarios is equivalent to just 6.4% of the area of potentially suitable lands that have been previously disturbed. Deploying solar on such lands can avoid conflict with current, productive land uses and high-value ecological systems. Contaminated lands—a subset of disturbed lands—are not currently suitable for any productive use but could be cleaned and made suitable for solar. Using contaminated lands helps local communities by removing blight, and these lands are often located near infrastructure that facilitates solar development. However, contaminated lands suitable for solar are not plentiful enough to meet the maximum estimated land use area under the *Solar Futures* scenarios, and they would require site-specific assessment to evaluate economic feasibility. In a larger context, maximum total land requirements across all technology types for ground-based solar in 2030, 2040, and 2050 are approximately 0.2%, 0.3%, and 0.5%, respectively, of the total contiguous U.S. surface area. Figure ES-2 compares the maximum modeled land requirement (0.5%) with solar-suitable disturbed and contaminated land areas and examples of other areas in the United States. The maximum total solar land requirements are not expected to exceed 5% of any state's land area by 2050, with the exception of Rhode Island (6.5%).

Opportunities exist to deploy solar in ways that promote rural economic development and social justice while avoiding conflict with other land uses. In addition to siting solar on disturbed or formerly contaminated lands as described above, strategies include avoiding lands important for biodiversity conservation or farming, managing vegetation to provide ecosystem services, colocating solar systems with agriculture, and deploying water-based (floating) PV systems as an alternative to land-based PV systems.

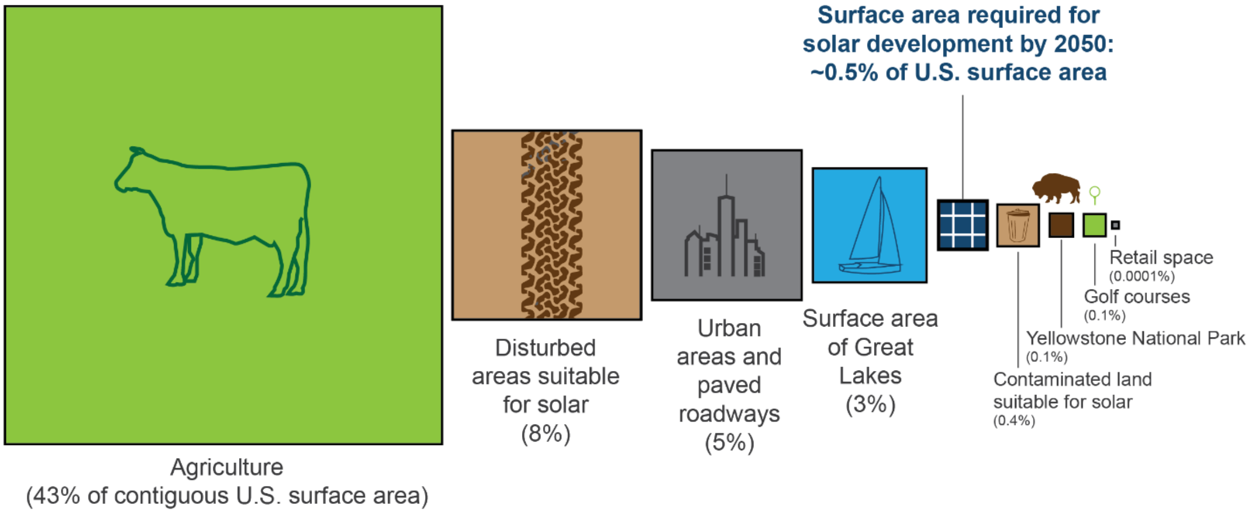

Figure ES-2. Maximum land use required for solar in 2050 in the *Solar Futures* scenarios compared with solar-suitable disturbed and contaminated areas and examples of other U.S. land uses

We analyze water use in the *Solar Futures* scenarios with a model that includes water constraints. Results show that water withdrawals decline over time, mainly from retirements of coal, nuclear, and natural gas combined-cycle plants. The Decarb+E scenario achieves the lowest yearly U.S. water withdrawals, declining from 48,500 billion gals/yr (bgal/yr) in 2010 to 6,040 bgal/yr in 2050. Although CSP never contributes more than 1% of total power-system withdrawals over the 2010–2050 timeframe, it can account for a large portion of state-level power-sector water withdrawals even when dry cooling technologies are used,[ii] rising to almost 100% of power-sector withdrawals in Colorado and New Mexico starting in 2040 for the Decarb scenario. These values are still less than current power-sector water withdrawals in both states, given the current reliance on fossil (thermal) power plants in those states.

We also present order-of-magnitude monetary estimates of the air-quality benefits of the *Solar Futures* scenarios. In the Decarb scenario, reducing air pollution from electricity generation results in air-quality and health benefits worth roughly $300 billion, based on the discounted value of all emission reductions (compared with the Reference scenario) between 2021 and 2050. Approximately $100 billion of additional health benefits could be realized from the Decarb+E scenario owing to the replacement of a larger number of gasoline and diesel vehicles by electric vehicles and the associated reduction in pollutant emissions. These air-quality benefits alone offset the incremental costs of decarbonization in the *Solar Futures* scenarios, even before

[ii] Dry cooling technologies cool the working fluid by ejecting heat into the air, whereas wet cooling (which is not allowed in some states owing to water consumption concerns) cools the working fluid by evaporating water.

accounting for the much larger GHG-reduction benefits in the scenarios; together, the air-quality and GHG benefits yield net benefits of more than $1 trillion over the 2020–2050 period.[iii]

Various CE strategies can be applied during the PV use phase. Product service system approaches (known in the U.S. as third-party ownership) can delink ownership of PV modules from the generation of PV electricity, lower cost barriers for individual customers to consume PV electricity, transfer the economic and operational burdens of PV system purchase and maintenance to third-party owners, and help address social and energy justice issues by widening access to PV electricity. Repowering in-service PV systems can help increase renewable electricity generation over the lifetime of the PV project by installing newer, more efficient modules, and it can extend the lifetime of other system components—both of which can reduce environmental burdens normalized over the lifetime generation of the system. In-field repair of PV system components is another option for lifetime extension, although questions remain about inspection and regulatory requirements, safety, reliability, and legal liability related to in-field repairs.

End of Life

Using the PViCE model, we project the mass of EOL materials from c-Si PV modules considering the known degradation and failure rates that affect lifetime. Because of long module lifetimes, most modules deployed in the *Solar Futures* scenarios do not reach EOL until after 2050. The Decarb and Decarb+E scenarios result in nearly identical 2050 cumulative EOL material, at around 6.5 million metric tons, consisting mostly of glass. The PViCE model also calculates the mass of manufacturing scrap, which is estimated to be approximately half of the mass of materials in EOL modules. Compared with the availability of materials recovered at EOL, the availability of manufacturing scrap is better aligned in time with virgin material demands, emphasizing the importance of efficient manufacturing and closed-loop manufacturing scrap recycling to reduce virgin material needs. Geospatial analysis provided in this report can enable stakeholders to plan proactively for EOL materials on a regional basis, which can lead to more efficient deployment of capital for recycling and other EOL management infrastructure.

Substituting EOL materials for virgin materials could mitigate material demands in a growing PV sector, improve supply chain resilience, reduce the environmental and social justice burdens of mining, provide markets for recycling facilities, and reduce critical material demands. Our modeling suggests that EOL material, on a technical potential basis, could supply around 25%–30% of demand for silver, aluminum, and silicon in the Decarb+E scenario after 2040.

Recycling is the most widely applied and analyzed PV CE strategy. However, R&D has focused more on recovery of bulk materials (glass, aluminum, silicon) and less on recovery of trace materials (tin, lead, copper, and silver). Other key recycling challenges include delamination to eliminate the ethylene vinyl acetate (EVA) and separate the glass and silicon wafer, lack of robust and publicly available assessments of the economic viability of commercial-scale PV recycling, and variability across legacy and current-generation PV modules.

[iii] See the *Solar Futures Study* (www.energy.gov/eere/solar/solar-futures-study) for a detailed discussion of scenario costs and benefits.

Another option for EOL PV components is repair and reuse, which can extend component lifetime and avoid the economic and environmental burdens associated with disassembly, separation, and recycling of individual material constituents. Data are needed on reliability, failure mechanisms, and standards to ensure quality and performance of repaired and reused modules. There is also a need to robustly assess and compare the economic and environmental trade-offs between module repair/reuse and alternative CE strategies (e.g., recycling). CE strategies at PV EOL could provide environmental justice and social benefits including employment opportunities and safer management of hazardous materials.

The report concludes with a summary of key recommendations for applying CE strategies to improve the environmental, social, and environmental justice outcomes associated with solar deployment at the *Solar Futures* scale.

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1. Introduction

The U.S. Department of Energy's (DOE's) *Solar Futures Study* projects deployment of solar technologies—including photovoltaics (PV) and concentrating solar power (CSP)—of up to nearly 1.6 terawatts (TW) by 2050 (see Text Box 1, page 2).[1] This report supports the larger *Solar Futures Study* of which it is part by focusing on certain opportunities and challenges with regard to large-scale solar deployment and the circular economy (CE) for materials as well as effects on the environment.

PV and CSP are rapidly evolving technologies. They account for far lower levels of greenhouse gas (GHG) emissions than conventional power generation technologies based on fossil fuels, both during their operation and across their full life cycles.[4] Text Box 1 depicts U.S. electric-sector carbon dioxide (CO_2) emissions resulting from the *Solar Futures Study* scenarios, demonstrating the decarbonization potential from solar and other zero-carbon technologies, especially wind. In the past, however, PV and CSP have confronted environmental sustainability challenges related to design and deployment. For instance, some first-generation CSP systems increased electricity generation using supplemental natural gas combustion, resulting in a much higher carbon footprint than solar-only mode. Overall, the chief concern for both technologies has been high material requirements (per unit of generation) and, for PV, the need for materials that are scarce, valuable, or potentially hazardous to human health and the environment if uncontrolled (see, e.g., [2,3]). Another concern for PV and CSP is the quantity and location of land required. CSP requires high direct normal irradiation and large tracts for favorable economics, which generally limits U.S. siting to the Southwest, where ecosystems are fragile and water availability is low. PV can be sited anywhere, including rooftops, but even historical deployment has raised concerns about the quantity of land used for utility-scale, ground-mounted systems and their impacts on ecosystems and rural character.

Industry, government, nongovernmental organizations, and academia have attempted to address these issues, yet continued exponential growth in deployment scales highlights the need to clarify the challenges and continue to work on solutions. The benefits of increased solar deployment, such as reduced pollutant emissions, should also be considered, as should new challenges that are arising. For instance, significant PV deployment has been occurring for a decade or more, which is raising questions about the fate of system components that have reached end of life (EOL) early (e.g., from damage by extreme weather events, vandalism, or component failures) or are still functional but have been retired early, for instance to repower a site with newer, better-performing products, including use of CE approaches.[5]

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[4] See "Life Cycle Assessment Harmonization," NREL, https://www.nrel.gov/analysis/life-cycle-assessment.html and references therein.

[5] EOL, as used in this report, can include what might be called "end of first use," or a first owner's use—whereby the technology could be directly reused or repaired and then reused—in addition to its more precise meaning whereby the technology cannot be used further and must be recycled or discarded. To date, the literature has not established broadly adopted terminology to succinctly differentiate these two lifetimes. Thus, in this report, EOL is a shorthand phrase that can include products still functional (or repairable to be functional) for their original purpose, whether or not ownership changes.

This report addresses environmental and CE considerations related to solar technologies via novel analysis of the three *Solar Futures* core scenarios as well as synthesis of published research. We organize these issues into the three basic life cycle phases of a solar technology: manufacturing, operation (including site selection and construction), and EOL. Related environmental justice issues are also explored. Finally, we recommend research and development (R&D) activities that could help clarify challenges and identify solutions. Because PV deployment is projected to be much larger than CSP deployment, we focus on PV-related issues.

Text Box 1. *Solar Futures Study* Scenarios and CO_2 Emissions

The *Solar Futures Study* explores pathways for solar energy to drive deep decarbonization of the U.S. electric grid and considers how further electrification could decarbonize the broader energy system; for more information, see "*Solar Futures Study*," NREL, https://www.nrel.gov/analysis/solar-futures.html). The study focuses on three core scenarios.

The Reference scenario outlines a business-as-usual future that includes existing state and federal clean energy policies and assumes ongoing, moderate technology cost reductions but lacks a comprehensive effort to decarbonize the grid.

The Decarbonization (Decarb) scenario assumes policies drive a 95% reduction (from 2005 levels) in the grid's CO_2 emissions by 2035 and a 100% reduction by 2050. This scenario assumes more-aggressive cost-reduction projections than the Reference scenario for solar as well as other renewable and energy storage technologies, but it uses standard future projections for electricity demand.

The Decarbonization with Electrification (Decarb+E) scenario goes further by including large-scale electrification of buildings and transportation, meaning a significant increase in electricity demand and an expanded role for the grid in decarbonizing the broader U.S. energy system. Under this scenario, solar grows from 3% of the U.S. electricity supply in 2020 to 42% by 2035 and 45% by 2050. Figure 1 summarizes the CO_2 emissions reductions in the core scenarios.

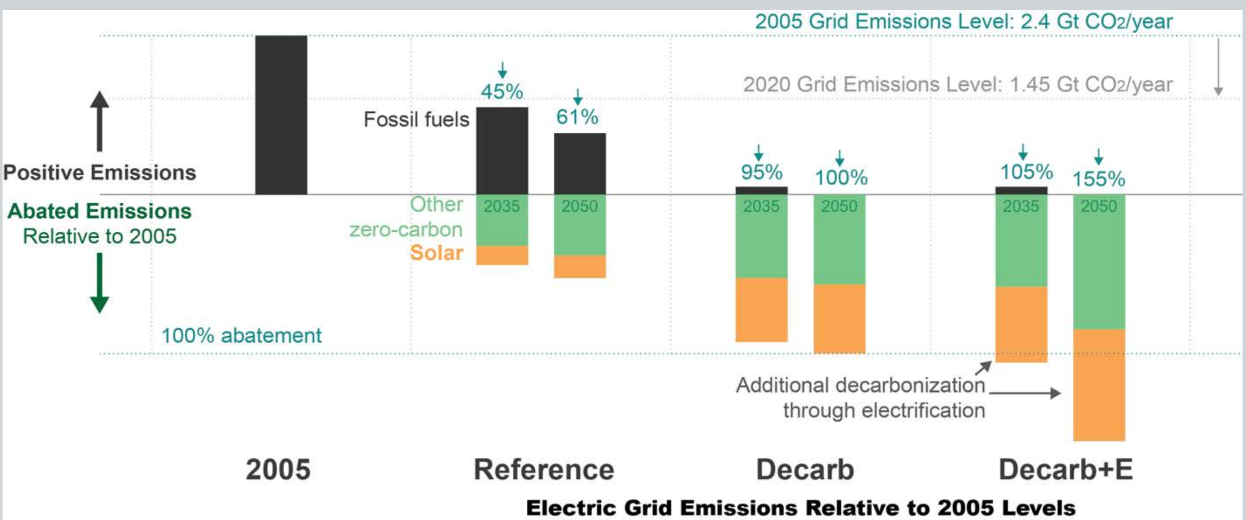

Figure 1. Grid emissions and abated grid emissions by *Solar Futures* scenario in 2035 and 2050, relative to 2005 grid emissions[1]

Most analyses in this report—for materials, land and water use, and waste generation—relate to the scale of solar capacity deployed. Figure 2 summarizes cumulative solar deployment in each core *Solar Futures* scenario. The United States installed about 15 GW alternating current (GW_{AC}) of PV capacity in 2020. In the Decarb scenario, the average annual deployment rate increases to 28 GW_{AC} from 2021 to 2025, 48 GW_{AC} from 2026 to 2030, and 46 GW_{AC} from 2031 to 2035. In the Decarb+E scenario, average annual deployment rates reach 66 GW_{AC} in 2026–2030 and 72 GW_{AC} in 2031–2035.

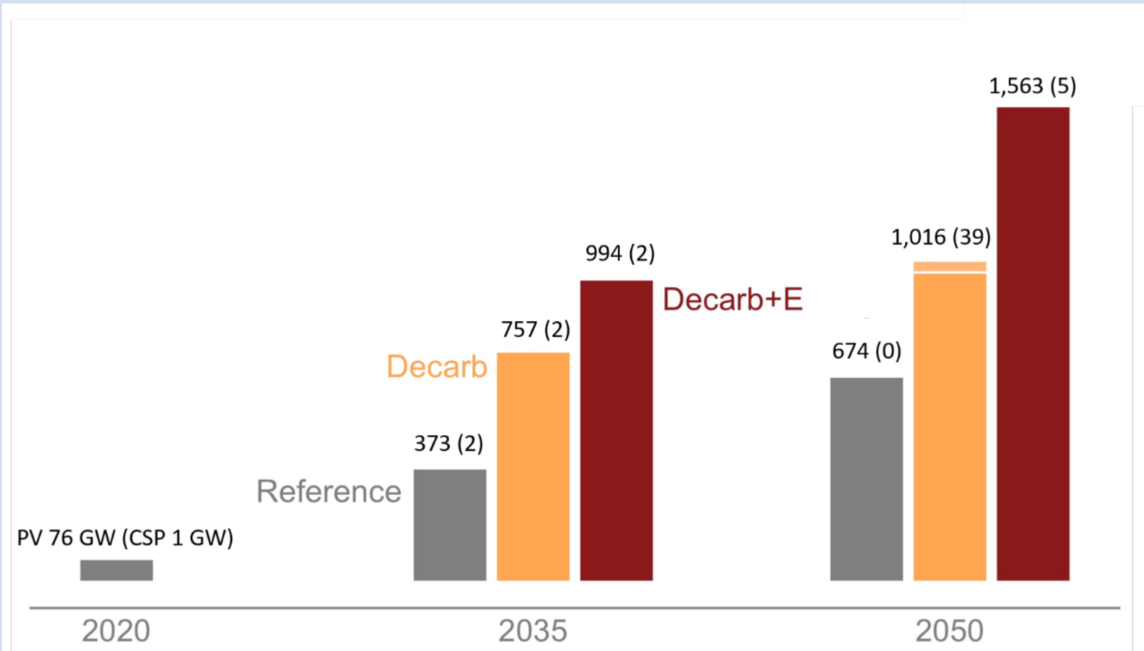

Figure 2. Cumulative deployed capacity of PV and CSP in 2020, 2030, and 2050 in the three core *Solar Futures* scenarios

2. Overview of the Circular Economy for PV

The CE is relevant for all three solar life cycle phases. Many definitions of the CE have been proposed.[4] Leveraging the pioneering work of the Ellen MacArthur Foundation, the World Economic Forum defines it as follows:

> A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the end-of-life concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse and return to the biosphere, and aims for the elimination of waste through the superior design of materials, products, systems and business models.[5]

In addition to synthesizing literature on CE strategies for PV, we employ a novel open-source tool—developed by the National Renewable Energy Laboratory (NREL)—called PV in the Circular Economy (PViCE) to estimate material demands for future generations of PV modules and EOL materials, both of which are based on the deployment projections (and historical deployment in the case of EOL materials) from the *Solar Futures* scenarios. This first-of-its-kind analysis uses a stock-vintage approach to track annual changes to the amount of five specific materials used in PV modules and, by market share, of several prominent designs. CSP material demands and EOL materials are also estimated. We also review private-sector and policy options in the manufacturing phase to improve the sustainability of solar.

In the operation phase, we review key considerations for site selection, construction, and operation pertaining to land, ecosystems, water, and air pollutant emissions. Environmental justice and CE are also discussed, although the latter is less prominent in this phase.

CE is well recognized as an EOL material management strategy; our comprehensive consideration of CE strategies in the other life cycle phases is a notable addition to typical prior treatment. Policies and other legal issues (such as waste characterization) are important considerations for CE at EOL. CE presents opportunities to address historical environmental justice in terms of locations of waste management facilities by diverting waste to more productive uses and creating jobs in the sustainability sector.

The framework in Figure 3 comprehensively depicts the extant literature in terms of strategies that can be implemented across the three main life cycle stages to enable the transition to a CE for PV—outlining physical material and energy flows (right side) and information flows (left side). During manufacturing, the material flows account for the raw materials required for the production of a PV system. After completion of manufacturing, the material flows account for potential operational CE pathways such as repowering,[6] repair, and reuse. For PV systems that require recycling after collection at EOL, the material flows account for the individual materials that can be recovered from the PV system and recipient industries.

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[6] Repowering replaces certain components of a system for better performance without replacing the whole system, for instance replacing inverters or modules in a PV power plant but retaining racking, tracking, and other balance of system components. In Europe, repowering is often called "revamping."

Information flows are required to operationalize or enhance the CE across the different life cycle stages. For example, digital service providers can facilitate the coordination of supply and demand in the secondary market for PV modules and facilitate the repair and reuse of PV modules after the collection stage.[6,7]

Stakeholders can influence the CE by leveraging the mechanisms and tools categorized as the "Decision Enablers." For example, government could incentivize the transition to a CE through policies,[8,9] and analytical tools such as life cycle assessment (LCA) and techno-economic assessment can help industry commercialize the most environmentally and economically preferable technologies to realize sustainable CE outcomes for PV systems.

By impacting the material, energy, and waste flowing in and out of natural systems, the CE strategies in each of the PV life cycle stages (denoted M for manufacturing, U for use, and EOL for end of life) impact ecological services. For example, reuse and recycling of materials offset virgin material use and thereby prevent the environmental impact associated with upstream mining and material extraction processes.

Figure 3 identifies two broad pathways of recycling: open loop and closed loop. In closed-loop recycling, the materials recovered from PV modules are reused in PV modules. By contrast, open-loop recycling involves the sourcing or supply of recycled materials between PV and non-PV industries.

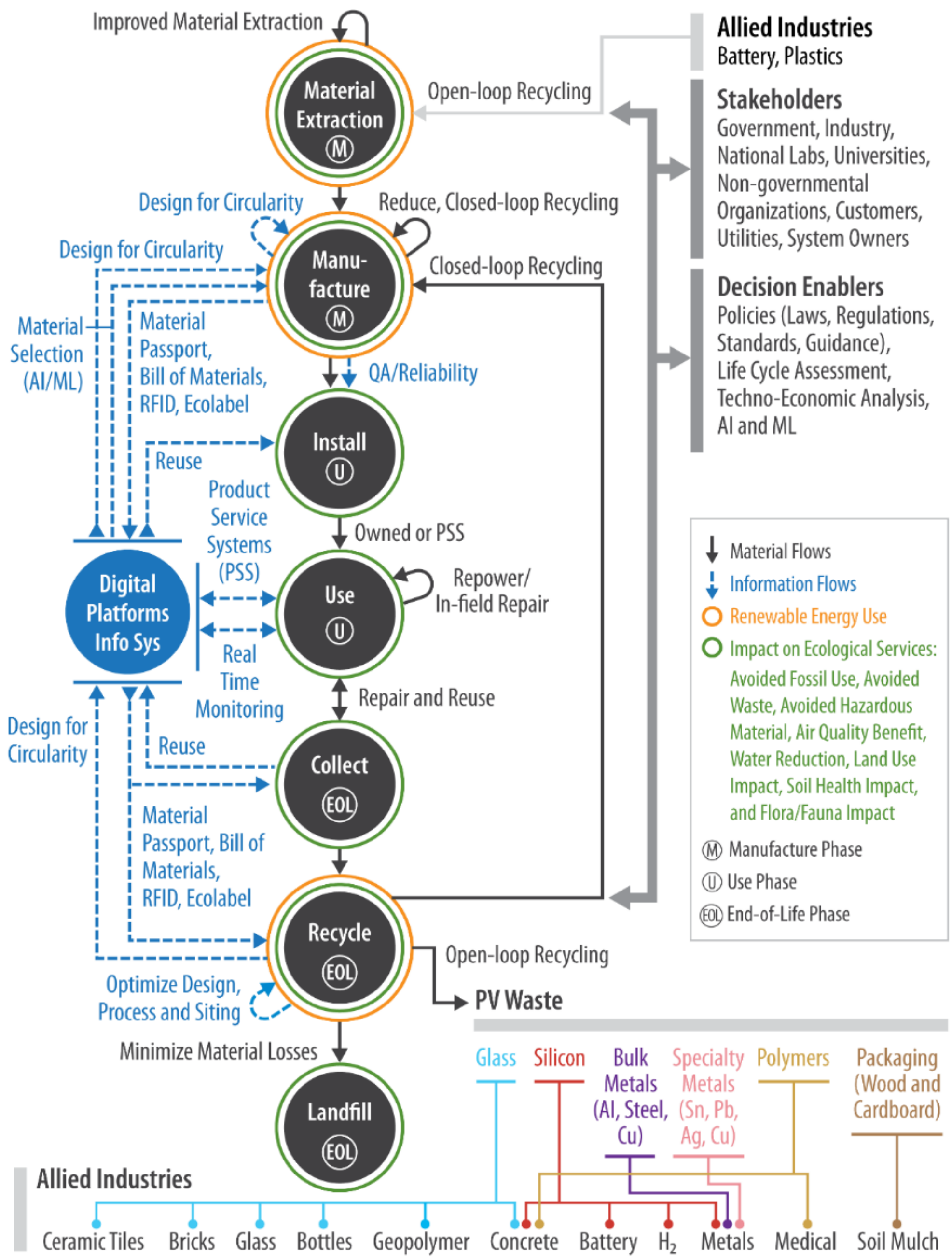

Figure 3. Systems framework to assess the current state-of-the-art and identify opportunities to advance the CE for PV

Material flows are in solid black arrows, and information flows are in dashed blue arrows, both of which flow through different stages within the three main life cycle phases denoted “M”, “U,” and “EOL” in circles representing the manufacturing, use, and EOL stages of PV systems respectively. Renewable energy can be used to lower the CO_2 footprint of the stages within orange circles. The stages within green circles have an impact on ecological services. The framework includes stakeholders and decision enablers who affect the transition to a CE for PV. Allied industries are the downstream, non-PV CE pathways to reuse materials recovered from a PV system and non-PV sources for secondary materials that can be reused in the manufacture of PV systems. Product service systems (PSS) entail the consumption of PV electricity without ownership of the PV system (e.g., leasing a residential PV system). (QA = quality assurance; AI = artificial intelligence; ML = machine learning; RFID = radio frequency identification; Info Sys = information system)

The systems framework in Figure 3 is based on a detailed literature review conducted to identify key historical trends and recent advances in research and development (R&D) of a CE for PV systems. The review identified 358 data sets consisting of scientific articles, conference proceedings, technical reports, and trade articles focusing on technology development as well as environmental, economic, and social assessment of CE approaches and strategies to facilitate a transition to a PV CE. Figure 4 categorizes the CE strategies that can be applied across PV life cycle stages and the degree to which the strategies have been analyzed in extant literature.

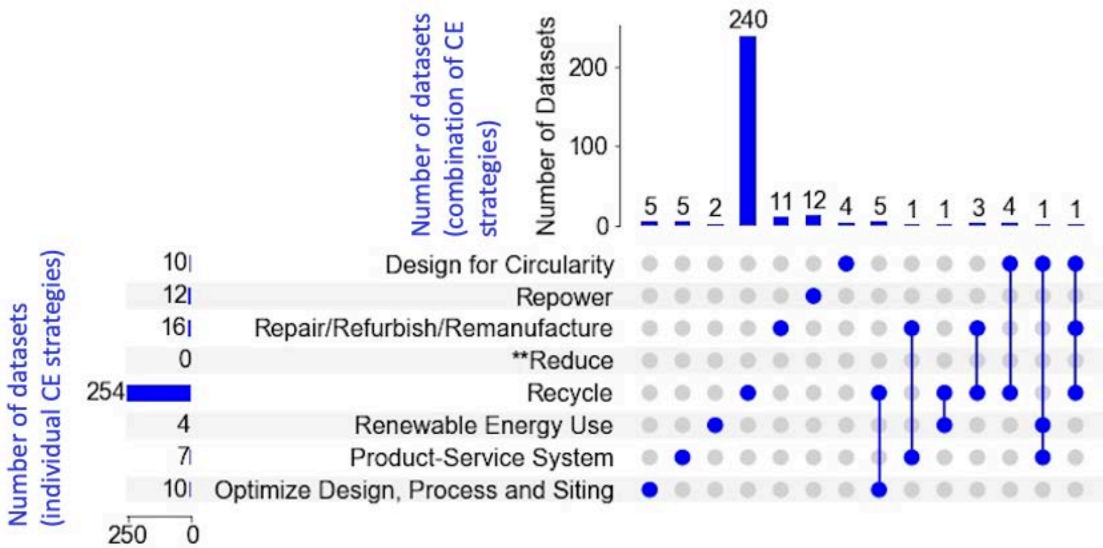

Figure 4. PV CE strategies by number of data sets found in the literature, alone and in combination

The horizontal bars represent the number of data sets focusing on an individual CE strategy (rows). For example, the fifth row from the top shows 254 data sets focusing on recycling of PV modules out of a total of 358 identified in the literature. The vertical bars represent the number of data sets focusing on a combination of CE strategies, which are identified by the solid blue circles in the column corresponding to the bar. (Linking of blue circles with blue lines is done solely for visual convenience; it does not indicate inclusion of all intervening CE strategies.) For example, the last column on the right indicates one study discusses three CE strategies: design for circularity, repair/refurbish/remanufacture, and recycling. ** This literature review did not focus on the reduction of material use (e.g., reduced silicon and silver use in crystalline silicon [c-Si] panels), which has been pursued to decrease the costs of manufacturing of PV modules, although such dematerialization does in fact decrease material intensity.

3. Key Considerations for Manufacturing

U.S. solar manufacturing has not kept up with domestic demand, and worldwide the United States lost 80% of its market share for solar-grade polysilicon, PV cells, and PV modules in the last decade.[10] The United States is reliant on imports of raw materials for domestic solar manufacturing as well as imports of PV cells, modules, and balance of system (BoS) equipment needed to meet domestic demand.[10–12] In 2017, the United States imported 60% of the domestic market demand for c-Si cells and 92% of the domestic market demand for c-Si and thin-film modules.[10] The U.S. solar market also depends on imports of BoS equipment, such as junction boxes, connectors, aluminum frames, and inverters.[10–12] In terms of raw materials, despite ample polysilicon production, the United States relied on imported wafers in 2017 owing to the relative lack of solar silicon manufacturers.[10] Moreover, in 2019, U.S. manufacturers indicated that they relied entirely on glass imports to meet c-Si module demand.[10]

The recent impacts of COVID-19 on the solar market demonstrate vulnerabilities in the PV supply chain and a need for domestic manufacturing and improved resource recovery in the United States. In addition to impacting customer demand, the pandemic has disrupted supply chains and distribution channels along the entire solar value chain from raw material extraction through construction.[10–13] One study found that the BoS supply shortages alone, due to COVID-19 impacts, could result in 300–700 MW direct current (MW_{DC}) of utility-scale project delays in the United States in 2020.[11] The study also found that supply chain delays and supply shortages, in conjunction with U.S. construction disruptions, may result in 2 GW direct current (GW_{DC}) to 5 GW_{DC} of utility-scale project development delays in the United States in 2020.[11]

3.1 PV Material Demands

3.1.1 Material Demand Estimation Approach

To estimate the environmental and resource impacts of rapid solar growth, the manufacturing material demands associated with various quantities and types of solar technologies must be understood. We use PViCE[14] to calculate material demands for PV module manufacturing during 2010–2050 based on deployment in the *Solar Futures* scenarios. PViCE is a novel python-based tool with validated baseline scenarios and values. Its bottom-up approach estimates material demands and EOL materials dynamically over time and can evaluate trade-offs among CE pathways. It captures PV manufacturing and technology evolution, including improvements to cells, quality/reliability, and module lifetime.

PViCE estimates mass flow annually, representing different generations or cohorts of PV modules described by module design, performance, and material characteristics. The annual cohort properties capture a distribution of efficiency and material content for each of several module designs, obtained through an exhaustive literature review and harmonization of different sources further described in a Jupyter journal document on PViCE's GitHub web page.[14] Average module efficiency starts at 14.7% in 2010 and increases to 25.1% by 2050, based on published estimates from the International Technology Roadmap for Photovoltaic (ITRPV, on which the *Solar Futures* scenario efficiency improvements are also based) and on projections from "The 2020 Photovoltaic Technologies Roadmap."[15] The module designs considered are today's standard of a single glass layer and backsheet plus bifacial modules (glass-glass), following market trends from the ITRPV. Note the same annual module cohort characteristics apply no matter the scenario.

Each generation starts with year zero at installation. The modules "age" owing to predictable degradation rates, or they suddenly fail according to a Weibull distribution of annual early failure rates. EOL is defined as including three modes: a product failure to where it does not function, degradation resulting in modules that produce 80% of their initial power rating, or the end of the expected project lifetime. The failure rates, degradation rate, and project lifetimes improve over time, reflecting manufacturer improvements in module quality and reliability.[15–18] Therefore, installed capacity in a given year equals the year's new installations plus all the previous generations deployed, minus power degradation and the three EOL modes.

Several PV module EOL pathways are possible in PViCE. Effects of repair, remanufacturing, and refurbishment can be quantified. However, for this analysis, these are set to zero to evaluate virgin material needs and EOL materials in a worst-case scenario of a completely linear economy.

In addition, we only examine c-Si modules, which are assumed to represent a constant 85% of new capacity in the *Solar Futures* scenarios. Our focus on c-Si excludes waste from other technologies and underestimates materials demands from all U.S. PV deployment, yet it could overestimate c-Si material demands if other technologies are deployed in the future at a higher rate. Details on the data assumptions and inputs can be found in Appendix B.

3.1.2 Results: Manufacturing Material Demands

We calculate virgin material demands for PV manufacturing for the three core *Solar Futures* scenarios: Reference, Decarb, and Decarb+E. The demands account for PV manufacturing efficiency, capturing manufacturing materials efficiency improvements over time. We assume no recycled content; if module manufacturing could use recycled materials, virgin demands would decrease proportionally. Thus, the estimates reported here are gross material demands and may overestimate material requirements if some manufacturers use secondary materials, although this does not appear to be a prevalent practice today.

Figure 5 compares cumulative virgin material demands for c-Si PV for 2020–2050 by scenario. Glass accounts for the majority of the mass in each scenario, which corresponds to typical PV module design. The Decarb+E scenario has the greatest cumulative material demand through 2050. Though high in value, silver is barely visible within the scale of the chart. See Appendix B for tabulated results.

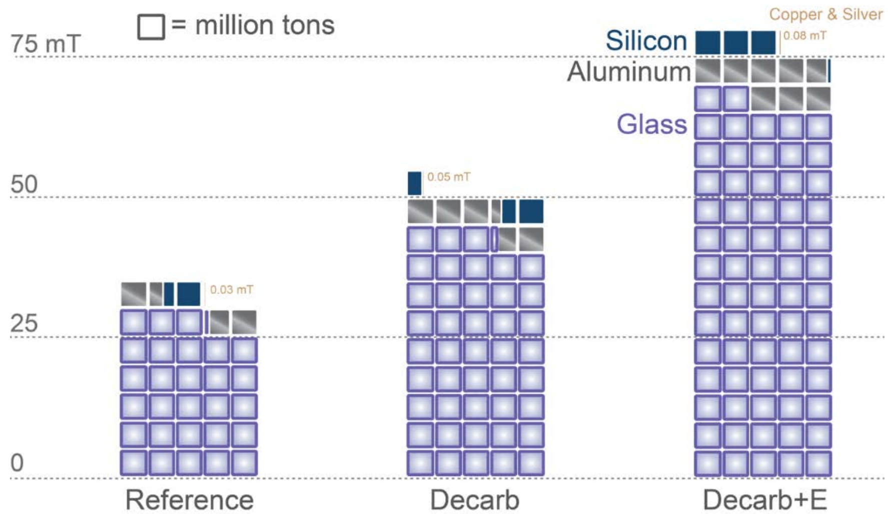

Figure 5. Comparison of virgin material demands for each silicon-based PV material cumulatively (2020–2050) across the three scenarios

Annual virgin material demands for each resource are shown by scenario in Figure 6. Figure 7 puts average annual c-Si module material demands in context of the 2020 global production of silver, silicon, and aluminum. No increase in mining is assumed for these analyses, and, for this comparison, material demands are not assumed to be met with either material stockpiles or recycled content. Thus, this analysis estimates "worst case" material demands and waste based on a completely linear economy (noncircular). Analysts project global PV deployment to average approximately 300 GW_{DC}/year,[19] while a global decarbonization study estimated roughly 1 TW_{DC}/year.[20] Global PV deployment is assumed to be composed of 99% c-Si modules based on extrapolation of historical trends.[21] Silver is the material demanded at the highest fraction of global supply. While the U.S. demand of silver is under 5% of global supply in the Decarb+E scenario, silver demand from PV could reach almost 40% of 2020 global production in a global decarbonization scenario. Concerns regarding the supply and expense of silver contacts have spurred research into copper substitutes. In addition, the mining industry has a history of adjusting capacity to meet demand.

Silver represents a major opportunity for CE strategies to alleviate future supply constraints by reducing material demands through dematerialized designs and by recovering materials from EOL solar technologies (see Section 5.1). In contrast to the silver projections, demand for copper within modules[7] barely registers against 2020 global production, and the International Energy Agency found that global copper demands for the energy transition (including transmission and distribution infrastructure investments, as well as electric vehicles) double historical levels.[3]

[7] Copper within junction boxes, external connector wiring, and field wiring are not considered within PViCE.

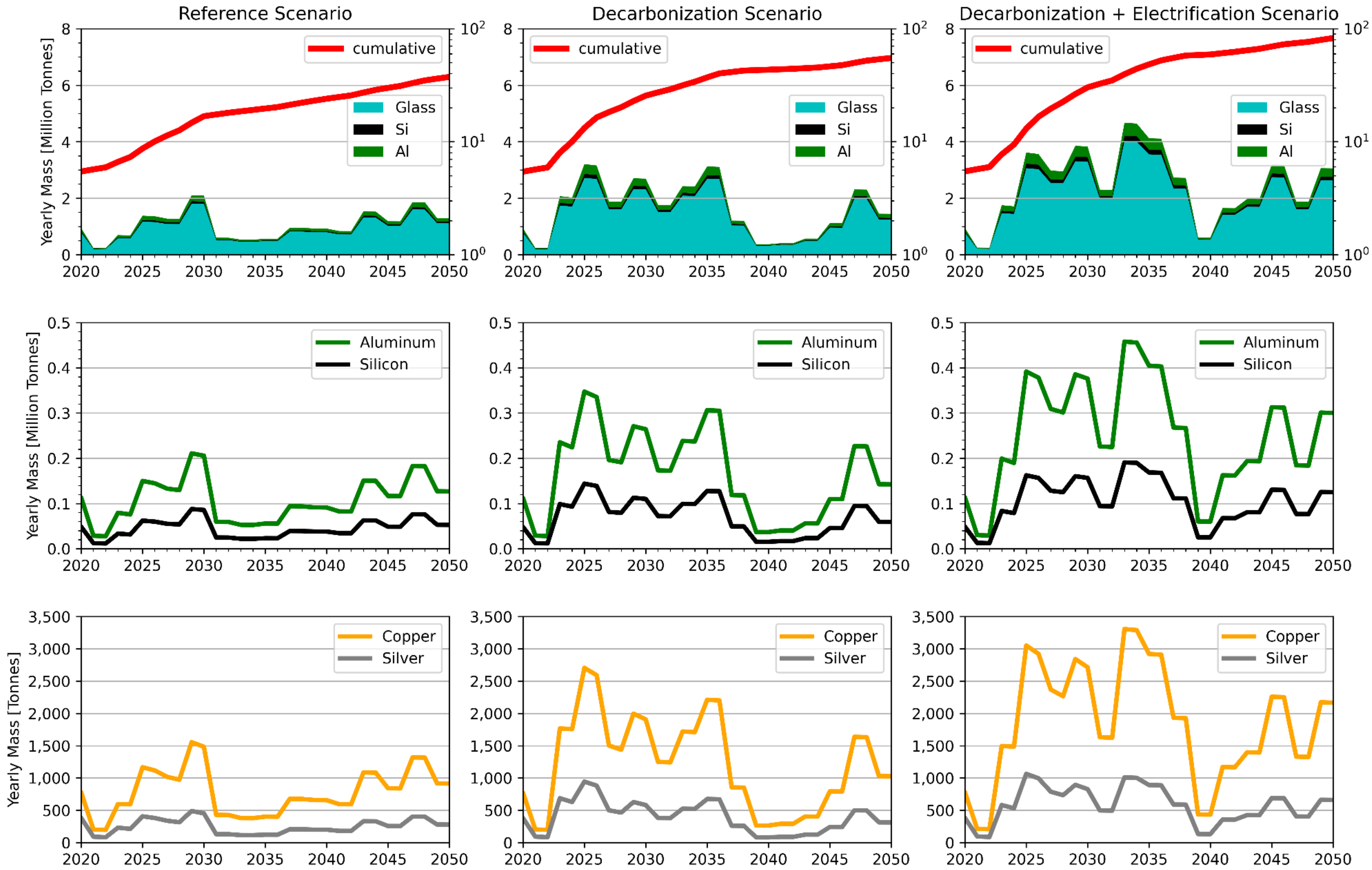

Figure 6. Annual demand of selected materials for PV manufacturing across the three core *Solar Futures* scenarios, 2020–2050

The red lines in the upper row of plots represent cumulative mass installed in each scenario (right axis; note that it uses a log scale).

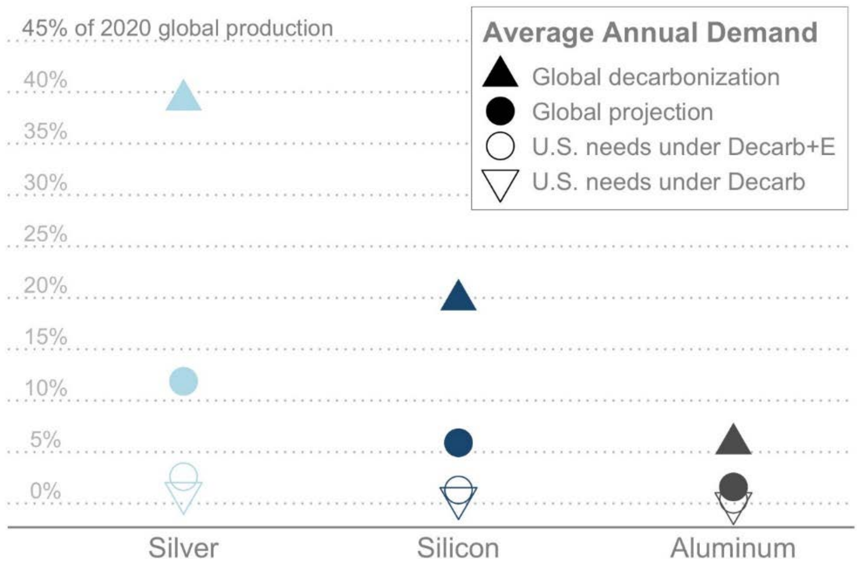

Figure 7. Percentage of 2020 global production of various materials needed to supply average annual virgin materials demand for c-Si PV in the two decarbonization-based *Solar Futures Study* scenarios

The material needs in the global projection scenario are based on projected global PV deployment from the International Renewable Energy Agency (IRENA).[19] The material needs in the global decarbonization scenario are based on projected global PV deployment in Bogdanov et al. (2019).[20] 2020 mining production (metric tons): silver 22,260,[22] silicon 8,000,000,[23] aluminum 65,267,000,[24] copper 20,000,000.[25]

3.2 CSP Material Demands

The material demand for CSP systems is a product of the installed capacity and the materials required per unit of installed capacity. The projected U.S. installations between 2020 and 2050 are from the *Solar Futures* study.

The material requirements are quantified for the manufacturing and construction of power tower CSP systems and include site improvement, the collector system, the receiver system, the thermal energy storage (TES) system, the steam generation system, and the electric power generation system. The material requirements for power tower CSP is sourced from a published study[26] and detailed in Appendix D. This analysis assumes all CSP installations are power tower technology, because this technology accounts for the most electricity generated by CSP systems globally[27] and is more economically competitive than other CSP alternatives.[28]

The results in Figure 8 demonstrate that concrete, aggregate, carbon steel, sodium nitrate, and solar glass are the most consumed materials in the manufacturing and construction of power tower CSP systems. Construction and manufacturing of the receiver and collector systems require 83% of the concrete, 99% of the aggregate is used in the site maintenance process, and the collector system accounts for 70% of the carbon steel requirement. The TES system and the collector system account for all the sodium nitrate and solar glass consumed respectively. Mining from natural sources accounts for 60% of sodium nitrate used in CSP.[29] Alternatively, sodium nitrate can be produced synthetically, which is an order of magnitude more GHG-emission intensive than mined sodium nitrate.[29]

Beyond the bulk materials discussed above, the requirement for critical materials in the production of power tower CSP systems is unlikely to be constrained by supply. A recent study on critical materials required in a global transition to renewable energy systems showed that power tower CSP systems could necessitate a 75-fold increase in chromium (to 91 kt), 67-fold increase in copper (to 42 kt), 92-fold increase in manganese (to 105 kt), and 89-fold increase in nickel (to 35 kt) requirements from 2020 to 2040 in a high-deployment scenario.[3] Despite the significant increase, the projected requirements of chromium, copper, manganese, and nickel in 2040 are unlikely to be constrained by supply, because they represent less than 0.1% of the global mine production levels in 2020.[30–33]

Scarcity in supply is unlikely to impact the raw material requirements for CSP installation.[34] The list of all 27 materials required for the construction and manufacturing of power tower CSP plants is detailed in Appendix D.

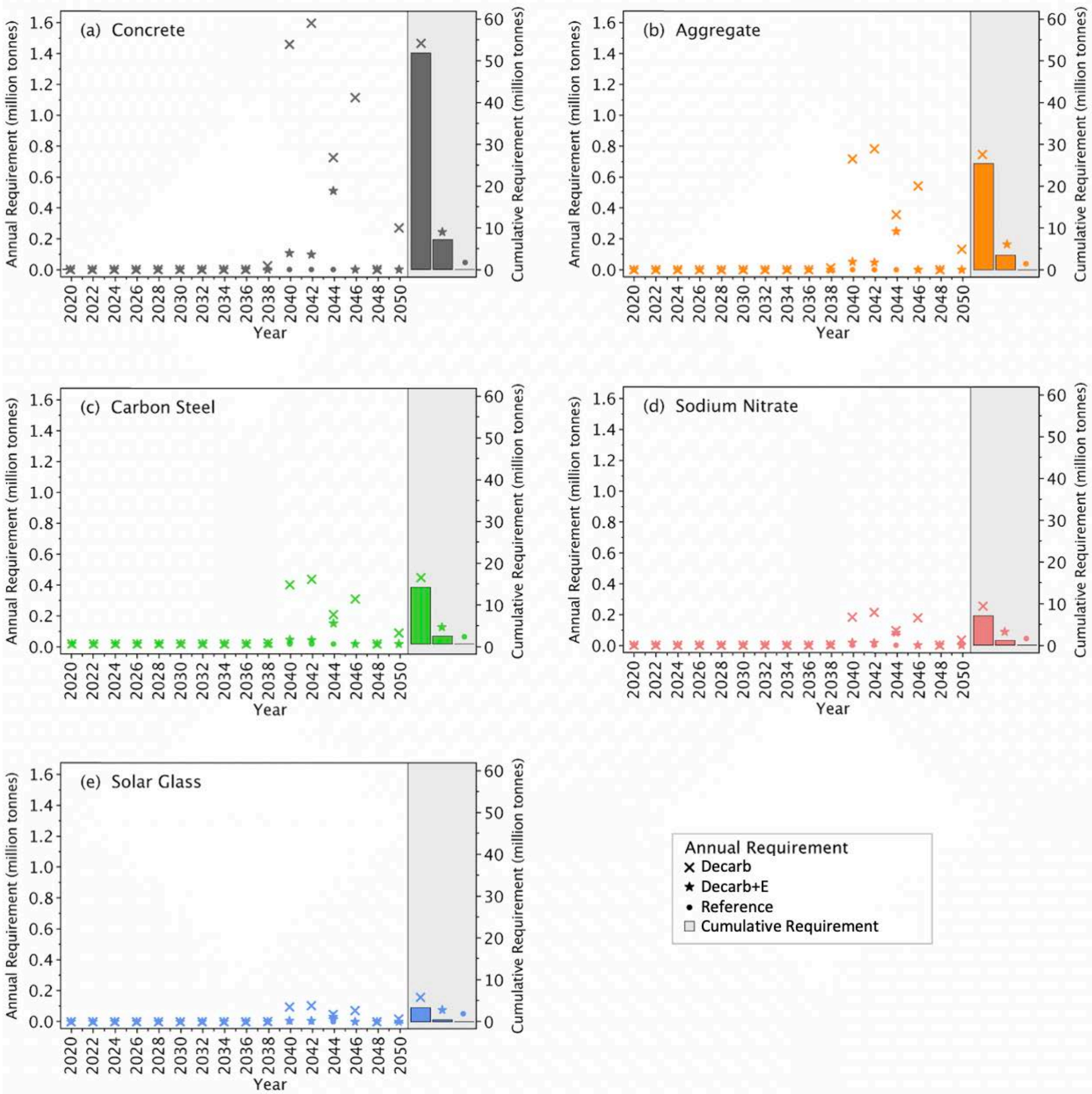

Figure 8. Five most-used materials in the manufacturing and construction of power tower CSP plants in the three core *Solar Futures Study* scenarios

The axis on the left plots the annual requirement from 2020 to 2050 based on projected U.S. installations. The bar graphs on the right with the gray background quantify the cumulative material requirement from 2020 to 2050.

3.3 Policies: Regulation

Concerns about supply chain vulnerabilities and PV system equipment waste have led to government and industry discussions, policies, and initiatives that could have important impacts on domestic resource recovery and U.S. PV manufacturing. For example, Washington state implemented a product stewardship regulation that directly impacts solar module manufacturers. The regulation will require PV module manufacturers, beginning July 1, 2023, to finance the takeback and reuse or recycling of PV modules sold within or into the state, after July 1, 2017, at no cost to the owners.[9] Although Washington is the only jurisdiction in the United States to implement manufacturer takeback requirements, policymakers and regulators in New York, North Carolina, Minnesota, and Maryland have considered similar stewardship policies in recent years.[35]

There are also policies in states, such as Washington and California, which could indirectly impact U.S. solar manufacturing through the CE. California regulators have recently allowed PV modules to be managed as universal waste, a subset of hazardous waste, which has less stringent handling, transport, and storage requirements.[36–39] California's universal waste regulation may reduce some of the costs and liabilities associated with collecting, storing, and transporting PV modules classified as hazardous waste, as compared to fully regulated hazardous waste.[35,40] However, some critics have warned that California's universal waste regulation may act as a barrier to PV module recycling under current market conditions, because the regulation treats disposal and recycling of hazardous PV modules in the same manner (e.g., the same handling, storage, and transport requirements and associated liabilities for noncompliance), and disposal is currently more economically favorable than recycling. Moreover, California's regulations prohibit universal waste handlers and universal waste destination facilities from using heat or chemicals to treat PV modules, which are processes used in most module recycling today.[35,40] In contrast, Washington allows PV modules that are being recycled to be regulated under less stringent requirements than modules destined for disposal.[41,42] Managing PV modules under an alternative regulatory scheme that treats recycling differently than disposal, such as Washington's policy, could reduce the costs and liability associated with regulatory compliance as compared to disposal, which could support increased rates of resource recovery and increase domestic supply of manufacturing material (e.g., glass, silicon, tellurium).[40] States including Arizona, Hawaii, Illinois, Minnesota, New Jersey, and North Carolina are also considering a variety of policy mechanisms to mandate or incentivize PV module and BoS equipment recycling, which could enable investment in new and expanded domestic recycling opportunities.[35,40]

Moreover, industry-led policies, such as the NSF/ANSI 457 Sustainability Leadership Standard for PV Modules and Inverters and the Silicon Valley Toxics Coalition's Solar Scorecard, could impact solar manufacturing in the United States. The NSF/ANSI 457 standard sets sustainable performance objectives related to design, manufacturing, and EOL management of PV modules.[35] PV manufacturers may find that compliance with voluntary industry standards, such as NSF/ANSI 457, can enhance their corporate responsibility image and may in turn increase consumer trust and overall competitiveness in the marketplace.[40]

These recent government- and industry-led policies and initiatives may signal a paradigm shift toward increased domestic resource recovery and sustainable PV manufacturing. It may also present opportunities for growth in upstream U.S. manufacturing sectors, such as the U.S. flat glass industry.[10]

3.4 Circular Economy Methods for PV Manufacturing

A broad range of CE methods can be incorporated in the PV manufacturing stage to improve the economic and environmental performance of PV systems.

3.4.1 Reduced Material Intensity and Closed-Loop Recycling

Efforts to reduce the material[43–48] and energy[49,50] intensity of PV manufacturing over the last two decades have predated the formal definition and integration of CE practices and have generated economic and environmental benefits.[48,50,51]

Of the mass of energetically intensive solar-grade silicon (which represents 25% of the total material cost of c-Si PV cells),[43] a significant fraction (40% is reported by the ITRPV[52]) is wasted as kerf loss during the sawing of wafers from the purified c-Si ingot. In addition, solar-grade silicon is lost as scrap when the top, bottom, and sides of the silicon ingot (the parts containing impurities) are cut.[53] To reduce the material intensity of c-Si PV manufacturing, R&D has focused on reducing the kerf losses by shifting to less wasteful sawing methods[54,55] and kerf-free wafering,[56] the recovery and reuse of silicon from the kerf loss,[57,58] and recycling and reuse of silicon from ingot cuts in manufacturing PV cells.

R&D as well as developing and refining standards and guidelines to reuse secondary silicon from PV manufacturing waste can further accelerate CE practices. A key concern in the reuse of silicon recovered from kerf losses and ingot cuts are impurities that can degrade the PV cell performance.[59] Further research is required to robustly characterize the level and type of impurities from ingot and kerf losses and benchmark the purity and properties of recovered silicon with those of virgin silicon.[60] The CE in PV manufacturing can be facilitated via R&D focused on optimizing the recovery process to minimize impurities[57,61] as well as evaluating the trade-offs in cell performance,[58] economic costs, and environmental impact from replacing virgin solar-grade silicon with secondary silicon[62] across a broad range of silicon manufacturing conditions. In addition, the supply of kerf loss as feedstock in alternate applications (e.g., hydrogen production,[63] lithium-ion batteries[64]) may be economically and environmentally preferable to landfilling.

In closed-loop recycling, materials recovered from a PV module at EOL are reused in PV manufacturing. Beyond the reuse of silicon, as discussed above, bulk (e.g., glass) and other specialty (e.g., silver) materials can be recovered and potentially reused in the PV module, yielding life cycle GHG and energy-return-on-investment benefits, yet these have yet to be comprehensively researched alongside industry testing and validation to make these into market-ready solutions.

3.4.2 Open-Loop Recycling to Reuse Materials from Allied, Non-PV Industries

The open-loop recycling pathway offers opportunities to reuse materials recovered from non-PV systems in PV manufacturing, which can be an economically and environmentally preferable pathway to source raw materials. For example, post-consumer plastic waste can be reused in the production of encapsulants in PV modules.[65]

3.4.3 Use of Renewable Electricity

Energy used in the extraction and purification of silicon accounts for half of the overall energetic footprint and climate impact of a c-Si PV module.[66] The CO_2 emitted from energy use in the early stages of the PV life cycle can significantly increase the climate footprint of PV systems.[62,67] A switch from CO_2-intensive fossil fuel electricity to renewable electricity, which is a widely pursued CE strategy, can significantly decrease the climate footprint of PV modules.[62]

The potential to decrease the climate footprint has motivated industry to explore opportunities to decarbonize the manufacturing process by using renewable electricity.[68] Developing market-recognized labels and valuations—which should be based on new, robust quantitative metrics—for the benefits of reduced embodied GHG emissions and energy is a promising research direction best accomplished in collaboration with industry and nongovernmental organization stakeholders.

3.4.4 Design for Circularity

The traditional approach to designing PV modules has been motivated by the need to drive down manufacturing costs,[51] increase system durability[69] and reliability,[70,71] and increase module efficiency,[72] with the overall goal of making PV cost-competitive with other sources of electricity.[73] Beyond driving down the costs of PV electricity, there is a need to reassess and redefine the key parameters of PV system design to address emerging sustainability challenges as the volumes of raw materials required and waste produced have increased exponentially with global PV installations reaching several terawatts.[74] For example, hazardous materials in c-Si PV modules (e.g., lead),[74] fluorine in the backsheet, and the challenges of removing the ethylene vinyl acetate (EVA) laminate can hinder efficient recycling of PV waste.[75–78]

Design for circularity—which encompasses the use of novel PV module designs and materials in the manufacturing stage to enhance recyclability, transition away from supply-constrained materials to abundant materials,[79] and decrease risks to human health and the environment over the PV life cycle—can address these emerging sustainability challenges. Machine-learning (ML) and artificial intelligence (AI) methods can inform the selection of nonhazardous and environmentally benign materials during the design of PV modules.[80] The use of recyclable materials in the PV module can enhance recyclability at EOL and decrease landfilling.[81] Substituting abundant materials for constrained materials (e.g., copper metallization replacing silver metallization)[82] can decrease the cost of manufacturing PV systems.[44]

Replacing hazardous materials in the PV module can decrease the environmental and human health risks during the use and EOL stages. For instance, for c-Si modules, substituting fluorinated backsheets with fluorine-free polymers or a double-glass design can decrease human health risks during EOL and allow for high-temperature recycling processes for faster and more efficient recycling of the spent PV module.[76,77] Eliminating lead solders can prevent potential lead emissions during thermal recycling and potentially prevent c-Si PV modules from being classified as hazardous waste.[83] Frameless modules help reduce the aluminum content, decrease transportation burdens, eliminate the need for deframing during recycling, and, thereby, simplify the recycling process and decrease the climate and energy footprint.[84] A laminate-free design[85] or replacing the EVA with edge sealants decreases the time and energy required for recycling by avoiding the need for thermal, chemical, or mechanical processes required to eliminate the EVA during PV recycling.[83] The examples mentioned above focus on the currently dominant module technology – crystalline silicon. Other issues may emerge or not be relevant if newer technologies reach substantial market share, e.g., perovskite.

Design for circularity strategies may impose trade-offs in other life cycle stages of the PV system. Copper metallization can degrade cell performance and the durability of the PV module.[86] A laminate-free design impacts the electricity generation profile and durability of the PV module, which impacts the economic and environmental performance of PV systems.[87] Lead-free alternatives can increase costs and elevate temperatures for soldering, which can cause thermomechanical stress and breakage of the silicon wafer during manufacturing.[88] Preliminary field studies have found that the durability of modules with fluorine-free backsheets is lower than the durability of those with fluorinated backsheets.[89]

A holistic approach assessing the trade-offs that material and design choices impose on both the technical performance of the module (e.g., electricity generation) and the life cycle economic and environmental impact[90,91] will help in selecting the most sustainable design for circularity alternative. This will prioritize design for circularity methods that generate the highest net economic and environmental benefit over the life cycle of the PV system.

3.5 Potential for Sustainability Factors to Be Preferentially Identified for Purchase

The integration of CE strategies in the manufacturing phase is a potential strategy for PV module suppliers to improve sustainability across the PV supply chain and establish themselves as environmentally preferable PV suppliers,[92] which is aligned with emerging procurement requirements defined in regulations.[93,94]

3.5.1 Potential for Low-Carbon Solar to Reduce Life Cycle GHG Emissions

The net CO_2 benefit of a PV system is the difference between the CO_2 avoided by displacing the marginal source of grid electricity (which in most U.S. balancing areas is still a fossil fuel source, but in some places and at sometimes could be another low-carbon source) during the use phase and the CO_2 emitted when manufacturing the PV system.[95] The net CO_2 benefit can, therefore, be improved by decreasing the consumption and wastage of CO_2-intensive raw materials and increasing use of low-carbon electricity in PV manufacturing,[74] which are two widely recommended CE strategies. Studies show that energy and GHG payback times decrease significantly by locating PV manufacturing in less CO_2-intensive geographies.[62,66,96] Based on these findings, some in the PV industry are currently incorporating CE strategies in the PV supply chain and manufacturing to decrease PV's embodied carbon.[68] Recovery and reuse of manufacturing scrap as well as EOL materials can provide similar benefits, yet they require quantification and promotion to raise awareness and increase uptake.

3.5.2 Fluorine- and Lead-Free Modules

To decrease potential downstream environmental and human health risks during use and recycling, R&D has focused on decreasing the content of hazardous materials in PV modules.[97] The industry currently manufacturers lead- and fluorine-free modules,[97,98] and projections show that lead and fluorine content is expected to decrease in the future.[44,84] Suppliers of modules with low or no lead and fluorine are incentivized by the potential to obtain higher sustainability scores in emerging standards than suppliers with high lead or fluorine content, and consumers could be motivated by the likelihood that when end of life is reached, those modules should be determined as nonhazardous thereby reducing costs and environmental impacts.[99,100]

3.5.3 Ranking Mechanisms and Alliances

PV sustainability scorecards,[100] standards and regulations offer mechanisms to guide,[8,101,102] operationalize,[103] declare, and measure the adoption of industrywide CE practices and, thereby, help procurers and consumers rank PV suppliers based on key environmental performance indicators.[99] The NSF/ANSI 457 standard[99] incentivizes the incorporation of CE practices by assigning a higher rank to PV suppliers who declare the content of recycled material and substances of very high concern in the product, comply with existing directives (e.g., the European Restriction of Hazardous Substances [RoHS] directive), quantify and declare the environmental footprint through the use of quantitative tools such as LCA, and minimize use of water and energy in manufacturing. NSF/ANSI 457 further promotes CE solutions for EOL by requiring that manufacturers provide takeback services (including reuse, refurbishment, and recycling) to earn higher accreditation levels, define material recovery targets, and declare materials contained in the PV module and the availability of replacement components. Furthermore, recent regulatory mechanisms, such as the European Union's Ecodesign Directive in development, propose mandatory CE (e.g., repairability, refurbishment) and minimum environmental sustainability requirements for the different life cycle stages of PV systems to be procured in the European Union.[102] With emerging clarity on the regulations and standards, alliances have developed to coordinate industrywide efforts to improve the sustainability of PV panels through CE strategies such as decreasing manufacturing energy requirements and carbon emissions.[68]

3.6 Environmental Justice and Social Benefit Through Circular Economy During PV Manufacturing

CE strategies in PV manufacturing offer significant potential to improve environmental justice outcomes and increase social benefits. The use of renewable electricity helps decrease the reliance on fossil fuels and thereby minimize climate change and health effects, including deaths, attributable to air pollutant emission from fossil fuel combustion, which disproportionately impact minority and low-income communities and the developing world while exacerbating socioeconomic inequities.[104,105] By following closed-loop recycling and increasing emphasis on substituting hazardous materials with environmentally benign materials in the supply chain, CE strategies in PV manufacturing can significantly decrease the likelihood of environmental and health hazards, which have previously impacted communities in the vicinity of PV manufacturing facilities.[106] The ratings provided by scorecards[100] to rank socially responsible PV suppliers help incentivize transparency in the supply chain to avoid the sourcing of conflict minerals and prevent the violation of worker rights[107] and health and safety requirements. Further, the emergence of industry alliances, which prioritize CE strategies in the PV supply chain, can increase PV manufacturing competitiveness and, thereby, increase employment potential in the U.S. PV sector.[108] Finally, all CE strategies that reduce material demands consequently reduce burdens experienced in frontline communities neighboring the extraction industries.

4. Key Considerations for Site Selection, Construction, and Operation

This section addresses solar impacts in the use phase related to land use, water requirements, and air quality, and it discusses CE approaches and environmental justice issues related to this phase.

4.1 Land-Use Considerations

The large-scale solar deployment envisioned in the *Solar Futures* scenarios will require land for ground-mounted solar systems.[viii] Life cycle assessments[ix] of large-scale solar systems have concluded that upstream and downstream land use is much less than operation phase land use both for PV and CSP solar systems (estimates range from less than 1% to 10% of operation phase land use).[109,110] Therefore, in this analysis we focus on land requirements during the operation phase of solar electricity generation; however, we start with a brief review of prior investigations of life cycle land use for solar and other electricity generation technologies.

Comparing the life cycle land requirements of solar and other generation technologies is difficult owing to differences in land-use intensity, length of land use, and other factors.[111] An early comparison of land-use impacts suggested PV requires amounts of land through its life cycle similar to the amounts used by nuclear, natural gas, and coal-fired electricity generation sources, and less than the amounts used by other renewable sources including biomass, geothermal, hydroelectric, and wind.[109] Recent studies have updated and increased life cycle land-use projections for natural gas,[112] PV,[113] and nuclear.[114] Life cycle land-use estimates for wind have decreased,[115] partially owing to excluding indirect land-use area (area between turbines). A harmonization effort comparing 39 land-use studies found that high-end land use intensity (area/MWh) for wind and geothermal is less than half of the high-end land use for PV and CSP.[116]

Our analysis here compares operation phase solar land use under *Solar Futures* scenarios with quantities of existing disturbed and contaminated land areas; we also examine methods for mitigating solar land-use impacts.

4.1.1 Solar Futures Study Land Requirements

This section evaluates solar land requirements under the three core *Solar Futures Study* scenarios. Technologies evaluated include utility-scale PV (UPV) sited in rural areas, distributed UPV (DUPV) sited in urban areas, and CSP. Although rooftop solar contributes a substantial portion of *Solar Futures Study* projections, this technology by definition does not require ground-mounted installation and is therefore excluded from this evaluation. Methods to quantify and evaluate land requirements are fundamentally similar to the methods outlined in Macknick et

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[viii] Roof-mounted PV uses land already developed for another purpose, and thus no new land converted from other uses is required. Therefore, the added capacity of roof-mounted PV is not counted in this solar land use requirements assessment, which aims to assess how much *additional* land is required under the Solar Futures scenarios.
[ix] Life cycle land-use evaluations include land use at the location of energy generation as well as for upstream (mining of natural components such as fossil fuels or rare earth elements and manufacturing), and downstream (component disposal) uses.

al.[117] and Hartmann et al.,[118] with updated data to improve land-use and land-availability estimates.

Methods

Similar to the approach described in Hartmann et al.,[118] we calculate land requirements on a regional basis (by electric grid balancing areas,[x] then aggregated to states). We quantify future land requirements for utility-scale solar energy deployment additions and subtractions (decommissioning), and we quantify the amount of land potentially suitable for solar development, with emphasis on identifying the amount of potentially suitable disturbed and contaminated lands.

Land requirements are based on estimates of net future solar energy deployment derived from ReEDS[120] and geospatial land exclusion categories as used in the Renewable Energy Potential (reV) model.[121] Details on how the ReEDS model was developed for the *Solar Futures Study* are provided in the main study report.[1] Future solar deployment is modeled for all solar technology types at 2-year intervals from 2020 to 2050. This analysis focuses on projections from the three core *Solar Futures Study* scenarios and the DUPV, UPV, and CSP technology types. Land-use requirements are estimated using recent, empirically derived estimates of land used by existing solar facilities per unit of installed capacity (MW).[113,118,122] UPV and DUPV are assumed to require approximately 7.5 acres (3.0 hectares [ha]) per installed MW, and CSP is assumed to require approximately 10 ac (4.0 ha) per installed MW.[xi] We refer to land use per unit of capacity as land-use intensity. Multiplying land-use intensity by estimated capacity yields an estimate of the total land area required for ground-based solar.

Our results represent conservatively high estimates of land requirements in 2030, 2040, and 2050 using the maximum predicted land requirement for each core scenario in each year. These land requirements are based on the cumulative capacity of solar energy facilities installed as of each year. Graphical representations of land requirements for the three core scenarios by state across all modeled years are provided in Appendix A.

Our analysis of land availability focuses on the regional availability of lands potentially suitable for solar development, with emphasis on previously disturbed and contaminated lands. We use a stepwise geographic information system framework. First, we spatially delineate the footprint of potentially available land for each technology type based on the exclusion criteria used by the

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[x] A balancing (authority) area is defined as "The collection of generation, transmission, and loads within the metered boundaries of the balancing authority. The balancing authority maintains load resource balance within this area."[119]

[xi] The PV estimate is based primarily on analysis in Walston et al.,[122] which uses geographic information system (GIS) techniques to measure the total footprint of 192 UPV installations in the Midwest in 2018. The relationship between total footprint and nameplate capacity yields a total land-use requirement of about 7.5 ac (3.0 ha) per MW_{AC}. This estimate is supported by analysis in Bolinger,[123] which also uses GIS techniques but measures the land directly occupied by arrays for 736 UPV installations across the United States in 2019. A median direct land-use requirement of 4.2 ac (1.7 ha) per MW_{DC} is calculated for systems with one-axis tracking, which equates to 5.5 ac (2.2 ha) per MW_{AC} at a median inverter loading ratio (ILR) of 1.30. Accounting for non-array space used within the fenced PV system area (e.g., disturbed ground and operational facilities) would increase the area per MW_{AC}. A ratio of direct to total area of 0.73, which broadly aligns with some anecdotal observations, would result in the same total footprint of 7.5 ac (3.0 ha) per MW_{AC} found in Walston et al.[122] The CSP estimate of 10 ac (4.0 ha) per MW_{AC} is based on analysis in Ong et al.[113] and Hartmann et al.[118]

reV model. These exclusion criteria include slope, land cover type, land ownership and status, and amount of urban development. Next, starting with the potentially available lands footprint, we apply additional geospatial filters to identify previously disturbed areas that might be used for solar development (Table 1). Potentially suitable lands are first filtered by screening out areas protected from surface disturbance for natural or cultural resource protections, using the U.S. Geological Survey (USGS) Protected Areas Database (PADUS), Gap Codes 1 and 2.[124] Then, remaining lands identified as developed or otherwise disturbed in land cover data[125] are categorized as disturbed lands potentially suitable for solar development. The minimum parcel size assumed for PV development is the size of a single 90-m raster pixel used in the geospatial analysis (approximately 2 acres in size). The minimum area required for solar developments is likely somewhat larger than 2 acres; see the Uncertainties section on page 26 for additional discussion.

Table 1. Data and Filtering Criteria to Determine Suitability of Disturbed and Contaminated Lands for Solar Energy Development

Data Set and Source	Purpose	Criteria
Protected Areas Database[124]	To exclude areas protected for natural and cultural resources from available lands (USGS)	Gap Codes 1 & 2 excluded from available lands
2016 LANDFIRE Existing Vegetation Type[125]	To filter available lands to suitable disturbed lands, after excluding protected areas (Protected Areas Database)	Land cover types considered to be disturbed: Developed Developed (high intensity) Developed (mod. Intensity) Developed (low intensity) Exotic/invasive species Quarries, mines, wells, and pads
Contaminated Sites[126]	To identify previously disturbed lands that have been contaminated and currently listed in a federal or state remedial program, e.g., the Resource Conservation and Recovery Act (RCRA) or Superfund	Suitable contaminated lands for solar development are within the available lands footprint and at least 7.5 ac in size for PV and at least 500 ac in size and >6 kWh/m^2/day for CSP.

Siting installations on disturbed or contaminated lands is recommended for minimizing the land-use impacts of solar development (e.g.,[117,118]). The USGS defines disturbed land as land in an altered and often non-vegetated state owing to prior disturbances.[127] For the purposes of this study, disturbed lands include areas identified in the 2016 LANDFIRE program as developed areas, invasive species-impacted lands, and other types of non-vegetated lands such as quarries or gravel pits (Table 1). Disturbed lands are not designated by the U.S. Environmental Protection Agency (EPA) as reaching the necessary threshold to be considered environmentally contaminated, yet they still might not be suitable for productive agriculture or other beneficial use.

One other category of previously disturbed lands considered here includes lands identified on federal and state lists as contaminated by improper handling or disposal of toxic and hazardous materials and wastes but remediated to make them suitable for some forms of reuse, such as industrial development. Such lands include Resource Conservation and Recovery Act and Superfund sites as well as landfills, abandoned mine lands, brownfields, and nonfederally-owned Resource Conservation and Recovery Act and Superfund sites. We evaluate the potential suitability of these contaminated sites for solar development using data from EPA's RE-Powering America's Land screening tool (Table 1).[126] We filter contaminated lands to locations with a slope of less than 5%,[118] and we assume a minimum size of 7.5 ac (3.0 ha) for PV projects on contaminated lands. We assume CSP projects are at least 50 MW in capacity and therefore require at least 500 ac (202 ha), with an additional restriction that insolation levels in CSP locations must be at least 6 kWh/m^2/day.[128]

Although the areas we identify as potentially suitable disturbed and contaminated lands pass a screening-level review for valuable resources (by excluding protected areas identified in the Protected Areas Database), actual solar siting requires location-specific and jurisdictional reviews and input from various stakeholders. Thus, although we identify these lands as potentially suitable for solar development, actual determination of suitability will require project-specific analysis.

Estimates of Land Requirements and Comparisons with Land Availability

We calculate land requirements on a regional basis and then aggregate them to each state. Each state's projected deployment of ground-based solar varies in accordance with the economic optimization performed within the ReEDS model from 2020 to 2050. Estimates of land requirements and areas of land suitability within balancing areas at the target years (2030, 2040, 2050) are provided in Appendix A. Maximum aggregated land-use requirements among the core scenarios at the target years are compared to the estimated areas of potentially suitable disturbed and contaminated lands. Scenario-based total land required for all modeled years, summed across all ground-based solar technologies, is also graphically illustrated by state in Appendix A.

Figure 9 shows national solar land-use projections for the three core scenarios from 2010 to 2050. In the scenario with the largest land requirement (Decarb+E), the total aggregated solar deployment area across the contiguous United States is approximately 10.3 million ac (41,683 km^2) by 2050—roughly equivalent to the combined surface area of Connecticut, Massachusetts, and Rhode Island. Table 2 shows that, in 2050, the maximum amount of land required among the three core scenarios is equivalent to just 6.4% of the area of potentially suitable disturbed lands; however, this maximum estimated land use area is about 20% larger than the area of all potentially suitable contaminated lands. In a larger context, maximum total land requirements across all technology types for ground-based solar in 2030, 2040, and 2050 are approximately 0.2%, 0.3%, and 0.5%, respectively, of the total contiguous U.S. surface area. Figure 10 compares the maximum modeled land requirement (0.5%) with solar-suitable disturbed and contaminated land areas and examples of other areas in the United States. Table 3 shows maximum land requirements by state. The maximum total solar land requirements are not expected to exceed 5% of any state's land area by 2050, with the exception of Rhode Island (6.5%).

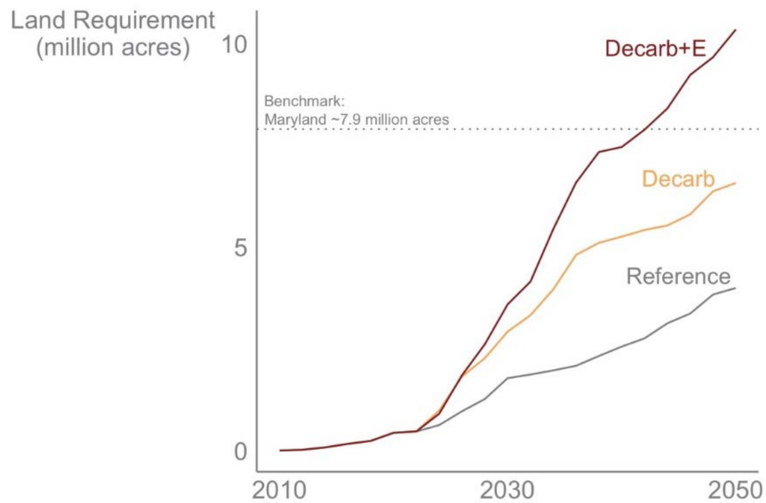

Figure 9. National solar land-use projections for the three core scenarios, 2010–2050

Table 2. Summary of Solar Energy Development Land Needs in 2030, 2040, and 2050 Aggregated Across the Contiguous United States

Solar Energy Deployment[1]	Maximum Amount of Land Required Across *Solar Futures Study* Scenarios (ac)[2]	Percentage of Total Potentially Available U.S. Disturbed Lands	Percentage of Total Potentially Available U.S. Contaminated Lands
2030			
PV	3,578,000	2.2%	40%
CSP	19,000	<0.01%	0.3%
2040			
PV	7,437,000	4.5%	83%
CSP	22,000	0.1%	1.4%
2050			
PV	10,292,000	6.2%	115%
CSP	53,000	0.2%	3.4%

[1] PV deployment includes DUPV and UPV technologies.
[2] Maximum cumulative land requirement estimated among the *Solar Futures Study* core scenarios.

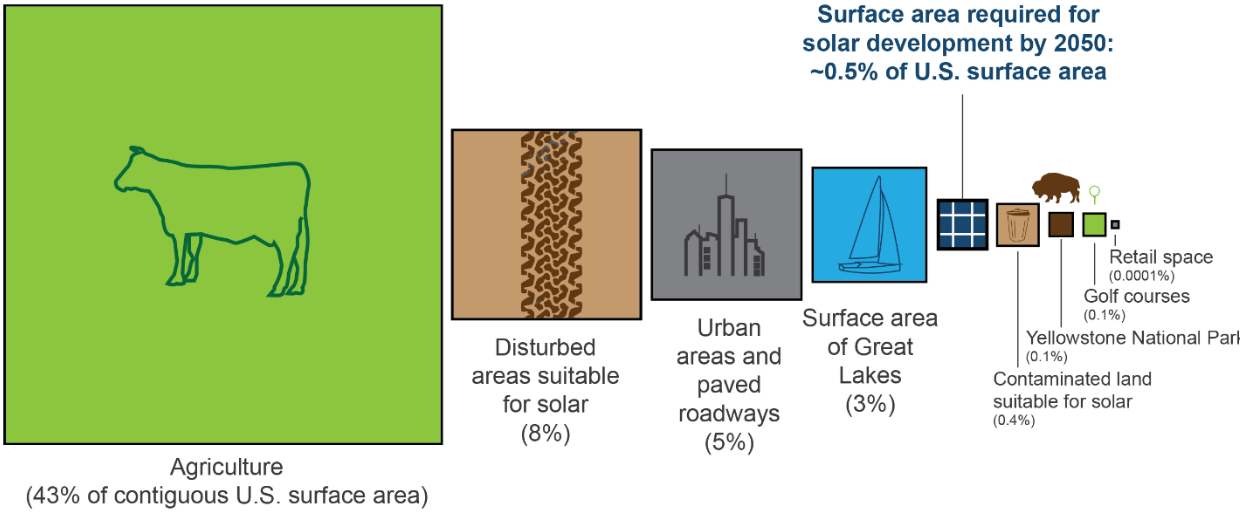

Figure 10. Maximum land use required for solar in 2050 in the *Solar Futures Study* scenarios compared with solar-suitable disturbed and contaminated areas and examples of other U.S. areas

Amounts of disturbed and contaminated lands depicted here represent the amounts suitable for solar energy development calculated in the *Solar Futures Study*. Sources: EPA,[126] USDA,[129] LANDFIRE.[130]

Potential for Rural Economic Development, Social Justice, and Avoidance of Conflict with Other Land Uses

Most of the contiguous 48 states contain enough potentially suitable disturbed lands for future ground-mounted solar projections through 2050 (Table 3), but not all states do, despite adequate potentially suitable disturbed and contaminated lands at the national level (Table 2). For example, many states do not have any suitable land area for CSP (Table 3), primarily because these states do not meet CSP insolation requirements (>6 kWh/m^2/day). Although some states do not have enough potentially suitable contaminated lands to meet maximum CSP and PV land requirements, development on contaminated lands could greatly contribute to meeting *Solar Futures Study* goals. These findings are consistent with previous DOE assessments of land requirements for utility-scale solar development.[117,118] Many of the disturbed and contaminated lands identified as potentially suitable for solar development will not meet other siting requirements or requirements of project developers, local communities, or regulatory agencies. However, our analysis shows the potential of these lands to provide much of the area needed in the *Solar Futures Study* scenarios. Appendix A contains detailed results within balancing areas.

Many stakeholders have noted a preference for siting solar on nonproductive disturbed or formerly contaminated lands. These lands are often situated in rural areas or in marginal regions of urban areas, which may need economic revitalization. Siting a financially attractive project in an area without other productive land-use opportunities could improve temporary and permanent local economic conditions. Recognizing these potential advantages, EPA and DOE have explored the feasibility of renewable energy development on contaminated lands through the RE-Powering America's Land initaitve.[126] When carefully implemented, using formerly contaminated lands (after cleanup, as needed) for solar can minimize stress on intact, undeveloped lands and—in some areas—improve soil stability and decrease potential health risks. Previously developed or contaminated lands may also have existing onsite infrastructure (e.g., roads, water service), potentially lower transaction costs, greater public support for development, and streamlined permitting and zoning processes, and they are often already close to roads, rail, and transmission lines.[126]

As solar development increases, more of it is expected to be in rural areas where an opportunity exists to target marginal or previously disturbed lands. Approximately 90% of projected *Solar Futures Study* PV deployment by 2050 is expected to be generated from UPV projects in rural settings. This development could benefit rural communities as an economically valuable local resource.[131,132] Many rural development plans aim to invest in renewable energy on rural lands to boost economic development.[132] The wind and solar industries have already begun investing in these rural areas. In fact, approximately two-thirds of existing utility-scale solar facilities tracked by the U.S. Energy Information Administration[133] are in rural areas as defined by ReEDS. Solar is an economically valuable local resource with potential to benefit the local community, solar facility owners, and landowners leasing to solar facility operators.[131] Powering a majority clean grid with large-scale PV can benefit these rural areas by increasing rural land use, providing tax benefits to rural communities, providing local workers with jobs, creating new markets for local contractors, diversifying income for landowners, and increasing available local resources.[131,134,135] Solar projects also can serve underserved communities. In a study conducted in parts of Arizona and Mexico, researchers found that small-scale solar projects assisted women in meeting household and livelihood needs as part of community-level sustainability initiatives.[136]

Another siting consideration is avoiding sensitive ecological resources that may be affected by solar development. Our filtering criteria exclude areas protected for biodiversity conservation (PADUS, Table 1), removing many sensitive ecological areas from the potentially suitable lands for solar development. However, if the broader category of available lands identified by the reV model is eventually used for solar development, avoidance of other lands important for biodiversity conservation may need to be considered. For example, the U.S. Fish and Wildlife Service has designated over 111 million ac of critical habitat for 704 species listed as threatened or endangered under the Endangered Species Act.[137] Approximately 90 million ac of designated critical habitat exist in the 48 contiguous states, of which approximately 20% (18 million ac) intersects lands identified as potentially available for utility-scale solar development estimated by the reV model. While critical habitat designation does not necessarily prohibit industrial land development, additional project siting considerations should be made within these areas to ensure solar development does not adversely impact sensitive species or critical habitat.[137]

Minimizing land-use conflicts with agriculture is also a goal. Avoiding solar siting on prime farmland—and instead focusing on marginal farmland or other disturbed areas—is one approach. Some states and local jurisdictions have developed guidelines and policies to restrict solar development on prime farmland, such as Minnesota's guidelines for solar energy production and prime farmlands.[138] Another technique for minimizing conflicts that is receiving considerable interest is colocating solar with onsite restoration of native vegetation, providing habitat for pollinators such as bumblebees and possibly benefiting surrounding agriculture through increased pollination and pest-control services provided by managed and/or native pollinators (see Section 4.1.2). Seven or more states have developed pollinator "scorecards" to evaluate the quantity and quality of such pollinator habitat at solar facilities, in order to provide consistency and certification for facilities to be classified as "pollinator friendly."[139] Conflicts with agricultural interests many also be addressed by growing crops under and around solar panels, as described in Section 4.1.2.

Uncertainties in Land-Use Estimates and Future Research Directions

The following are uncertainties associated with future solar land-use estimates, aside from the uncertainties associated with the *Solar Futures Study* scenarios (see Section 2 of the *Solar Futures Study*[1]):

- **Increased Solar Technology Efficiency:** The efficiency of solar cells and CSP facilities will likely increase over the study period, thus reducing land-use requirements. Assuming the reduction in land use would be approximately linear (e.g., a 10% efficiency increase would reduce land use by 10%), higher efficiency could decrease land use substantially.
- **Non-Land-Based PV Technologies:** Non-land-based PV technologies such as "floatovoltaics"[140] or solar cells incorporated into the sides of buildings (building integrated PV)[141] or other infrastructure surfaces could decrease land use. Projections of their future use are not available, and thus their potential for reducing land requirements is not quantified but could be a productive future research topic.
- **Energy Storage Impacts:** Energy storage capacity increases to about 1,700 GW under the Decarb+E scenario in 2050 and, assuming the energy stored is obtained from ground-mounted solar facilities, supplying energy for this storage capacity would require additional land for solar energy generation. The amount of additional land required for storage could increase the estimates herein substantially but will require further study to develop quantitative estimates.
- **System Longevity:** If goals for increasing the lifetime of PV modules and other system components are met, the same sites can be kept in service longer than were modeled in the *Solar Futures Study*. At end of facility life, it is expected that land previously used for solar can be returned to productive uses such as agriculture, unless the facility was constructed on previously contaminated lands.
- **Life Cycle Considerations:** Much is still unknown about solar life cycle land-use impacts, including land requirements of the full supply chain for manufacturing through EOL. Although the potential global impacts from mineral mining have been recognized,[142] we found no quantification of land-use requirements related to mining solar-relevant minerals. Additionally, while there is hope for broad-scale recycling of solar materials at EOL, the fate of PV modules and other solar equipment is far from determined (see Section 5). Lack of recycling options for solar panels would result in increased downstream (disposal)-associated land use impacts if a high volume of solar panels are placed in landfills.

Considering the first four bullets, it is not clear whether our land-use results for the *Solar Futures Study* scenarios are overestimates or underestimates. Life cycle considerations are outside the scope of our analysis but would benefit from future study.

In addition, our calculation of available disturbed lands for PV development is based on the resolution of the input land cover data (90-m pixels). Each 90-m pixel equates to approximately 2 ac, so the minimum PV parcel size is about 2 ac. However, UPV is generally considered to consist of facilities with a minimum capacity of 1 MW, and the corresponding minimum land required would be 7.5 ac. Nonetheless, the results reported in Table 2 do not apply a minimum

PV parcel size to the GIS-based screening of available lands, because there is no robust citable source for PV development size thresholds, and there is great variability in PV project sizes in urban and rural settings. For example, a recent report indicates that utility scale may include smaller projects (100 kW) but that many developers and financiers would not invest in projects of less than 25 MW.[143] To contextualize how a minimum parcel size threshold may affect the amount of available land for PV development, Table A-2 in Appendix A contains a comparison of disturbed land availability using conservative minimum parcel size thresholds of 7.5 ac (~1 MW) for urban PV development and 15 ac (~2 MW) for rural PV developments. While these minimum size thresholds reduce the overall amount of available land and disturbed land, the potentially available disturbed land would still meet projected 2050 solar needs.

Table 3. Availability of Disturbed and Contaminated Lands to Meet Maximum Net[1] Solar Deployment in 2030, 2040, and 2050, by State and Solar Technology

		CSP					PV (DUPV and UPV)				
State	Land Needed for Solar as Percent of State Land Area	2030 Land Need (ac)	2040 Land Need (ac)	2050 Land Need (ac)	Potential Disturbed Land Available for CSP (ac)	Potential Contaminated Land Available for CSP (ac)	2030 Land Need (ac)	2040 Land Need (ac)	2050 Land Need (ac)	Potential Disturbed Land Available for PV (ac)	Potential Contaminated Land Available for PV (ac)
Alabama	0.74%	—	9,499	43,128	—	—	5,703	100,302	196,851	5,517,166	40,735
Arkansas	0.33%	—	14,766	14,766	—	—	2,010	33,388	96,048	2,586,580	18,855
Arizona	0.48%	3,049	3,505	34,331	2,399,098	2,731,4842	135,676	215,960	312,602	5,399,774	2,737,590
California	0.55%	13,720	9,655	4,883	2,930,086	268,874	306,178	514,329	533,037	5,472,492	617,554
Colorado	0.11%	300	2,680	11,188	1,497,196	2,382	39,598	62,535	58,017	2,672,426	27,212
Connecticut	2.36%	—	—	—	—	—	28,495	32,202	73,027	261,724	6,926
Delaware	4.45%	—	—	—	—	—	17,995	54,555	55,547	218,526	6,732
Florida	3.29%	—	—	543	—	—	448,632	936,835	1,126,931	4,695,180	219,018
Georgia	0.50%	—	59	569	—	—	91,585	136,998	184,964	6,223,300	21,547
Iowa	0.42%	—	—	—	—	—	34,629	62,589	150,683	3,329,102	4,997
Idaho	0.39%	—	—	—	773,660	—	2,650	34,582	204,284	2,172,944	581,383
Illinois	0.90%	—	—	—	—	—	167,397	227,734	320,071	3,832,176	35,060
Indiana	0.71%	—	—	—	—	—	84,493	84,493	163,745	3,055,150	75,956
Kansas	0.13%	—	—	3,595	333,276	—	65,238	65,238	65,978	4,700,026	102,574
Kentucky	2.52%	—	—	—	—	—	181,530	489,785	635,645	1,754,846	24,863
Louisiana	0.87%	—	27,637	92,612	—	—	73,417	121,719	146,598	3,575,836	24,959
Massachusetts	2.09%	—	—	—	—	—	33,687	98,469	104,350	670,580	16,627
Maryland	4.40%	—	—	—	—	—	115,601	122,842	273,662	866,418	22,166
Maine	0.07%	—	—	—	—	—	5,718	6,856	14,127	701,490	4,642
Michigan	0.70%	—	—	—	—	—	121,644	218,386	252,629	3,560,912	38,860
Minnesota	0.17%	—	—	—	—	—	28,374	83,175	85,130	3,771,980	169,250
Missouri	0.40%	—	—	—	—	—	41,386	135,859	175,228	3,069,262	86,632
Mississippi	0.85%	—	35,734	35,734	—	—	93,108	200,842	219,509	6,131,038	11,213
Montana	0.02%	—	—	—	—	—	128	128	14,238	2,884,932	233,608

State	Land Needed for Solar as Percent of State Land Area	CSP					PV (DUPV and UPV)				
		2030 Land Need (ac)	2040 Land Need (ac)	2050 Land Need (ac)	Potential Disturbed Land Available for CSP (ac)	Potential Contaminated Land Available for CSP (ac)	2030 Land Need (ac)	2040 Land Need (ac)	2050 Land Need (ac)	Potential Disturbed Land Available for PV (ac)	Potential Contaminated Land Available for PV (ac)
North Carolina	1.27%	—	—	—	—	—	88,486	392,867	394,382	5,278,630	14,158
North Dakota	0.10%	—	—	—	—	—	24,058	36,018	44,406	3,439,552	2,110
Nebraska	0.23%	—	—	—	—	—	97,800	101,889	112,019	3,110,992	78,739
New Hampshire	0.88%	—	—	—	—	—	8,633	22,779	50,185	284,880	1,147
New Jersey	0.99%	—	—	—	—	—	6,924	39,493	46,460	645,728	121,126
New Mexico	0.06%	10	9,113	26,422	2,048,696	1,074,180	18,024	17,799	13,664	2,175,718	1,100,001
Nevada	0.10%	1,785	1,100	—	3,678,096	158,374	53,647	67,294	61,023	3,838,372	164,063
New York	0.81%	—	—	—	—	—	86,048	195,200	253,204	2,044,416	103,653
Ohio	1.06%	—	—	—	—	—	95,954	187,425	276,268	3,717,672	25,440
Oklahoma	0.44%	—	—	18,928	213,898	—	75,409	112,448	172,301	5,693,936	17,516
Oregon	0.13%	—	—	—	341,788	—	36,735	55,823	81,211	2,329,181	1,054,427
Pennsylvania	0.98%	—	—	—	—	—	360	137,091	281,288	1,663,470	62,701
Rhode Island	6.54%	—	—	—	—	—	1,318	2,162	43,248	89,998	1,647
South Carolina	4.06%	—	—	—	—	—	302,341	560,455	780,244	3,526,486	222,607
South Dakota	0.19%	—	—	—	—	—	377	83,041	91,037	3,731,440	1,388
Tennessee	1.31%	—	—	2,829	—	—	51,587	54,804	342,998	2,749,216	82,775
Texas	0.86%	—	19,724	107,030	8,336,526	45,860	489,315	1,098,653	1,322,869	32,517,678	246,054
Utah	0.12%	15	15	6,244	2,487,264	2,520	13,705	49,491	56,623	2,896,994	37,867
Virginia	1.55%	—	—	177	—	—	140,417	290,063	391,079	2,750,536	79,662
Vermont	0.21%	—	—	—	—	—	917	5,078	12,222	154,896	1,987
Washington	0.24%	—	—	—	—	—	48,666	89,432	101,983	1,726,818	344,202
Wisconsin	0.75%	—	—	—	—	—	103,775	131,864	261,032	2,800,868	12,625
West Virginia	0.52%	—	—	—	—	—	76,571	76,682	79,519	288,666	46,100
Wyoming	0.06%	—	—	—	184,184	—	4,805	36,339	36,339	1,149,620	10,048

[1] Net of capacity additions and subtractions (decommissioning) in a given period.
[2] The large area of contaminated land in Arizona is attributable to classifying entire areas of Yuma Proving Ground and Goldwater Range as contaminated.

4.1.2 Opportunities to Improve Solar-Environmental Synergies with Regard to Land and Ecosystems

Ground-based solar energy facilities are increasing in agricultural landscapes, due in large part to the siting of utility-scale solar energy development on former agricultural fields.[144] Croplands are generally flat, open, and relatively undeveloped, making them ideal locations for solar energy development.[144] The potential for future use is great; there are over 365 million ac of agricultural lands in the contiguous United States (in addition to the disturbed lands identified in Section 4.1.1). In fact, a recent study found that approximately 70% of utility-scale solar facilities in the Midwest are on sites formerly used for commercial agricultural production.[122]

There is increasing awareness of the pressure on land resources for food and energy production. Agricultural lands are under pressure owing to soil erosion caused by agricultural practices such as tilling and overgrazing.[145] Increasing biodiversity loss indicates a need to protect additional land areas of high value for species of conservation concern.[146–148] Studies also note that, in some cases, solar development has occurred in unsuitable locations, for example high-quality forested areas[149] or near protected areas.[150] Many recent research efforts have accordingly focused on strategies to improve the environmental compatibility of solar energy by integrating solar development with other beneficial land uses, which can maximize the co-benefits of multiple ecosystem services (including soil and water retention, carbon sequestration, and increasing biodiversity[122]) and improve surrounding agriculture.[151–153] Few estimates of the cost implications of dual use facility construction are available; one study estimated an increased cost of $0.07/W$_{DC}$ to $0.80/W$_{DC}$, with lower increases associated with PV plus pollinator habitat and higher increases associated with PV plus crops.[154] Additional cost studies that account for other potential benefits provided by vegetation (such as water and soil retention benefits, changes in operation and maintenance costs, and changes in PV panel efficiency) are needed to fully understand the cost implications of various dual use strategies. These strategies, which are discussed below, are often interrelated and can be broadly categorized as vegetation management to provide ecosystem services at solar energy facilities, colocating agriculture (including grazing) and solar energy, and other opportunities such as installing solar panels on water.

Vegetation Management to Provide Ecosystem Services

With the large increase in U.S. utility-scale solar installations since about 2010, the feasibility and benefits of establishing a diverse plant community under solar panels and/or at the perimeters of solar facilities have been increasingly investigated as a means to mitigate land-use impacts.[122,155–157] Conventional solar site preparation generally has involved grading and removal of all vegetation, to make installation easier, and then introduction of gravel or turf grass ground cover to minimize fire risk, dust generation, and panel shading.[155] Establishing a varied, deep-rooted plant community (often but not always consisting of species native to the facility location) has many potential ecological benefits. Such habitat has been termed "solar-pollinator" habitat,[152] although it can benefit many ecological and other endpoints in addition to pollinators. Solar-pollinator habitat has been characterized as representing a techno-ecological synergy, where technical and ecological benefits are achieved simultaneously.[153] A study of potential ecosystem services provided by solar-pollinator habitat in the U.S. Midwest indicated a potential threefold increase in pollinator supply, 65% increase in carbon storage potential, 95% increase in soil/sediment retention, and 19% increase in water retention.[122] However, these potential ecosystem services will vary by geographic region, and they remain largely unquantified for other U.S. regions. Other potential benefits include pest control, eased permitting requirements, increased aesthetic quality of the solar facility, and greater community acceptance,[152,158] as well as potentially increased pollination services and crop yields for nearby agricultural lands.[152]

Cost impacts from installing solar-pollinator habitat remain understudied, although one analysis suggests an approximate 6% increase in the value of energy produced per acre from solar facilities with pollinator habitat established throughout, versus conventional vegetation management (assumed to be turf grass).[159] This increase in value is due to efficiency gains from a cooler microclimate under solar panels. Lifetime costs to facility owners largely depend on the cost of the seed mixes used, extent of solar-pollinator habitat established at the facility, and site-specific changes in required mowing frequency and vegetation management over the life of the facility.

Siegner et al. also estimated social and environmental benefits (in addition to those accruing to solar facility owners) from establishing pollinator-supportive habitat at solar facilities.[159] The benefits they quantified include avoided carbon emissions, reduced soil erosion, additional groundwater recharge, and increased crop yields (although other benefits, such as avoided health impacts, could also be estimated). The authors found a cost benefit of about 13% for facilities with solar-pollinator habitat near pollinator-dependent soy crops, owing to higher soil retention and crop yields. Walston et al. also estimated substantial potential benefits for pollinator-dependent crops near solar facilities owing to increased yields.[152] Some assumptions (e.g., amount of crop yield increase) used in these studies lack empirical supporting data, although other studies of pollination benefit for soy crops support the increased yield assumptions.[160] DOE's Solar Energy Technologies Office is supporting new research on the economic, ecological, and performance impacts of colocated pollinator plantings that may answer some of the outstanding questions regarding costs and benefits of various vegetation management practices at utility-scale solar facilities.[161]

Colocation of Agriculture and Solar Energy

In recent years, the U.S. Department of Agriculture has supported use of "integrated agricultural systems" to provide improved agricultural sustainability.[162] The colocation of solar energy and agriculture, often termed "agrivoltaic systems," can be considered a form of integrated agricultural systems that improve the total value of these dual-use sites from energy and food production.[163–167] In some locations, agrivoltaic systems can decrease yields because of crop shading, but for some crops the microclimate created by the solar panels can benefit vegetation growth and agricultural yields. Additionally, a recent study showed increased PV panel efficiency when vegetation is present under the panels,[167] although this effect requires further investigation. Overall, combined energy and crop production from agrivoltaic systems can increase land productivity by 70%.[168]

Dinesh and Pierce found that, in the United States, from 40 to 70 GW of PV could be supported if farms growing lettuce (a shade-tolerant crop) converted to agrivoltaic systems.[164] Another study showed that PV arrays benefited the growth and production of crops such as Chiltepin peppers (*Capsicum annuum* var. *glabriusculum*), jalapenos (*C. annuum* var. *annuum*), and tomatoes (*Solanum lycopersicum* var. *cerasiforme*) by increasing yields and reducing water requirements while creating cooler microclimate conditions that improve solar energy production.[167] Novel systems for combining agriculture and PV energy production are being demonstrated to increase crop yields even for shade-intolerant crops.[169]

In many locations, rural development guidelines recommend avoidance of prime farmland (e.g.,[138]) and focusing on areas of marginally productive or disturbed soils, so solar development locations may not be the most suitable sites for crop production. However, methods are being developed to maximize the efficiency of solar fields for colocated agricultural production.[163] For example, water used for cleaning panels can be conserved for irrigation to benefit soil moisture. In semi-arid pastures with wet winters, agrivoltaic systems increase water use efficiency, where water is stored in shaded areas of the field.[170] Another potential benefit of agrivoltaic systems is to provide off-grid power to rural communities, increasing their resiliency while adding economic value to the crops produced.[168]

Approximately 26% of Earth's terrestrial surface is used for livestock grazing.[171] If done improperly, livestock grazing can lead to negative ecosystem impacts such as intensified desertification of rangeland; ecologically sustainable grazing requires careful management to maintain light to moderate intensity.[172] Grazing is another form of agricultural land use that is proving to be compatible with PV facilities.[173–175] Solar panels placed in pasturelands open for grazing have a positive impact on soil moisture and biomass.[170] Solar grazing can benefit livestock, because the PV facilities provide food and shade, and they can decrease water needs.[174,176] Grazing can reduce solar facility operation and maintenance costs by decreasing the need for mowing. Well-managed grazing has proven to benefit plant diversity through a natural process of winter and spring sheep grazing.[177] To date, most solar grazing operations have employed sheep.[175] Research is also being done on combining rabbit farming with solar energy production.[178] Additionally, DOE's Solar Energy Technologies Office has recently funded research on the feasibility of developing solar facilities that will support cattle grazing.[161]

Honey production may also be a natural agricultural pairing for solar facilities. The colocation of beekeeping operations with solar facilities that have established pollinator-friendly vegetation could provide multiple benefits to honeybees and native pollinators.[159] By establishing varied plant species that flower from spring through fall, among other requirements, these solar facilities would receive high scores on state pollinator-friendly scorecards.[179] In addition to benefiting apiary operations, honeybee hives likely benefit surrounding agriculture by providing pollination services.[179] There are questions as to whether the presence of honeybee colonies would adversely impact native bees, although studies showing these effects are inconclusive.[180] In a study where both native and managed bees were present, native bee abundance and species diversity positively correlated with honey production, indicating that locations supporting successful honeybee colonies also supported successful wild bee communities.[181]

Floating Photovoltaic Systems

Floating PV systems, also known as "floatovoltaics," provide an alternative to land-based PV systems. Floating PV systems may produce energy more efficiently than land-based systems owing to lower operating temperatures; performance is also enhanced because of the lower temperatures that result from higher wind speeds which occur over water.[140,182,183] Siting floating PV on water also reduces shading loss and dusting of panels. Floating PV systems may have positive ecosystem services for the hosting water body overall, reducing algal blooms and decreasing the rate of water evaporation.[140,182,183] Potential long-term impacts to aquatic ecosystems require further investigation.[184] Challenges associated with floating PV systems include susceptibility to fouling organisms, corrosion, and high maintenance costs.[140,182]

To date, most floating PV systems have been installed in enclosed freshwater reservoirs (often associated with artificial dams) and small lakes. Deployment of floating PV systems in the marine environment has been infrequent. The cumulative global installed capacity of floating PV rose from 132 MW in 2016 to 1.1 GW in mid-2018; Asia had the highest installed capacity, followed by Europe.[185]

Spencer et al. estimated the potential electricity requirements that could be provided from floating PV systems on suitable human-created water bodies in the United States.[182] Suitable water bodies were defined as having a surface area greater than 1 ac, depth greater than or equal to 7 ft (2 m), and transmission lines within 80 km (50 mi) and being used for recreation, navigation, fish and wildlife, or tailings storage. If equipped with floating PV systems, the area of these suitable water bodies could produce almost 10% of current national generation. These systems could be particularly useful in areas with high land-acquisition costs and electricity prices.

Another recent study estimated the potential for use of the 6,350-km California canal network for generating electricity using PV mounted over the canals.[186] The authors estimated that the net present value of this system would exceed the value of conventional overground solar by 20%–50%, and that the system would reduce annual evaporation by an average of 39,000 m^3 per km of canal. Such systems show particular promise for water-constrained areas such as California.

4.2 Water Requirements

Water is a key sustainability factor for electricity generation. The power sector accounted for 41% of total U.S. water withdrawals in 2015.[187] Spatial and temporal variations in water supply (e.g., from drought, climatic changes) increase the importance of considering water use in energy scenarios. Water availability can constrain power plant operations; for instance, without enough cooling water, thermal power plants cannot operate safely.[188] A version of ReEDS has been created to account for water availability and its effect on generation. Running ReEDS under water-constrained conditions requires a simulated plant to obtain access to water over the entire plant lifetime at the time of construction. To model this, ReEDS uses water-constraint supply curves that reflect the impact of water rights, the cost of access to water, and the impact of water seasonal variability on generation decisions when the plant is built.

For the analysis reported in this section, all the *Solar Futures Study* core scenarios were run with the version of ReEDS including water constraints (and thus differ in this way from ReEDS results reported in the main *Solar Futures Study*). Results show that water withdrawals decline over time, mainly from retirements of coal, nuclear, and natural gas combined-cycle plants (Figure 11). The Decarb+E scenario achieves the lowest yearly water withdrawals, declining from 48,500 billion gals/yr (bgal/yr) in 2010 to 6,040 bgal/yr in 2050; this is roughly equivalent to reducing annual power sector withdrawals of 51 times the Hoover Dam's capacity (2010) to withdrawals of only six times that capacity (2050). Over the 2010–2050 time frame, CSP never contributes more than 1% of total power-system withdrawals. Water withdrawals for PV generation are only for panel washing activities and are effectively zero when compared to other technologies.[189] However, CSP can account for a large portion of state-level power-sector water withdrawals even when dry cooling technologies are used (some water is still needed), rising to almost 100% of power-sector withdrawals in Colorado and New Mexico starting in 2040 for the Decarb scenario (Figure 12). These values are still less than current power-sector water withdrawals in both states, given the reliance on thermal (fossil) power plants in both states. There are minor differences (~3%) in water withdrawals between water-constrained and non-water-constrained ReEDS runs; water constraints affect system build-out, but not drastically for a given year. Also, the difference in overall system price between water-constrained and non-water constrained runs is minimal (~$0.50/MWh in a given year).

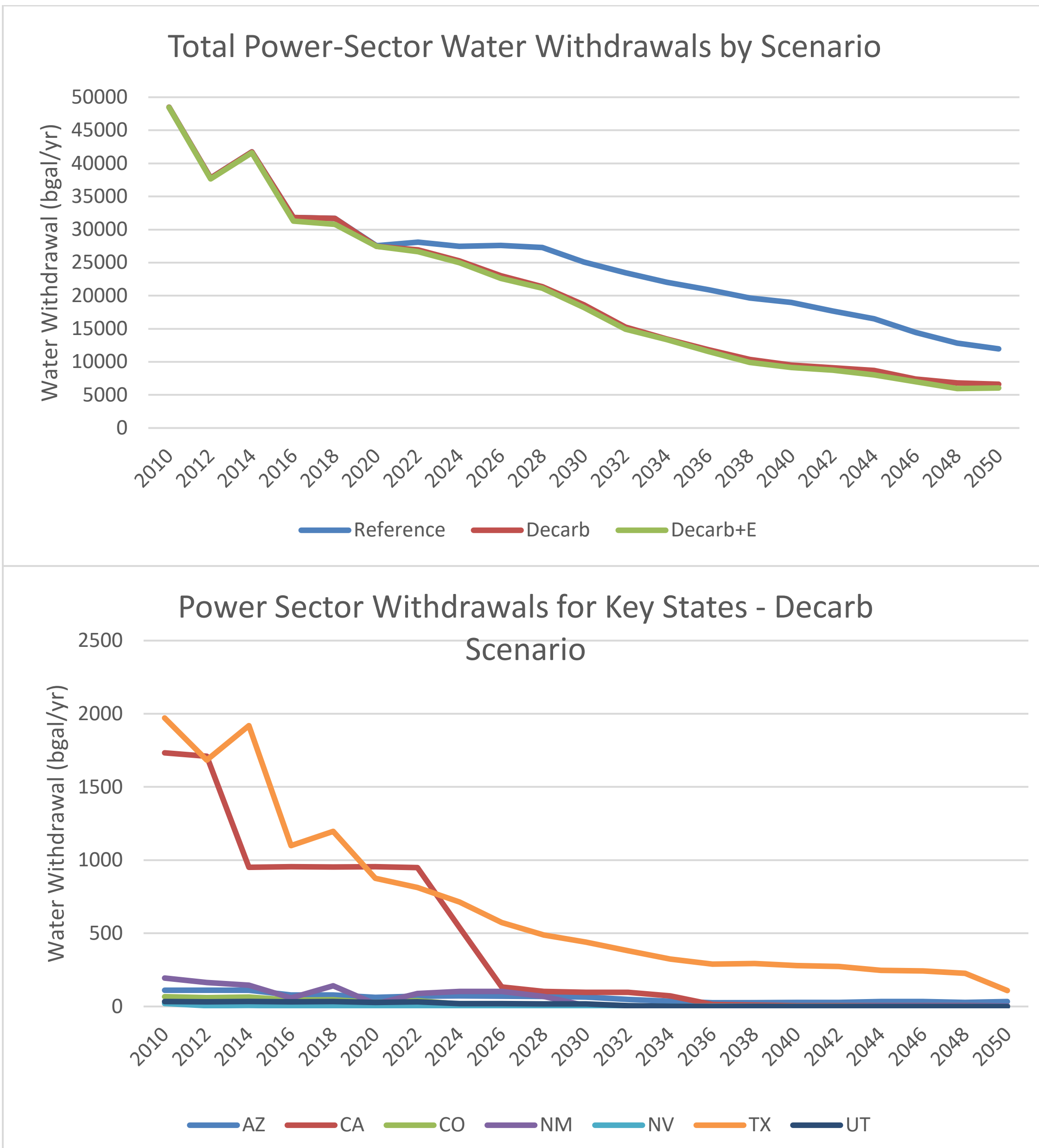

Figure 11. Total U.S. power-sector water withdrawals under the *Solar Futures Study* core scenarios (top) and withdrawals for key states in the Decarb scenario (bottom), assuming water constraints

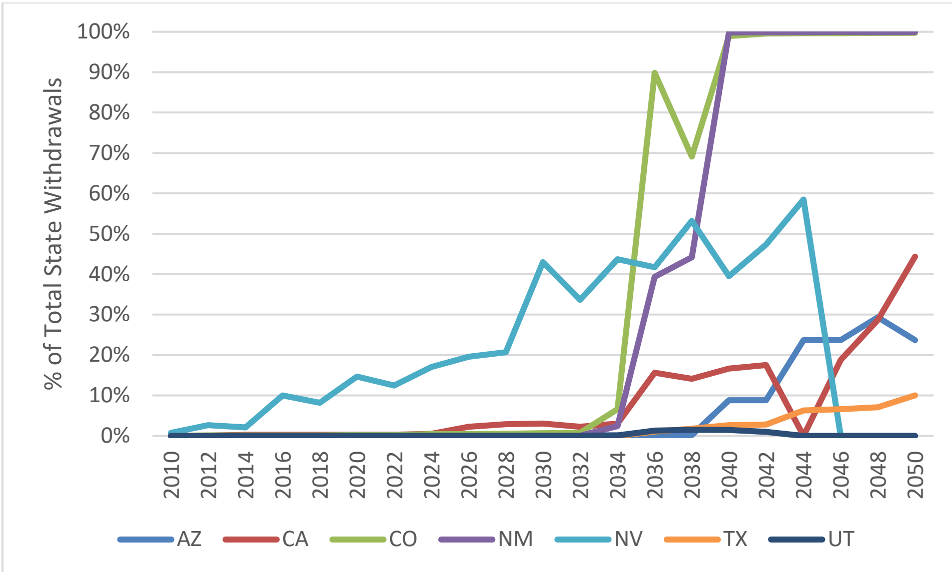

Figure 12. CSP water withdrawals as percentage of total power-sector water withdrawals in key states in the Decarb scenario

4.3 Estimated Air-Quality Benefits

Here we present order-of-magnitude monetary estimates of the air-quality benefits of the *Solar Futures Study* scenarios, based on reduced electricity-generation and vehicle emissions. Our simplifying assumptions and methods are detailed in Appendix C.

4.3.1 Results Summary

Figure 13 and Figure 14 summarize the results. In the Decarb scenario, reducing air pollution from electricity generation results in air-quality and health benefits worth roughly $300 billion, based on the discounted value of all emission reductions (compared with the Reference scenario) between 2021 and 2050. Approximately $100 billion of additional health benefits could be realized from the Decarb+E scenario owing to the replacement of gasoline and diesel vehicles by electric vehicles and the associated reduction in pollutant emissions. Only a small portion of total vehicle air pollution damages are eliminated under the Decarb+E scenario. The remaining damages are largely due to heavy-duty diesel emissions, because the Decarb+E scenario focuses primarily on electrifying light-duty vehicles. Vehicle electrification is held constant between the Reference and Decarb scenarios.

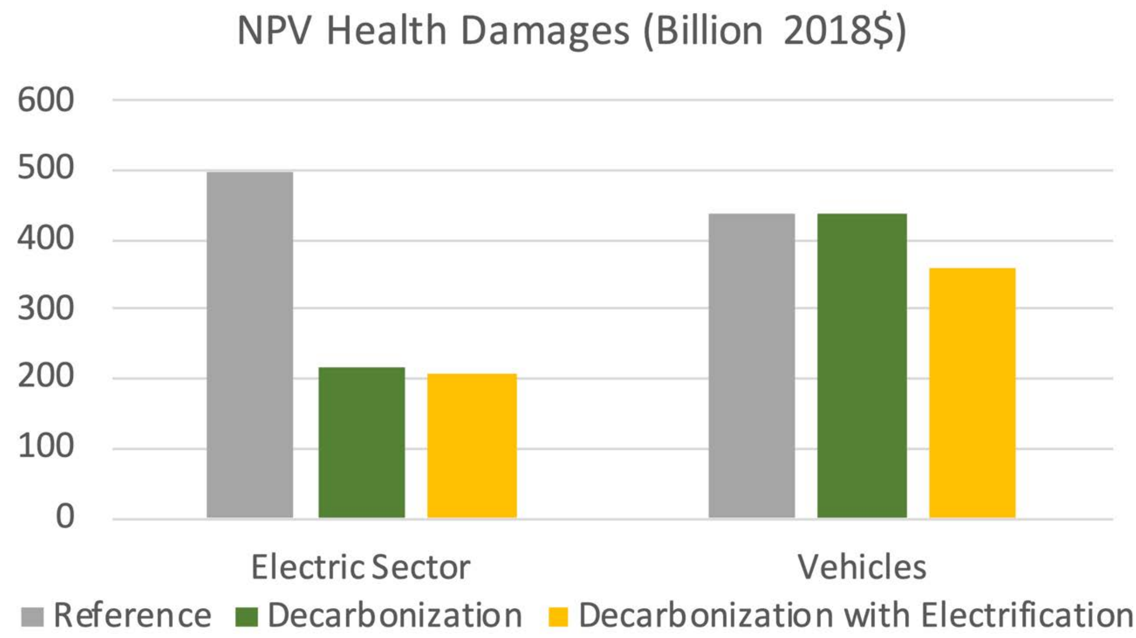

Figure 13. Net present value of health damages from electric-sector and vehicle emissions, 2021–2050

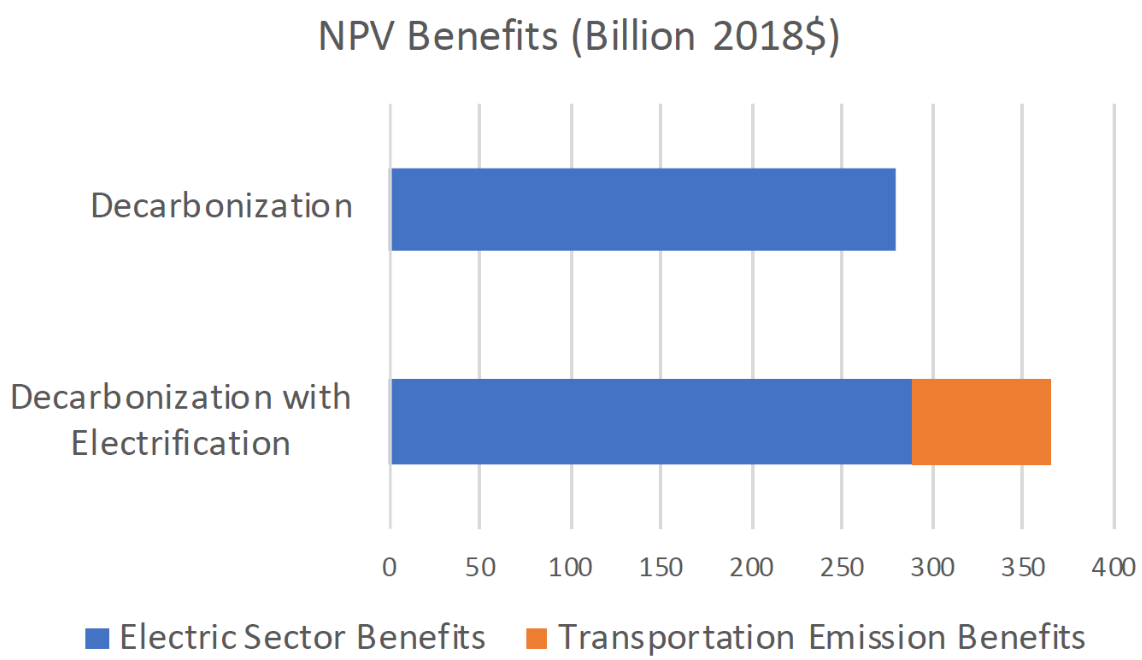

Figure 14. Net present value of the benefits from the Decarb and Decarb+E scenarios

4.3.2 Approach and Discussion

Reducing air pollution helps reduce heart attacks, asthma, hospitalizations, and deaths as well as lost work and school days. Air pollution can also damage agricultural productivity, and emissions of heavy metals can lead to neurological damage. An in-depth discussion of these impacts is available.[190] We focus on a subset of air pollution impacts, primarily the impact of particulate matter (PM) on premature mortality, but for more context regarding various damage pathways see Fann et al.[191] Of outdoor air pollutants, PM is the leading contributor to increased premature mortality and therefore accounts for the vast majority of monetized damages. We analyze the impacts of three important pollutants: directly emitted PM as well as sulfur dioxide (SO_2) and nitrogen oxides (NO_x), which can both be transformed into PM after their release through chemical reactions in the atmosphere. Electricity generation is a major U.S. source of SO_2 and NO_x, and vehicles are a major source of NO_x and directly emitted PM. Although we focus on a subset of pollutants and damage pathways, this subset captures a large portion of the total value of reducing emissions.

We estimate the value of emissions reductions across the full study period (2021–2050). The forward-looking scope means we must capture the dynamics of changes to electricity-generating plants and vehicles. For example, replacing an old vehicle provides *much* greater health benefits than replacing a new vehicle that already contains state-of-the-art emission-control systems. In fact, the differences in emissions rates between old and new vehicles can span orders of magnitude; thus, it is critical to track emission rates as they change over time. Similarly, and for certain pollutants, emissions rates can vary by orders of magnitude across electric power plant types (e.g., coal versus natural gas). Fortunately, electric-sector pollutant emissions are calculated directly within the *Solar Futures Study* scenario modeling, so variations in emissions rates between power plant types are taken into account. In contrast, we must estimate vehicle emissions externally to the scenario modeling. We use the total fuel use specified in the Reference and Decarb+E scenarios and estimated future vehicle emission rates, developed from a default formulation of the EPA MOtor Vehicle Emission Simulator (MOVES) model,[192] to estimate total vehicle emissions by year.

Over the past two decades, SO_2 and NO_x emissions from the electricity sector have declined dramatically. For example, in 2020, the 3,100 premature deaths and $40 billion of air pollution health damages from electricity generation accounted for less than 10% of the damages from the sector in 2005.[193] Despite this progress, substantial health benefits can still be realized if power-sector emissions are further reduced. The Decarb scenario anticipates the elimination of greater than 85% of power-sector SO_2 and NO_x emissions by 2035, with complete elimination by 2050. NO_x emissions are shown in Figure 15, and SO_2 emissions are shown in Appendix C. Emissions associated with renewable combustion turbines are omitted from this analysis. Overall fuel use from renewable combustion turbines is expected to be fairly low, so this omission should not have a large impact on the national totals. However, if these turbines are powered by biofuels (rather than hydrogen), they may have important local impacts on air quality, which may also be important to consider from an environmental justice perspective.

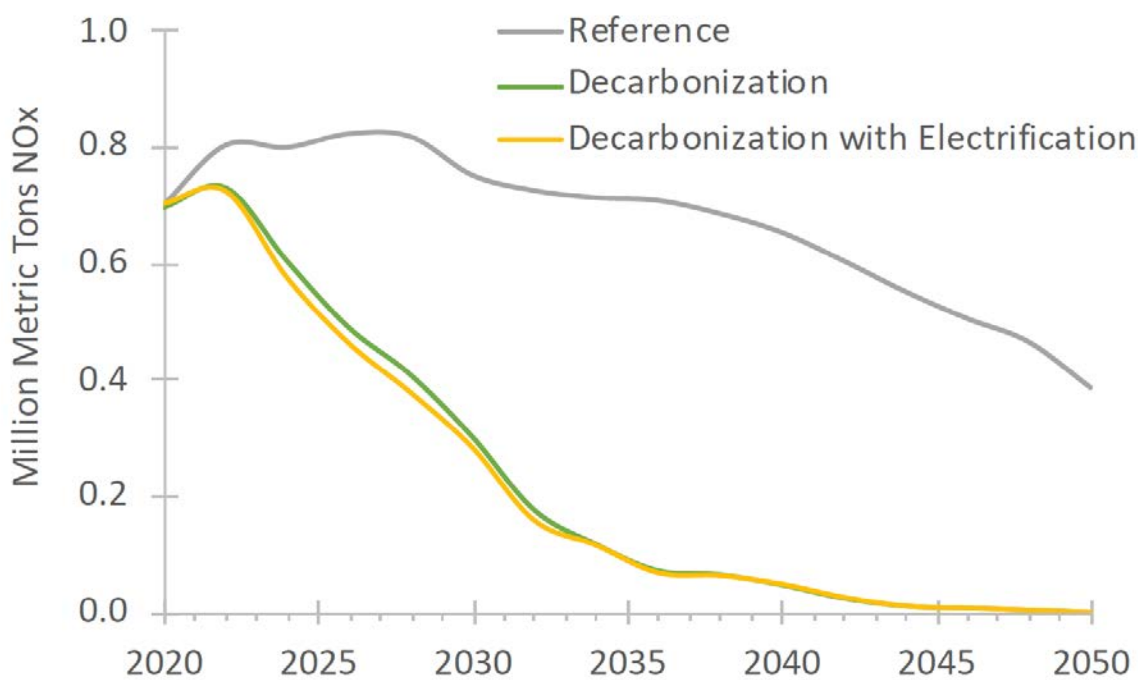

Figure 15. Total NO_x emissions from the power sector in the *Solar Futures Study* core scenarios

Emissions from vehicles have also declined dramatically over the past two decades. Figure 16 shows the observed decline in U.S. on-road-fleet average NO_x emissions per unit of fuel input ("emission rate") due to emissions controls on cars and trucks.[xii] Declines in PM emission rates have been even more rapid (see Appendix C). Fleet emission rates are expected to continue declining, as vehicle turnover leads to more vehicles equipped with state-of-the-art emissions-control equipment. Figure 17 shows estimated NO_x emission rates from light-duty gasoline vehicles and heavy-duty diesel trucks into the future (PM rates are shown in Appendix C). The forecasted emission rates roughly match recent observed fleet-average rates in 2020, and then continue to decline through 2030.

Combining fuel use from the Reference and Decarb+E scenarios with the fuel-normalized fleet average emission rates allows us to develop order-of-magnitude estimates of total NO_x and PM emissions from the vehicle sector (Figure 18; see Appendix C for total PM emissions). Most vehicle emissions reductions in the Decarb+E scenario occur after 2030, which contrasts with earlier reductions in power-sector emissions.

[xii] In accordance with the goal of an order-of-magnitude estimate of vehicle emissions, we only consider gasoline-powered cars and diesel-powered heavy-duty vehicles, because only small amounts of other fuels are used in those vehicles.

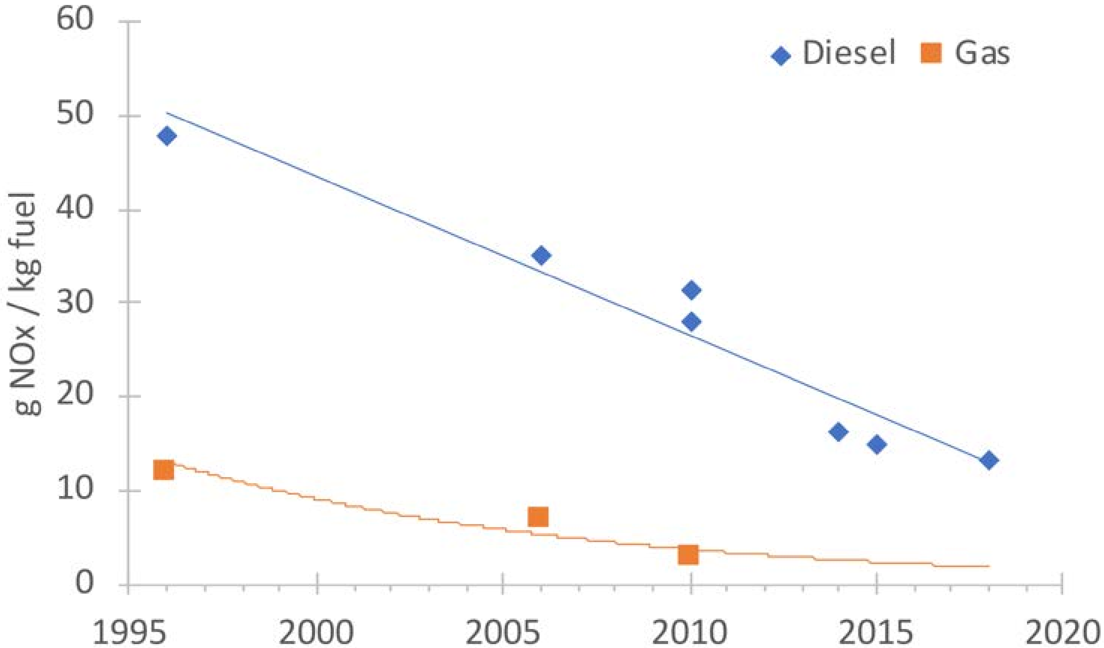

Figure 16. Fleet-average NO_x emission rates of U.S. light-duty gasoline vehicles and heavy-duty diesel trucks, based on observed emissions[194–197]

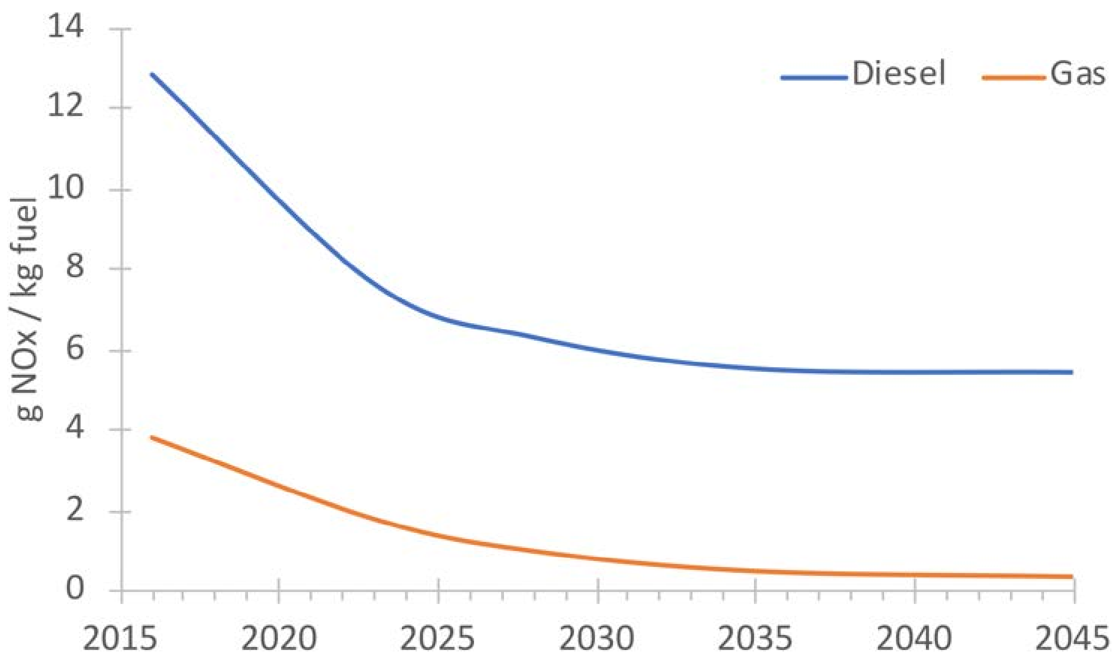

Figure 17. Future fleet-average NO_x emission rates for U.S. light-duty gasoline vehicles and heavy-duty diesel trucks based on the EPA MOVES model

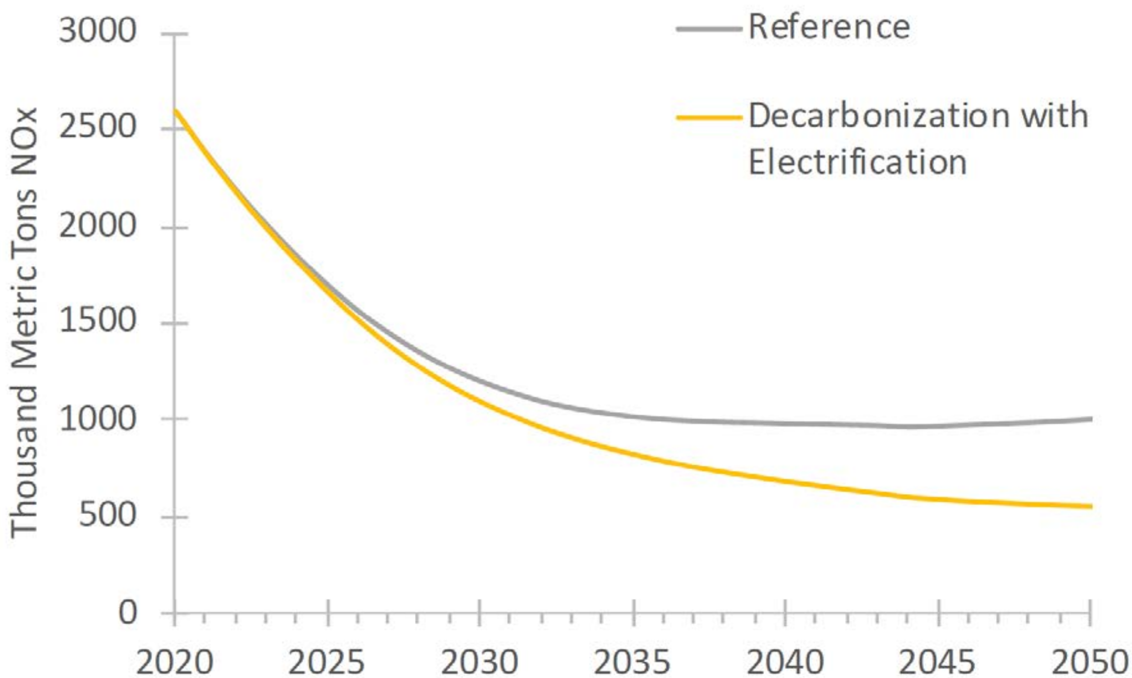

Figure 18. Total vehicle NO_x emissions in the Reference and Decarb+E scenarios

We use these results to estimate the health impacts of emissions in each scenario. In the Reference scenario, the present value of cumulative air-quality health damages from 2021 to 2050 is roughly $500 billion *each* for the power sector and vehicle sector (Figure 13). The Decarb scenario saves roughly $300 billion in cumulative health damages due to reductions in power-sector pollution, and the Decarb+E scenario saves roughly an additional $100 billion in cumulative health damages from reduced vehicle emissions (Figure 14).

The Decarb+E scenario does not eliminate emissions from the vehicle sector in the same manner as the Decarb and Decarb+E scenarios eliminate emissions from the power sector. The additional Decarb+E savings mostly derive from the electrification of light-duty vehicles (in which gasoline use is reduced by ~75% by 2050). Additional savings would be created by electrifying a greater portion of diesel trucks (the Decarb+E scenario reduces diesel use by roughly 40% by 2050) and electrifying all vehicle types sooner. The savings are particularly sensitive to the timing of electrification, because fleet-average emission rates decline with time; thus, retiring an average truck in 2025 would provide a greater benefit than retiring an average truck in 2035. For example, an electrification program that focused on replacing older trucks or other high-emitting vehicles in the near term would reap greater cumulative health benefits owing to retirement of higher-emitting vehicles and benefits accumulating over a greater number of years.

4.3.3 Emission Reduction Valuation

We estimate damages from emissions, or the total benefits of avoided emissions, using literature-based "marginal emission damage factors" or "benefit-per-ton" estimates.[190,198] For example, the damage factor we use to value 1 metric ton of NO_x emissions from vehicles is roughly $7,000.[198] The damage factors consider premature mortality and morbidity (all other health effects that are not mortality), although by far the largest monetary damages from air pollution are due to premature deaths. The value of eliminating a premature death is calculated based on the value of reducing the risk of mortality for each individual across the population. This concept of value is often referenced as the "value of statistical life." The overall "benefit-per-ton" approach is discussed elsewhere.[190]

Estimates of marginal damage factors depend on the health risks associated with exposure to the pollutant and the size of the total population exposed to the pollutant. These risks vary significantly by pollutant, and by the location of the emission. Because we are producing order-of-magnitude estimates, we use literature-based national average marginal damage factors for three different pollution sources (power plants, light-duty gasoline vehicles, and heavy-duty diesel vehicles). A more detailed analysis would estimate emission benefits based on the location and height above ground of emissions. In our case, the location information is embedded in the national average estimate for each source. Our national marginal damage factors are based on two sources.[190,198] Details can be found in Appendix C.

4.4 Circular Economy Approaches During the PV Use Phase

Figure 3 presents the CE approaches currently being applied in the installation and use of PV systems. The emergence of commercial entities leveraging digital platforms and information systems[199] and business models[200–203] has helped delink ownership of PV modules from the service provided by the PV system (generation of PV electricity). For example, 39% of modules in U.S. residential markets are owned by third-party owners.[204] Delinking ownership of the PV system from the consumption of PV electricity is aligned with the product service system (PSS, aka third-party ownership) strategy for a CE.[205] PSS lowers the cost barrier and upfront capital costs for individual customers to consume PV electricity,[206] transfers the economic and operational burdens of purchase and maintenance from the individual customer to the third-party owner of the PV system,[207] and could address social and energy justice issues by widening access to PV electricity. By operating at a greater scale of PV ownership and maintenance than an individual owner, the third-party owner may be better positioned to realize the benefits from economies of scale and learning, which can further decrease the cost of PV electricity. Despite the promise of PSS for PV, there is a need to address information barriers that prevent financiers from evaluating the economics of PV PSS projects,[200] optimally design policy incentives to accelerate PSS for PV systems,[208,209] increase funding for PSS PV projects,[200] and continually assess the environmental and social efficacy of PV PSS projects at a national scale.

Repowering refers to the replacement of aging PV system components with newer components to improve performance and durability, address maintenance issues (e.g., hard-to-find parts), extend project lifetime, and prevent outages due to increased frequency of faults in older components.[210–213] Repowering helps increase renewable electricity generation over the lifetime of the PV project with decreased maintenance of parts.[211] For example, inverters for 100 GW_{DC} of PV systems are expected to be repowered by 2025 in Europe,[214] because inverter lifetimes (10 to 15 years) are shorter than PV system lifetimes (25 to 30 years). Repowering should be combined with proper EOL management of decommissioned components (e.g., recycling or reuse of decommissioned components) to prevent unfavorable outcomes when an influx of decommissioned PV systems (from repowering) is landfilled or improperly managed. For example, in 2017, a 30% increase in used PV modules on a platform for trading secondhand modules was ascribed to decommissioned modules from repowering.[210] Importantly, repowering can be a material demand reduction (CE) strategy, because many of the same BoS components could be retained while modules or inverters (or other) system components (as well as interconnection infrastructure) are replaced, with significant material savings compared to a case where a power plant is retired and a completely new one is built in its place. Repowering can also reduce land requirements compared to a case where the retired plant is replaced at a new site, occupying additional land.

During system operation, owners and operators may need to repair PV modules and BoS equipment because of manufacturing defects, faulty installations, and extreme weather events, among other factors. Poor manufacturing practices alone have led to more than 10 GW of PV modules with faulty backsheets deployed worldwide.[215–217] Dupont's 2019 Global Field Reliability Study showed a 47% increase in backsheet defects over 2018 results.[218] Backsheets made with polyamide, polyethylene, and polyvinylidene fluoride have shown signs of rapid in-field degradation with failures as early as 5 years after installation.[89,216] One estimate found that 1.1 GW of the forecasted 112 GW of installed capacity in 2020 risk some degree of backsheet failure, which could result in $500 million worth of repairs.[219]

Growing concerns about backsheet failures and overall system efficiencies have led to industry discussions and initiatives around in-field module repair. Seen as the most cost-effective solution for system owners, solar companies (such as Cybrid Technologies) and research institutes (such as the Polymer Competence Center Leoben GmbH) are working on new technologies that could be used in the field to repair module backsheets.[40] These technologies may provide a solution to module backsheet repair and may drive innovation toward other repair technologies.

However, many questions must be answered before the commercialization of these technologies and others can be realized. There are questions about the module inspection process and the safety and reliability of the repair product, as well as the regulatory requirements and legal liability associated with the technology and the installation.[40] Currently, there is no publicly available guidance on the initial module inspection process, the types of repairs that are possible or equitable, repaired module installation, and the tests necessary to ensure the safety and reliability of repaired modules.[40] Moreover, there is no publicly available information about the regulatory compliance and legal liability associated with repaired modules or the installation of repaired modules.[40] Unanswered regulatory and legal questions include the following:

- Who bears the legal liability of a repaired module (e.g., manufacturer or repair technology company)?
- How may interconnection, fire, building, electric, and equipment regulations and other laws impact the viability of using a repaired module in all or certain installations (e.g., grid-tied, rooftop)?
- Can a repaired module use the original manufacturer safety and reliability certifications?
- Do new labels need to be applied to a repaired module?
- Can the repair technology and technicians installing the repairs be certified instead of requiring certificate review of each module?

Because backsheet durability plays a critical role in extending the life of modules and the PV system, industry experts are working to provide solutions for durable, safe, and cost-effective module repair. In the meantime, system owners and operators are left with limited guidance, which—beyond performance issues and increased operation and maintenance costs—has raised several safety concerns.[216,219–221] The application of repair as a CE strategy for PV is described further in Section 5.4.2.

4.5 Environmental Justice and Social Benefit Through Circular Economy During the PV Use Stage

Repowering reduces the cost of renewable electricity generation by substituting older PV system components with newer and more efficient system components. The reduction in PV electricity costs could ameliorate the cost barriers that prevent low-income communities from accessing renewable electricity. Decommissioned modules from repowering can be supplied to the reuse PV markets.[222] Markets for reused PV systems can help ensure access to PV electricity at a lower cost in the developing world,[222] thereby decreasing reliance on energy from fossil fuels.

By delinking ownership of PV systems from use of PV electricity, PSS decreases upfront capital costs and could increase access to PV electricity for low- and medium-income residents. Thus, PSS can be a socio-environmentally just mechanism to leverage low- and medium-income rooftops, which account for 42% of the U.S. rooftops that are PV viable.[209] See Heeter et al.[223] for more on this topic.

5. Key Considerations at End of Life

In 2019, cumulative PV operating capacity reached 76 GW_{DC} in the United States.[13] As capacity increases, so eventually will the volume of EOL PV modules and BoS equipment.[40,74] In addition, a growing stockpile of early-retired modules in the United States still have reuse potential.[40] Industry experts have observed a large volume of PV modules in the United States being retired after only 10 to 12 years in service, long before the life expectancy of 25–30 years.[40,220,221] Anecdotal evidence suggests this growing trend is largely driven by partial and full system repowering due to increased extreme weather events and efficiency upgrades.[35,40,220,221] While there is no available quantitative tracking of PV modules stockpiled, this section projects the mass of EOL materials from PV modules considering just the known degradation and failure rates that affect lifetime. Using a more simplified approach, we make the same projection of EOL materials for CSP systems. We review policy considerations and the literature on many CE strategies relevant at EOL. Finally, benefits of the application of CE approaches at EOL with regard to environmental justice are discussed.

5.1 PV End-of-Life Materials Projection

Figure 19 shows projected PV EOL materials by scenario through 2050 as calculated by PViCE[xiii] for c-Si installations, which are assumed to constitute 85% of all installations following past market trends for the United States.[xiv] PViCE calculates module lifetime based on PV project life expectations over time,[18] Weibull failure probability curves, and cohort-dependent degradation. PV module lifetimes have continually improved and are currently above 32 years for utility scale projects[18]. This means a module installed in 2028 will not reach EOL until 2060. Therefore, most of the modules deployed in these scenarios do not reach EOL until after 2050. Figure 19's pre-2050 EOL modules are due to older installations (e.g., installations from 2010 to 2020) and premature failures. The *Solar Futures Study* Decarb and Decarb+E scenarios result in nearly identical 2050 cumulative EOL material (approximately 6.43 million metric tons each). Overall, because glass is such a large fraction of PV module weight (for historical and future module designs), it makes up an equally large fraction of total EOL materials in all scenarios.

[xiii] PViCE was validated by reproducing the mass of PV in service and cumulative PV EOL materials from a 2016 report from the International Energy Agency PV Power Systems Task 12 and IRENA.[224] The material demand results are also compared to a recent EOL material projection from the CSA Group.[301] A comparison of predictions is presented in Appendix B.

[xiv] The effect of a nontrivial market share for thin-film PV technologies on EOL module materials as well as manufacturing scrap is beyond the current capability of PViCE, and it can be the subject of future research. In most years, the market share in U.S. deployment for thin-film modules is less than 10%, so the results presented here would change to a commensurate degree, though the precise answer depends on modeling of cohort-dependent degradation, expected lifetimes, and other factors. Furthermore, thin-film technologies such as cadmium telluride (CdTe) are largely recycled via product takeback programs of the largest CdTe manufacturer, First Solar.

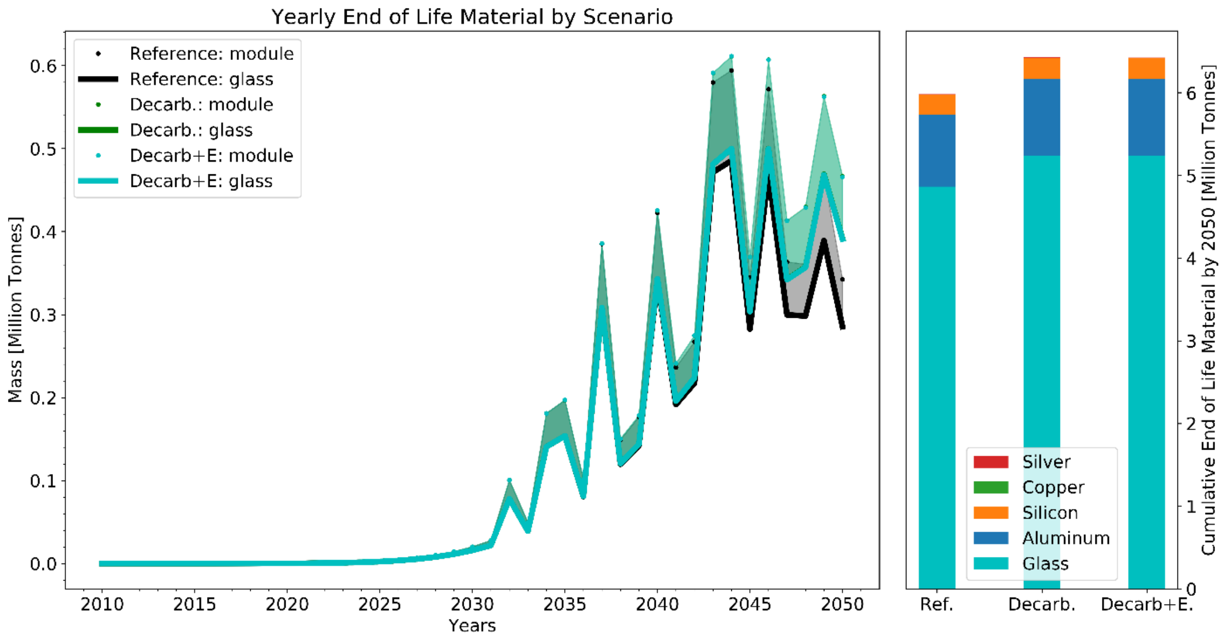

Figure 19. Annual and cumulative PV EOL material mass by *Solar Futures Study* scenario through 2050

Glass has such a high magnitude in this chart that copper and silver cannot be seen, though are included.

A unique feature of PViCE is that manufacturing scrap is accounted for separately and additionally from EOL materials. Comparing the cumulative quantities (bar graphs of Figure 20 and Figure 19), manufacturing scrap is approximately half of the mass of materials in EOL modules but better aligned in time with virgin material demands, emphasizing the importance of efficient manufacturing and closed-loop manufacturing scrap recycling to reduce virgin material needs. Silicon makes up a large proportion of manufacturing scrap due to manufacturing inefficiencies, including ingot wafering, whereas glass manufacturing is a more efficient manufacturing process in terms of materials. In fact, silicon scrap in manufacturing is even greater than that in EOL modules, cumulatively, which reflects that modules deployed under the Solar Futures Study scenarios are largely still operational by 2050. As expected, the highest deployment scenario, Decarb+E, generates the most manufacturing scrap, annually and cumulatively.

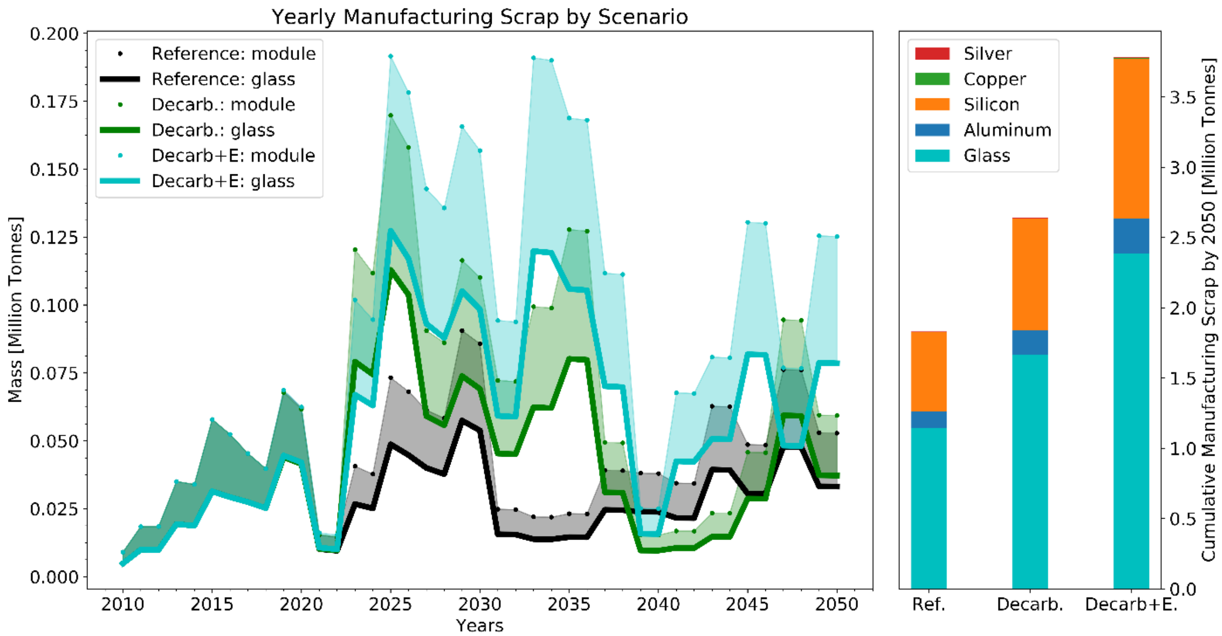

Figure 20. Annual and cumulative mass of c-Si PV manufacturing scrap by *Solar Futures Study* scenario through 2050

Glass and silicon have such high magnitudes in this chart that copper and silver cannot be seen, though are included.

Another novel feature of PViCE is the capability to track a deployed cohort by location. Figure 21 shows cumulative regional PV EOL glass (as a proxy for all PV EOL materials) through 2050 by scenario. Relative magnitude differences are similar among scenarios, with the largest difference among scenarios regionally in the Southeast.

Such geospatial results could enable stakeholders to plan proactively for EOL materials on a regional basis, which can lead to more efficient deployment of capital for recycling and other EOL management infrastructure. Efficient infrastructure build-out can accelerate trends toward a sustainable CE. For example, tighter circular loops, such as repair and reuse, could keep PV modules in the field longer (offsetting material demands and EOL) and create regional, higher-skilled jobs in the sustainability sector. Longer circular loops, such as recycling, could enable industries (e.g., glass manufacturing) to use a local supply of EOL materials from PV modules. Further analysis of PV module lifetime extensions, recycling, and the associated social, environmental, and economic impacts of each can clarify potential pathways toward circular, symbiotic, cross-sector economic opportunities to address challenges communities will face in coming decades.

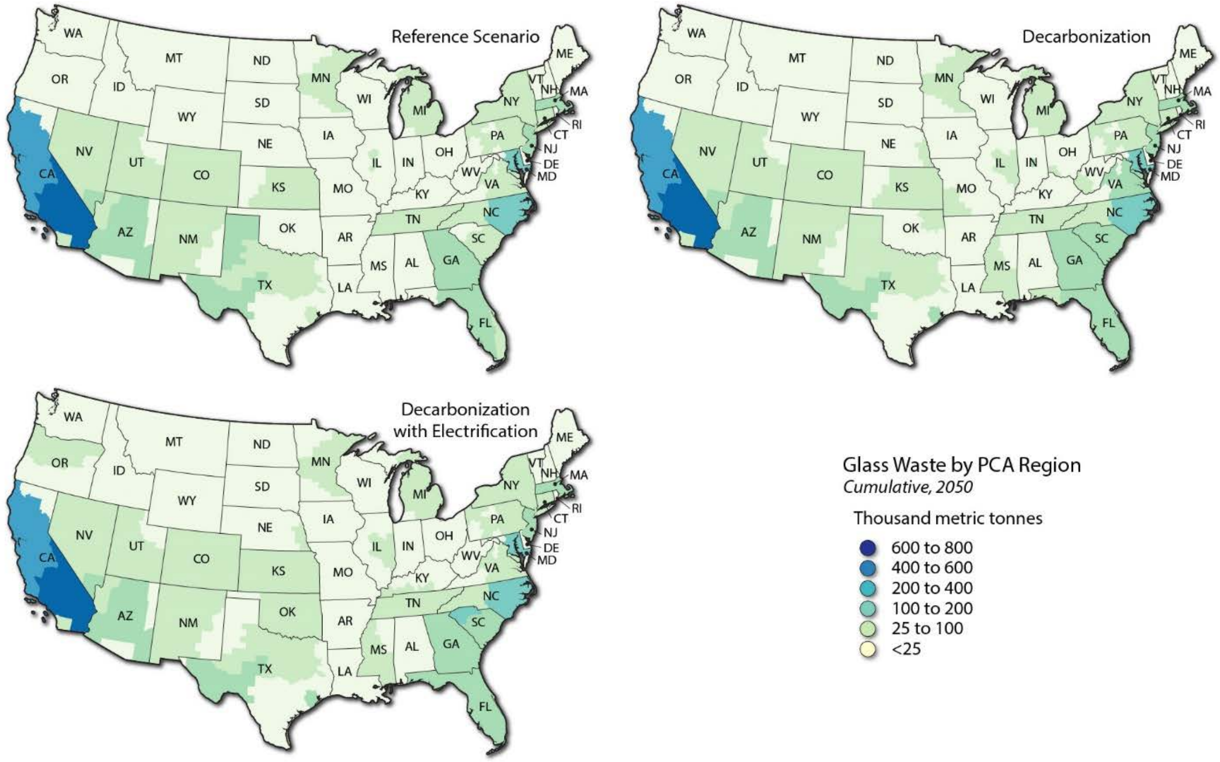

Figure 21. Cumulative regional EOL PV glass through 2050 by scenario

Finally, an important potential strategy to mitigate material demands in a growing PV sector while improving resilience of supply chains is to substitute EOL materials for virgin materials. Additional benefits of such a strategy include reduced environmental and social justice burdens of mining, providing markets for recycling facilities looking to sell recovered materials, reducing critical material demands, and so forth. Figure 22 displays the annual installations and decommissions in terawatts from 2020 through 2050 for the Reference and Decarb+E scenarios. Decommissions outpace installations by 2032 in the Reference scenario, and by 2038 in the Decarb+E scenario. Thus, module reuse, refurbishment, and recycling could offset a portion of the needed PV installations, primarily closer to 2030.

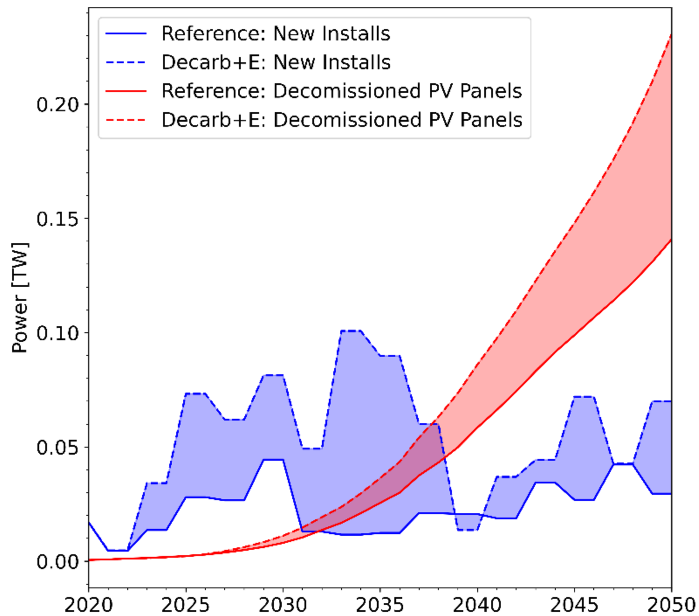

Figure 22. Annual installations and decommissions for 2020 through 2050

Figure 23 shows how silver, aluminum and silicon material demands can be met partially with EOL materials for the Decarb+E scenario. Pre-2040, at the high deployment rate, EOL material can supply less than 20% of material demands. After 2040, when deployment slows, EOL material can supply ~25% to 30% of these material demands. EOL material depends on the material composition of the generations of PV modules being decommissioned, which is accounted for in PViCE's cohort framework. Due to the ReEDS simulation and optimization methods, the annual deployment rate appears highly variable. The sudden decrease in deployment rate in 2040 is not industry realistic and should be considered an outlier.

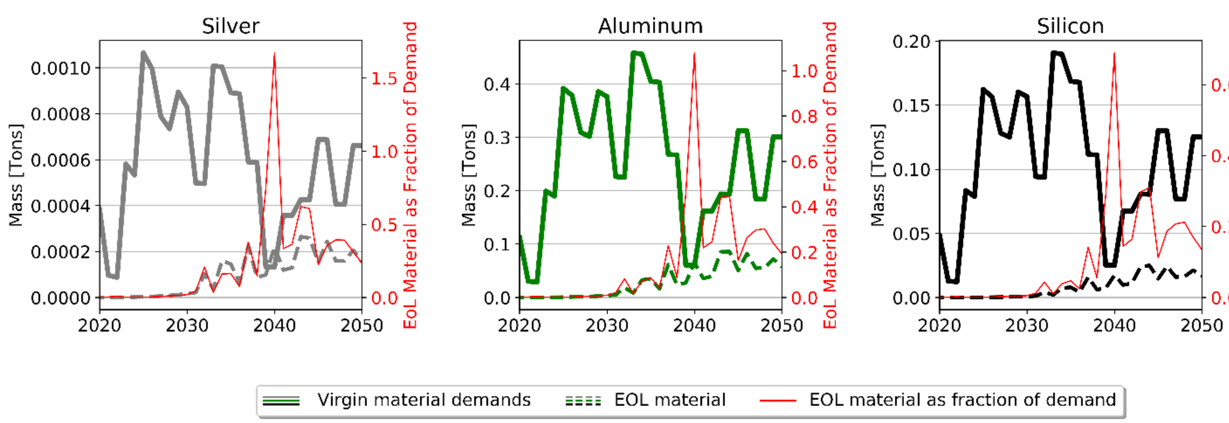

Figure 23. Yearly virgin material demands and EOL silver, aluminum, and silicon, with right axis showing the fraction of Decarb+E scenario demand that could be supplied by the EOL material

5.2 CSP Waste Projection

The material waste for CSP systems (Figure 24) is a product of the decommissioned capacity and the materials recovered per unit of decommissioned capacity. The decommissioned capacity between 2020 and 2050 was determined via ReEDS (see Appendix D for details). With no publicly available data on the rate of material recovery from decommissioned CSP systems, this analysis assumes the material recovered per unit of decommissioned capacity is the same as the material required per unit of installed capacity as described in Section 3.2.

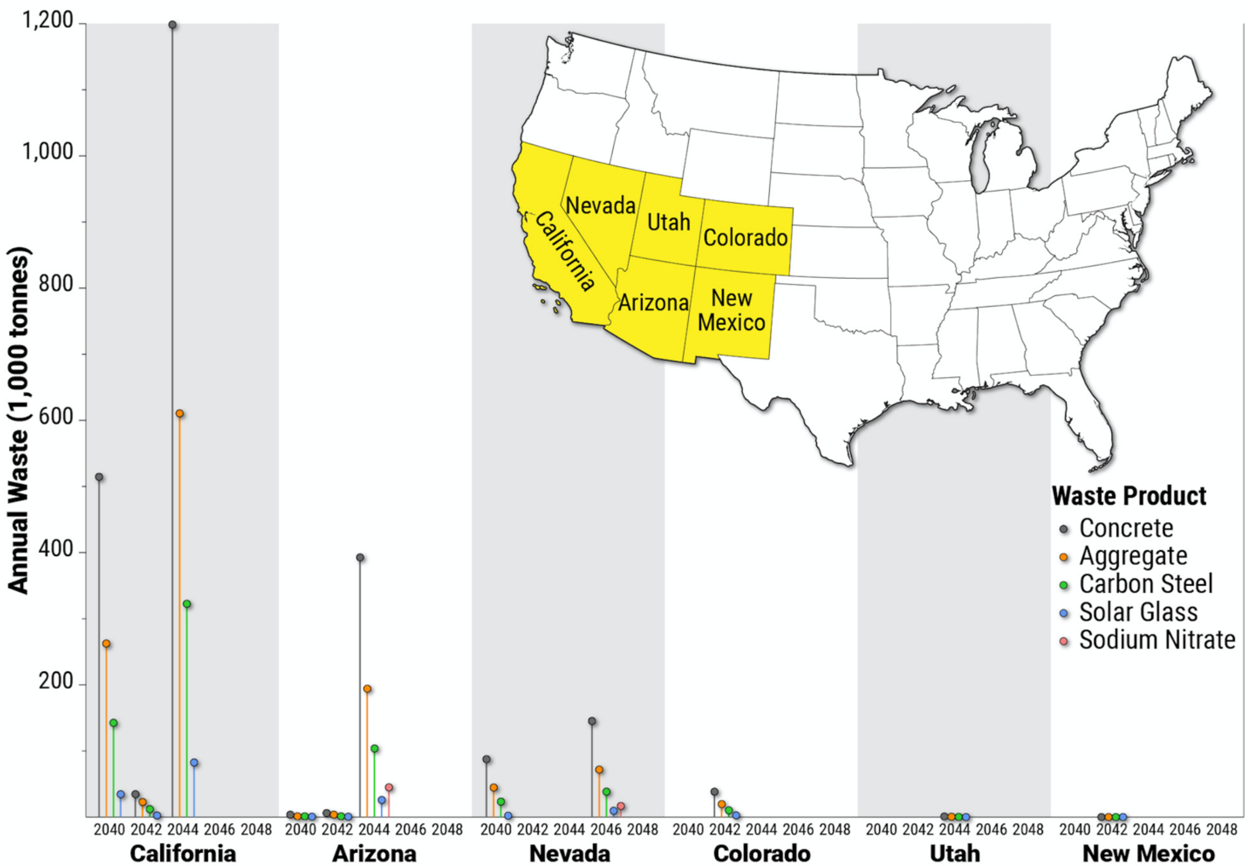

Figure 24. Five materials that contribute most to projected waste from power tower CSP plants between 2020 and 2050 in the Decarb scenario

In the Decarb scenario, CSP waste occurs only in the six states shown and only between 2040 and 2050. The results for the Reference and Decarb+E scenarios are identical to the Decarb scenario as the waste projections are driven by the CSP installations before 2020, which are the same across the three scenarios.

Four of the materials—concrete, aggregate, carbon steel, and solar glass—in Figure 24 are bulk materials and can leverage existing recycling infrastructure. The likelihood of recycling the concrete and aggregate waste as aggregates can be increased by supplying them to the construction and demolition waste market.[225,226] While carbon steel and solar glass represent significant volumes in the waste, they can be recycled through the existing network of glass and steel recyclers. Given the geographical spread of the projected CSP waste volumes, the recovered materials can leverage the existing network of glass and metal recyclers in the Southwest.[227–229]

No publicly available data exist on the recycling of sodium nitrate and the associated economic and environmental impacts. However, if recycling is available in practice, it could potentially offset the production of sodium nitrate from mines or the more environmentally intensive synthetic route.

A recent study combined the metrics of LCA and material circularity to quantify the environmental benefits of recycling and reusing the TES system of CSP systems.[230] The results show that reuse and recycling of materials from the TES system reduce the environmental impact by 23% on a life cycle basis when compared to a scenario without reuse or recycling. The study also identifies the current lack of reuse or recycling pathways for molten salts as an obstacle to further reducing the environmental impact of TES on a life cycle basis.

5.3 Policy, Market, and Regulatory Considerations for Recycling, Reuse, and Repair

Despite the potential economic and environmental benefits of reuse and recycling, there is evidence that EOL and early-retired PV modules are often stored in warehouses or discarded in landfills in the United States.[35,40] Industry experts have noted several technical, economic, and regulatory barriers to repair for reuse, direct reuse, and recycling of PV modules.[35,40,220,221,231–233] For example, although direct reuse of a PV module is arguably more viable than current repair for reuse and recycling options, direct reuse may be prohibited by interconnection and equipment standards, and fire, building, and electric codes for certain applications.[40] For instance, older modules that are not compatible with smart inverters are prohibited for grid-tied applications in jurisdictions that have adopted the IEEE 1547 Standard or UL 1741 Standard.[40,234,235]

Modules are not designed for easy repair or recycling, and a limited number of U.S. companies provide repair and recycling services.[40] In addition, current technology, infrastructure, and processes are not designed for cost-effective repair or recycling.[40] Moreover, most U.S. solid and hazardous waste regulations do not incentivize recycling modules over disposal, because the requirements as well as the financial and legal liability associated are often the same.[40] As a result, U.S. solid and hazardous waste regulations may not incentivize recycling over disposal especially under current market conditions which favor disposal over recycling in terms of cost and accessibility.[35,40,220,221,232]

Concerns about current practices, supply chain vulnerabilities, and PV system waste—as well as the potential for new and expanded opportunities—have led to government and industry discussions, policies, and initiatives that could have important impacts on material management options for early-retired and EOL PV modules and BoS equipment in the United States.[9,35,40] Industry-led initiatives, such as the Solar Energy Industries Association's (SEIA) National PV Recycling Program, are also focused on providing sustainable solutions for EOL PV modules and BoS equipment. SEIA's National PV Recycling Program, launched in 2016, provides EOL material management best practices for asset owners and recycling resources to encourage module and BoS equipment recycling among its membership.[40] These recent government and industry-led policies and initiatives signal a growing trend in the United States to prioritize sustainable material management practices for early-retired and EOL PV modules and BoS equipment and may present new and expanded market opportunity for the solar industry.

5.4 Circular Economy as an Approach to Addressing EOL Issues

5.4.1 Recycling

Recycling is the most widely applied and analyzed PV CE strategy (Figure 4). A detailed analysis of the literature on recycling c-Si PV modules (Figure 25) reveals that R&D has focused extensively on recovering the bulk module materials; 46 and 23 data sets have focused on the recovery of silicon wafer and glass respectively.

Literature reveals open-loop recycling pathways wherein materials recovered from PV modules are used in non-PV applications. The materials recovered from c-Si PV modules can potentially be reused in lithium-ion batteries,[236] cement and concrete,[237–239] paper production,[240] ceramic tiles,[241] geopolymers,[242] clay bricks,[243] and medical applications[244] (Figure 3). Conversely, there is scope to reuse materials recovered from non-PV products in PV systems. By comprehensively reviewing existing R&D efforts and commercial operations, three recent studies[245–247] have identified key trends and challenges for c-Si PV recycling, which are highlighted below.

R&D has focused less on the recovery of trace materials (tin, lead, copper, and silver), which occur at significantly lower concentrations than glass and silicon in a c-Si module. The reduced R&D focus may be attributed to the existence of mass-based recovery targets specified in PV recycling regulations, wherein a minimum portion of module mass must be recycled. For example, the Waste Electrical and Electronic Equipment (WEEE) Directive mandates that 85/80% of the mass of a PV module must be recovered/recycled, respectively,[248] which makes bulk materials attractive candidates for recycling because they contribute around 90% of the module weight.[249] However, the exponential growth in PV waste may motivate an expansion in the scope of regulations to include recovery of both bulk and trace materials. This will help manage hazardous materials, such as lead, in an environmentally responsible manner and prevent toxicity and environmental risks in scenarios of improper management at EOL.[250]

The rightmost vertical bar in Figure 25 demonstrates that only one study focuses on the recovery of bulk and trace materials from c-Si PV modules. However, this study recovers the trace materials as a part of larger aggregates containing other bulk materials, which is not well suited for direct reuse and requires further downstream processing.[251] Furthermore, only 33.2% of the mass of silver present in the module is recovered, which leads to a potential loss in revenue. Another study uses sequential electrowinning to recover the trace metals from a simulated solution of metals, which falls short of demonstrating an integrated process with the ability to recover the trace metals from the leachate obtained during module recycling.[252] In addition, the use of platinum electrodes in the electrowinning process may increase recycling process costs. The above shortcomings demonstrate the need for a low-cost, integrated, high-value recycling process that can recover bulk and trace materials at high efficiencies from c-Si PV modules.[245]

Another key recycling challenge is delamination to eliminate the EVA and separate the glass and silicon wafer.[253] The use of organic solvents to dissolve the EVA is time intensive and increases human health risks,[75,254] mechanical processes increase energy consumption,[91] and high-temperature processes present the risk of releasing hazardous emissions.[77] While commercial processes use combinations of mechanical, thermal, and optical processes, there is scope to facilitate easier delamination through design for circularity approaches such as laminate-free design.[85,255]

There is a lack of robust and publicly available assessments of the economic viability of PV recycling at a commercial scale. Such assessments could help in designing better policies and incentives to transition to a CE for PV systems. Despite existing commercial operations,[256,257] estimates show significant variability in recycling costs based on the recycling technology,[246] and recyclers charge a fee because the revenue from the recovered materials alone cannot economically sustain PV recycling.[246,247]

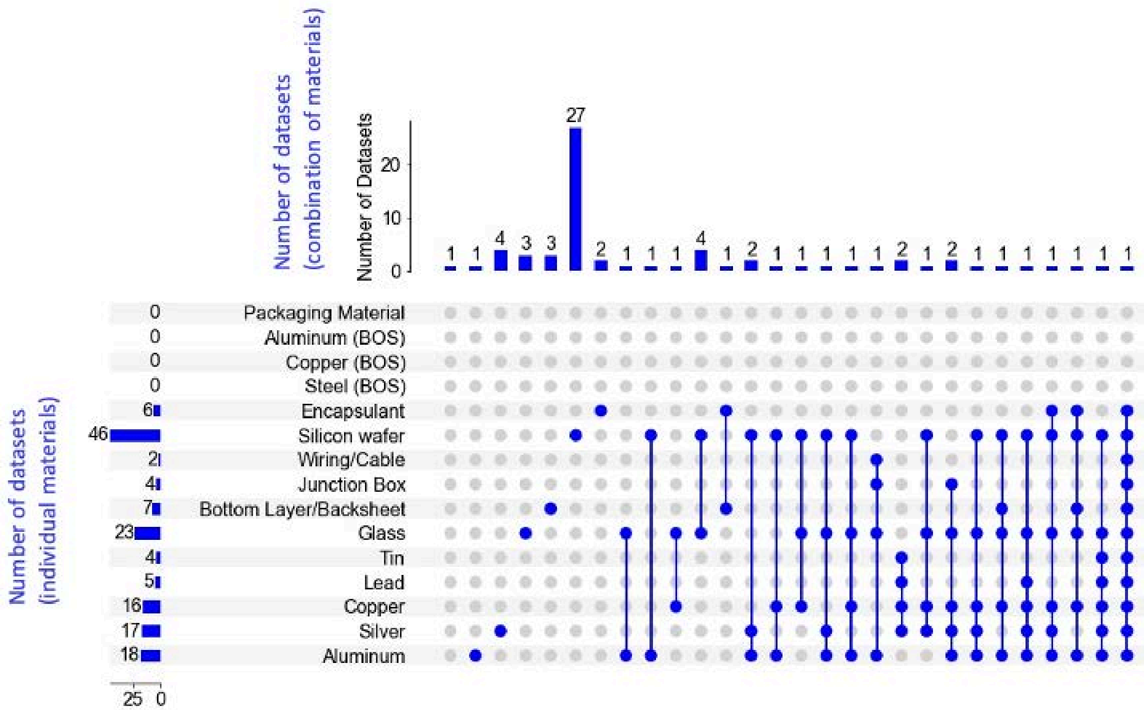

Figure 25. Literature on material recovery from recycling c-Si PV modules

The horizontal bars represent the number of data sets focusing on the recovery of an individual material from a c-Si PV module. For example, the 10th row from the top shows that 23 data sets focus on recovery of glass. The vertical bars represent the number of data sets focusing on the recovery of a combination of materials from a c-Si PV module. The combination of materials is identified by the solid blue circles in the column corresponding to the bar. For example, the 11th column from the left indicates that four studies recover both the silicon wafer and glass.

Variability in the designs and evolution of manufacturing trends across legacy and current-generation PV modules may pose challenges to the commercialization and economic viability of recycling technologies. The decline in silver content and the reduction of silicon wafer thickness[44] decrease the potential to generate revenue by reselling the recovered materials. The use of high-temperature recycling processes, while being well suited for glass-glass and fluorine-free PV modules, may release hazardous fluorinated emissions when Tedlar is used as a backsheet.[76] The variability in the design and material content of PV modules can introduce variability in the results for toxicity compliance (e.g., toxicity characteristic leaching procedure [TCLP]), so the toxicity test will change based on the method used to obtain samples from the PV module.[258]

To address recycling challenges due to the variability in module design and material content, a repository of the different PV module designs and material content, which stakeholders can access and continually update, could be beneficial. The repository could facilitate collaboration and information sharing between PV manufacturers and recyclers, address the concerns of data confidentiality of the manufacturer, increase transparency on the design and material constitution of past and present PV modules, ensure repeatability of results and compliance with toxicity tests (e.g., TCLP[259]), and help better customize recycling strategies. Manufacturers can share information with recyclers through bill of materials, material passport, radio-frequency identification, or ecolabels.[260,261]

Given the above challenges, there is a need to prospectively quantify economic and environmental impacts to identify and accelerate the commercialization of the most promising novel PV recycling technologies. The application of anticipatory analytical methods[262] in the early stages of technology development can help prospectively quantify and compare the economic and environmental effectiveness of novel recycling technologies.

The growth in PV capacity additions globally will require the collection and transport of waste modules from geographically dispersed installation sites to centralized recycling facilities. Recycling the modules at the installation site in small-scale decentralized plants can avoid the CO_2 emitted from transporting PV modules. However, recycling in smaller-scale recycling plants forgoes the opportunity to realize efficiency gains from economies of scale in a centralized recycling plant. As a result, there is opportunity to optimally locate recycling facilities to minimize the economic and environmental cost of PV recycling,[75,263–266] when transitioning to a CE for PV systems.

5.4.2 Repairs

We discuss repair in this section dedicated to EOL CE strategies because repair is required before reuse of PV modules, although repair can also occur in the use phase.

The results from the literature review (Figure 4) identify repair as an emerging and alternative CE strategy to recycling. Repair can address defects in parts such as the junction box, backsheet, bypass diodes, encapsulant, breakage in glass, and connectors without the destructive processing of the module.[248,267–269] As shown in Figure 3, repair can also be applied in the use phase to address module degradation and enhance electricity generation, durability, and reliability. The repairs to external module components such as backsheets and junction boxes most likely to occur, with some solutions emerging, include; data are not available about the efficacy, performance and reliability effects, cost, equipment and skill requirements, and so forth—presenting a clear research opportunity.

In addition, repair is not limited to modules, but is also an important strategy for the full suite of BoS components, from inverters and switchgear to racking and cabling. Little research has been focused on these components, yet repair of these components is expected to yield financial and environmental savings in supporting a CE.

Repair avoids the economic and environmental burdens associated with the destructive processes of disassembly, separation, and recycling of individual material constituents and extends the lifetime of PV modules, which is a key CE strategy.[270] The promise in the repair of PV systems is demonstrated by estimates showing that the repair and maintenance market for PV is expected to be worth $9 billion by 2025.[214] In addition, repaired PV modules on the secondhand market cost less than new PV modules and decrease the cost barrier to purchase PV systems in price-sensitive markets.[222]

Repair opportunities and needs can be identified through real-time monitoring, infrared thermographic imaging,[271,272] electroluminescence imaging,[273] and leveraging ML- and AI-based diagnostic approaches.[268] The emergence of information system/digital service providers has helped link suppliers with potential buyers and expand the markets internationally for repaired and reusable PV systems.[6,7]

Despite the promise of repair and reuse of EOL PV modules, there is a need to address the lack of publicly available data on reliability, failure mechanisms, and standards to ensure quality and performance of repaired and reused modules, which can provide an objective mechanism to price and improve market confidence for these modules. Furthermore, there is a need to robustly assess and compare the economic and environmental trade-offs between module repair/reuse and alternative CE strategies (e.g., recycling).[274] This assessment could help decrease the variability[248,275] in the economic costs of repairing PV systems, how the costs vary based on module conditions (e.g., type of defect, age of module, reason for decommissioning), diagnostic approach being used for repair, and market conditions (e.g., cost of repaired module versus revenue from recycling the module).[274,276]

5.5 Environmental Justice and Social Benefit Through Circular Economy at PV End of Life

The recycling, repair, and maintenance of PV systems could increase employment opportunities; this area is emerging as among the fastest-growing job categories in the U.S. economy.[108] Further research is required to quantify the trade-offs related to increased employment opportunities in repair, which may diminish the volumes of PV waste and, thereby, the downstream job creation in recycling or landfilling. In addition, there is need to enhance planning and collaboration between various stakeholders (e.g., researchers, policymakers, the PV and waste management industries) to identify relevant skill sets and develop training programs to ensure creation of a workforce to staff U.S. PV repair, repowering, and recycling jobs without the need to export the PV waste.

By managing hazardous materials (e.g., lead) in an environmentally responsible manner, the potential negative impacts on human health are minimized, and environmental justice outcomes are improved. Historically, minority and low-income communities have disproportionally borne the negative health impacts from waste management operations.[277–281]

To design policies that maximize potential social benefits and improve environmental justice outcomes, there is a critical need to develop tools to explore the behavioral responses of stakeholders to incentives (e.g., recycle versus landfill PV waste), account for policy incentives (e.g., tax rebates), include market signals (e.g., price of secondary materials), and determine the social outcomes (e.g., decrease in energy poverty) of CE strategies. Frameworks such as social LCA,[282] agent-based modeling,[283,284] and discrete event simulation,[285,286] and tools such as ML and AI, are promising candidates to determine the social outcomes of CE at PV EOL.[287]

6. Conclusions and Recommendations

This report uses novel analysis and literature synthesis to assess prioritized environmental challenges and opportunities for solar energy technologies in the context of the tremendous growth envisioned in the *Solar Futures Study*. Key issues include materials, land and water availability, ecosystem health, air quality, waste generation, environmental justice, and GHG emissions.

The role of solar technologies in mitigating GHG emissions from the power sector is presented in the *Solar Futures Study*.[1] Also, solar mitigates air pollutants such as NO_x and SO_2, which react in the atmosphere to form ozone and fine particulate matter ($PM_{2.5}$). Based on preliminary analysis, reducing these emissions via the *Solar Futures Study* Decarb scenario (power-sector reductions) and Decarb+E scenario (power- and transportation-sector reductions) could produce air-quality and health benefits worth roughly $300 billion–$400 billion between 2021 and 2050. Both scenarios also reduce power-sector water withdrawals dramatically. With regard to these traditional environmental indicators, solar deployment under the *Solar Futures Study* scenarios provides important contributions to tackling critical national and international challenges such as climate change, respiratory health effects (including premature death), and future water availability under a changing climate.

Although solar requires similar or less land per unit of capacity than other generation technologies, the deployment envisioned in the *Solar Futures Study* scenarios will entail significant land use: in the Decarb+E scenario, about 10 million ac for ground-mounted PV and CSP installations by 2050, which is equivalent to about 0.5% of the total contiguous U.S. surface area. Solar land requirements are not expected to exceed 5% of any state's land area by 2050, with the exception of Rhode Island (6.5%). Our siting analysis excludes protected lands and identifies ample potentially suitable disturbed and contaminated lands to host the vast majority of the ground-mounted solar capacity. Using such lands would reduce land-use conflicts and could provide local societal and ecological benefits. We explore various ways to further reduce solar land-use conflicts and enhance land value via solar deployment, including managing vegetation to provide ecosystem services at solar facilities, co-locating solar with agriculture (including grazing) in agrivoltaic systems, and other pursuing opportunities such as installing PV panels on water (floatovoltaics).

Our analysis of U.S. solar material demands under the *Solar Futures Study* scenarios suggests material supplies likely will not limit solar deployment growth, especially if EOL materials are recovered and used. In any case, management of EOL solar materials will become both a critical challenge for the expanding solar industry and an environmental, economic, and social opportunity. CE strategies—such as recycling, repair, reuse, dematerialization, and use of renewable energy to power manufacturing supply chains—can improve outcomes across the full solar life cycle. In addition, management of information flows can enhance CE strategies across the full life cycle, for instance leveraging AI/ML methods for alternative material selection or development during manufacturing and securely containing information about materials in material passports using blockchain or radio-frequency identification. Real-time monitoring (to get ahead of failures that could lead to early decommissioning) and PSS business models (third-party ownership) are also information-centered CE strategies. These various CE strategies merit additional R&D, analytical, and policy-oriented efforts.

A benchmark global projection of PV EOL materials estimated approximately 80 million metric tons will be cumulatively produced by 2050 based on projections for deployment developed in 2014.[288] We find that under the *Solar Futures Study* scenarios, and using more accurate and up-to-date data on PV reliability and performance, EOL materials from PV modules in the United States are projected to be under 10% of this global figure: ~6.5 million metric tons. The benchmark report also estimated the value of materials in the cumulative EOL PV modules at $15 billion, with enough raw materials to produce approximately 2 billion new PV modules if recovered in closed-loop recycling—equivalent to 630 GW of capacity—to which our results here can be similarly scaled.[288] Our projection of cumulative EOL materials in PV modules in the United States can be compared with global electronic waste, of which PV is a category: annual global electronic waste in 2050 is estimated at approximately 111 million metric tons per year.[289]

We also find connections between solar impacts and social and environmental justice. Solar, especially in the use phase—but also along the value chain (especially if manufacturing facilities are powered by renewable energy)—reduces air pollution by offsetting incumbent combustion-based energy sources. Air pollution from incumbent electricity generation contributes significantly to health disparities for disadvantaged populations. In addition, industrial facility locations correlate with the locations of disadvantaged populations, where near-source exposure to air pollutant emissions likewise causes health disparities. With regard to land, solar deployment can boost rural economies in terms of increased tax base and employment. Using degraded or contaminated lands can enhance societal and ecological land value, leading to conversion of previously underutilized lands to beneficial use, increased tax bases for rural communities, provision of local workers with jobs, creation of new markets for local contractors, diversification of income for landowners, and an increase in available local resources, including for underserved populations. And agrivoltaic systems can provide off-grid power to rural communities, increasing their resilience along with the income streams of agricultural families.

Solar CE strategies can provide social and environmental justice benefits as well. For example, design for circularity approaches that decrease use of hazardous materials can prevent negative health impacts related to release of those materials. Scorecards, ecolabels, and preferential purchasing schemes incentivize transparency in supply chains and manufacturing, prevent sourcing of conflict minerals, and improve worker health and safety. PSS and reuse decrease upfront capital costs for residential PV ownership and could widen access to PV electricity. Recycling decreases upstream social, environmental, and health impacts from PV manufacturing supply chains, increases domestic employment opportunities, leads to synergies with allied industries, and prevents negative health impacts from environmental release of hazardous materials. Recycling also prevents perpetuation of historically disproportionate burdens experienced by disadvantaged communities in the siting of landfills and hazardous waste management facilities.

Key Recommendations

There has been almost no quantitative investigation of the potential of CE strategies to further cost-effective decarbonization and environmental justice. Anticipatory analytical methods, such as life cycle assessments and techno-economic assessments, are important for fairly comparing CE strategies and clarifying the economic and environmental impacts of technology and policy design. However, such analyses are currently lacking across the range of CE pathways. LCAs are one approach to comprehensively quantifying GHG emissions and the mitigation potential of CE strategies; when assembled from across several pathways, integrated scenarios and the overall system potential can be evaluated. Promising quantitative approaches for considering environmental justice include near-source air-quality modeling, complex system science methods such as agent-based or systems dynamics modeling (which apply behavioral science principles to assess adoption potential), and social LCA.

There is need to study the employment trade-offs and workforce-development needs related to CE strategies. For example, increased employment opportunities in repair may diminish the volumes of PV waste and, thereby, the downstream job creation in recycling or landfilling. In addition, there is need to enhance planning and collaboration between various stakeholders (e.g., researchers, policymakers, the PV and waste management industries) to identify relevant skill sets and develop training programs to ensure creation of a workforce to staff U.S. PV repair, repowering, and recycling jobs without the need to export the PV waste.

R&D investments in partnerships or consortiums involving multiple actors in the value chain—including allied industries—would be valuable, especially for larger investments. In addition, there is need for a repository of different PV module designs and material content, which stakeholders could access and continually update.

Although recycling is the most studied CE strategy, recycling R&D should continue. This includes (1) clarifying the benefits and costs of different policy designs and (2) connecting the full value chain of recyclers, raw material manufacturers, and customers to identify the most viable market pathways for using recovered materials. For instance, determining how the impurity profile of recovered silicon might necessitate change to silicon manufacturing processes, manufacturer cost structures, and product characteristics is an important research area. Development of high-value products and markets for the largest PV module constituent—glass—is another area deserving significant research attention. Additional challenges for PV recycling technology design include the lack of an integrated method to completely recover bulk and specialty materials (lead, tin, silver, copper); delamination; variability in module design; lower silver content; fluorinated polymers; and lead content.

Lead is the primary metal of concern with regard to regulatory characterization of module toxicity. Reducing or eliminating lead content in modules could address questions about treatment as hazardous material at EOL. Working with industry on recognizable standards to ensure modules have lower lead content than the TCLP conformance limit (the strongest demonstration of which would be lead-free), final owners could be relieved of the costs of testing and burdens of potential hazardous waste treatment. Developing a standard protocol for sampling of PV modules before TCLP testing is also needed to reduce the demonstrated variability in results when using unstructured sampling.

Fluorine is also a concern for module recycling. Clarifying the costs of treatment and the corrosive effects on equipment in recycling of fluorine-containing modules could inform manufacturers' and purchasers' decisions about the continued use of fluorine-containing backsheets.

Because PV and CSP are undergoing rapid technological change, the capital-intensive recycling industry should carefully consider how their infrastructure could be designed to be as adaptive as possible to handle not only anticipated amounts of EOL materials but also changes to form factor, materials content, assembly, and so forth.

Design for circularity R&D should include holistic assessment of the trade-offs that material and design choices impose on module technical performance as well as their life cycle impacts. Such efforts could prioritize design for circularity methods that generate the highest net economic and environmental benefit over the PV life cycle.

In general, product service systems are understudied with regard to quantifying differences in PV performance and lifetime between this ownership model and others, as well as developing metrics to quantify the effectiveness of PSS as a CE strategy. Given the prevalence of this ownership model for U.S. PV, this topic is important for further research.

Other than anecdotal data, no data exist on the reasons for and total flow of PV modules reaching EOL. Partnering across the PV value chain (from owners to installers/servicers, insurers, and financiers) to develop commitments for regular surveying of modules reaching EOL could provide the data needed to reduce investment risks in the nascent EOL management industry (inclusive of repair, recycling, reuse, and secondary markets). Conceptually, a tagging system akin to a vehicle identification number could be considered for more robust tracking from first sale to EOL disposition. As the resolution of satellite imagery continues to increase, empirically tracking module removal and replacement at the facility or even per-module level might become conceivable.

Developing standards to evaluate the performance of in-field repairs is critical for assuring owners, insurers, and financiers about the efficacy and safety of repaired PV. Doing so could ultimately reduce the total cost of ownership and improve circularity by keeping existing products in service longer.

Renewable electricity use significantly increases the life cycle-climate benefit from PV by providing earlier GHG emission reductions, thus reducing cumulative radiative forcing. Use of this or a similar metric to understand the relative benefits of the role that different CE strategies can play in mitigating climate change could be pursued.

Circularity studies could reflect the current recycled content of each material as well as more extensive CE pathways. For example, for each scenario, some percentage of virgin material demand could be offset by recycling the annual EOL PV materials in a closed loop back into PV material feedstock. This pathway would require research into reverse logistics and high-quality recycling of PV modules. Alternatively, increasing the longevity of PV modules (e.g., via reduced degradation or repair) would reduce required annual deployments, because fewer panels would be required to attain and maintain capacity and generation levels—resulting in reduced virgin material demands and, eventually, EOL materials. This pathway would require research into module and system reliability, degradation modes, repairs, and optimized system design. Also, the PV industry is also moving toward modules with higher energy yield per unit area, which will also affect material demands.

To ensure fulfillment of the implicit promise that solar will be sustainable throughout its life cycle—including EOL—technical and policy solutions better than landfilling should be identified, studied, piloted, demonstrated, and deployed throughout the country. Additional efforts to characterize the landfill volume required for solar components under the *Solar Futures Study* scenarios could serve to prioritize solar component recycling development. Additionally, increased awareness of the upstream land use and other impacts of mineral mining for solar components is important for avoiding unforeseen social equity impacts within the United States and globally.

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Appendix A. Supplemental Information Regarding Land Requirements

Table A-1. Total Land Area Required for All Ground-Mounted Solar Technologies by Balancing Area (BA)

				CSP					PV (DUPV and UPV)				
BA	State	BA Size (ac)	Total Solar Land Need Relative to BA Size (%)	2030 CSP Land Need (ac)	2040 CSP Land Need (ac)	2050 CSP Land Need (ac)	Available Dist. Land for CSP (ac)	Available Contam. Land for CSP (ac)	2030 PV Land Need (ac)	2040 PV Land Need (ac)	2050 PV Land Need (ac)	Available Dist. Land for PV (ac)	Available Contam. Land for PV (ac)
1	Washington	10,712,462	0.1%	0	0	0	0	0	11,287	14,727	14,540	626,183	33,969
2	Washington	16,094,383	0.1%	0	0	0	0	0	44	4,061	16,943	668,134	375,968
3	Washington	13,455,441	0.0%	0	0	0	0	0	5,273	5,273	5,129	545,595	987
4	Washington	2,969,526	2.2%	0	0	0	0	0	32,062	65,371	65,371	229,001	7,680
5	Oregon	29,732,910	0.1%	0	0	0	0	0	7,656	21,183	20,110	914,572	16,107
6	Oregon	12,091,160	0.2%	0	0	0	46,674	0	12,771	15,017	28,336	174,938	237
7	Oregon	20,225,942	0.2%	0	0	0	300,931	0	16,308	19,623	32,764	572,073	373
8	California	9,773,474	0.1%	0	0	0	394,227	0	2,772	2,922	7,479	412,500	38,618
9	California	47,101,279	0.4%	335	300	0	1,378,926	0	59,655	190,283	201,944	4,229,580	259,059
10	California	41,595,674	0.7%	13,322	9,292	0	1,919,289	1,420,046	228,253	295,140	298,459	2,869,663	1,449,894
11	California	2,711,562	1.0%	63	63	0	121,448	0	15,498	25,984	25,155	217,789	3,759
12	Nevada	65,580,867	0.0%	1,100	1,100	0	3,709,534	53,500	8,409	8,476	5,103	3,757,841	54,030
13	Nevada	5,177,948	1.1%	685	0	0	249,878	12,641	45,238	58,818	55,920	249,878	13,128
14	Idaho	4,933,855	0.0%	0	0	0	0	0	30	148	148	135,069	40
15	Idaho	34,771,769	0.5%	0	0	0	737,439	0	1,500	14,781	179,833	1,345,072	6,701
16	Idaho	13,777,720	0.2%	0	0	0	88,334	0	1,120	19,653	24,302	740,588	21,096
17	Montana	23,814,686	0.1%	0	0	0	0	0	0	0	14,238	424,719	189,743
18	Montana	32,971,048	0.0%	0	0	0	0	0	105	105	0	1,201,613	19,600
19	Montana	6,341,652	0.0%	0	0	0	0	0	0	0	0	166,129	0
20	Montana	15,569,992	0.0%	0	0	0	0	0	23	23	0	487,878	174
21	Wyoming	31,658,850	0.0%	0	0	0	190,115	0	690	690	690	445,403	100
22	Wyoming	4,289,013	0.7%	0	0	0	0	0	159	31,025	31,025	30,289	0

BA	State	BA Size (ac)	Total Solar Land Need Relative to BA Size (%)	CSP					PV (DUPV and UPV)				
				2030 CSP Land Need (ac)	2040 CSP Land Need (ac)	2050 CSP Land Need (ac)	Available Dist. Land for CSP (ac)	Available Contam. Land for CSP (ac)	2030 PV Land Need (ac)	2040 PV Land Need (ac)	2050 PV Land Need (ac)	Available Dist. Land for PV (ac)	Available Contam. Land for PV (ac)
23	Wyoming	6,446,075	0.1%	0	0	0	0	0	3,904	4,572	4,572	128,682	560
24	Wyoming	20,206,020	0.0%	0	0	0	28	0	53	53	53	554,890	11,825
25	Utah	45,842,812	0.1%	15	15	6,244	2,447,482	814,718	10,780	44,905	48,229	2,938,658	869,736
26	Utah	8,490,314	0.1%	0	0	0	119,571	0	2,925	4,586	8,394	143,931	160
27	Arizona	8,622,006	2.3%	0	0	0	268,376	0	69,461	98,616	199,245	268,376	0
28	Arizona	50,426,520	0.1%	2,979	2,954	15,027	2,276,696	16,312	14,861	17,553	14,734	2,277,368	19,156
29	Arizona	7,179,819	0.0%	0	0	0	119,835	0	136	1,673	1,610	119,835	0
30	Arizona	6,584,705	1.8%	70	550	19,303	534,916	14,265	51,218	98,118	97,012	534,916	14,832
31	New Mexico	64,114,256	0.0%	10	10	0	3,185,227	1,369,855	16,289	16,064	13,598	3,185,227	1,369,855
32	South Dakota	5,861,877	0.0%	0	0	0	0	0	0	712	712	225,036	0
33	Colorado	30,443,408	0.1%	0	0	317	600,481	0	36,381	41,787	40,230	1,805,084	62,356
34	Colorado	36,176,102	0.1%	300	2,679	10,870	1,161,027	162,349	3,218	20,748	17,786	1,170,909	162,862
35	Montana	15,403,475	0.0%	0	0	0	0	0	0	0	0	631,695	71
36	North Dakota	21,315,649	0.2%	0	0	0	0	0	24,058	24,058	32,445	1,445,760	1,477
37	North Dakota	23,929,002	0.0%	0	0	0	0	0	0	11,961	11,961	2,020,952	372,963
38	South Dakota	43,491,916	0.2%	0	0	0	0	0	377	82,329	90,326	3,541,059	1,109
39	Nebraska	12,526,114	0.1%	0	0	0	0	0	251	4,340	14,607	714,794	4,257
40	Nebraska	32,494,327	0.0%	0	0	0	0	0	3,749	3,749	3,659	2,053,118	59,115
41	Nebraska	4,485,510	2.1%	0	0	0	0	0	93,800	93,800	93,753	449,883	23,370
42	Minnesota	13,194,031	0.1%	0	0	0	0	0	0	19,722	19,722	797,027	70
43	Minnesota	30,498,050	0.1%	0	0	0	0	0	5,535	15,838	14,442	2,454,806	61,131
44	Minnesota	4,901,332	0.6%	0	0	0	0	0	779	25,555	29,255	409,207	0
45	Iowa	13,896,983	0.9%	0	0	0	0	0	15,261	43,181	131,353	1,174,954	452
46	Wisconsin	12,831,660	0.5%	0	0	0	0	0	163	19,855	66,279	757,473	831
47	New Mexico	13,703,130	0.2%	0	9,103	26,422	889,175	81,480	1,735	1,735	65	889,175	81,577
48	Texas	22,257,743	0.4%	0	11,411	14,928	1,831,769	25,760	66,932	66,932	66,932	1,961,884	29,726

BA	State	BA Size (ac)	Total Solar Land Need Relative to BA Size (%)	CSP					PV (DUPV and UPV)				
				2030 CSP Land Need (ac)	2040 CSP Land Need (ac)	2050 CSP Land Need (ac)	Available Dist. Land for CSP (ac)	Available Contam. Land for CSP (ac)	2030 PV Land Need (ac)	2040 PV Land Need (ac)	2050 PV Land Need (ac)	Available Dist. Land for PV (ac)	Available Contam. Land for PV (ac)
49	Oklahoma	3,652,841	1.6%	0	0	220	216,127	0	0	0	59,961	250,266	0
50	Oklahoma	33,539,151	0.2%	0	0	18,707	0	0	33,977	33,977	33,767	4,836,268	160,835
51	Oklahoma	7,543,105	1.0%	0	0	0	0	0	41,431	78,470	78,573	897,353	29,369
52	Kansas	13,162,268	0.2%	0	0	1,374	282,217	0	20,263	20,263	20,254	852,683	362
53	Kansas	39,494,876	0.1%	0	0	2,220	55,749	0	44,975	44,975	45,724	4,066,474	45,722
54	Missouri	10,511,702	0.0%	0	0	0	0	0	189	2,456	2,268	1,069,244	5,038
55	Missouri	9,158,815	0.7%	0	0	0	0	0	37,260	47,055	61,296	670,367	513,200
56	Arkansas	9,162,466	1.0%	0	0	0	0	0	45	25,425	87,644	436,278	72,465
57	Texas	3,709,787	2.7%	0	0	0	0	0	21,669	98,152	98,903	596,708	26,481
58	Louisiana	25,511,691	0.5%	0	27,637	92,611	0	0	5,325	6,260	31,140	3,333,748	272,662
59	Texas	641,656	8.2%	0	0	395	133,656	125,295	52,081	52,081	51,966	133,820	126,234
60	Texas	13,627,085	0.6%	0	160	2,784	1,191,467	0	54,121	56,769	76,247	3,080,757	1,869
61	Texas	32,040,227	0.3%	0	7,770	8,741	3,374,282	0	57,187	74,780	66,830	6,093,698	10,523
62	Texas	6,834,311	2.0%	0	0	22,045	2,064,707	859	11,700	11,700	111,278	2,065,074	1,721
63	Texas	34,956,126	0.4%	0	381	57,585	0	0	7,713	74,643	92,425	9,856,011	242,608
64	Texas	17,913,989	1.4%	0	0	131	0	0	56,648	212,264	256,445	3,836,456	1,434
65	Texas	25,723,675	0.0%	0	0	418	0	0	1,612	6,958	10,586	4,611,799	19,412
66	Texas	8,595,962	1.5%	0	0	0	0	0	9,283	81,748	128,706	1,172,332	17,163
67	Texas	2,883,527	12.6%	0	0	0	0	0	150,369	362,625	362,550	1,194,057	25,002
68	Minnesota	5,381,751	0.4%	0	0	0	0	0	22,060	22,060	21,711	453,657	313
69	Iowa	4,794,677	0.4%	0	0	0	0	0	18,767	18,808	18,781	496,907	647
70	Iowa	17,321,803	0.0%	0	0	0	0	0	601	601	549	1,776,144	7,199
71	Missouri	3,685,935	0.7%	0	0	0	0	0	182	24,686	24,665	276,170	5,109
72	Missouri	9,876,393	0.0%	0	0	0	0	0	76	76	23	925,855	58,623
73	Missouri	3,339,003	0.9%	0	0	0	0	0	3,647	4,028	29,437	104,459	987
74	Michigan	7,686,288	1.0%	0	0	0	0	0	3	49,561	80,679	226,279	1,366

BA	State	BA Size (ac)	Total Solar Land Need Relative to BA Size (%)	CSP					PV (DUPV and UPV)				
				2030 CSP Land Need (ac)	2040 CSP Land Need (ac)	2050 CSP Land Need (ac)	Available Dist. Land for CSP (ac)	Available Contam. Land for CSP (ac)	2030 PV Land Need (ac)	2040 PV Land Need (ac)	2050 PV Land Need (ac)	Available Dist. Land for PV (ac)	Available Contam. Land for PV (ac)
75	Wisconsin	7,936,635	0.1%	0	0	0	0	0	5,022	5,022	5,022	568,921	2,868
76	Wisconsin	6,344,000	0.6%	0	0	0	0	0	30,990	39,377	39,336	704,704	976
77	Wisconsin	4,702,521	1.0%	0	0	0	0	0	19,057	19,057	46,048	308,949	72,834
78	Wisconsin	1,631,388	2.9%	0	0	0	0	0	46,877	46,877	46,808	226,453	509
79	Wisconsin	2,425,431	2.4%	0	0	0	0	0	1,667	1,677	57,539	636,729	2,653
80	Illinois	8,097,197	1.3%	0	0	0	0	0	13,200	64,835	102,880	1,885,136	32,426
81	Illinois	16,978,069	0.3%	0	0	0	0	0	780	947	56,397	1,814,504	20,081
82	Illinois	2,384,692	3.3%	0	0	0	0	0	70,649	79,184	78,081	325,892	1,285
83	Illinois	8,597,011	1.0%	0	0	0	0	0	82,768	82,768	82,712	943,281	12,452
84	Missouri	8,038,882	0.7%	0	0	0	0	0	32	57,558	57,539	371,138	85
85	Arkansas	24,872,087	0.1%	0	14,766	14,766	0	0	1,965	7,963	8,404	2,235,121	70,944
86	Louisiana	4,401,604	2.6%	0	0	0	0	0	68,092	115,459	115,459	555,368	359
87	Mississippi	22,391,371	0.3%	0	35,733	35,733	0	0	31,357	32,281	31,823	4,578,807	10,677
88	Mississippi	8,114,532	2.3%	0	0	0	0	0	61,751	168,561	187,686	1,627,525	4,144
89	Alabama	14,074,123	0.0%	0	0	1,545	0	0	2,429	3,574	3,410	2,017,789	15,677
90	Alabama	18,985,895	1.2%	0	9,498	41,582	0	0	3,273	96,728	193,441	3,703,831	14,993
91	Florida	4,926,046	2.9%	0	0	543	0	0	118,574	141,324	140,995	809,247	470,155
92	Tennessee	26,971,838	1.3%	0	0	2,828	0	0	51,587	54,804	342,998	2,988,445	112,477
93	Kentucky	6,304,778	2.7%	0	0	0	0	0	32,857	135,280	167,865	611,532	5,530
94	Georgia	37,651,815	0.5%	0	59	568	0	0	91,585	136,998	184,964	6,614,742	524,281
95	ReEDS	5,123,447	8.2%	0	0	0	0	0	233,248	318,347	420,935	965,792	4,777
96	ReEDS	14,685,332	2.4%	0	0	0	0	0	69,093	242,108	359,308	2,799,811	277,036
97	North Carolina	12,639,527	2.4%	0	0	0	0	0	58,659	282,426	302,429	1,579,409	18,522
98	North Carolina	18,953,980	0.6%	0	0	0	0	0	29,827	110,442	91,953	4,067,643	156,735
99	Virginia	16,304,858	1.8%	0	0	177	0	0	122,484	222,916	296,037	2,779,293	115,192
100	Virginia	1,202,690	2.8%	0	0	0	0	0	10,994	10,994	33,939	69,962	705

BA	State	BA Size (ac)	Total Solar Land Need Relative to BA Size (%)	CSP					PV (DUPV and UPV)				
				2030 CSP Land Need (ac)	2040 CSP Land Need (ac)	2050 CSP Land Need (ac)	Available Dist. Land for CSP (ac)	Available Contam. Land for CSP (ac)	2030 PV Land Need (ac)	2040 PV Land Need (ac)	2050 PV Land Need (ac)	Available Dist. Land for PV (ac)	Available Contam. Land for PV (ac)
101	Florida	26,043,389	2.7%	0	0	0	0	0	196,485	499,878	692,462	4,772,221	152,527
102	Florida	5,265,718	5.6%	0	0	0	0	0	133,572	295,634	293,474	1,188,395	174,979
103	Michigan	27,694,609	0.3%	0	0	0	0	0	36,195	80,405	80,005	3,768,527	30,544
104	Michigan	1,800,456	5.1%	0	0	0	0	0	85,446	88,420	91,945	319,477	2,863
105	Indiana	12,398,515	0.5%	0	0	0	0	0	3,180	3,180	62,874	2,104,360	25,882
106	Indiana	515,690	19.5%	0	0	0	0	0	80,655	80,655	100,609	291,448	1,810
107	Indiana	10,242,331	0.0%	0	0	0	0	0	659	659	262	1,235,055	16,273
108	Kentucky	3,547,916	4.7%	0	0	0	0	0	134,900	150,278	165,012	309,258	1,331
109	Kentucky	13,229,165	2.2%	0	0	0	0	0	8,239	196,963	292,203	987,717	132,676
110	Kentucky	2,779,927	0.4%	0	0	0	0	0	5,534	7,264	10,566	35,303	351
111	Ohio	5,207,548	2.5%	0	0	0	0	0	248	44,669	131,849	1,665,991	18,158
112	Ohio	17,584,366	0.1%	0	0	0	0	0	2,555	11,307	11,212	2,055,791	20,618
113	Ohio	2,179,286	3.6%	0	0	0	0	0	53,521	77,510	77,378	448,379	9,683
114	Ohio	1,435,518	3.9%	0	0	0	0	0	39,630	53,938	55,828	395,272	2,999
115	Pennsylvania	3,789,478	1.3%	0	0	0	0	0	10	28,127	49,989	249,321	76,757
116	`West Virginia	10,986,993	0.4%	0	0	0	0	0	44,594	44,705	46,252	222,564	14,183
117	West Virginia	4,520,034	0.7%	0	0	0	0	0	31,977	31,977	33,267	102,203	8,436
118	Virginia	7,703,829	0.8%	0	0	0	0	0	6,189	55,403	61,103	278,554	6,520
119	Pennsylvania	2,766,191	0.6%	0	0	0	0	0	11	11	15,924	64,168	11,799
120	Pennsylvania	774,818	0.0%	0	0	0	0	0	0	0	0	56,902	2,205
121	Maryland	1,421,175	6.1%	0	0	0	0	0	944	944	86,469	104,121	334
122	Pennsylvania	21,662,069	1.0%	0	0	0	0	0	339	108,954	215,374	1,844,699	204,085
123	Maryland	5,020,301	3.7%	0	0	0	0	0	114,657	121,899	187,193	1,088,954	18,552
124	Virginia	374,900	0.2%	0	0	0	0	0	750	750	0	43,742	32
125	Delaware	1,288,004	4.3%	0	0	0	0	0	17,995	54,555	55,547	289,841	10,903
126	New Jersey	4,828,772	1.0%	0	0	0	0	0	6,924	39,493	46,460	1,288,096	63,952

				CSP					PV (DUPV and UPV)				
BA	**State**	**BA Size (ac)**	**Total Solar Land Need Relative to BA Size (%)**	**2030 CSP Land Need (ac)**	**2040 CSP Land Need (ac)**	**2050 CSP Land Need (ac)**	**Available Dist. Land for CSP (ac)**	**Available Contam. Land for CSP (ac)**	**2030 PV Land Need (ac)**	**2040 PV Land Need (ac)**	**2050 PV Land Need (ac)**	**Available Dist. Land for PV (ac)**	**Available Contam. Land for PV (ac)**
127	New York	30,349,585	0.8%	0	0	0	0	0	85,120	194,272	252,661	2,399,365	302,786
128	New York	768,786	0.1%	0	0	0	0	0	929	929	543	432,775	12,776
129	Vermont	6,153,046	0.2%	0	0	0	0	0	917	5,078	12,222	163,184	2,206
130	New Hampshire	5,929,194	0.8%	0	0	0	0	0	8,633	22,779	50,185	322,886	5,943
131	Massachusetts	5,195,760	2.0%	0	0	0	0	0	33,687	98,469	104,350	1,017,034	12,232
132	Connecticut	3,184,259	2.3%	0	0	0	0	0	28,495	32,202	73,027	482,105	9,372
133	Rhode Island	696,877	6.2%	0	0	0	0	0	1,318	2,162	43,248	170,722	2,574
134	Maine	20,780,154	0.1%	0	0	0	0	0	5,718	6,856	14,127	731,477	15,740

Dist. = disturbed; Contam. = contaminated

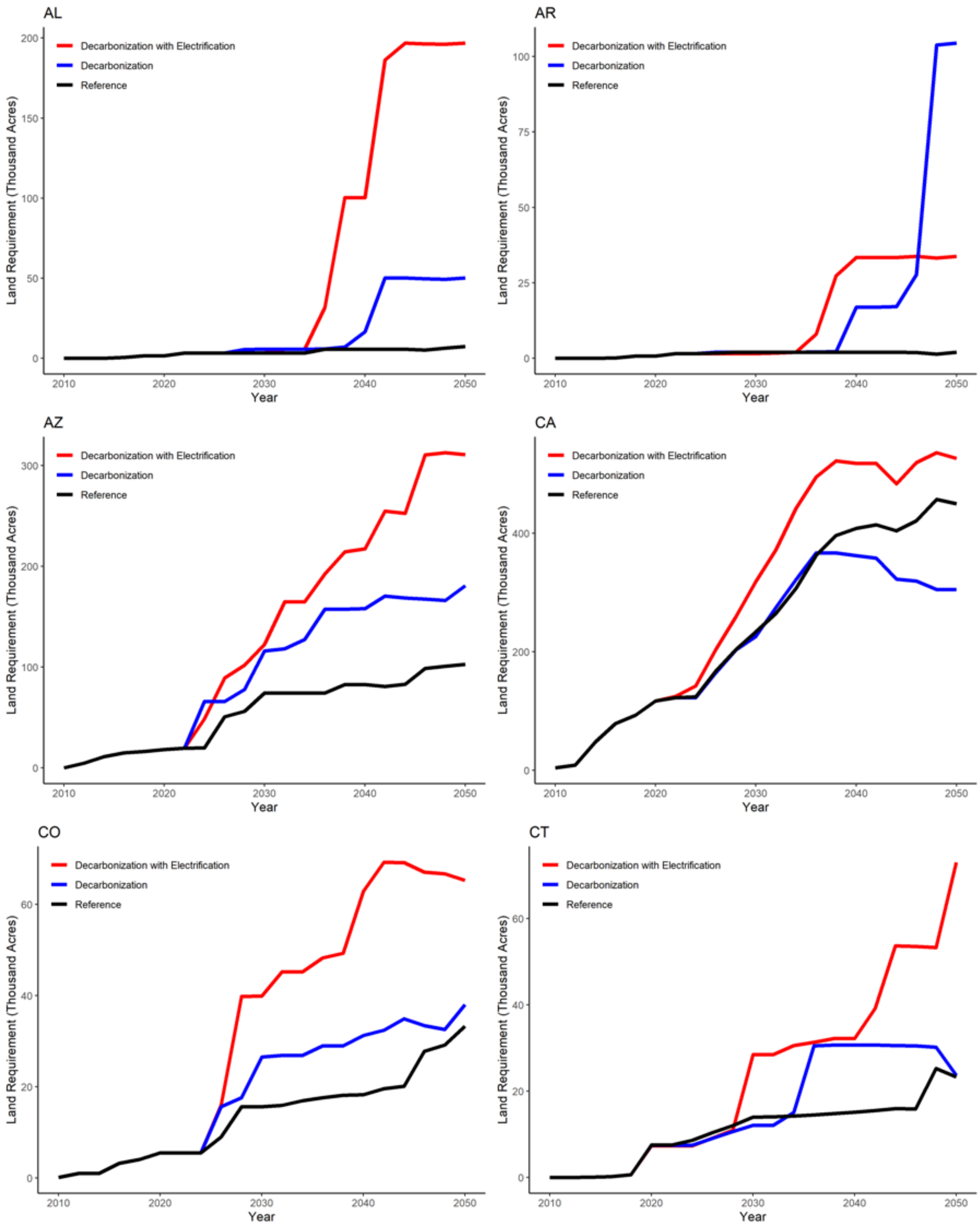


Figure A-1. Estimated cumulative solar land requirement by state for the three core scenarios projected by the ReEDS model by year from 2020 to 2050

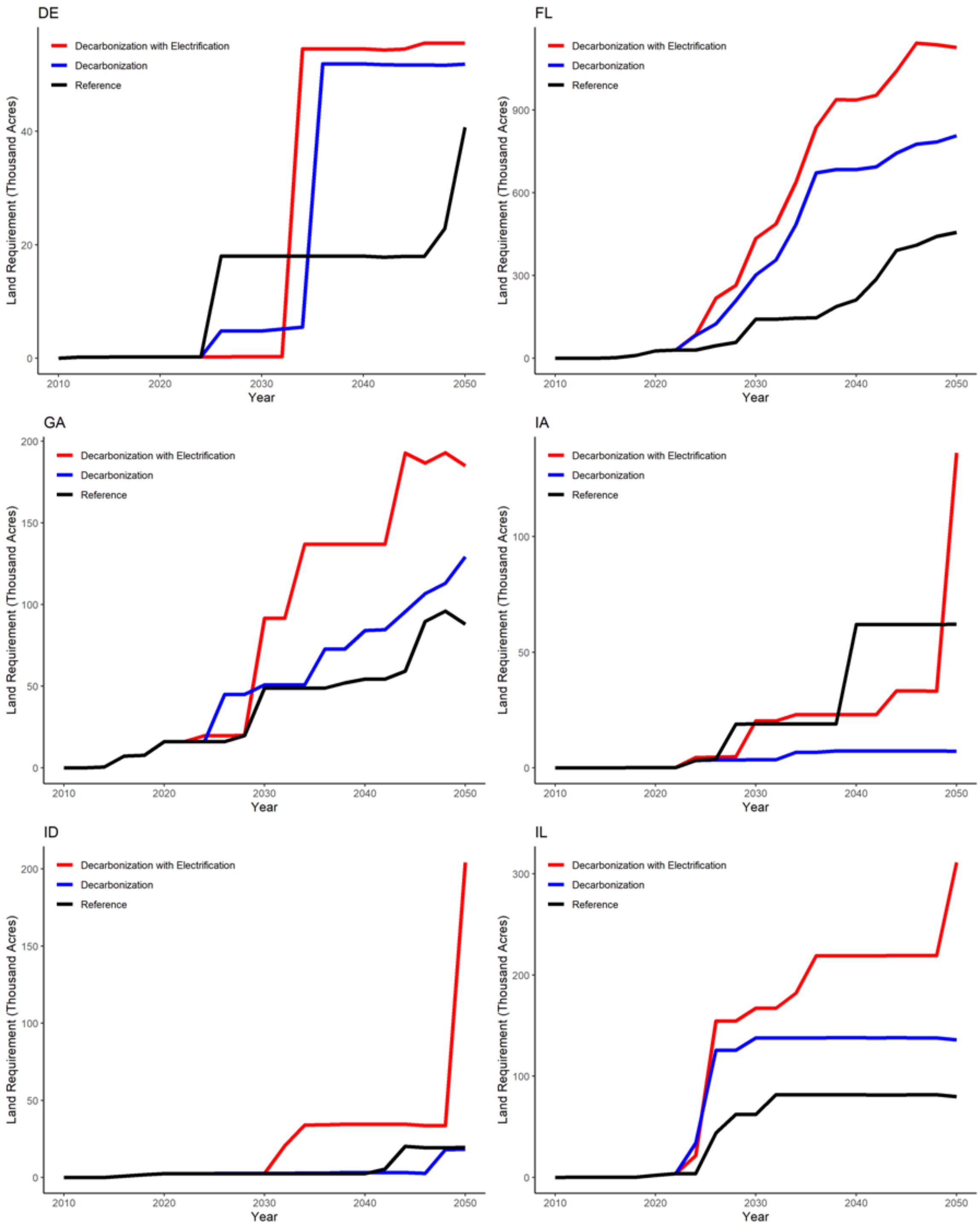


Figure A-1 (continued). Estimated cumulative solar land requirement by state for the three core scenarios projected by the ReEDS model by year from 2020 to 2050

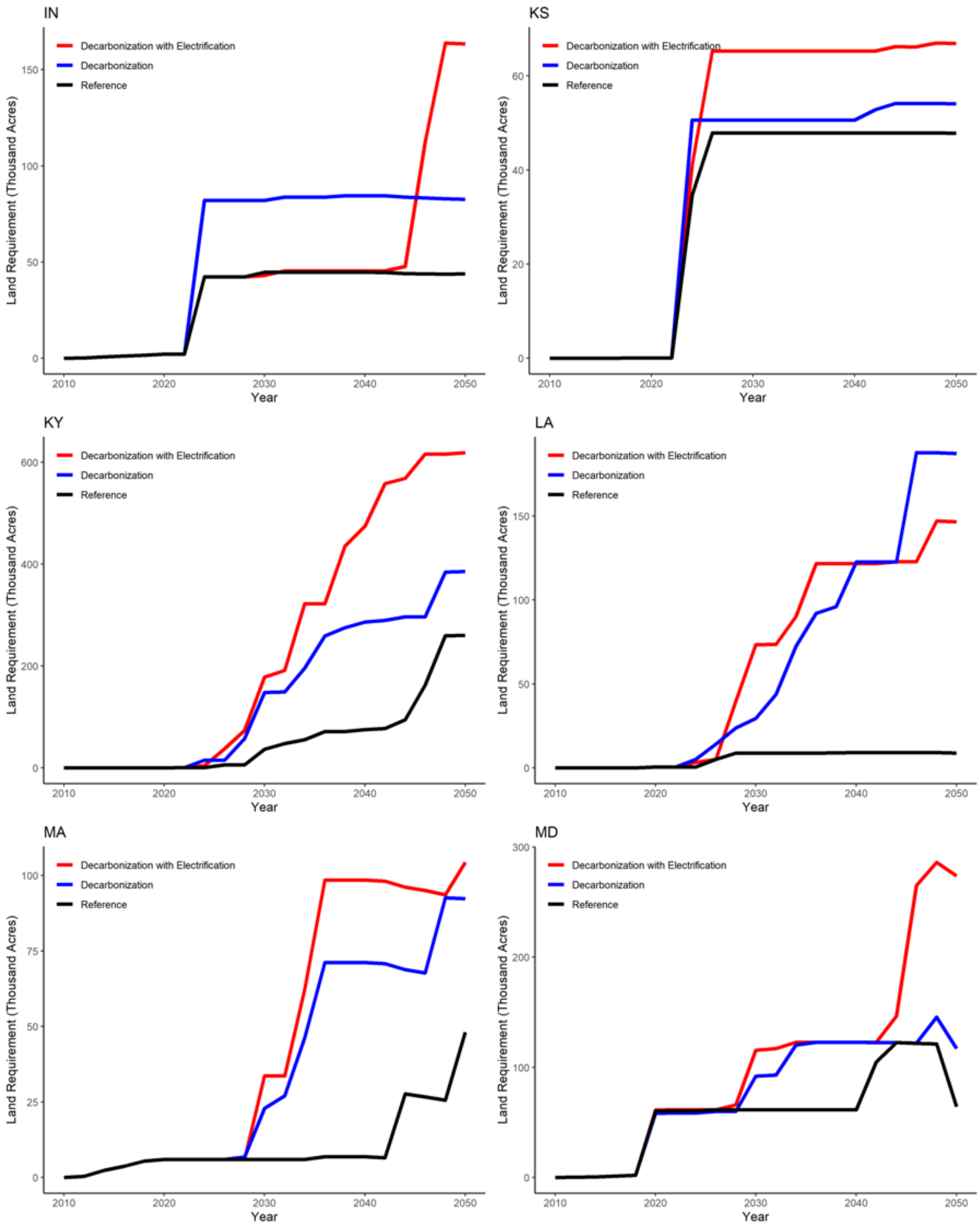


Figure A-1 (continued). Estimated cumulative solar land requirement by state for the three core scenarios projected by the ReEDS model by year from 2020 to 2050

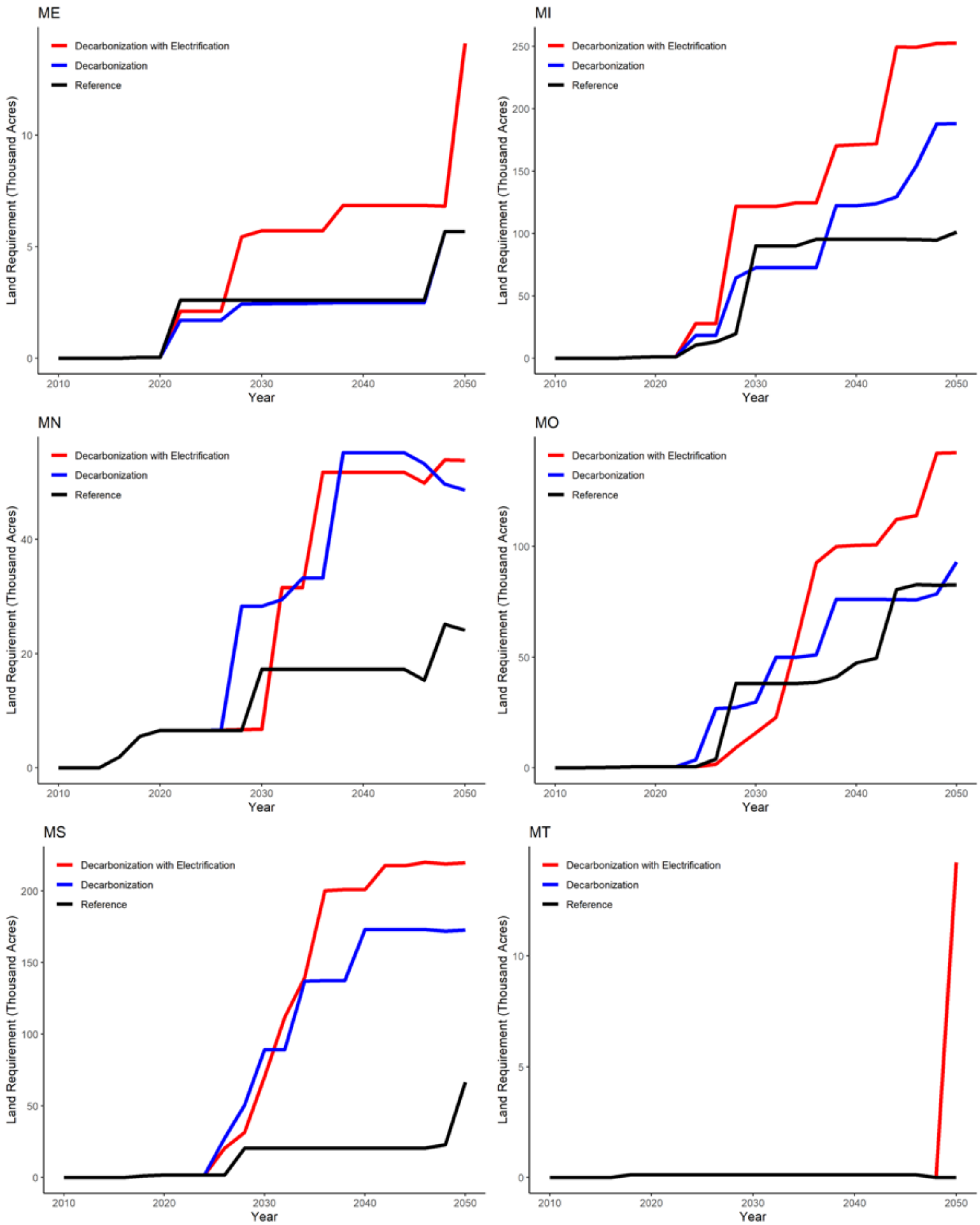


Figure A-1 (continued). Estimated cumulative solar land requirement by state for the three core scenarios projected by the ReEDS model by year from 2020 to 2050

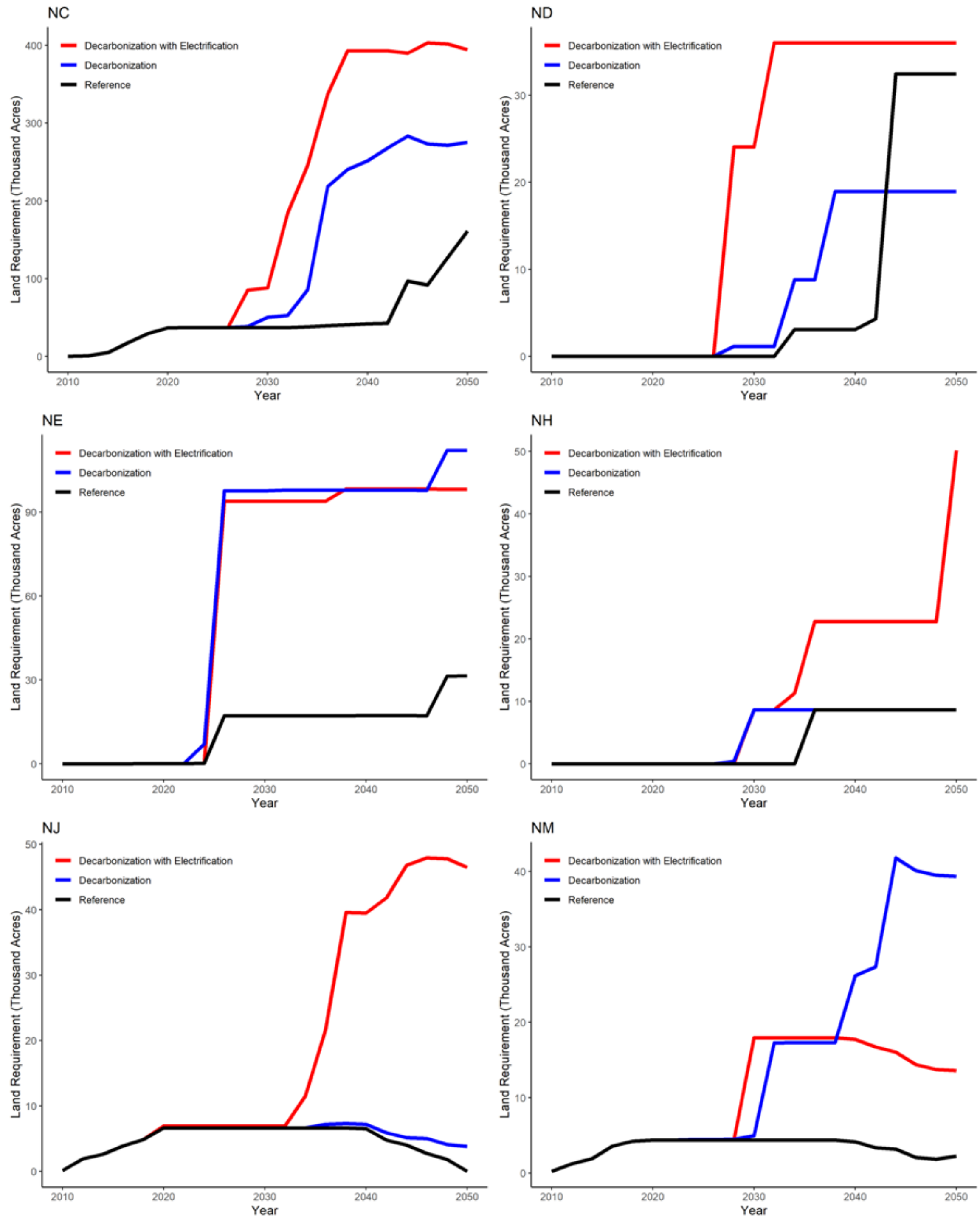


Figure A-1 (continued). Estimated cumulative solar land requirement by state for the three core scenarios projected by the ReEDS model by year from 2020 to 2050

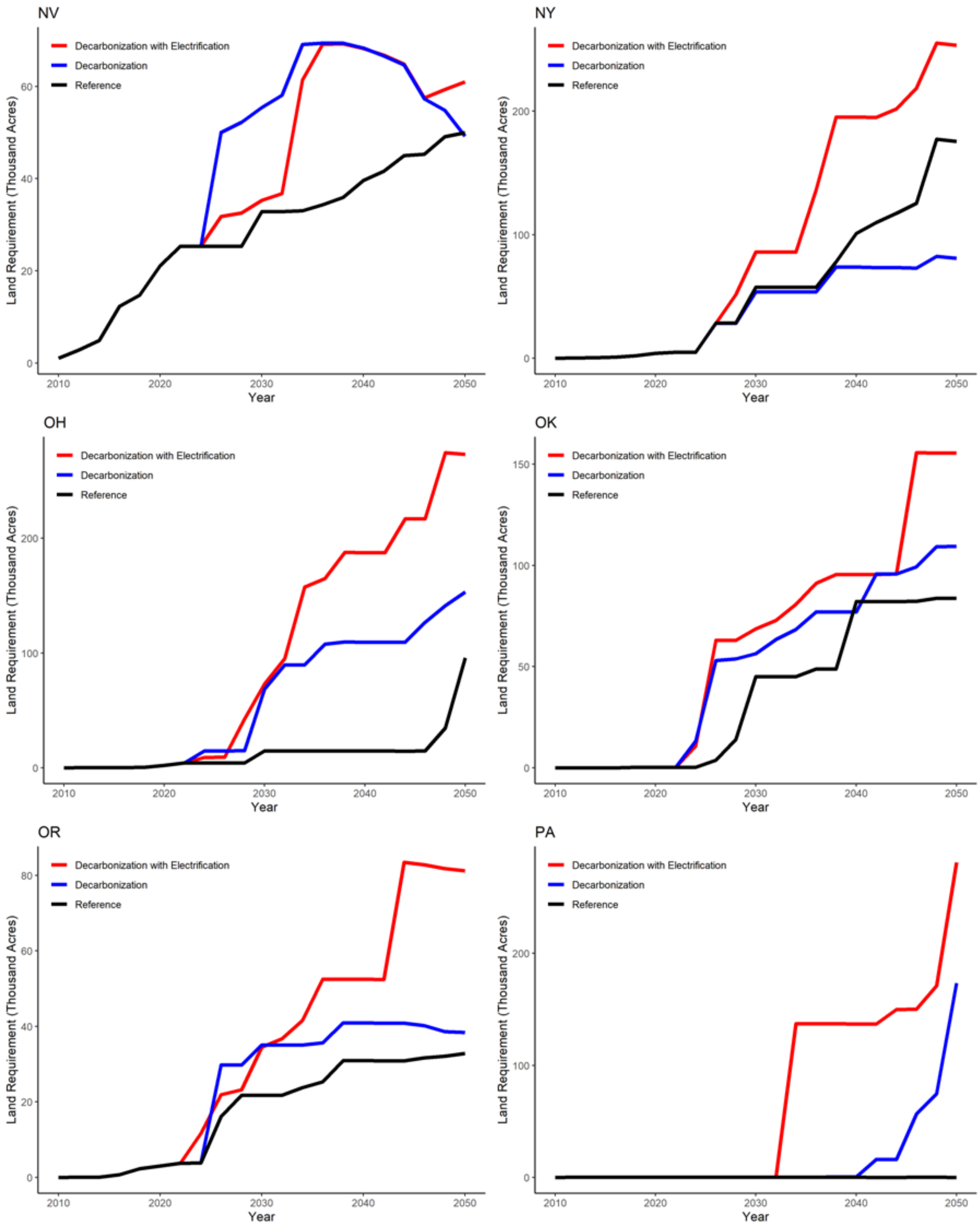


Figure A-1 (continued). Estimated cumulative solar land requirement by state for the three core scenarios projected by the ReEDS model by year from 2020 to 2050

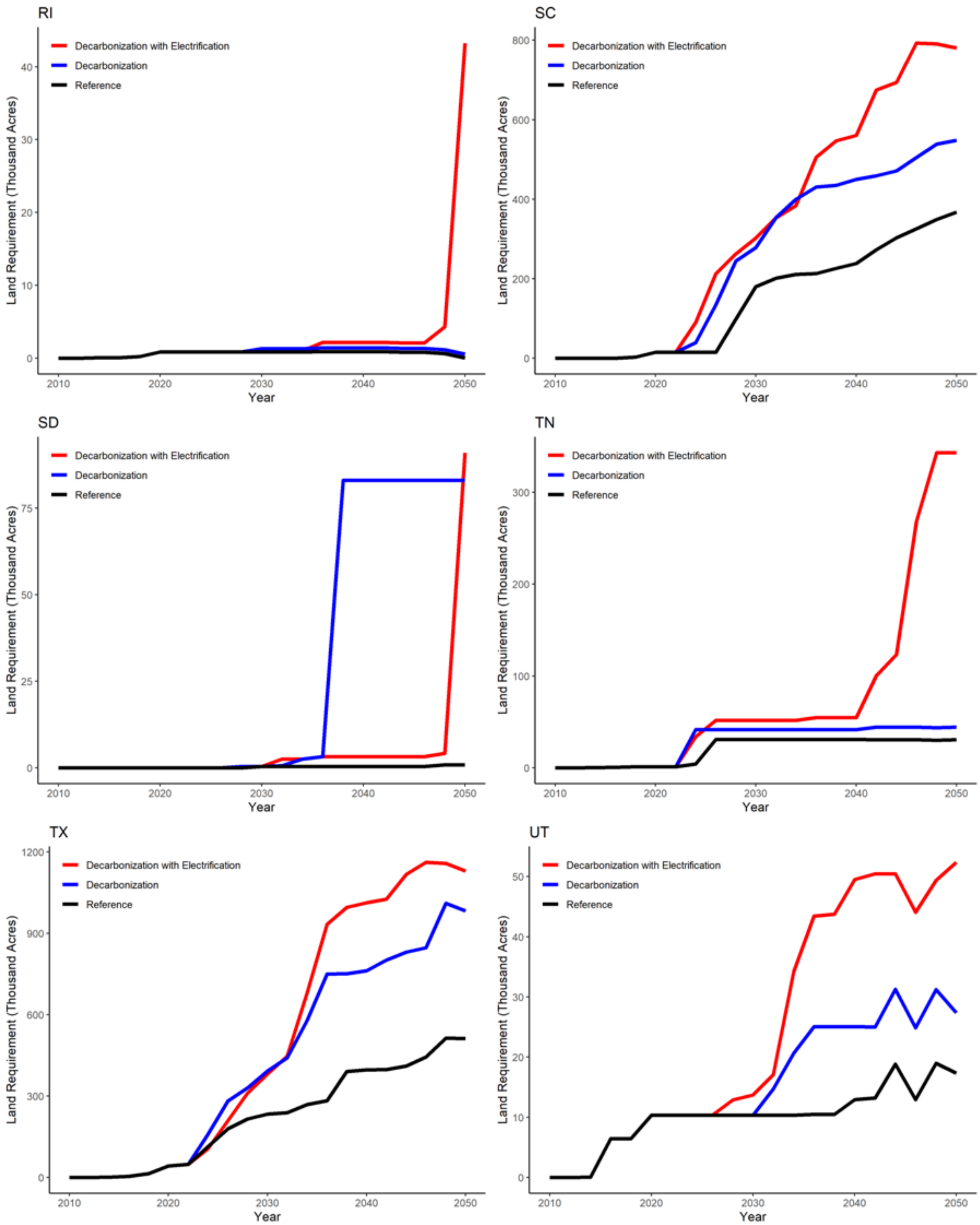


Figure A-1 (continued). Estimated cumulative solar land requirement by state for the three core scenarios projected by the ReEDS model by year from 2020 to 2050

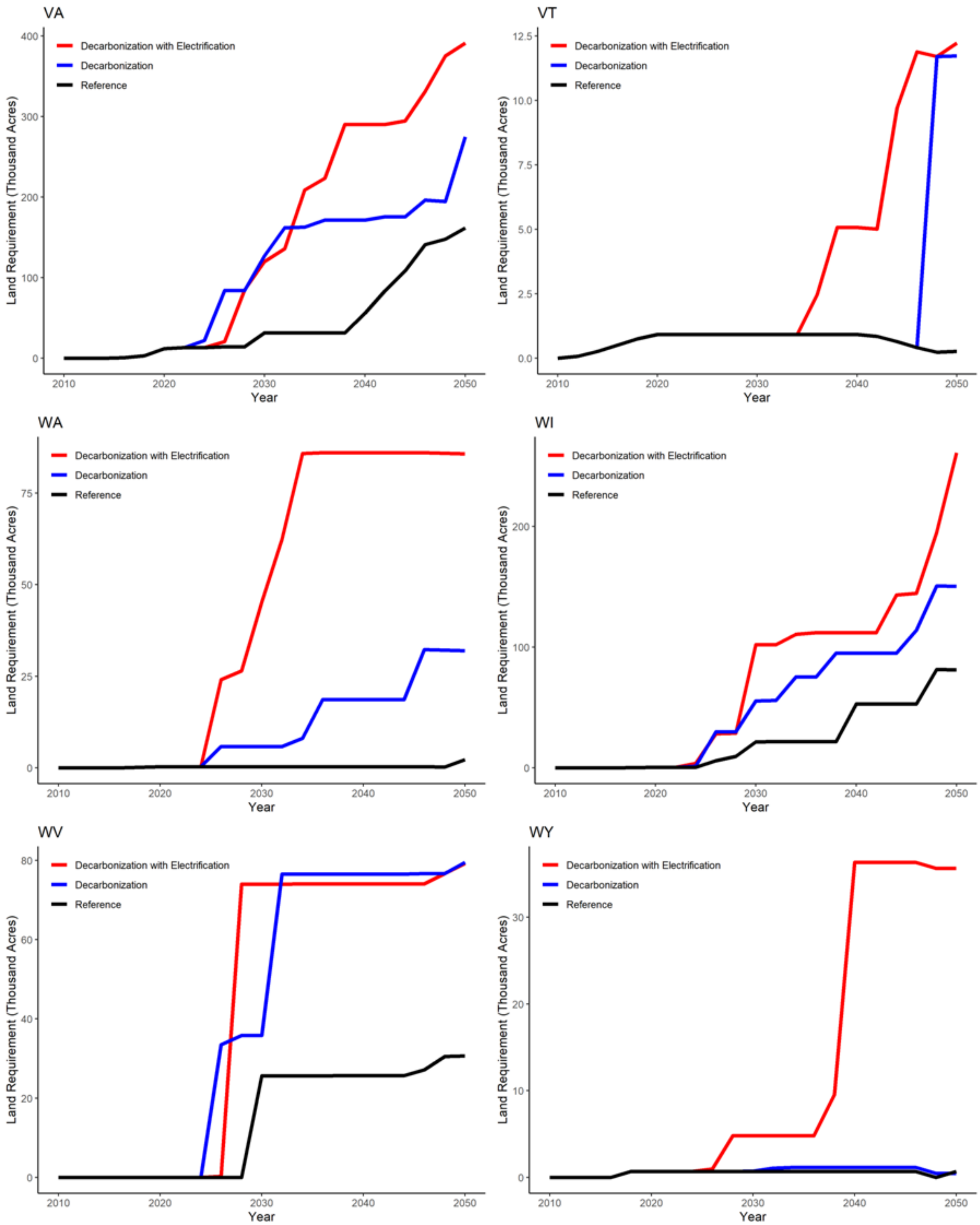


Figure A-1 (continued). Estimated cumulative solar land requirement by state for the three core scenarios projected by the ReEDS model by year from 2020 to 2050

Table A-2. Comparison of Disturbed Land Availability for Ground-Mounted PV with and without a Minimum Parcel Size Threshold

State Name	Original Calculation of Available Lands		Revised Lands Available (based on minimum parcel size)[1]		
	Total Disturbed Acres	Total Contaminated Acres	Total Disturbed Acres	Percentage Change in Disturbed Acres	Total Contaminated Acres[2]
Alabama	5,517,166	40,735	3,043,214	-45%	40,735
Arkansas	2,586,580	18,855	1,347,024	-48%	18,855
Arizona	5,399,774	2,737,590	1,654,272	-69%	2,737,590
California	5,472,492	617,554	3,842,784	-30%	617,554
Colorado	2,672,426	27,212	1,646,746	-38%	27,212
Connecticut	261,724	6,926	130,586	-50%	6,926
Delaware	218,526	6,732	144,272	-34%	6,732
Florida	4,695,180	219,018	3,385,182	-28%	219,018
Georgia	6,223,300	21,547	3,200,294	-49%	21,547
Iowa	3,329,102	4,997	2,126,860	-36%	4,997
Idaho	2,172,944	581,383	1,368,366	-37%	581,383
Illinois	3,832,176	35,060	2,349,168	-39%	35,060
Indiana	3,055,150	75,956	1,904,190	-38%	75,956
Kansas	4,700,026	102,574	3,034,064	-35%	102,574
Kentucky	1,754,846	24,863	761,866	-57%	24,863
Louisiana	3,575,836	24,959	2,365,354	-34%	24,959
Massachusetts	670,580	16,627	470,606	-30%	16,627
Maryland	866,418	22,166	537,526	-38%	22,166
Maine	701,490	4,642	248,450	-65%	4,642
Michigan	3,560,912	38,860	2,071,902	-42%	38,860
Minnesota	3,771,980	169,250	2,536,306	-33%	169,250
Missouri	3,069,262	86,632	1,578,872	-49%	86,632
Mississippi	6,131,038	11,213	3,860,580	-37%	11,213
Montana	2,884,932	233,608	1,614,150	-44%	233,608
North Carolina	5,278,630	14,158	3,196,862	-39%	14,158
North Dakota	3,439,552	2,110	2,104,170	-39%	2,110
Nebraska	3,110,992	78,739	1,767,336	-43%	78,739
New Hampshire	284,880	1,147	146,360	-49%	1,147
New Jersey	645,728	121,126	478,454	-26%	121,126
New Mexico	2,175,718	1,100,001	1,294,890	-40%	1,100,001

State Name	Original Calculation of Available Lands		Revised Lands Available (based on minimum parcel size)[1]		
	Total Disturbed Acres	Total Contaminated Acres	Total Disturbed Acres	Percentage Change in Disturbed Acres	Total Contaminated Acres[2]
Nevada	3,838,372	164,063	2,820,142	-27%	164,063
New York	2,044,416	103,653	1,080,802	-47%	103,653
Ohio	3,717,672	25,440	2,514,390	-32%	25,440
Oklahoma	5,693,936	17,516	3,898,650	-32%	17,516
Oregon	2,329,181	1,054,427	731,852	-69%	1,054,427
Pennsylvania	1,663,470	62,701	771,242	-54%	62,701
Rhode Island	89,998	1,647	58,756	-35%	1,647
South Carolina	3,526,486	222,607	1,976,990	-44%	222,607
South Dakota	3,731,440	1,388	2,641,802	-29%	1,388
Tennessee	2,749,216	82,775	1,592,840	-42%	82,775
Texas	32,517,678	246,054	24,141,566	-26%	246,054
Utah	2,896,994	37,867	2,048,988	-29%	37,867
Virginia	2,750,536	79,662	1,358,094	-51%	79,662
Vermont	154,896	1,987	60,656	-61%	1,987
Washington	1,726,818	344,202	982,950	-43%	344,202
Wisconsin	2,800,868	12,625	1,528,572	-45%	12,625
West Virginia	288,666	46,100	116,778	-60%	46,100
Wyoming	1,149,620	10,048	543,010	-53%	10,048

[1] Assumed minimum parcel size of 7.5 ac (~1 MW) for urban PV developments and 15 ac (~2 MW) for rural PV developments.[2] There is no change for contaminated lands because all contaminated lands in the EPA database of contaminated lands are at least these minimum sizes.

Appendix B. PViCE Material Demand and EOL Material Projections

PV historical technology data needed for the bottom-up dynamic mass flow are sparse and scattered, so it was necessary to blend and reconcile information from multiple sources. Our material and module baselines, used as inputs to PViCE, capture the average characteristics of the various deployed PV module technologies in any given year. Therefore, averages and/or market share weightings are used to reconcile differences in sourced data. Additionally, where U.S.-specific data were not available, world average data are used as a proxy. Given that our tool is concerned with the flow of material in and out of the field (i.e., actively producing energy in a solar farm or on a roof), and there can be a 6- to 18-month time lag between advances made on the manufacturing line and their deployment in the field, the deployment date data are used whenever available.

These varying data were collected, averaged, and normalized to create a best approximation of an average PV module deployed for each year from 1995 through 2050, per technology. Figure B-1 shows the market share of c-Si technology both in the United States and globally. The PViCE market share (black line) was used to weight the installation projections from ReEDS to account for c-Si (PViCE currently neglects other technologies). After 2019–2020, all data are based on projections. The complete descriptions of the baseline average PV technology module are detailed in the online documentation of PViCE on GitHub.[14]

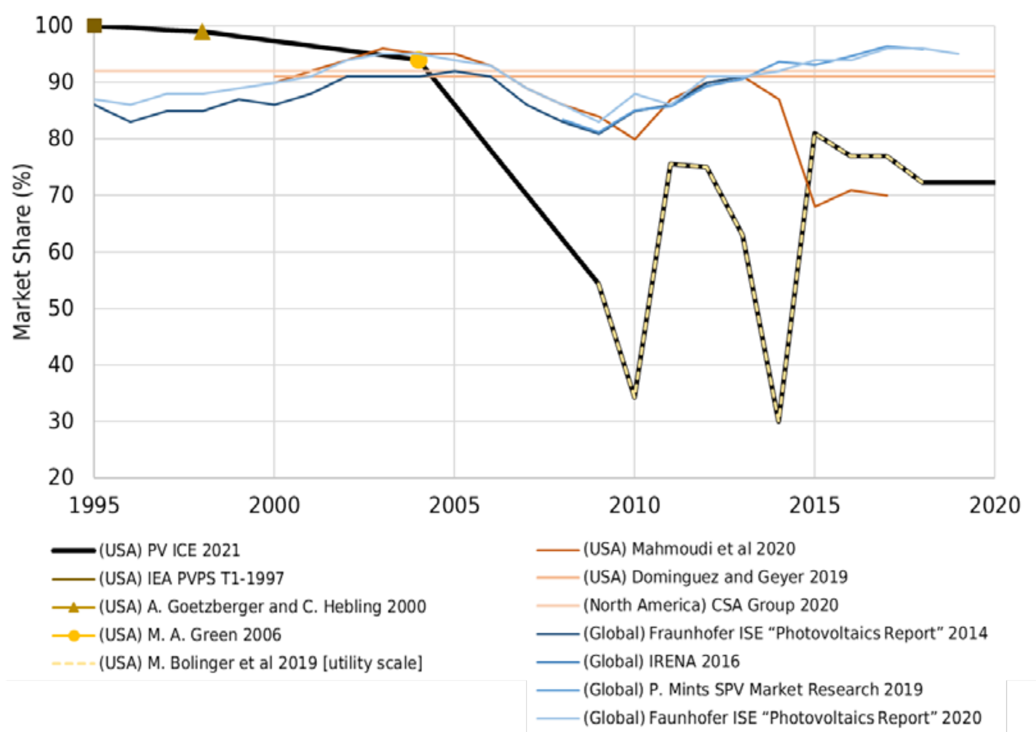


Figure B-1. Market share of c-Si technologies from various literature sources and PViCE averaged market share (black)

Yellow sources were used to create PViCE U.S. c-Si market share, orange sources were referenced for the United States, and blue sources are global c-Si market shares[288,290–299]

Throughout the mass flow analysis, some processes are defined in terms of the module's properties and some in terms of the material. This enables flexibility to work at different scales, because, throughout the mass flow, the materials are at times embedded into the PV modules.

Figure B-2 shows the (a) mass per module area of the materials considered, demonstrating an evolving material composition. Figure B-2 (b) shows the manufacturing efficiencies of the materials considered, which dictates the amount of manufacturing scrap created annually. These material manufacturing efficiencies were derived from historical data using a diverse set of sources or reasonable assumptions where data were lacking. Silicon manufacturing efficiencies are primarily associated with sawing/wafering losses, which have improved with time with the advent of diamond wire sawing and larger wafer sizes. Improvements from 2020 through 2030 were taken from ITRPV projections and then held constant through 2050. Glass manufacturing efficiency was derived from a variety of sources.[300–304] Forward projections for glass efficiency were not available; therefore, 2020 levels were maintained through 2050. Simple assumptions were used for aluminum, copper, and silver and were held constant through 2050. Table B-1 notes the material yields and circular settings in PViCE as used for this analysis. For a complete derivation of manufacturing efficiency baselines, refer to the open-source PViCE documentation on GitHub.[14]

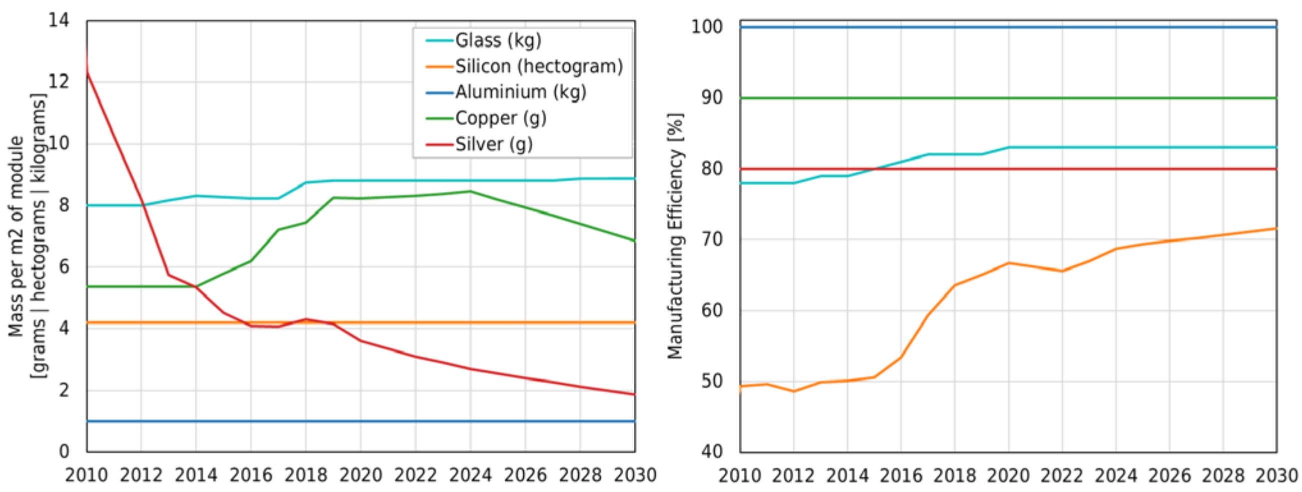


Figure B-2. All materials on a mass per meter squared of module basis over time (a) and the manufacturing efficiency of all materials over time (b)

Note the different units of grams (silver and copper), hectograms (silicon), and kilograms (glass and aluminum). All 2030 values are held constant through 2050. With all circular loops set to zero, the mass losses associated with these manufacturing efficiencies contribute to the EOL stream.

Table B-1. Baseline Material Circularity and Yield Settings for PViCE Calculations

Virgin material efficiency	100%
Manufacturing material efficiency	Material-dependent; see Figure B-2.
Manufacturing recycling	0%
Reuse, repair, refurbish	0%
EOL collection and CE pathways	0%

Material manufacturing efficiencies were recorded from historical data from a diverse set of sources, with some reasonable assumptions where data were lacking. Silicon manufacturing efficiencies are primarily associated with sawing/wafering losses, which have improved with time with the advent of diamond wire sawing and larger wafer sizes. Improvements from 2020 through 2030 were taken from ITRPV projections, then held constant through 2050. Glass manufacturing efficiency was derived from a variety of sources.[300–304] Forward projections for glass efficiency were not available; therefore, 2020 levels were maintained through 2050. Simple assumptions were used for aluminum, copper, and silver and were held constant through 2050. For a complete derivation of manufacturing efficiency baselines, refer to the open-source PViCE documentation on GitHub.[14]

PViCE was validated against published installations and waste projections. This was accomplished by using the parameters and inputs of those projections when available. Table B-2 compares prior material demand estimates to our new projections using PViCE baselines and methods. The recent CSA Group estimate is close in installed capacity by 2030 to the Decarb scenario. Excluding the copper, which PViCE currently only considers within the module, all estimates are at a comparable order of magnitude, indicating that differences are most likely derived from varying predictions of future technology improvements and the underlying bottom-up baseline mass approach in PViCE. Furthermore, the CSA case includes all types of PV module technologies, whereas the PViCE tool only include monocrystalline and multicrystalline silicon (because CdTe waste is already addressed successfully by First Solar, and other technologies will have a negligible market share). Please note that different from the results provided in the report, Appendix Tables B-2 and B-4 also consider polymers, including backsheet and encapsulants, which have recently been added to PViCE, documented in Ovaitt et al. (2022).[305]

Table B-2. Comparison of 2030 Installed PV Mass, with Material Breakdown, Between CSA Group's Recent 2030 Material Demands Projection and PViCE + ReEDS Projections

Material	Metric Tons Installed in Field in 2030			
	CSA Group (437 GW)[306]	PViCE Results by Scenario		
		Reference (314 GW)	Decarb (488 GW)	Decarb+E (586 GW)
Module	27,200,000	17,500,000	26,700,000	31,700,000
Glass	20,600,000	13,400,000	20,500,000	24,400,000
Polymers	2,800,000	1,752,900	2,650,000	3,091,200
Aluminum	2,100,000	1,850,000	2,760,000	3,210,000
Copperxv	239,000	11,200	17,500	21,000
Silicon	1,270,000	535,000	799,000	935,000
Silver	11,000	5,000	7,000	8,000
Other	170,000	—	—	—

[xv] Other material compositions include copper external to the module, including junction boxes and cabling, while currently the baseline used in PViCE only includes the busbar and cell stringing internal to the module.

Table B-3 shows a similar comparison for U.S. installed capacity. Installed capacity considers all new installations in previous years minus the retired modules due to failures or EOL. In the table, IEA/IRENA's Regular Loss and Early Loss lifetime assumptions are compared with PViCE lifetime assumptions. EOL is determined by three modes in PViCE: project lifetime, degradation beyond 80% nameplate, and Weibull-based failures. The Weibull functions used in PViCE are calculated based on the expected number of functioning modules at the end of the project lifetime. In contrast, the IEA/IRENA approach used by the CSA Group[307,306] uses the same Weibull function for both failure and wear-out, and it classifies 64% of the cohort as waste by the 30th year in the field. Because of this, by 2050, PViCE lifetime assumptions predict a 30% higher capacity compared with Early Loss assumptions [307] and a 10% higher capacity compared with Regular Loss assumptions.

Table B–3. Comparison of U.S. Installed Capacity (GW) up to 2030 and 2050

	2030			2050		
	Lifetime Assumptions					
Installation Scenario	Early Loss	Regular Loss	PViCE	Early Loss	Regular Loss	PViCE
IEA/IRENA[307]	—	240	—	—	512	—
CSA[306]	—	437	—	—	NA	—
Solar Futures Study Reference	277	312	314	376	520	642
Solar Futures Study Decarb	448	487	489	416	714	952
Solar Futures Study Decarb+E	547	585	587	769	1,230	1,530

NA = not applicable; "--" = no data available

Table B-4 compares cumulative EOL material for the U.S. developed in three projections—by IEA/IRENA, the CSA Group and in the *Solar Futures Study* using PViCE. Manufacturing waste is excluded from the IEA/IRENA[307] and CSA[306] sources, because this mass would enter the waste stream in areas other than North America. While PViCE does calculate manufacturing waste for each year, that waste is not included in the table to enable direct comparison with the published literature.

Table B-4. Comparison of Cumulative U.S. EOL Materials for Various Years Based on Different Lifetime Assumptions

		Cumulative EOL Material (metric tons)				
Year	Lifetime Assumptions	IEA/IRENA [307]	CSA[306]	*Solar Futures Study* Scenarios		
				Reference	Decarb	Decarb+E
2016	Early Loss	24,000	—	6950	6950	6950
	Regular Loss	6,500	—	35	35	35
	PViCE	NA	—	10	10	10
2020	Early Loss	85,000	—	52,800	52,800	52,800
	Regular Loss	13,000	—	1000	1000	1000
	PViCE	NA	—	400	400	400
2030	Early Loss	1,000,000	1,200,000	821,000	920,000	922,000
	Regular Loss	170,000	214,900	112,000	113,000	113,000
	PViCE	NA	NA	71,100	71,100	71,100
2040	Early Loss	4,000,000	—-	3,900,000	5,510,000	6,110,000
	Regular Loss	1,700,000	—-	1,590,000	1,800,000	1,830,000
	PViCE	NA	NA	2,090,000	2,090,000	2,090,000
2050	Early Loss	10,000,000	—	10,200,000	16,400,000	20,300,000
	Regular Loss	7,500,000	—	7,450,000	10,500,000	11,600,000
	PViCE	NA	—	6,740,000	7,240,000	7,240,000

NA = not applicable, "--" = no data available

Installed capacity by 2050 in the *Solar Futures Study* Reference scenario is 25% more the installed capacity projected in IEA/IRENA,[307] and waste projections in 2050 are comparable between IRENA[307] with the Regular Loss and Early Loss assumption (7.5 million metric tons). Past projections of waste (2016 and 2020) differ in magnitude because *Solar Future Study scenarios installation data start in 2010*. IRENA's data for 2016 may or may not include installations back to 1985 and potentially uses a ton per watt calculation in excess of 100 metric tons per kW. Recall that PViCE does not use a mass-power factor but also a dynamic baseline. Furthermore, PViCE analysis only considers market share of c-Si. Unfortunately, there is no empirical data at a national scale to evaluate whether the waste generated in 2016 and 2020 match any of the literature projections. The Decarb and Decarb+E scenarios have more deployment (1 TW and 1.5 TW) in 2050 than PViCE installed capacity projections, which consider degradation as well as PV modules retired due to failures or EOL. While early-loss and regular-loss lifetime assumptions predict large quantities of EOL material prior to 2050, PViCE predicts that the majority of EOL materials will leave the field after 2050 owing to use of more recent, and better, module performance data incorporated into the model than what was assumed in the other two projections.

Additional Tables

Table B-5. U.S. Annual Demand by Material for Select Years (metric tons)

Material	Year	Reference	Decarb	Decarb+E
Glass	2030	1,810,000	2,320,000	3,300,000
	2040	799,000	322,000	528,000
	2050	1,110,000	1,250,000	2,640,000
Aluminum	2030	206000	264000	376,000
	2040	91100	36700	60100
	2050	127,000	142,000	300,000
Copper	2030	1,480	1,910	2,710
	2040	657	265	434
	2050	915	1,030	2,170
Silicon	2030	85,700	110,000	157,000
	2040	37,900	15,300	25,000
	2050	5,2800	59,300	125,000
Silver	2030	453	582	828
	2040	200	80	132
	2050	279	313	661

Table B-6. U.S. Cumulative Demand by Material for Select Years (metric tons)

Material	Year	Reference	Decarb	Decarb+E
Glass	2030	14,100,000	21,500,000	25,500,000
	2040	20,200,000	36,800,000	50,300,000
	2050	31,800,000	46,900,000	70,600,000
Aluminum	2030	1,920,000	2850,000	3,320,000
	2040	2,620,000	4,590,000	6,150,000
	2050	3,940,000	5,740,000	8,460,000
Copper	2030	12,700	19,900	23,400
	2040	17,800	32,500	43,800
	2050	27,300	40,800	60,500
Silicon	2030	847,000	1,240,000	1,430,000
	2040	1,140,000	1,960,000	2,610,000
	2050	1,690,000	2,440,000	3,570,000
Silver	2030	5,970	8,450	9,570
	2040	7,520	12,300	15,800
	2050	10,400	14,800	20,900

Table B-7. Yearly Material Requirements (metric tons) for Scenario 1: Reference

Yearly Material Requirements **(metric tons)** for **Scenario 1: Reference**															
	Glass			Silicon			Silver			Copper			Aluminum		
State	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Ohio	36400	12800	178000	1730	609	8450	9	3	44	30	10	146	4150	1460	20300
Mississippi	2200	1260	125000	104	59	5920	0	0	31	1	1	103	250	143	14200
North Carolina	14700	9310	121000	696	442	5720	3	2	30	12	7	99	1670	1060	13700
Florida	294000	76400	95200	13900	3620	4520	73	19	23	241	62	78	33500	8700	10900
South Carolina	251000	37600	88400	11900	1780	4200	63	9	22	206	30	72	28600	4280	10100
Texas	103000	32900	84100	4870	1560	3990	25	8	21	84	27	69	11700	3750	9580
Virginia	61000	76500	71300	2890	3630	3380	15	19	17	50	62	58	6950	8720	8130
Massachusetts	1980	1170	64600	94	55	3060	0	0	16	1	0	53	226	133	7350
California	112000	56700	64100	5320	2690	3040	28	14	16	92	46	52	12800	6460	7300
Delaware	1770	254	49900	83	12	2370	0	0	12	1	0	41	201	29	5680
Michigan	217000	5200	22800	10300	247	1080	54	1	5	179	4	18	24800	593	2600
Nevada	25200	14300	20800	1200	680	987	6	3	5	20	11	17	2870	1630	2370
Colorado	4540	4200	17800	215	199	843	1	1	4	3	3	14	517	478	2020
Connecticut	7280	1560	14200	345	74	674	1	0	3	5	1	11	830	178	1620
Arizona	60000	1860	11600	2850	88	551	15	0	2	49	1	9	6840	212	1320
Washington	3240	1220	7710	154	57	366	0	0	1	2	1	6	369	139	879
Utah	1400	8160	7530	66	387	357	0	2	1	1	6	6	159	929	858
Georgia	88500	9760	6950	4200	463	330	22	2	1	72	8	5	10100	1110	792
Tennessee	1950	2500	6510	92	119	309	0	0	1	1	2	5	222	285	741
Indiana	11800	4900	6340	558	233	301	2	1	1	9	4	5	1340	559	722
Oregon	2710	1270	4890	129	60	232	0	0	1	2	1	4	309	144	557
Missouri	1730	21700	4740	82	1030	225	0	5	1	1	17	3	197	2470	540
Alabama	2760	965	4670	131	45	221	0	0	1	2	0	3	315	110	532
Other States	499000	417000	34800	23700	19800	1650	125	105	8	410	343	28	56900	47500	3970
U.S. Total	**1810000**	**799000**	**1110000**	**85700**	**37900**	**52800**	**453**	**200**	**279**	**1480**	**657**	**915**	**206000**	**91100**	**127000**

Table B-8. Yearly Material Requirements (metric tons) for Scenario 2: Decarb

Yearly Material Requirements (metric tons) for Scenario 2: Decarb															
	Glass			Silicon			Silver			Copper			Aluminum		
State	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Pennsylvania	26600	4480	278000	1260	212	13200	6	1	69	21	3	229	3030	510	31700
Virginia	144000	8340	255000	6830	396	12100	36	2	63	118	6	209	16400	951	29000
Florida	332000	13600	131000	15700	643	6200	83	3	32	273	11	107	37800	1540	14900
California	101000	27600	80900	4810	1310	3840	25	6	20	83	22	66	11600	3140	9220
Maryland	98700	1370	78900	4680	65	3740	24	0	19	81	1	64	11200	156	8990
Georgia	19100	36100	75800	906	1710	3600	4	9	19	15	29	62	2180	4110	8640
South Carolina	109000	47700	65300	5180	2260	3100	27	12	16	89	39	53	12400	5440	7440
Missouri	10200	4990	48300	482	237	2290	2	1	12	8	4	39	1160	569	5510
Ohio	166000	7010	45300	7870	333	2150	41	1	11	136	5	37	18900	799	5160
North Carolina	56500	46000	41200	2680	2180	1960	14	11	10	46	37	33	6440	5230	4700
Texas	245000	21000	27600	11600	994	1310	61	5	6	201	17	22	27900	2390	3140
Colorado	32900	1550	11100	1560	73	527	8	0	2	27	1	9	3750	177	1260
West Virginia	981	810	9750	46	38	462	0	0	2	0	0	8	112	92	1110
Tennessee	3420	3390	7930	162	161	376	0	0	1	2	2	6	390	386	904
Kentucky	271000	32400	7830	12900	1540	372	68	8	1	223	26	6	30900	3700	892
Michigan	34600	8920	7650	1640	423	363	8	2	1	28	7	6	3950	1020	872
Mississippi	118000	2450	7100	5600	116	337	29	0	1	97	2	5	13500	279	809
New Jersey	11600	1890	6150	551	89	292	2	0	1	9	1	5	1320	215	700
Indiana	7460	7840	6060	354	372	287	1	1	1	6	6	4	850	894	690
Alabama	4660	1650	5300	221	78	251	1	0	1	3	1	4	531	188	603
Oklahoma	11400	7840	4890	541	372	232	2	1	1	9	6	4	1300	893	557
New York	89700	776	3830	4260	36	182	22	0	0	73	0	3	10200	88	436
Kansas	1990	1730	3780	94	82	179	0	0	0	1	1	3	226	197	431
Other States	423000	32900	40800	20100	1560	1930	106	8	10	348	27	33	48200	3750	4650
U.S. Total	**2320000**	**322000**	**1250000**	**110000**	**15300**	**59300**	**582**	**80**	**313**	**1910**	**265**	**1030**	**264000**	**36700**	**142000**

Table B-9. Yearly Material Requirements (metric tons) for Scenario 3: Decarb+E

Yearly Material Requirements (metric tons) for Scenario 3: Decarb+E															
	Glass			Silicon			Silver			Copper			Aluminum		
State	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Idaho	2460	665	476000	116	31	22600	0	0	119	2	0	391	280	75	54200
Pennsylvania	26600	4480	310000	1260	212	14700	6	1	77	21	3	255	3030	510	35300
Iowa	47800	2270	287000	2270	107	13600	12	0	72	39	1	236	5440	258	32700
Illinois	47300	2330	262000	2240	110	12400	11	0	65	38	1	215	5380	265	29900
South Dakota	430	385	241000	20	18	11500	0	0	60	0	0	198	49	43	27500
Wisconsin	224000	3240	186000	10600	154	8830	56	0	46	184	2	153	25500	369	21200
Maryland	152000	1370	131000	7210	65	6220	38	0	32	125	1	108	17300	156	14900
Rhode Island	2160	374	112000	103	17	5310	0	0	28	1	0	92	246	42	12700
New Hampshire	26400	437	76400	1250	20	3620	6	0	19	21	0	62	3010	49	8700
Virginia	121000	8340	75900	5730	396	3600	30	2	19	99	6	62	13800	951	8640
Connecticut	54700	936	74200	2600	44	3520	13	0	18	45	0	61	6230	107	8460
California	212000	27600	54400	10100	1310	2580	53	6	13	175	22	44	24200	3140	6200
Florida	565000	12900	41800	26800	614	1980	142	3	10	465	10	34	64400	1470	4760
Montana	833	806	40200	39	38	1910	0	0	10	0	0	33	94	91	4570
Massachusetts	86000	1590	32600	4080	75	1550	21	0	8	70	1	26	9800	181	3720
Texas	271000	49900	27600	12900	2370	1310	68	12	6	223	41	22	30900	5680	3140
Nevada	11700	1120	23200	555	53	1100	2	0	5	9	0	19	1330	128	2640
Maine	1650	578	20900	78	27	990	0	0	5	1	0	17	188	65	2380
Utah	5150	17800	20400	245	847	967	1	4	5	4	14	16	587	2030	2320
Kentucky	314000	114000	11700	14900	5400	556	78	28	2	258	93	9	35700	13000	1340
North Carolina	29200	13800	11000	1390	656	524	7	3	2	24	11	9	3330	1570	1260
South Carolina	127000	44800	10600	6000	2130	502	31	11	2	104	36	8	14400	5100	1200
West Virginia	969	810	9000	46	38	427	0	0	2	0	0	7	110	92	1030
Other States	973000	217000	99300	46200	10300	4710	244	54	24	800	179	81	111000	24700	11300
U.S. Total	**3300000**	**528000**	**2640000**	**157000**	**25000**	**125000**	**828**	**132**	**661**	**2710**	**434**	**2170**	**376000**	**60100**	**300000**

Table B-10. Cumulative Material Requirements (metric tons) for Scenario 1: Reference

Cumulative Material Requirements (metric tons) for Scenario 1: Reference															
	Glass			Silicon			Silver			Copper			Aluminum		
State	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
California	2050000	3290000	4360000	152000	211000	261000	1200	1510	1780	1780	2800	3680	321000	462000	584000
Texas	1670000	2910000	3920000	95200	154000	202000	657	967	1220	1620	2640	3470	222000	363000	479000
Florida	843000	1590000	3230000	47500	82700	161000	320	506	919	780	1390	2740	110000	195000	382000
South Carolina	902000	1480000	2350000	47100	74700	116000	296	442	661	822	1300	2020	112000	178000	277000
Kentucky	130000	436000	1490000	6530	21100	71300	38	116	381	116	368	1240	15600	50600	171000
North Carolina	343000	497000	1450000	27000	34300	79400	205	243	482	299	426	1210	55000	72600	181000
New York	399000	761000	1290000	23800	40900	66100	165	256	389	367	664	1100	54000	95200	156000
Virginia	196000	400000	1210000	11800	21400	59900	83	135	338	185	352	1020	26800	50000	142000
Maryland	493000	508000	874000	33300	34000	51400	269	272	364	486	498	798	74000	75700	117000
Arizona	496000	631000	860000	33000	39400	50300	263	297	355	440	551	740	73800	89100	115000
Michigan	357000	674000	760000	18200	33200	37300	110	189	211	323	583	654	43500	79600	89400
Ohio	88800	218000	734000	5200	11300	35800	38	70	200	80	187	611	12100	26800	85500
Georgia	233000	365000	699000	15100	21300	37100	103	135	219	206	314	589	32600	47500	85600
Illinois	421000	625000	636000	22200	31900	32400	144	195	198	403	571	580	53200	76500	77700
Oklahoma	194000	434000	577000	9690	21000	27800	57	117	153	174	371	488	23300	50500	66800
Missouri	243000	305000	573000	12600	15600	28300	78	94	161	223	273	493	30000	37100	67600
Wisconsin	108000	275000	545000	5600	13500	26300	34	76	145	99	237	459	13400	32400	63200
Nevada	224000	293000	484000	17100	20300	29400	138	155	203	196	252	409	36000	43800	65600
Massachusetts	170000	192000	465000	14600	15600	28600	117	123	191	141	159	384	29100	31600	62800
Mississippi	130000	154000	444000	6810	7940	21700	42	48	121	120	139	378	16100	18800	51900
Indiana	296000	353000	416000	17000	19700	22600	117	132	148	297	344	395	40000	46500	53600
Iowa	123000	259000	401000	6400	12900	19600	40	74	110	114	226	343	15300	30800	46900
Colorado	150000	206000	348000	10100	12700	19500	79	93	129	133	179	296	22200	28600	44800
Other States	1980000	2590000	3680000	124000	153000	205000	918	1070	1340	1850	2340	3240	281000	350000	474000
U.S. Total	**12200000**	**19400000**	**31800000**	**762000**	**1100000**	**1690000**	**5520**	**7320**	**10400**	**11300**	**17200**	**27300**	**1710000**	**2530000**	**3940000**

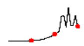
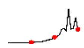
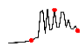
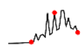
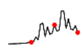
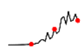
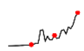
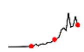
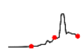
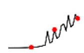
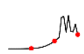
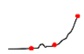
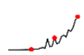
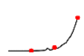
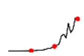
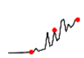
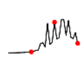
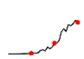
Table B-11. Cumulative Material Requirements (metric tons) for Scenario 2: Decarb

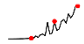
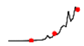
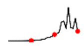
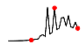
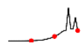
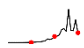
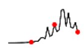
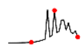
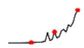
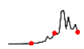
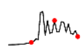
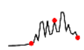
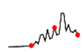
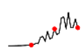
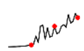
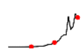
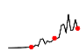
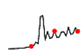
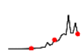
Cumulative Material Requirements (metric tons) for Scenario 2: Decarb															
	Glass			Silicon			Silver			Copper			Aluminum		
State	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Texas	2560000	5180000	6450000	142000	266000	326000	956	1610	1930	2480	4630	5670	334000	633000	777000
Florida	1830000	4580000	5530000	99100	229000	274000	650	1340	1580	1730	3980	4760	234000	547000	655000
California	2070000	3200000	3730000	153000	207000	231000	1210	1490	1620	1800	2730	3160	323000	452000	512000
South Carolina	1660000	2780000	3510000	87600	141000	175000	564	843	1030	1580	2500	3100	209000	337000	419000
Kentucky	623000	1670000	2280000	31300	81000	110000	187	450	603	564	1420	1930	75200	194000	264000
North Carolina	410000	1710000	2230000	30300	92200	117000	224	551	680	358	1430	1850	62900	211000	270000
Virginia	717000	1230000	1970000	38900	63200	98500	256	385	571	687	1110	1720	92100	150000	235000
Michigan	450000	870000	1330000	23300	43300	65100	146	252	367	421	767	1150	55900	104000	156000
Pennsylvania	137000	199000	1230000	8080	11000	59900	60	76	335	126	177	1020	18900	25900	143000
Maryland	586000	884000	1190000	37600	51800	66500	291	366	443	564	810	1060	84500	119000	154000
Arizona	703000	1100000	1160000	44400	63100	66100	340	439	455	645	968	1020	101000	146000	153000
Ohio	286000	804000	1150000	15200	39800	56300	98	229	316	261	687	972	36100	95100	135000
Illinois	850000	992000	1020000	45400	52100	53400	299	335	341	835	952	973	109000	125000	128000
Wisconsin	276000	638000	981000	14300	31500	47700	90	181	267	260	558	840	34300	75600	115000
Georgia	321000	525000	961000	19900	29600	50300	138	189	298	302	469	828	44400	67600	117000
Mississippi	431000	860000	907000	22000	42400	44600	135	243	255	399	751	790	52800	102000	107000
New York	396000	697000	777000	23600	37900	41700	164	240	260	365	613	678	53800	88000	97100
Massachusetts	226000	581000	749000	17300	34100	42100	133	222	264	190	481	620	35800	76200	95400
Indiana	546000	642000	729000	30800	35400	39500	213	237	259	552	631	703	73300	84200	94100
Nebraska	605000	616000	710000	31900	32400	36900	207	210	234	594	603	680	76900	78200	88800
Oklahoma	358000	534000	676000	19000	27300	34100	124	168	204	352	496	613	45700	65700	81900
Louisiana	194000	630000	666000	10200	30900	32600	65	175	184	184	542	572	24400	74100	78200
Missouri	191000	508000	666000	10400	25500	33000	68	148	188	185	445	575	24700	60800	78800
Other States	2720000	5020000	6270000	170000	279000	339000	1250	1830	2140	2550	4440	5470	385000	647000	789000
U.S. Total	**19100000**	**36400000**	**46900000**	**1130000**	**1950000**	**2440000**	**7870**	**12200**	**14800**	**18000**	**32200**	**40800**	**2590000**	**4560000**	**5740000**

Table B-12. Cumulative Material Requirements (metric tons) for Scenario 3: Decarb+E

Cumulative Material Requirements (metric tons) for Scenario 3: Decarb+E															
	Glass			Silicon			Silver			Copper			Aluminum		
State	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Texas	2450000	6620000	7620000	134000	332000	380000	891	1940	2190	2330	5760	6590	316000	792000	906000
Florida	2410000	6080000	7410000	129000	303000	366000	838	1760	2090	2280	5300	6390	306000	724000	876000
California	2520000	4140000	5030000	176000	253000	295000	1360	1760	1980	2230	3550	4290	379000	563000	665000
South Carolina	1810000	3440000	4860000	97000	175000	242000	639	1050	1400	1760	3100	4260	232000	418000	579000
Kentucky	763000	2690000	3640000	38300	130000	175000	230	713	952	696	2280	3060	92300	312000	420000
North Carolina	666000	2590000	2950000	43100	134000	151000	301	784	874	594	2170	2470	93800	313000	354000
Virginia	690000	1910000	2640000	36400	94200	129000	232	537	721	636	1640	2240	86200	225000	309000
Arizona	795000	1440000	2100000	49100	79700	111000	370	531	698	736	1270	1810	112000	186000	261000
Maryland	677000	890000	2090000	42400	52500	110000	321	375	676	646	821	1810	95800	120000	257000
Tennessee	340000	391000	2070000	18900	21400	101000	130	143	563	339	381	1760	45100	50900	242000
Illinois	1030000	1470000	2020000	54400	75500	102000	356	467	605	1010	1370	1820	131000	182000	244000
Pennsylvania	137000	1000000	1870000	8080	49000	90200	60	277	495	126	835	1550	18900	117000	216000
Ohio	382000	1260000	1840000	19900	61600	89200	127	347	493	349	1070	1550	47500	147000	214000
New York	564000	1410000	1770000	32000	72000	89300	214	426	517	517	1210	1510	73800	170000	211000
Michigan	772000	1160000	1720000	39800	58400	84800	249	347	486	724	1050	1500	95500	140000	203000
Wisconsin	413000	746000	1610000	20900	36800	77700	127	211	427	377	651	1360	50300	88300	187000
Mississippi	316000	1230000	1380000	16200	59400	66800	99	328	367	290	1040	1170	38700	143000	160000
Georgia	365000	873000	1300000	21600	45700	65900	140	267	374	322	739	1090	48200	106000	155000
Alabama	33500	618000	1210000	2180	29900	58200	15	162	311	31	512	1000	4780	71400	139000
Idaho	32800	233000	1200000	2290	11800	57500	16	66	308	30	195	987	4860	27600	137000
Indiana	298000	396000	1160000	17000	21700	57700	118	143	333	298	379	1000	40200	51400	138000
Oklahoma	423000	644000	1050000	22300	32800	51800	145	200	301	415	596	926	53800	78900	125000
Louisiana	373000	790000	968000	18900	38700	47100	114	218	263	338	681	827	45200	92700	113000
Other States	3930000	7770000	11000000	235000	417000	572000	1660	2620	3440	3630	6780	9470	536000	973000	1350000
U.S. Total	**22200000**	**49800000**	**70600000**	**1280000**	**2580000**	**3570000**	**8750**	**15700**	**20900**	**20700**	**43400**	**60500**	**2950000**	**6090000**	**8460000**

Table B-13. Yearly EOL Materials by Material, by State (metric tons) for Scenario 1: Reference

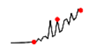
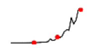
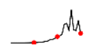
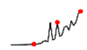
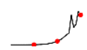
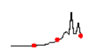
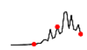
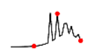
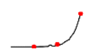
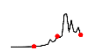
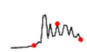
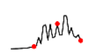
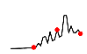
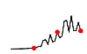
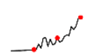
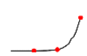
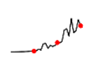
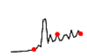
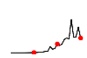
Yearly EOL Materials by Material, by State (metric tons) for Scenario 1: Reference																
	Glass				Silicon			Silver			Copper			Aluminum		
State	2030	2040	2050		2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Alabama	16	515	1120		0.81	25.8	50.9	0.00836	0.266	0.489	0.0125	0.413	0.991	2.78	88.2	174
Arkansas	6.57	257	637		0.331	12.8	29	0.00341	0.133	0.28	0.00541	0.214	0.571	1.12	43.6	98.7
Arizona	1730	23200	8430		89.9	1180	374	1.86	16.6	3.52	1.17	15.6	7.29	405	4600	1280
California	6350	158000	55800		328	8010	2630	6.73	104	26.4	4.33	107	48	1410	30300	8980
Colorado	465	5060	3060		24.1	257	142	0.51	3.59	1.4	0.316	3.55	2.65	108	992	484
Connecticut	107	3320	5130		5.45	165	233	0.0891	1.98	2.31	0.0772	2.49	4.71	22.1	602	791
Delaware	68.8	615	1960		3.58	30.9	75.5	0.0763	0.454	0.595	0.0465	0.433	1.76	16.3	122	259
Florida	284	6020	17800		14.5	295	797	0.279	3.36	7.67	0.21	5.02	16.3	60.1	1030	2700
Georgia	177	5250	6030		9.03	264	283	0.116	2.99	2.84	0.128	3.87	5.32	33.7	947	964
Iowa	9.04	516	833		0.459	25.9	34.3	0.00546	0.312	0.299	0.0065	0.362	0.762	1.67	95.5	119
Idaho	23.1	712	1300		1.17	35.6	61.5	0.012	0.366	0.611	0.018	0.576	1.15	4.01	121	208
Illinois	56.6	673	5630		2.93	32.2	221	0.0614	0.423	1.82	0.0391	0.542	5.13	13.3	121	760
Indiana	57	2770	7740		2.92	138	308	0.0437	1.69	2.6	0.0396	1.94	7.22	11.5	513	1070
Kansas	8.41	712	7120		0.426	33.7	275	0.00528	0.388	2.22	0.00585	0.53	6.64	1.58	124	959
Kentucky	2.84	109	770		0.143	5.32	30.6	0.00149	0.0542	0.253	0.00225	0.0893	0.691	0.491	18.2	105
Louisiana	18.3	703	1030		0.94	35.2	43.1	0.0164	0.432	0.383	0.0129	0.494	0.932	3.76	130	147
Massachusetts	649	19900	6130		33.4	1010	302	0.576	12.8	3.11	0.446	13.5	5.15	139	3790	1020
Maryland	334	10400	30300		16.9	504	1370	0.276	5.79	13.7	0.251	8.61	28.4	68.3	1790	4650

Yearly EOL Materials by Material, by State (metric tons) for Scenario 1: Reference																
	Glass				**Silicon**			**Silver**			**Copper**			**Aluminum**		
State	**2030**	**2040**	**2050**		**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Maine	14.7	470	880		0.76	23.5	36.6	0.0144	0.297	0.335	0.0101	0.326	0.807	3.22	88.3	129
Michigan	11.6	603	2600		0.583	29.6	106	0.00647	0.331	0.91	0.00902	0.468	2.39	2.05	105	365
Minnesota	86.5	3020	4560		4.37	152	222	0.0453	1.59	2.23	0.0692	2.45	3.98	14.9	518	742
Missouri	43.4	2010	762		2.22	102	33	0.0345	1.29	0.302	0.0296	1.34	0.657	8.93	383	113
Mississippi	8.45	348	810		0.421	17.2	38.7	0.00425	0.175	0.385	0.00736	0.305	0.726	1.4	57.3	129
Montana	1.59	65.2	104		0.0801	3.27	4.93	0.000845	0.0352	0.0487	0.00129	0.0524	0.0916	0.274	11.3	16.5
North Carolina	733	22900	13500		37.6	1160	651	0.587	14.1	6.6	0.518	16.1	11.6	150	4260	2200
North Dakota	7.86	504	90.1		0.401	25.5	4.4	0.00503	0.32	0.0459	0.00538	0.335	0.074	1.5	95.9	15.1
Nebraska	9.19	573	1730		0.468	28.6	66.3	0.00572	0.349	0.515	0.00642	0.394	1.56	1.73	107	228
New Hampshire	7.09	261	283		0.36	13.1	13.4	0.0039	0.147	0.134	0.0053	0.194	0.247	1.27	46.7	45.5
New Jersey	1620	16000	5390		84.5	814	255	1.8	12	2.58	1.1	10.9	4.7	385	3230	869
New Mexico	390	4480	1430		20.3	228	68.5	0.443	3.23	0.689	0.264	3.05	1.2	91.5	887	235
Nevada	783	12700	7820		40.6	645	365	0.819	8.47	3.65	0.536	8.89	6.85	177	2440	1250
New York	369	7500	7980		19	378	353	0.354	4.78	3.31	0.257	5.37	7.08	81.3	1410	1200
Ohio	127	1360	1940		6.62	68.4	84.7	0.149	0.977	0.811	0.0866	0.981	1.79	30.2	266	292
Oklahoma	2.04	91.5	620		0.103	4.45	24.9	0.00106	0.0456	0.206	0.00171	0.0775	0.558	0.346	15.1	84.9
Oregon	118	1490	2990		6.09	74.9	129	0.122	0.955	1.18	0.0823	1.14	2.67	26.6	277	440
Pennsylvania	292	2130	2120		15.2	108	91	0.334	1.7	0.842	0.197	1.49	1.93	70.1	437	313
Rhode Island	8.63	442	727		0.432	22	33.9	0.00478	0.249	0.339	0.00691	0.346	0.662	1.51	77.9	114

Yearly EOL Materials by Material, by State (metric tons) for Scenario 1: Reference															
	Glass			Silicon			Silver			Copper			Aluminum		
State	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
South Carolina	46.7	2310	8900	2.28	111	404	0.0234	1.14	4	0.0411	2.09	8.27	7.67	373	1370
South Dakota	7.99	507	93.5	0.407	25.7	4.56	0.0051	0.321	0.0475	0.00547	0.337	0.0768	1.52	96.4	15.7
Tennessee	86.7	1660	3600	4.49	83.6	142	0.0879	1.1	1.15	0.0592	1.16	3.25	19.8	318	486
Texas	396	11300	41800	20.2	554	1780	0.338	6.33	16.2	0.294	9.13	38.6	81.3	1970	6080
Utah	137	3730	4480	6.96	188	215	0.0742	1.98	2.16	0.101	2.82	3.84	24.4	657	731
Virginia	44.2	1990	6840	2.19	96.3	309	0.0227	1	3.04	0.037	1.72	6.33	7.44	328	1050
Vermont	51.8	1380	571	2.67	70	27.6	0.0457	0.883	0.28	0.0358	0.952	0.483	11.1	262	94
Washington	33.5	736	625	1.73	37.1	29.3	0.0312	0.466	0.291	0.0234	0.53	0.557	7.32	138	99
Wisconsin	18.6	342	927	0.962	17.1	37.7	0.0186	0.218	0.321	0.013	0.253	0.838	4.19	63.7	129
West Virginia	7.92	508	150	0.404	25.7	6.81	0.00506	0.322	0.0665	0.00543	0.34	0.128	1.51	96.6	23.4
Wyoming	4.46	178	330	0.223	8.88	16.3	0.00225	0.0902	0.165	0.00388	0.155	0.291	0.74	29.5	54
U.S. Total	**15800**	**340000**	**285000**	**818**	**17200**	**12800**	**16.1**	**220**	**123**	**10.9**	**239**	**256**	**3520**	**64400**	**43700**

Table B-14. Yearly EOL Materials by Material, by State (metric tons) for Scenario 2: Decarb

Yearly EOL Materials by Material, by State (metric tons) for Scenario 2: Decarb															
	Glass			Silicon			Silver			Copper			Aluminum		
State	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Alabama	16	515	1130	0.81	25.8	51.2	0.00836	0.266	0.491	0.0125	0.413	0.998	2.78	88.2	175
Arkansas	6.55	257	656	0.33	12.8	29.7	0.00341	0.133	0.284	0.0054	0.213	0.588	1.12	43.5	101
Arizona	1730	23400	13200	89.9	1190	563	1.86	16.7	5.13	1.17	15.8	11.9	405	4630	1950
California	6350	158000	55900	328	8010	2630	6.73	104	26.4	4.33	107	48.1	1410	30300	9000
Colorado	465	5070	3710	24.2	258	167	0.51	3.59	1.58	0.316	3.56	3.24	108	994	568
Connecticut	107	3310	4910	5.45	165	225	0.089	1.98	2.24	0.0771	2.48	4.51	22.1	600	762
Delaware	68.8	591	741	3.58	30	30.3	0.0763	0.448	0.258	0.0465	0.412	0.662	16.3	119	104
Florida	284	6320	29300	14.5	307	1240	0.279	3.45	11.2	0.211	5.31	27	60.1	1080	4230
Georgia	177	5300	8720	9.03	266	383	0.116	3.01	3.59	0.128	3.92	7.75	33.7	953	1310
Iowa	9.04	515	786	0.459	25.8	32.6	0.00546	0.312	0.287	0.0065	0.362	0.721	1.67	95.4	113
Idaho	23.1	712	1320	1.17	35.6	62.3	0.012	0.366	0.617	0.018	0.576	1.17	4.01	122	211
Illinois	56.7	906	15400	2.93	41.1	591	0.0614	0.493	4.7	0.0392	0.758	14.1	13.3	152	2040
Indiana	57.2	2960	14300	2.92	145	563	0.0437	1.75	4.68	0.0397	2.12	13.4	11.6	540	1970
Kansas	8.46	766	8530	0.429	35.8	331	0.0053	0.406	2.71	0.0059	0.581	8.02	1.59	132	1160
Kentucky	2.89	170	2760	0.145	7.7	108	0.0015	0.0738	0.892	0.00229	0.147	2.58	0.498	26.6	378
Louisiana	18.3	730	2250	0.938	36.2	89.2	0.0164	0.44	0.744	0.0128	0.52	2.06	3.76	134	308
Massachusetts	649	19900	6160	33.4	1010	303	0.576	12.8	3.12	0.446	13.5	5.18	139	3790	1030
Maryland	331	10200	29500	16.7	496	1340	0.275	5.71	13.4	0.249	8.45	27.6	67.9	1760	4530

Yearly EOL Materials by Material, by State (metric tons) for Scenario 2: Decarb																
	Glass				**Silicon**			**Silver**			**Copper**			**Aluminum**		
State	**2030**	**2040**	**2050**		**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
Maine	14.7	459	636		0.759	23	26.7	0.0144	0.293	0.246	0.0101	0.316	0.581	3.21	86.8	93.8
Michigan	11.6	637	3700		0.584	31	149	0.00648	0.342	1.27	0.00904	0.5	3.45	2.05	110	516
Minnesota	86.5	3020	4610		4.37	152	224	0.0453	1.59	2.24	0.0692	2.45	4.03	14.9	519	749
Missouri	43.4	2060	3090		2.23	103	120	0.0345	1.3	0.967	0.0296	1.39	2.78	8.93	390	414
Mississippi	8.45	393	3230		0.422	18.9	129	0.00426	0.188	1.06	0.00737	0.346	2.91	1.4	63.1	439
Montana	1.59	65.2	105		0.0801	3.27	5.01	0.000845	0.0352	0.0492	0.00129	0.0525	0.0933	0.274	11.3	16.8
North Carolina	733	22900	13600		37.6	1160	657	0.587	14.1	6.65	0.518	16.1	11.7	150	4260	2220
North Dakota	7.86	504	94		0.401	25.5	4.55	0.00503	0.32	0.047	0.00538	0.335	0.0774	1.5	95.9	15.6
Nebraska	9.23	735	9710		0.469	34.7	365	0.00573	0.395	2.77	0.00646	0.542	8.81	1.73	128	1260
New Hampshire	7.1	261	293		0.36	13.2	13.8	0.0039	0.147	0.136	0.0053	0.194	0.255	1.27	46.8	46.7
New Jersey	1620	16000	5450		84.5	814	258	1.8	12	2.6	1.1	10.9	4.76	385	3230	878
New Mexico	390	4480	1470		20.3	228	70	0.443	3.23	0.7	0.264	3.05	1.24	91.5	887	240
Nevada	783	12800	10100		40.6	647	452	0.819	8.49	4.29	0.536	8.93	8.95	177	2450	1550
New York	369	7500	8040		19	378	356	0.354	4.78	3.33	0.257	5.37	7.14	81.3	1410	1210
Ohio	127	1410	3700		6.62	70.4	153	0.149	0.993	1.36	0.0867	1.03	3.44	30.2	272	530
Oklahoma	2.1	218	6130		0.105	9.26	233	0.00107	0.0831	1.81	0.00176	0.194	5.62	0.353	31.8	806
Oregon	118	1510	4270		6.09	75.8	177	0.122	0.962	1.53	0.0823	1.16	3.83	26.6	280	604
Pennsylvania	292	2130	2200		15.2	108	93.9	0.334	1.7	0.865	0.197	1.49	2.01	70.1	438	323
Rhode Island	8.63	443	737		0.432	22	34.3	0.00479	0.249	0.342	0.00691	0.347	0.671	1.51	78	116

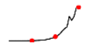
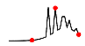
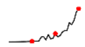
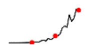
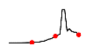
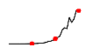
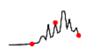
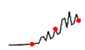
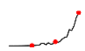
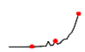
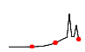
Yearly EOL Materials by Material, by State (metric tons) for Scenario 2: Decarb																
	Glass				Silicon			Silver			Copper			Aluminum		
State	**2030**	**2040**	**2050**		**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
South Carolina	46.8	2600	21800		2.29	122	891	0.0234	1.22	7.72	0.0412	2.35	20.1	7.68	411	3050
South Dakota	7.99	507	96.5		0.407	25.7	4.68	0.0051	0.322	0.0484	0.00547	0.337	0.0796	1.52	96.5	16.1
Tennessee	86.8	1800	7330		4.5	88.9	290	0.088	1.15	2.41	0.0593	1.29	6.86	19.8	337	1010
Texas	396	11700	54900		20.2	567	2280	0.338	6.43	20.2	0.295	9.44	50.7	81.4	2010	7820
Utah	137	3730	4490		6.96	188	215	0.0742	1.98	2.16	0.101	2.82	3.84	24.4	657	733
Virginia	44.2	2140	14000		2.19	102	579	0.0227	1.05	5.09	0.0371	1.86	12.9	7.45	348	1980
Vermont	51.8	1380	578		2.67	70	27.9	0.0457	0.883	0.282	0.0358	0.952	0.49	11.1	262	95
Washington	33.5	743	1140		1.73	37.3	48.4	0.0312	0.468	0.433	0.0234	0.536	1.02	7.32	139	165
Wisconsin	18.6	387	3220		0.962	18.8	123	0.0186	0.231	0.963	0.013	0.293	2.92	4.19	69.5	424
West Virginia	7.93	567	3270		0.404	27.9	123	0.00506	0.338	0.932	0.00544	0.393	2.94	1.51	104	423
Wyoming	4.46	178	332		0.223	8.88	16.4	0.00225	0.0902	0.166	0.00388	0.155	0.293	0.74	29.5	54.3
U.S. Total	**15800**	**343000**	**392000**		**818**	**17300**	**16800**	**16.1**	**221**	**155**	**10.9**	**242**	**354**	**3520**	**64800**	**57700**

Table B-15. Yearly EOL Materials by Material, by State (metric tons) for Scenario 3: Decarb+E

Yearly EOL Materials by Material, by State (metric tons) for Scenario 3: Decarb+E															
	Glass			Silicon			Silver			Copper			Aluminum		
State	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Alabama	16	515	1120	0.81	25.8	51.1	0.00836	0.266	0.491	0.0125	0.413	0.995	2.78	88.2	175
Arkansas	6.55	256	609	0.33	12.7	28	0.00341	0.133	0.271	0.0054	0.213	0.545	1.12	43.4	95
Arizona	1730	23300	14100	89.9	1180	592	1.86	16.6	5.27	1.17	15.8	12.6	405	4630	2050
California	6350	158000	61300	328	8010	2840	6.73	104	28.1	4.33	107	53	1410	30300	9710
Colorado	465	5070	3760	24.2	258	169	0.51	3.59	1.59	0.316	3.56	3.29	108	994	574
Connecticut	107	3300	4890	5.44	164	224	0.089	1.97	2.22	0.077	2.47	4.48	22.1	599	757
Delaware	68.8	584	319	3.58	29.7	14.5	0.0763	0.445	0.141	0.0465	0.404	0.28	16.3	118	49.6
Florida	284	6490	38100	14.5	314	1570	0.279	3.5	13.6	0.211	5.46	35	60.1	1100	5370
Georgia	177	5270	6650	9.03	265	307	0.117	3	3.03	0.128	3.89	5.91	33.7	949	1050
Iowa	9.05	522	999	0.46	26.1	40.8	0.00546	0.313	0.354	0.00651	0.367	0.921	1.67	96.2	142
Idaho	23.1	712	1320	1.17	35.6	62.3	0.012	0.366	0.617	0.018	0.576	1.17	4.01	122	211
Illinois	56.8	929	17200	2.94	42	657	0.0615	0.5	5.14	0.0393	0.777	15.7	13.3	155	2260
Indiana	57	2770	7760	2.92	138	309	0.0437	1.69	2.61	0.0396	1.94	7.24	11.5	514	1080
Kansas	8.43	763	9200	0.427	35.6	354	0.00529	0.403	2.84	0.00587	0.576	8.57	1.59	131	1230
Kentucky	2.86	176	4090	0.144	7.86	155	0.00149	0.0736	1.19	0.00226	0.151	3.7	0.494	27	534
Louisiana	18.3	709	1310	0.938	35.4	53.9	0.0164	0.434	0.473	0.0128	0.5	1.2	3.76	131	186
Massachusetts	649	19900	6160	33.4	1010	303	0.576	12.8	3.12	0.446	13.5	5.18	139	3790	1030
Maryland	335	10500	30700	16.9	508	1390	0.277	5.83	13.9	0.253	8.69	28.8	68.5	1800	4720

Yearly EOL Materials by Material, by State (metric tons) for Scenario 3: Decarb+E															
	Glass			Silicon			Silver			Copper			Aluminum		
State	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Maine	14.7	464	750	0.759	23.2	31.3	0.0144	0.295	0.287	0.0101	0.321	0.686	3.22	87.5	110
Michigan	11.6	683	5310	0.586	32.7	211	0.00649	0.357	1.77	0.00908	0.543	4.95	2.05	116	733
Minnesota	86.5	3020	4580	4.37	152	223	0.0453	1.59	2.24	0.0692	2.45	4.01	14.9	519	746
Missouri	43.4	2000	533	2.22	101	24.5	0.0345	1.29	0.239	0.0296	1.34	0.451	8.93	383	83.7
Mississippi	8.45	380	2560	0.422	18.5	104	0.00425	0.184	0.87	0.00737	0.335	2.31	1.4	61.5	353
Montana	1.59	65.2	105	0.0801	3.27	5.01	0.000845	0.0352	0.0492	0.00129	0.0525	0.0933	0.274	11.3	16.8
North Carolina	733	22900	13700	37.6	1160	659	0.587	14.1	6.66	0.518	16.1	11.8	150	4260	2230
North Dakota	7.86	504	125	0.401	25.5	5.65	0.00503	0.32	0.0546	0.00538	0.335	0.103	1.5	95.9	19.4
Nebraska	9.2	708	8870	0.468	33.6	332	0.00572	0.386	2.49	0.00643	0.516	8	1.73	124	1140
New Hampshire	7.1	261	293	0.36	13.2	13.8	0.0039	0.147	0.136	0.0053	0.194	0.255	1.27	46.8	46.7
New Jersey	1620	16000	5590	84.5	815	264	1.8	12	2.66	1.1	10.9	4.89	385	3230	899
New Mexico	390	4480	1470	20.3	228	69.7	0.443	3.23	0.698	0.264	3.05	1.23	91.5	887	239
Nevada	783	12800	8450	40.6	645	388	0.819	8.48	3.82	0.536	8.9	7.41	177	2440	1330
New York	369	7500	8070	19	378	357	0.354	4.78	3.33	0.257	5.37	7.16	81.3	1410	1210
Ohio	127	1390	2790	6.62	69.3	118	0.149	0.984	1.07	0.0867	1	2.59	30.2	269	406
Oklahoma	2.09	228	6890	0.104	9.62	261	0.00107	0.0855	2.01	0.00176	0.203	6.29	0.352	33	900
Oregon	118	1530	4110	6.09	76.3	173	0.122	0.966	1.53	0.0823	1.17	3.73	26.6	281	593
Pennsylvania	292	2130	2200	15.2	108	94.1	0.334	1.7	0.866	0.197	1.49	2.01	70.1	438	323
Rhode Island	8.63	443	737	0.432	22	34.3	0.00479	0.249	0.342	0.00691	0.347	0.671	1.51	78	116

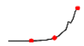
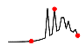
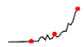
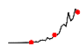
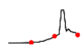
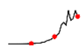
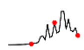
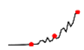
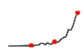
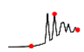
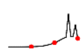
State	Glass 2030	Glass 2040	Glass 2050	Glass trend	Silicon 2030	Silicon 2040	Silicon 2050	Silver 2030	Silver 2040	Silver 2050	Copper 2030	Copper 2040	Copper 2050	Aluminum 2030	Aluminum 2040	Aluminum 2050
Yearly EOL Materials by Material, by State (metric tons) for Scenario 3: Decarb+E																
South Carolina	47	2890	32700		2.29	133	1310	0.0235	1.31	11.1	0.0414	2.62	30.3	7.71	450	4510
South Dakota	7.99	507	96.6		0.407	25.7	4.68	0.0051	0.322	0.0485	0.00547	0.337	0.0796	1.52	96.5	16.1
Tennessee	86.8	1790	7680		4.49	88.6	301	0.088	1.14	2.46	0.0593	1.28	7.12	19.8	336	1050
Texas	396	11400	44400		20.2	555	1870	0.338	6.34	16.9	0.294	9.16	40.9	81.3	1970	6410
Utah	137	3730	4500		6.96	188	215	0.0742	1.98	2.16	0.101	2.82	3.85	24.4	657	733
Virginia	44.2	2000	7590		2.19	96.8	337	0.0227	1.01	3.25	0.037	1.73	7	7.44	330	1140
Vermont	51.8	1380	578		2.67	70	27.9	0.0457	0.883	0.282	0.0358	0.952	0.49	11.1	262	95
Washington	33.5	775	2860		1.73	38.5	112	0.0312	0.477	0.908	0.0234	0.565	2.57	7.32	143	385
Wisconsin	18.6	391	3260		0.962	18.9	125	0.0186	0.232	0.985	0.013	0.298	2.96	4.19	70.1	431
West Virginia	7.92	509	262		0.404	25.7	10.9	0.00506	0.322	0.0954	0.00543	0.34	0.225	1.51	96.7	37.3
Wyoming	4.46	178	364		0.223	8.9	17.6	0.00225	0.0904	0.174	0.00388	0.155	0.322	0.74	29.6	58.4
U.S. Total	**15800**	**343000**	**391000**		**818**	**17300**	**16800**	**16.1**	**221**	**154**	**10.9**	**242**	**353**	**3520**	**64800**	**57600**

Table B-16. Cumulative EOL Materials by Material, by State (metric tons) for Scenario 1: Reference

Cumulative EOL Materials by Material, by State (metric tons) for Scenario 1: Reference															
	Glass			Silicon			Silver			Copper			Aluminum		
State	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Alabama	68	2490	11900	3.52	128	591	0.0682	2.05	7.01	0.0467	1.78	9.51	15.4	517	2120
Arkansas	13800	462000	1620000	714	23800	81600	15.9	413	1060	9.31	317	1200	3150	97300	302000
Arizona	55.8	5070	65900	2.78	247	3120	0.0291	2.57	31.5	0.0457	4.38	58.9	9.52	840	10500
California	562	21300	188000	29	1070	8980	0.635	16.8	96.6	0.4	16.9	164	126	4130	30800
Colorado	16.4	1330	17900	0.831	66.2	809	0.00941	0.742	7.77	0.0125	1.05	15.8	2.95	234	2770
Connecticut	103	5930	49700	5.32	299	2200	0.085	4.11	22.3	0.0708	4.2	42.5	21.6	1150	7840
Delaware	3.87	284	4950	0.196	14.1	221	0.00204	0.145	2.04	0.00303	0.23	4.28	0.675	48.1	752
Florida	297	7500	24300	15.5	387	1180	0.361	7.88	16.6	0.201	5.21	19.7	71.4	1700	4490
Georgia	683	16400	37700	35.6	850	1870	0.798	17.7	29.6	0.459	11.2	28.9	165	3840	7520
Iowa	13.1	943	3860	0.67	48.1	193	0.0085	0.621	2.25	0.00892	0.644	2.85	2.51	181	698
Idaho	1700	51200	188000	88.6	2640	9440	1.9	47.3	122	1.16	35.5	143	396	11100	35000
Illinois	601	30700	277000	30.7	1520	13000	0.562	21.2	140	0.431	24.7	249	130	5770	45000
Indiana	158	4000	15000	8.23	207	686	0.18	4.14	8.88	0.106	2.73	12.1	37.9	923	2610
Kansas	3730	95700	210000	194	4960	10700	4.25	99	169	2.51	64.9	154	894	22100	43000
Kentucky	762	26500	128000	39.5	1360	6290	0.789	22.4	74.4	0.522	18.8	102	173	5540	22600
Louisiana	103	4060	17000	5.3	209	862	0.0975	3.22	10.4	0.07	2.83	12.8	22.7	836	3130
Massachusetts	10.4	662	5510	0.528	33.5	275	0.00578	0.37	2.86	0.00764	0.5	4.4	1.87	118	945
Maryland	1290	53500	206000	66.5	2750	10500	1.23	42.4	128	0.876	37	155	285	11000	38100
Maine	199	9290	62700	10.2	469	3030	0.183	6.74	33.5	0.139	6.96	53	43	1810	10600
Michigan	11.9	1000	9560	0.599	50	466	0.00678	0.562	4.82	0.00927	0.807	8.31	2.12	175	1580
Minnesota	30.6	1220	7200	1.58	62.3	333	0.0325	1	3.77	0.0207	0.854	5.94	6.9	251	1210
Missouri	31.9	2070	21800	1.62	104	1080	0.0167	1.07	11	0.0245	1.66	18	5.57	356	3670
Mississippi	2.14	165	1720	0.108	8.31	85.4	0.00115	0.0888	0.868	0.00171	0.135	1.47	0.372	28.5	286
Montana	5.46	481	5820	0.274	24	291	0.00276	0.243	2.93	0.00474	0.419	5.11	0.908	79.7	961
North Carolina	201	11200	98700	10.2	567	4950	0.111	6.01	51	0.147	8.41	76.6	36.1	1980	17100
North Dakota	3900	109000	264000	203	5630	13300	4.33	107	199	2.62	73.6	191	925	24600	52500
Nebraska	897	23100	58800	46.7	1200	3000	1.06	23.8	44.8	0.604	15.7	42.6	214	5230	11700
New Hampshire	13.3	942	3670	0.677	48.1	186	0.00857	0.622	2.18	0.009	0.641	2.66	2.54	181	673

Cumulative EOL Materials by Material, by State (metric tons) for Scenario 1: Reference															
	Glass			Silicon			Silver			Copper			Aluminum		
State	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
New Jersey	1050	27700	83800	54.6	1430	4230	1.21	27.7	59.1	0.709	19.1	63.1	249	6230	16100
New Mexico	13.1	932	3580	0.667	47.6	181	0.00847	0.617	2.14	0.00887	0.634	2.59	2.51	180	658
Nevada	14.9	1090	10200	0.759	54.9	446	0.00941	0.687	4.27	0.0103	0.761	8.52	2.82	205	1560
New York	117	8290	86300	5.92	418	4310	0.0618	4.35	43.9	0.0924	6.74	72.4	20.3	1420	14500
Ohio	14.2	1030	7850	0.721	52.3	368	0.00873	0.639	3.8	0.01	0.744	6.48	2.65	192	1290
Oklahoma	39.5	1310	7830	2.05	67.1	363	0.042	1.15	4.08	0.027	0.942	6.58	9.15	279	1300
Oregon	730	34000	340000	37.5	1700	15700	0.708	24.2	162	0.522	26.7	299	159	6470	54300
Pennsylvania	2.63	228	4050	0.132	11.3	181	0.00137	0.116	1.68	0.00217	0.194	3.57	0.448	38	611
Rhode Island	253	7450	39300	13.1	383	1910	0.28	6.83	22.5	0.174	5.37	32.2	59	1600	6830
South Carolina	13.6	1250	29900	0.694	60.3	1200	0.00875	0.724	10.4	0.00933	0.927	27.2	2.6	224	4200
South Dakota	81.2	4300	16500	4.18	220	821	0.0689	3.16	9.85	0.0549	2.93	12.3	17.2	861	3000
Tennessee	8.61	679	8190	0.434	34	399	0.00452	0.352	4	0.007	0.567	7.08	1.48	115	1340
Texas	35.2	1650	10400	1.82	83.5	493	0.0359	1.23	5.41	0.0243	1.18	8.48	7.55	320	1740
Utah	127	3610	29800	6.59	183	1270	0.143	3.45	13.4	0.0862	2.62	26.2	30.3	794	4560
Virginia	10.3	931	11700	0.514	46.3	575	0.00519	0.469	5.79	0.00892	0.817	10.3	1.71	154	1910
Vermont	22.1	1460	16200	1.12	73.4	795	0.0116	0.758	7.99	0.0171	1.16	13.4	3.86	251	2700
Washington	188	6090	29300	9.74	313	1350	0.199	5.5	15.8	0.127	4.22	23.9	43.7	1320	4940
Wisconsin	290	14900	111000	14.8	754	5500	0.207	9.23	58.5	0.206	11	87.2	56.9	2760	19200
West Virginia	54.8	5840	81800	2.7	282	3860	0.0277	2.89	38.9	0.0476	5.25	74.7	9.09	946	13000
Wyoming	1350	61800	332000	69.6	3160	16700	1.19	44.7	189	0.939	44.2	259	287	12200	59100
U.S. Total	**33600**	**1130000**	**4860000**	**1740**	**58100**	**240000**	**36.8**	**992**	**2950**	**22.9**	**795**	**3830**	**7710**	**238000**	**873000**

Table B-17. Cumulative EOL Materials by Material, by State (metric tons) for Scenario 2: Decarb

Cumulative EOL Materials by Material, by State (metric tons) for Scenario 2: Decarb															
	Glass			Silicon			Silver			Copper			Aluminum		
State	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Alabama	68	2490	11900	3.52	128	591	0.0682	2.05	7.01	0.0467	1.78	9.51	15.4	517	2120
Arkansas	13800	462000	1620000	714	23800	81600	15.9	413	1060	9.31	317	1200	3150	97300	302000
Arizona	55.8	5070	65900	2.78	247	3120	0.0291	2.57	31.5	0.0457	4.38	58.9	9.52	840	10500
California	562	21300	188000	29	1070	8980	0.635	16.8	96.6	0.4	16.9	164	126	4130	30800
Colorado	16.4	1330	17900	0.831	66.2	809	0.00941	0.742	7.77	0.0125	1.05	15.8	2.95	234	2770
Connecticut	103	5930	49700	5.32	299	2200	0.085	4.11	22.3	0.0708	4.2	42.5	21.6	1150	7840
Delaware	3.87	284	4950	0.196	14.1	221	0.00204	0.145	2.04	0.00303	0.23	4.28	0.675	48.1	752
Florida	297	7500	24300	15.5	387	1180	0.361	7.88	16.6	0.201	5.21	19.7	71.4	1700	4490
Georgia	683	16400	37700	35.6	850	1870	0.798	17.7	29.6	0.459	11.2	28.9	165	3840	7520
Iowa	13.1	943	3860	0.67	48.1	193	0.0085	0.621	2.25	0.00892	0.644	2.85	2.51	181	698
Idaho	1700	51200	188000	88.6	2640	9440	1.9	47.3	122	1.16	35.5	143	396	11100	35000
Illinois	601	30700	277000	30.7	1520	13000	0.562	21.2	140	0.431	24.7	249	130	5770	45000
Indiana	158	4000	15000	8.23	207	686	0.18	4.14	8.88	0.106	2.73	12.1	37.9	923	2610
Kansas	3730	95700	210000	194	4960	10700	4.25	99	169	2.51	64.9	154	894	22100	43000
Kentucky	762	26500	128000	39.5	1360	6290	0.789	22.4	74.4	0.522	18.8	102	173	5540	22600
Louisiana	103	4060	17000	5.3	209	862	0.0975	3.22	10.4	0.07	2.83	12.8	22.7	836	3130
Massachusetts	10.4	662	5510	0.528	33.5	275	0.00578	0.37	2.86	0.00764	0.5	4.4	1.87	118	945
Maryland	1290	53500	206000	66.5	2750	10500	1.23	42.4	128	0.876	37	155	285	11000	38100
Maine	199	9290	62700	10.2	469	3030	0.183	6.74	33.5	0.139	6.96	53	43	1810	10600
Michigan	11.9	1000	9560	0.599	50	466	0.00678	0.562	4.82	0.00927	0.807	8.31	2.12	175	1580
Minnesota	30.6	1220	7200	1.58	62.3	333	0.0325	1	3.77	0.0207	0.854	5.94	6.9	251	1210
Missouri	31.9	2070	21800	1.62	104	1080	0.0167	1.07	11	0.0245	1.66	18	5.57	356	3670
Mississippi	2.14	165	1720	0.108	8.31	85.4	0.00115	0.0888	0.868	0.00171	0.135	1.47	0.372	28.5	286
Montana	5.46	481	5820	0.274	24	291	0.00276	0.243	2.93	0.00474	0.419	5.11	0.908	79.7	961
North Carolina	201	11200	98700	10.2	567	4950	0.111	6.01	51	0.147	8.41	76.6	36.1	1980	17100
North Dakota	3900	109000	264000	203	5630	13300	4.33	107	199	2.62	73.6	191	925	24600	52500
Nebraska	897	23100	58800	46.7	1200	3000	1.06	23.8	44.8	0.604	15.7	42.6	214	5230	11700
New Hampshire	13.3	942	3670	0.677	48.1	186	0.00857	0.622	2.18	0.009	0.641	2.66	2.54	181	673

Cumulative EOL Materials by Material, by State (metric tons) for Scenario 2: Decarb															
	Glass			Silicon			Silver			Copper			Aluminum		
State	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
New Jersey	1050	27700	83800	54.6	1430	4230	1.21	27.7	59.1	0.709	19.1	63.1	249	6230	16100
New Mexico	13.1	932	3580	0.667	47.6	181	0.00847	0.617	2.14	0.00887	0.634	2.59	2.51	180	658
Nevada	14.9	1090	10200	0.759	54.9	446	0.00941	0.687	4.27	0.0103	0.761	8.52	2.82	205	1560
New York	117	8290	86300	5.92	418	4310	0.0618	4.35	43.9	0.0924	6.74	72.4	20.3	1420	14500
Ohio	14.2	1030	7850	0.721	52.3	368	0.00873	0.639	3.8	0.01	0.744	6.48	2.65	192	1290
Oklahoma	39.5	1310	7830	2.05	67.1	363	0.042	1.15	4.08	0.027	0.942	6.58	9.15	279	1300
Oregon	730	34000	340000	37.5	1700	15700	0.708	24.2	162	0.522	26.7	299	159	6470	54300
Pennsylvania	2.63	228	4050	0.132	11.3	181	0.00137	0.116	1.68	0.00217	0.194	3.57	0.448	38	611
Rhode Island	253	7450	39300	13.1	383	1910	0.28	6.83	22.5	0.174	5.37	32.2	59	1600	6830
South Carolina	13.6	1250	29900	0.694	60.3	1200	0.00875	0.724	10.4	0.00933	0.927	27.2	2.6	224	4200
South Dakota	81.2	4300	16500	4.18	220	821	0.0689	3.16	9.85	0.0549	2.93	12.3	17.2	861	3000
Tennessee	8.61	679	8190	0.434	34	399	0.00452	0.352	4	0.007	0.567	7.08	1.48	115	1340
Texas	35.2	1650	10400	1.82	83.5	493	0.0359	1.23	5.41	0.0243	1.18	8.48	7.55	320	1740
Utah	127	3610	29800	6.59	183	1270	0.143	3.45	13.4	0.0862	2.62	26.2	30.3	794	4560
Virginia	10.3	931	11700	0.514	46.3	575	0.00519	0.469	5.79	0.00892	0.817	10.3	1.71	154	1910
Vermont	22.1	1460	16200	1.12	73.4	795	0.0116	0.758	7.99	0.0171	1.16	13.4	3.86	251	2700
Washington	188	6090	29300	9.74	313	1350	0.199	5.5	15.8	0.127	4.22	23.9	43.7	1320	4940
Wisconsin	290	14900	111000	14.8	754	5500	0.207	9.23	58.5	0.206	11	87.2	56.9	2760	19200
West Virginia	54.8	5840	81800	2.7	282	3860	0.0277	2.89	38.9	0.0476	5.25	74.7	9.09	946	13000
Wyoming	1350	61800	332000	69.6	3160	16700	1.19	44.7	189	0.939	44.2	259	287	12200	59100
U.S. Total	**33600**	**1130000**	**4860000**	**1740**	**58100**	**240000**	**36.8**	**992**	**2950**	**22.9**	**795**	**3830**	**7710**	**238000**	**873000**

Table B-18. Cumulative EOL Materials by Material, by State (metric tons) for Scenario 3: Decarb+E

Cumulative EOL Materials by Material, by State (metric tons) for Scenario 3: Decarb+E															
	Glass			Silicon			Silver			Copper			Aluminum		
State	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Alabama	67.9	2540	19500	3.52	129	873	0.0682	2.06	9.1	0.0467	1.82	16.4	15.4	523	3090
Arkansas	13800	463000	1640000	714	23800	82400	15.9	413	1070	9.31	318	1220	3150	97300	305000
Arizona	55.8	5080	68300	2.78	248	3210	0.0291	2.57	32.2	0.0457	4.39	61.1	9.52	841	10900
California	562	22000	260000	29	1100	11700	0.635	17	118	0.4	17.4	231	126	4220	40400
Colorado	16.5	1450	28000	0.832	70.7	1200	0.00942	0.779	11	0.0125	1.16	25.3	2.95	249	4140
Connecticut	103	5930	49800	5.32	299	2210	0.085	4.11	22.4	0.0708	4.2	42.6	21.6	1150	7850
Delaware	3.88	369	16400	0.196	17.3	650	0.00205	0.169	5.3	0.00303	0.309	14.7	0.676	59.3	2230
Florida	297	7540	27500	15.5	388	1300	0.361	7.89	17.6	0.201	5.24	22.7	71.4	1710	4910
Georgia	683	16400	38000	35.6	850	1880	0.798	17.7	29.7	0.459	11.2	29.1	165	3840	7550
Iowa	13.1	943	4150	0.67	48.1	204	0.0085	0.622	2.32	0.00892	0.644	3.1	2.51	181	734
Idaho	1700	51200	190000	88.6	2640	9520	1.9	47.3	123	1.16	35.5	145	396	11100	35300
Illinois	602	30900	280000	30.8	1530	13200	0.562	21.3	141	0.432	24.8	252	131	5800	45500
Indiana	158	3970	9430	8.23	206	476	0.18	4.13	7.32	0.106	2.7	6.99	37.9	918	1890
Kansas	3730	95800	212000	194	4970	10800	4.25	99	170	2.51	65	155	894	22100	43200
Kentucky	762	26500	128000	39.5	1360	6300	0.789	22.4	74.5	0.522	18.8	102	173	5540	22700
Louisiana	103	4060	17100	5.3	209	863	0.0975	3.22	10.4	0.07	2.83	12.9	22.7	836	3130
Massachusetts	10.4	663	5540	0.528	33.5	276	0.00578	0.371	2.87	0.00765	0.5	4.43	1.87	118	949
Maryland	1290	53500	206000	66.6	2750	10500	1.23	42.4	128	0.876	37	155	285	11000	38100
Maine	198	9250	61500	10.2	467	2980	0.183	6.72	33	0.139	6.92	51.9	43	1810	10400
Michigan	11.9	1000	9600	0.599	50	468	0.00679	0.563	4.84	0.00927	0.807	8.34	2.12	175	1580
Minnesota	30.6	1210	6650	1.58	61.9	310	0.0325	1	3.57	0.0207	0.845	5.44	6.9	249	1130
Missouri	31.9	2070	21900	1.62	104	1080	0.0167	1.07	11	0.0245	1.66	18.1	5.57	356	3680
Mississippi	2.13	165	1730	0.108	8.31	85.6	0.00115	0.0888	0.87	0.00171	0.135	1.48	0.371	28.5	287
Montana	5.46	481	5940	0.274	24.1	295	0.00276	0.244	2.96	0.00474	0.42	5.21	0.908	79.8	975
North Carolina	201	11200	98700	10.2	567	4950	0.111	6.01	51	0.147	8.41	76.7	36.1	1980	17100
North Dakota	3900	109000	285000	203	5640	14100	4.33	107	205	2.62	73.8	211	925	24600	55400
Nebraska	897	23100	58900	46.7	1200	3000	1.06	23.8	44.8	0.604	15.7	42.7	214	5230	11700
New Hampshire	13.3	942	3680	0.677	48.1	186	0.00857	0.622	2.19	0.009	0.641	2.67	2.54	182	675

Cumulative EOL Materials by Material, by State (metric tons) for Scenario 3: Decarb+E															
	Glass			Silicon			Silver			Copper			Aluminum		
State	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
New Jersey	1050	27700	86300	54.6	1430	4320	1.21	27.7	59.8	0.709	19.1	65.3	249	6230	16400
New Mexico	13.1	932	3660	0.667	47.7	184	0.00847	0.617	2.16	0.00887	0.634	2.67	2.51	180	668
Nevada	14.9	1250	34700	0.759	61	1360	0.00941	0.733	11.1	0.0103	0.908	30.6	2.82	225	4690
New York	117	8290	86400	5.92	418	4320	0.0618	4.35	43.9	0.0924	6.74	72.5	20.3	1420	14500
Ohio	14.2	1040	8510	0.721	52.6	394	0.00874	0.642	4.02	0.01	0.752	7.11	2.65	193	1380
Oklahoma	39.5	1370	15900	2.05	69.5	668	0.042	1.17	6.4	0.027	1	14	9.15	287	2350
Oregon	730	34100	349000	37.5	1700	16100	0.708	24.2	165	0.522	26.7	307	159	6470	55400
Pennsylvania	2.64	405	26100	0.133	18	1010	0.00138	0.168	8.05	0.00218	0.356	23.7	0.45	61.3	3480
Rhode Island	253	7500	43500	13.1	385	2070	0.28	6.84	23.8	0.174	5.41	36.2	59	1610	7410
South Carolina	13.6	1320	37300	0.695	62.9	1480	0.00875	0.745	12.6	0.00934	0.991	34.1	2.6	233	5190
South Dakota	81.2	4300	15800	4.18	220	793	0.0689	3.16	9.64	0.0549	2.93	11.6	17.2	860	2900
Tennessee	8.6	676	8080	0.434	33.8	395	0.00451	0.351	3.96	0.00699	0.564	6.97	1.48	115	1330
Texas	35.2	1650	11400	1.81	83.7	530	0.0359	1.23	5.72	0.0242	1.18	9.41	7.55	321	1880
Utah	127	3950	70500	6.6	196	2810	0.143	3.56	25.2	0.0863	2.93	63.5	30.3	839	9870
Virginia	10.3	971	17700	0.514	47.7	798	0.00519	0.48	7.45	0.00892	0.853	15.7	1.71	159	2670
Vermont	22.1	1460	16200	1.12	73.4	796	0.0116	0.758	8	0.0171	1.16	13.5	3.86	251	2700
Washington	188	6270	44800	9.74	320	1950	0.199	5.56	20.8	0.127	4.39	38.6	43.7	1350	7060
Wisconsin	290	14900	113000	14.8	755	5590	0.207	9.23	59.2	0.206	11	89.3	56.9	2770	19500
West Virginia	54.9	6620	167000	2.7	312	7120	0.0278	3.13	64.4	0.0477	5.98	154	9.1	1050	24300
Wyoming	1350	61800	333000	69.6	3160	16700	1.19	44.7	189	0.939	44.2	259	287	12200	59200
U.S. Total	**33600**	**1140000**	**5240000**	**1740**	**58200**	**254000**	**36.8**	**993**	**3060**	**22.9**	**798**	**4180**	**7710**	**239000**	**923000**

Appendix C. Order-of-Magnitude Estimates of Air-Quality Benefits of the *Solar Futures Study* Scenarios

Detailed in this appendix is the methodology for the order-of-magnitude estimation of the air-quality benefits of the *Solar Futures Study* scenarios. Included within each section is discussion of uncertainty in the inputs.

Emissions from the Power Sector

Power-sector emissions of SO_2 and NO_x are determined within the power-sector modeling itself. Direct emissions of PM from the power sector are not included. Direct PM benefits due to limiting total power-sector emissions are commonly considered small compared to NO_x and SO_2 benefits (due to relatively low emission rates of direct PM from power plants). For example, EPA estimated that the direct PM benefits of the Clean Power Plan were less than 10% of total benefits.[190] Total annual power-sector emissions are reported for the contiguous United States every 2 years, and results are interpolated for the off years (Figure C-1). Power-sector emissions are reduced to zero by 2050 but decline quickly through 2030. This means cumulative monetized health benefits are sensitive to the timing of the decline; delayed emission reductions would reduce the total benefits. The benefits are most sensitive to the counterfactual scenario (the Reference scenario). In the Reference scenario, emissions are roughly halved by 2050. This Reference emissions decline represents less decline than was observed over the last 15 years.

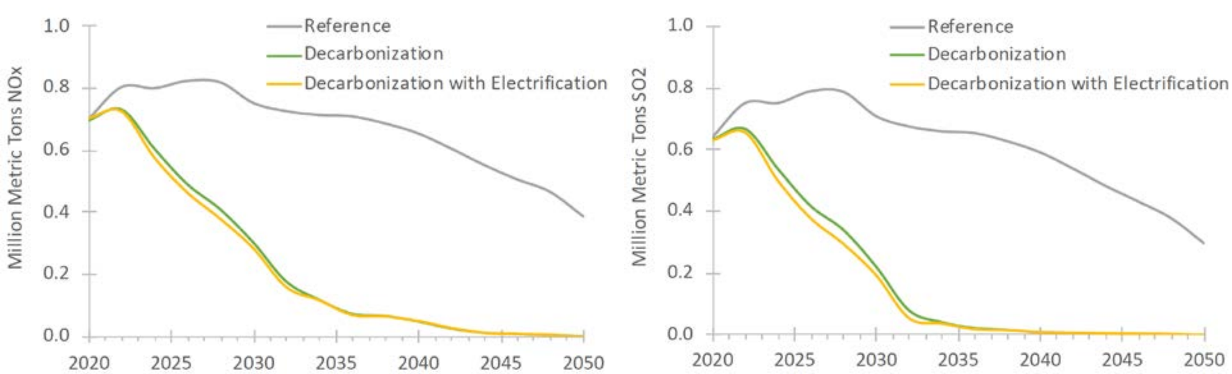


Figure C-1. Total NO_x and SO_2 emissions from the power sector

Emissions from Vehicles

Vehicle emissions are not directly calculated within the scenario modeling. However, energy use by sector and fuel type are calculated within the scenario modeling. We use total diesel and gasoline energy from the transportation sector from each scenario to estimate total fuel use. We then develop fleet-average emission factors to convert fuel use to total emissions, and finally we multiply the total emissions by marginal damage factors (or benefit-per-ton factors) to calculate total damages by scenario.

Vehicle fuel use: We make a simplifying assumption about vehicle types. We model all gasoline vehicles as light-duty vehicles, and we model all diesel vehicles as heavy-duty trucks. This simplification is justified because, in the 2020 Reference scenario, light-duty gasoline vehicles accounted for 94% of total gasoline use. Similarly, heavy-duty diesel trucks accounted for 59% of total diesel use, and medium-duty diesel trucks accounted for another 16%. Because medium-duty diesel trucks are subject to the same emission regulations as heavy-duty diesel trucks, the distinction between the two vehicle types is not impactful for our analysis, and the simplification of heavy-duty diesel vehicles representing all diesel fuel use is justified.

To find total fuel use, we convert quads of energy to kilograms of fuel using the conversion factors shown in Table C-1. In 2019, the United States used 1.4E+11 gallons of gasoline,[308] which is similar to the implied 2020 use under the Reference scenario of 1.54E+11 gallons. Modeled transportation-sector diesel use is also similar to actual 2020 use. Total vehicle fuel use by scenario and fuel type is shown in Figure C-2, which illustrates that the Decarb+E scenario assumes significant electrification of light-duty vehicles but less electrification of heavy-duty diesel vehicles. Because heavy-duty diesel vehicles have much higher emission rates per kilogram of fuel used, this scenario will only produce moderate air-quality benefits relative to the total sector air-quality damages. The electrification of vehicles is also weighted toward the final decade of the study period. This delay realistically represents the slow pace of vehicle stock turnover, though it would be conceivable to develop electrification programs that target the oldest and highest-emitting vehicles for replacement in the near term. A program following this replacement strategy would have much larger air-quality benefits, but it would likely be more expensive and challenging to implement.

Table C-1. Conversion Factors Used to Estimate Kilograms of Fuel Use from Quads of Energy

1 quad = 1E+15 British thermal units (Btu)
1 gallon gasoline = 120,286 Btu
1 gallon diesel = 137,381 Btu
1 gallon gasoline = 2.86 kilograms (kg)
1 gallon diesel = 3.13 kg

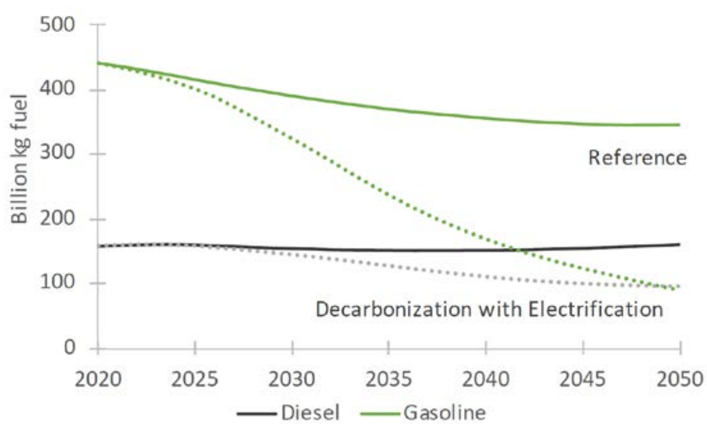


Figure C-2. Total vehicle fuel use by scenario

Vehicle emission rates: To find total pollutant emissions by vehicles, we develop emission rates to convert fuel burned into emissions. For vehicles, we are interested in emissions of NO_x and PM. We do not include SO_2 emissions from the vehicle sector, because sulfur has been largely removed from gasoline and diesel fuels. Of PM, we are interested in $PM_{2.5}$. As mentioned in the main text, emission rates from vehicles have declined rapidly in recent years and are expected to decline further in the years to come. Our emissions rates must reflect this expected decline, or risk substantially overestimating the benefits of electrification. It is theoretically possible that vehicle emission regulations could be reversed in the future, in which case our estimate will underestimate the benefits of electrification.

We base our emission rates on EPA's MOVES model,[192] run under default conditions (this includes existing emission regulations for new vehicles). The impact of existing regulations is to dramatically reduce total fleet-level emissions as the vehicle stock turns over. To understand how the emission factors implied by EPA MOVES relate to recent trends in emission factors, we examine historical observations of vehicle emissions in real-world settings. Measured fleet-average emissions are shown in Figure C-3 and Table C-2. Our forward-looking emission rates (Figure C-4) begin at roughly the level of the most recent measured emission rates shown in Figure C-3 and Table C-2. This rough match provides some confidence that the forecast emission rates are realistic, at least given current information.

Despite the rough match between current modeled and observed fleet-emission rates, there is some uncertainty about how emission factors will evolve in the future. Most importantly, regulations could change to be more or less strict. "Replacement" programs could be initiated, which would target on-road, high-emitting vehicles for replacement, rather than waiting for the vehicles to be retired at the end of their life. Also, there is uncertainty related to the performance of emission-control equipment over the lifetime of a vehicle. Technological improvements aside from electrification could also improve pollutant emissions.

We do not consider other pollutants, such as SO_2 and volatile organic compound (VOC) emissions. These pollutants also contribute to air-quality and health impacts, but sulfur has largely been removed from vehicle fuel, and vehicle VOC impacts are highly variable and challenging to quantify. Finally, our estimates of PM emissions only include tailpipe emissions, but not brake wear, tire wear, or dust. The simplest assumption is that these other sources of PM emissions will not change due to vehicle electrification. However, this is not necessarily true. The use of regenerative breaking from electric vehicles could substantially reduce brake wear emissions. In addition, the increased weight of electric vehicles could increase tire wear.

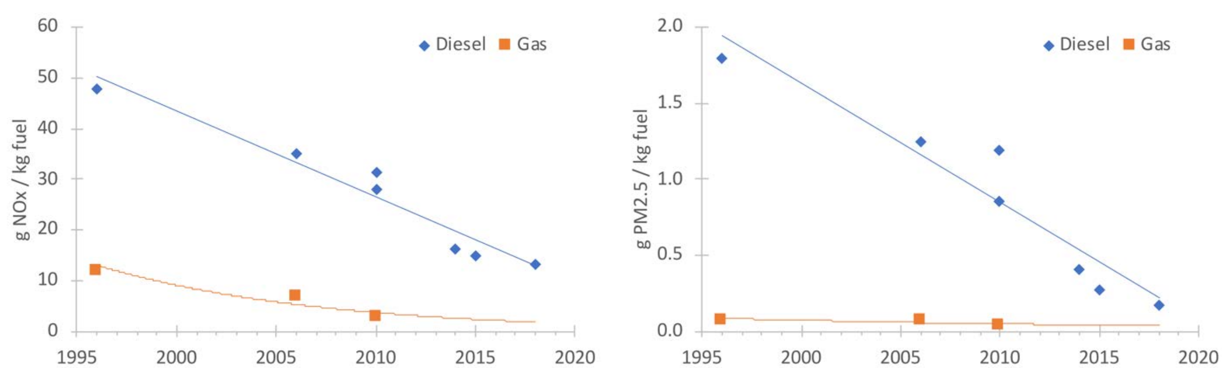


Figure C-3. Fleet-average NO_x and $PM_{2.5}$ emission rates of light-duty cars and heavy-duty diesel trucks, based on observed emissions[194–197]

See notes about these emission factors associated with Table C-2.

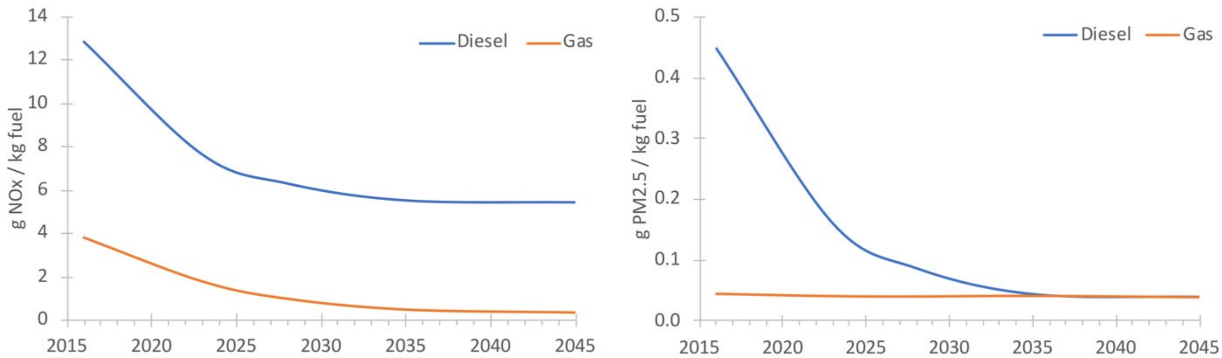


Figure C-4. Future vehicle NO_x and $PM_{2.5}$ emission rates based on EPA MOVES model

Table C-2. Summary of Observed Fleet-Average Emission (g/kg fuel) Factors from the Literature

Pollutant	Location	Reference[194–197]	Fuel Type	1996	2006	2010	2014	2015	2018
NOx	National	Dallmann & Harley (2010)[194]	Gas	12	7				
NOx	California	McDonald et al (2012)[195]	Gas			3			
NOx	National	Dallmann & Harley (2010)[194]	Diesel	48	35				
NOx	California	McDonald et al (2012)[195]	Diesel			28			
NOx	California	Preble et al (2019)[197]	Diesel			31.3	16.3	15	13.2
$PM_{2.5}$	National	Dallmann & Harley (2010)[194]	Gas	0.078	0.075				
$PM_{2.5}$	California	McDonald et al (2015)[196]	Gas			0.04			
$PM_{2.5}$	National	Dallmann & Harley (2010)[194]	Diesel	1.8	1.25				
$PM_{2.5}$	California	McDonald et al (2015)[196]	Diesel			1.2			
BC	California	Preble et al (2019)[197]	Diesel			0.86	0.41	0.28	0.18

BC stands for 'black carbon,' which is a subset of total $PM_{2.5}$ emissions. BC emission rates will be representative, but a bit lower than total $PM_{2.5}$ emissions. There are likely some differences between California and national vehicle fleets, as California has its own vehicle emissions regulations, in addition to federal regulations. Still, the California values provide insight into the overall trajectory of vehicle emissions.

To determine fuel input-normalized future emission rates from EPA MOVES, we first convert CO_2 emissions to fuel mass and then normalize total NO_x and $PM_{2.5}$ emissions by fuel. The key conversion factors here are 8.9 and 10.2 kg CO_2 per gallon of gasoline and diesel respectively. Total CO_2, NO_x, and $PM_{2.5}$ emissions are reported in Chapter 6 of EPA (2021).[192] Emissions were interpolated between years and extrapolated through to 2050 (from 2045).

To demonstrate the calculations described above, we present an example of the process here. EPA MOVES reports that diesel vehicles will emit 0.52 billion metric tons of CO_2 in 2028. This implies that 1.6E+11 kg of diesel fuel would be burned (10.2 kg CO_2 per gallon of diesel is used to convert the CO_2 emissions to volume of fuel, which is subsequently converted to kg of fuel). EPA MOVES also reports that 1.01 million tons of NO_x will be emitted by diesel vehicles in 2028. This implies a fleet-average emission factor of 6.3 g NO_x per kg diesel fuel in 2028. In this manner, emissions were calculated across the study period. Emission rates were interpolated between years without EPA MOVES data.

Though these emission rates are simply based on the MOVES model, the rates are consistent with the measured emissions of on-road vehicles (Figure C-3, Figure C-4, Table C-2). This consistency provides an independent validation of the MOVES model, and of other simplifications we have made. Of course, this validation only applies to the near-term prediction of emission rates, but it still adds confidence that at least our emission rates match general expectations and observations in the near term.

Total vehicle emissions: Total vehicle emissions are simply the product of each year's fuel use and emission factors. Figure C-5 shows total emissions from the vehicle sector. This figure also shows the split of total emissions by diesel and gasoline vehicles for the Reference scenario. From these plots, two aspects are clear. First, diesel vehicles represent the bulk of NO_x emissions, and the bulk of near-term $PM_{2.5}$ emissions. This implies that, because the Decarb+E scenario focuses on light-duty vehicles, it does not address the substantial emissions from heavy-duty vehicles. Second, Reference scenario emissions between 2021 and 2030 account for roughly half of the total emissions during the study period (for both NO_x and $PM_{2.5}$). In other words, vehicle emissions over the next decade are equal to the vehicle emissions of the following two decades (2031–2050). However, most of the emission savings from the Decarb+E scenario occur after 2030. Because Reference scenario vehicle emissions are weighted toward the near term (before 2030), Decarb+E scenario emission reductions do not ramp up until after 2030, and a time-based discount rate is applied to the value of the emission benefits, the ratio of the avoided vehicle health damages to total Reference scenario vehicle health damages (0.18) is smaller than the ratio of avoided vehicle fuel-use to total Reference scenario fuel use (0.29). To summarize, two aspects limit the effectiveness of the Decarb+E scenario for reducing air-quality and health damages: 1) emission reductions depend on fleet turnover rather than replacement, delaying impact until after 2030, and 2) electrification is focused on the light-duty sector, despite diesel vehicles contributing a majority of the total emissions. Expanding the vehicle electrification scenario to maximize benefits by including replacement of high emitters, early action, and increased focus on heavy-duty diesel would be more expensive than the current Decarb+E scenario. It is outside the scope of this analysis to estimate whether the benefits of that expansion would outweigh added costs.

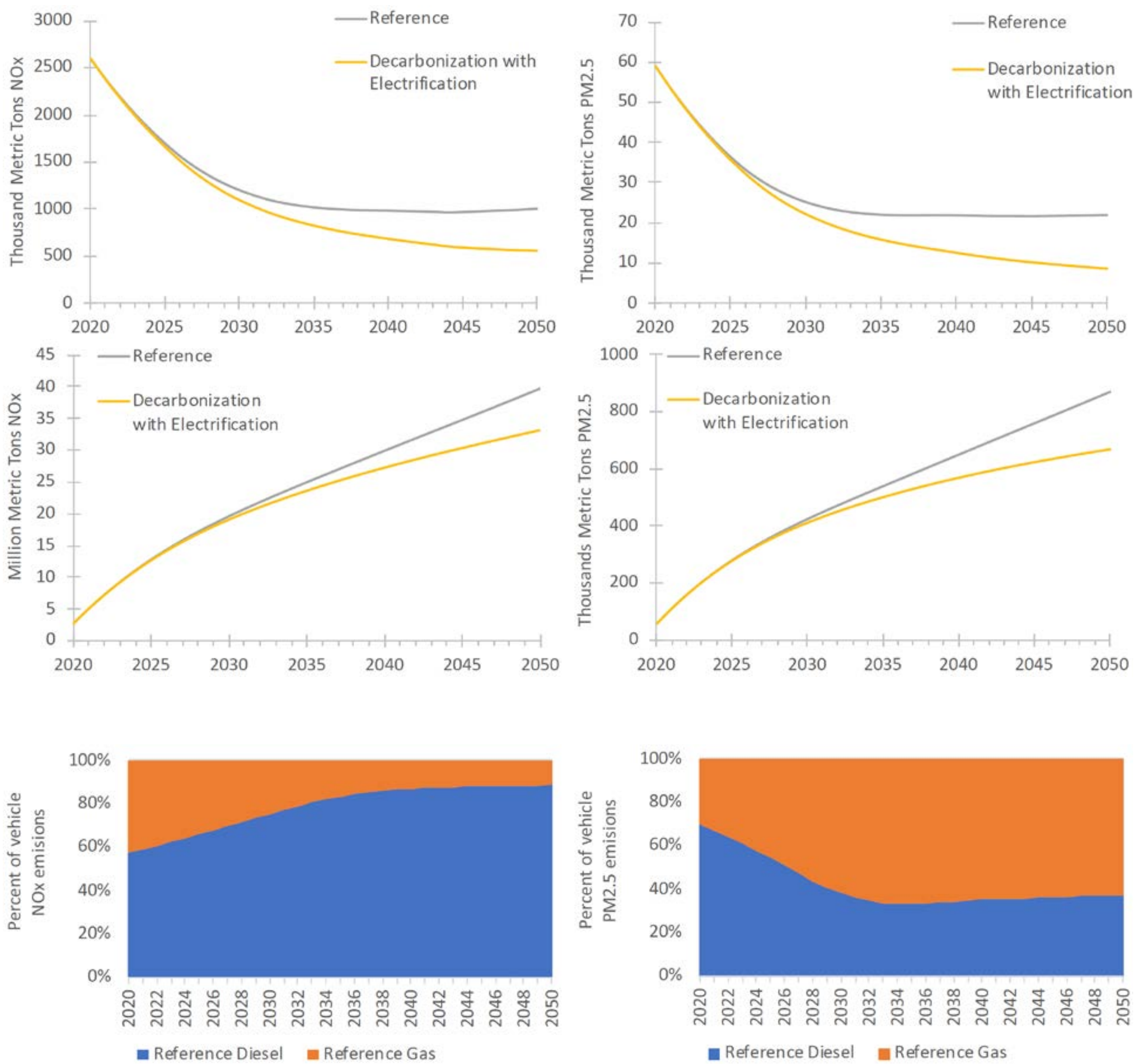


Figure C-5. Total annual (top) and cumulative (middle) NO_x and $PM_{2.5}$ emissions from vehicles and (bottom) split of emissions by diesel or gasoline vehicles within the Reference scenario

Benefit-per-Ton Estimates

We use literature-based estimates of the benefits per ton of avoided emissions. The same marginal factors are used to describe the benefit of avoiding a ton of emissions or the damage of releasing a ton of emissions (the "marginal damage" factor).

Power-sector benefit-per-ton estimates: Benefit-per-ton estimates for the power sector and transportation sector are based on different studies, because a study that presented benefit-per-ton estimates for both sectors and included forward-looking estimates was not available. Therefore, we use separate, but state-of-the-science, studies for each sector that include forward-looking estimates. The negative consequence of this choice is that the studies monetize moderately different sets of benefits from pollutant emissions. For example, the power-sector estimates include small benefits from reduced ozone exposure due to NO_x emission reductions.

The vehicle-sector estimates do not include this damage pathway. From an order of magnitude perspective, these differences are inconsequential, because total monetary benefits are dominated by the reduced incidence of death due to reduced exposure to PM. We compare both power-sector and vehicle-sector Reference scenario 2020 damages to independent literature estimates to confirm that our estimates are roughly similar to independent analyses.

Power-sector benefit-per-ton estimates are derived from the EPA's Regulatory Impact Analysis of the Clean Power Plan.[190] Specifically, we use the low-end, national, 3% discount rate, benefit-per-ton estimates from Tables 4A-3 through 4A-5 and Tables 4A-9 through 4A-11 in that source. NO_x emission reductions can reduce human exposure to both ozone and PM (NO_x can be a precursor to both ozone and PM). The NO_x ozone and PM benefits are calculated separately and then combined. To calculate NO_x ozone benefits, annual NO_x emissions are multiplied by 5/12 (to account for the fact that ozone benefits accrue only during warmer months, or "ozone season") prior to their multiplication with the NO_x-ozone benefit-per-ton numbers. Further details on these benefit estimates can be found in the EPA regulatory document.[190]

Benefit-per-ton estimates for each pollutant are provided for 2020, 2025, and 2030. To find benefits during other years, we interpolate and extrapolate in a linear manner. Power-sector benefit-per-ton estimates are shown in Figure C-6.

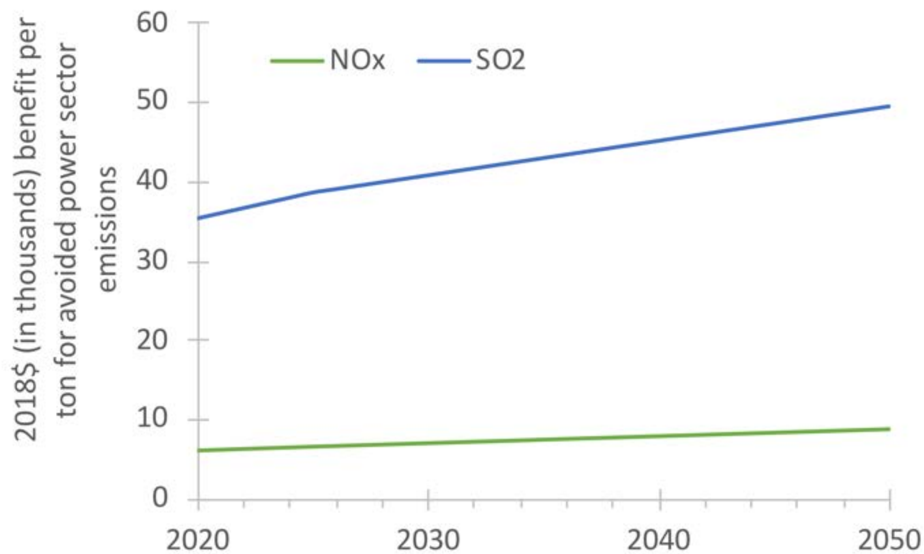


Figure C-6. Power-sector benefits per metric ton of avoided emissions

The Reference scenario air-quality and health damages from the power sector in 2020 are equal to $27 billion, roughly equal to independent literature estimates using alternate methods, specifically after accounting for the use of the lower (rather than centralized) marginal damage estimate.[193] This "sanity check," and a similar check in the vehicle sector, are based on total damages (emissions × marginal damage) rather than checking the total emissions and the damage factors independently. However, this check still provides some confidence that the results are consistent with existing literature; it is unlikely that large, but perfectly countervailing, errors are present in our analysis.

Important uncertainties are associated with these benefit-per-ton estimates, beyond the obvious uncertainty associated with any future predictions. These uncertainties are presented in great detail in EPA (2015).[190] We briefly summarize the most important areas of uncertainty here. First, there are two primary epidemiological study lines that quantify the mortality risk of population exposure to $PM_{2.5}$. Our benefit numbers represent the study with the lower risk assessment (i.e., Krewski et al.,[309] not Lepuele et al.[310]). However, each of these studies is equally valid, and there is an approximate factor of two between these studies. In other words, the total benefits would be doubled if we chose the higher risk estimate. It is common to find an average value between the two estimates, but because we are presenting order-of-magnitude estimates, this is not necessary. A second issue is that we are not calculating the benefits of directly emitted PM from the power sector. Accounting for direct PM power-sector emissions may increase total benefits of decarbonization by approximately 20%. Finally, the air-quality modeling, including both atmospheric chemistry and transport, is uncertain, and different models produce a variety of outcomes. Comparison across models, however, indicates that—when assessing national, sector-wide benefits—total benefit estimates are more sensitive to the epidemiological uncertainties than the air-quality modeling uncertainties.[311]

Vehicle-sector benefit-per-ton estimates: Vehicle-sector benefit-per-ton estimates are derived from Wolfe et al.,[198] which provides national estimates of damages by sector for 2025. Specifically, we use the national values for the "heavy-duty diesel" sector and "light-duty gas cars and motorcycles" sector presented in that study's Table 2 as the closest matches to our sectors. These values also depend on the exposure-risk relationships developed by Krewski et al.[309] We add an escalator of 1% per year to account for population and income growth. This escalator roughly mirrors the effective escalator found for power-sector benefit-per-ton estimates within the EPA regulatory document.[190] The final results are not particularly sensitive to the exact value of this escalator (e.g., total benefits from the Decarb+E scenario increase by about 30% if the escalator is tripled to 3%). Benefit-per-ton values are shown in Figure C-7.

The Reference scenario air-quality and health damages from the vehicle sector in 2020 are equal to roughly $50 billion. We would like to compare this estimate to an independent estimate from the literature. However, while estimates of vehicle-sector damages exist for historical years, we were unable to find current independent estimates of total monetary damages from the on-road sector. This makes it challenging to compare our damage estimates to literature values, because vehicle emission rates have declined dramatically over the past two decades (Figure C-3). Davidson et al.[312] estimate that emissions from the on-road sector caused about 10,000 deaths in 2011 and will cause 5,500 deaths in 2025. If we use a standard valuation of 9.7 million 2018$ per death, this equates to about $100 billion in 2011 and $50 billion in 2025 (the $9.7 million value is based on the reduced risk of mortality, a topic discussed below and in the main text, with the exact value matching that of Heo et al.[313] but inflated to 2018$). Linearly interpolating between 2011 and 2025 gives a value of $70 billion for 2020. Though $70 billion is larger than our $50 billion estimate, we would not expect a perfect match due to methodological differences. These estimates match on an order-of-magnitude basis. Note that, to make the comparison on an "apples-to-apples" basis, we isolated mortalities caused by PM exposure within the Davidson et al.[312] analysis, excluding ozone benefits.

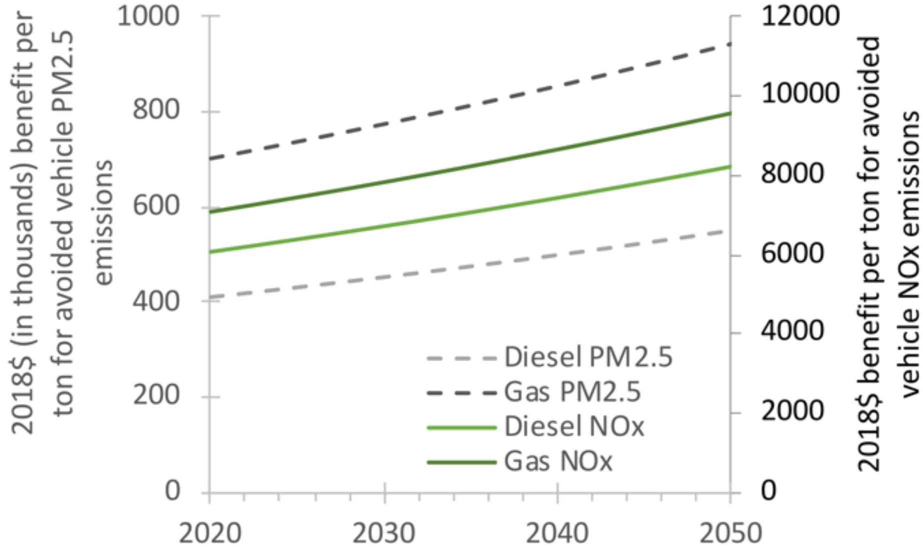


Figure C-7. Vehicle-sector benefit per metric ton of avoided emissions

$PM_{2.5}$ benefits are shown in the left axis and NO_x benefits on the right axis. The $PM_{2.5}$ values are listed in thousands of dollars (i.e., on a per-ton basis, they are an order of magnitude larger than the NO_x values).

These benefit-per-ton estimates are slightly sensitive to the choice of vehicle type. For example, the benefit per ton for "light-duty gas cars and motorcycles" is about 20% larger than that for light-duty gas trucks. Of course, the use of national rather than regional values adds some uncertainty. However, as in the power sector, the largest source of uncertainty is related to epidemiolocal relationships and the air-quality transport and chemistry modeling.

Finally, there is uncertainty about how to value premature death. As described in the main text, we use the value of reduced risk of mortality across the population to drive this valuation, often called the "value of statistical life." Further discussion of this topic can be found in EPA (2015).[190]

Summary of Total Benefit Estimates

We have now summarized how we estimate emissions and marginal damage rates. The product of these two quantities yields total damage (or total benefits), which are then time-discounted with a rate of 5%. Figure C-8 shows discounted total damages by sector, pollutant, and scenario. Benefits of the Decarb and Decarb+E scenario can be seen as the difference from the Reference scenario. It is clear from this figure that reducing power-sector SO_2 emissions provides the majority of the benefits. Near-term reduction of vehicle-sector emissions, NO_x and especially $PM_{2.5}$, have the potential to provide substantial additional benefit. However, this would require a different—and potentially more costly—scenario of vehicle replacement, focused on diesel trucks, rather than a scenario based on natural fleet turnover.

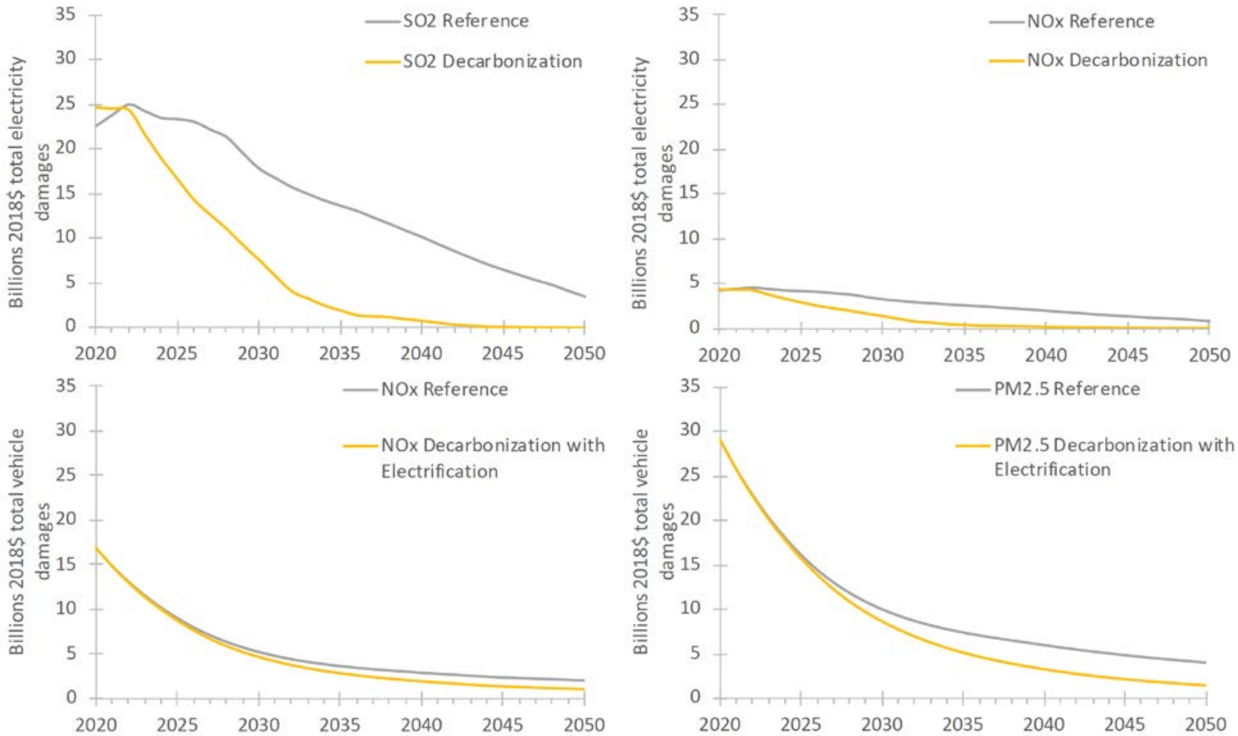


Figure C-8. Discounted annual damages by sector, pollutant, and scenario

The top row shows power-sector damages, and the bottom row shows vehicle-sector damages.

Summary of Key Caveats

Though we list several important caveats below, we believe that none of these uncertainties (aside from the scenario design itself) would change our findings from an order-of-magnitude perspective. Many, but not all, of these uncertainties imply that our benefit estimates are on the lower end of the range of defensible benefit estimates. We discuss most of these uncertainties above and in the main text.

The most uncertain aspect of our benefit estimates is the future scenarios themselves. Changing regulations, technology, fuel prices, economic conditions, and so forth could render these scenarios irrelevant. Our estimate is especially sensitive to the timing of emission reductions, both for the power sector and the vehicle sector, because both sectors face emission reductions even in the Reference scenario. In general, however, predictions are not so much statements of what will happen, but rather tools for decision making given the best information that is currently available. With that thought, we next discuss important caveats and uncertainties that remain after the scenarios themselves are accepted.

One of the most important uncertainties relates to the epidemiological representation of the health risk of exposure to PM. As described earlier, there are two seminal studies in this field, and we use the study with the lower estimates of risk. The difference between the studies is roughly a factor of two. We use the same main epidemiological study for the vehicle and power sectors. If we used a central value between these two studies, our damage and benefit estimates would increase by roughly 50%.

There is also uncertainty as to the value of reduced mortality risk, or "value of statistical life," which translates the estimates of avoided mortalities into monetary value. A similar value is used across all the studies we cite, which is close to $10 million per avoided death. This value has been used as a "standard" value across many studies over many years. However, this value is fundamentally challenging to quantify and thus represents an important source of uncertainty.

For both sectors, we use national-average benefit-per-ton estimates. There are differences in impact between emissions in different locations, and our analysis does not account for these differences. However, because the analysis is national in scope, the national-average emissions benefit estimates are appropriate.

For both sectors, we analyze only a subset of pollutants and damage pathways. The pollutant sets and damage pathways are not consistent between sectors; we focus on the most important pollutants within each sector and exclude pollutants with minor impacts. These exclusions are likely to be at the level of 10% to 20%; for example, Davidson et al.[312] found ozone damages accounted for about 20% of premature mortalities due to mobile source emissions in 2025, and EPA found that benefits from reducing directly emitted $PM_{2.5}$ were less than 8% of the total monetized benefits of the Clean Power Plan.[190] Our analysis excludes both ozone damages from vehicles and directly emitted PM from the power sector.

Regarding scope, we do not monetize benefits across all sectors of the economy. Instead, we focus only on the sectors that saw the most change in the scenarios: the power and vehicle sectors.

For the vehicle sector, we assume all gasoline is used in light-duty vehicles and all diesel is used by heavy-duty trucks. This simplification obscures the fact that different vehicle types have different emission rates and are used in different locations. Given that the majority of fuel use falls into the two selected vehicle type categories, and given the relatively narrow spread of emission factors between vehicle types (e.g., light-duty diesel emission rates are within about 20% of heavy-duty diesel emission rates), shown by Wolfe et al.,[198] we do not believe this uncertainty is critical. However, vehicle emission rates in general may change in the future, especially in response to regulations.

An uncertainty regarding vehicle electrification is the question of which vehicles will be switched to electric. Currently, we assume fleet-average emission rates do not vary by scenario. This assumption could lead to an underestimate or overestimate of vehicle air-quality benefits. Benefits would be underestimated if policies, or cost-benefit calculations by vehicle owners, lead vehicle owners to replace older trucks and cars substantially earlier than they would have without an electric vehicle option. Benefits would be overestimated if switching to electric vehicles occurred only at the end of the expected useful life of gasoline or diesel vehicles. In this latter case, electric vehicles would only replace the purchase of a new (and already relatively clean) vehicle, implying that the fleet average emission factors from the Reference scenario overestimate the emission savings from the switch to electric. However, in the Decarb+E scenario, the results are unlikely to be particularly sensitive to the assumptions of which vehicles will be replaced by electric vehicles, because most fuel reduction occurs after 2030, when fleet-average emission rates are largely stable. That is, fleet-average rates have already declined so that there is less difference between newer and older vehicle emission rates, and the vintages of vehicles replaced by electric vehicles will be less influential on overall emission benefits.

Finally, there is important uncertainty involved with the air-quality modeling. Many different models have been developed to estimate the benefits of emissions reductions, and there are important differences between these models. However, prior comparisons of these estimates show that the range between different models is generally smaller, or of the same magnitude as, the range between the epidemiological studies themselves.[311]

This discussion summarizes the most important uncertainties and sensitivities related to our benefit estimates. It also summarizes the issues that must be addressed to refine these estimates to be more precise than the current order-of-magnitude assessment.

Appendix D. CSP Tower Systems: Material Requirements and Retirements by Scenario

Table D-1. Material Requirements for CSP Tower Systems (from Whitaker et al.[26])

Material Name	Site Improvement (metric tons)	Receiver System (metric tons)	Collector System (metric tons)	TES System (metric tons)	SG1 System (metric tons)	EPG1 System (metric tons)	Total (metric tons)
Concrete	6.24E+02	5.30E+04	7.16E+04	2.88E+03	1.01E+04	1.22E+04	1.50E+05
Aggregate	7.47E+04	0	0	0	0	4.48E+02	7.51E+04
Carbon steel	9.91E+01	3.28E+03	2.78E+04	5.25E+02	2.90E+03	5.18E+03	3.98E+04
Sodium nitrate	0	0	0	1.05E+04	0	0	1.05E+04
Solar glass	0	0	1.00E+04	0	0	0	1.00E+04
Asphalt	9.22E+03	0	0	0	0	0	9.22E+03
Potassium nitrate	0	0	0	6.97E+03	0	0	6.97E+03
Rip rap	5.80E+03	0	0	0	0	0	5.80E+03
Stainless steel	0	2.11E+02	0	4.52E+02	1.43E+02	3.41E+01	8.40E+02
Brick	0	0	0	7.38E+02	0	0	7.38E+02
High-density polyethylene	3.50E+02	1.05E+00	0	4.94E-01	8.83E-01	5.02E+01	4.03E+02
Copper	1.13E+00	4.18E+01	0	9.99E+00	6.83E+01	1.84E+02	3.05E+02
Aluminum	2.39E-02	6.12E+00	0	1.66E+01	7.30E+00	2.57E+02	2.87E+02
Mineral wool	0	6.68E+01	0	1.47E+02	0	1.29E+00	2.15E+02
Foam glass	0	0	0	1.51E+02	0	0	1.51E+02
Calcium silicate	0	5.93E+01	0	0	2.58E+01	4.67E+01	1.32E+02
Transformer oil	0	0	0	0	0	5.53E+01	5.53E+01
Polypropylene	4.90E+01	2.85E-02	0	0	2.20E-02	2.58E-01	4.93E+01

Material Name	Site Improvement (metric tons)	Receiver System (metric tons)	Collector System (metric tons)	TES System (metric tons)	SG1 System (metric tons)	EPG1 System (metric tons)	Total (metric tons)
Polyvinyl chloride	0	1.25E+01	0	2.09E+00	9.78E+00	2.23E+01	4.66E+01
Zinc	8.52E+00	1.20E+01	0	3.50E-01	1.03E+01	8.42E+00	3.97E+01
Fiber glass	0	2.08E-02	0	0	1.60E-02	3.84E+01	3.84E+01
Fiber board	0	0	0	3.33E+01	0	0	3.33E+01
Lubricating oil	0	0	0	0	0	2.66E+01	2.66E+01
Propylene glycol	0	0	0	0	0	1.17E+01	1.17E+01
Rubber	0	7.12E-01	0	0	4.23E+00	3.41E+00	8.35E+00
Epoxy resin	0	6.99E-01	0	1.00E-01	6.72E-01	4.67E+00	6.14E+00
Nickel alloys	0	3.86E+00	0	5.81E-01	1.28E+00	1.31E-02	5.73E+00

[1] SG is steam generation system; EPG is the electric power generation system.

Table D-2. CSP Retirements by Scenario (from ReEDS)

Scenario	Year	State	Retired Capacity (GW)
Decarb	2044	Arizona	0.1477
Decarb	2046	Nevada	0.055
Decarb	2040	California	0.2015
Decarb	2040	Nevada	0.03425
Decarb	2040	Arizona	0.00125
Decarb	2040	California	0.00175
Decarb	2042	Arizona	0.0025
Decarb	2042	New Mexico	0.0005
Decarb	2042	Colorado	0.015
Decarb	2042	California	0.015024
Decarb	2044	California	0.4646
Decarb	2044	California	0.00315
Decarb	2044	Utah	0.00075
Decarb	2044	Arizona	0.001
Decarb+E	2044	Arizona	0.1477
Decarb+E	2046	Nevada	0.055
Decarb+E	2040	California	0.2015
Decarb+E	2040	Nevada	0.03425
Decarb+E	2040	Arizona	0.00125
Decarb+E	2040	California	0.00175
Decarb+E	2042	Arizona	0.0025
Decarb+E	2042	New Mexico	0.0005

Scenario	Year	State	Retired Capacity (GW)
Decarb+E	2042	Colorado	0.015
Decarb+E	2042	California	0.015024
Decarb+E	2044	California	0.4646
Decarb+E	2044	California	0.00315
Decarb+E	2044	Utah	0.00075
Decarb+E	2044	Arizona	0.001
Reference	2044	Arizona	0.1477
Reference	2046	Nevada	0.055
Reference	2040	California	0.2015
Reference	2040	Nevada	0.03425
Reference	2040	Arizona	0.00125
Reference	2040	California	0.00175
Reference	2042	Arizona	0.0025
Reference	2042	New Mexico	0.0005
Reference	2042	Colorado	0.015
Reference	2042	California	0.015024
Reference	2044	California	0.4646
Reference	2044	California	0.00315
Reference	2044	Utah	0.00075
Reference	2044	Arizona	0.001