April 17, 2024

EPA-SAB-24-007

The Honorable Michael S. Regan
Administrator
U.S. Environmental Protection Agency
1200 Pennsylvania Avenue, N.W.
Washington, D.C. 20460

Subject: Transmittal of the Final Science Advisory Board Report: *Review of the Science Supporting the Proposed Rule Titled, New Source Performance Standards for Greenhouse Gas Emissions from New, Modified, and Reconstructed Fossil Fuel-Fired Electric Generating Units; Emission Guidelines for Greenhouse Gas Emissions from Existing Fossil Fuel-Fired Electric Generating Units; and Repeal of the Affordable Clean Energy Rule (RIN 2060–AV09)*

Dear Administrator Regan,

The Environmental Research, Development, and Demonstration Authorization Act of 1978 (ERDDAA) requires the Environmental Protection Agency (EPA) to make available to the Science Advisory Board (SAB) proposed criteria documents, standards, limitations, or regulations provided to any other Federal agency for formal review and comment, together with relevant scientific and technical information on which the proposed action is based. The SAB may then make available to the Administrator, within the time specified by the Administrator, its advice, and any comments on the adequacy of the scientific and technical basis of the proposed action. Thus, the SAB is submitting the attached regulatory review report on the scientific and technical basis of the proposed rule titled *New Source Performance Standards for Greenhouse Gas Emissions from New, Modified, and Reconstructed Fossil Fuel-Fired Electric Generating Units; Emission Guidelines for Greenhouse Gas Emissions From Existing Fossil Fuel-Fired Electric Generating Units; and Repeal of the Affordable Clean Energy Rule (RIN 2060–AV09)* (GHG Power Plant Rule) published in the Federal Register on May 23, 2023.

On May 23, 2023, EPA proposed emission standards under section 111 of the Clean Air Act for new or modified or reconstructed fossil fuel-fired electricity generating units along with emission guidelines for existing fossil fuel-fired electricity generating units in the United States. The proposal sets limits and provides guidelines on the atmospheric emission of carbon dioxide. The proposal applies to fossil fuel-fired electricity generating units including new gas-fired combustion turbines, existing coal, oil and gas-fired steam generating units, and certain existing gas-fired combustion turbines. The EPA evaluated technologies, costs, energy requirements, performance, and other statutory factors, consistent with the "traditional" approach to establishing standards under section 111 of the Clean Air Act. The SAB elected to conduct a review of the science and technology considerations underlying the EPA proposal at a public meeting held on June 23, 2023.

In conducting this review, the SAB followed the science supporting EPA decisions review process outlined in the memo of February 28, 2022, signed by the Associate Administrator in the Office of Policy, the Deputy Assistant Administrator for Science Policy in the Office of Research and Development, and the Director of the Science Advisory Board Staff Office. A workgroup of SAB members developed charge questions on topics addressed in the proposed rule, reviewed the science supporting the proposed rule and developed a draft report containing responses to the charge questions. The workgroup took the lead in SAB deliberations on the draft report at a public meeting of the Chartered SAB held on February 29, 2024. The SAB's advice and comments on the science supporting the proposed rule are provided in the enclosed regulatory review report.

The SAB acknowledges the unprecedented challenge of achieving ambitious emission reduction targets in a dynamic technological and regulatory environment. However, the SAB finds that the greenhouse gas (GHG) emission reductions that would be achieved by the proposed rule are insufficient to align the United States electricity sector's emissions with established national goals, and that the use of both natural gas and hydrogen as fuels to generate electricity have atmospheric consequences that may not be accounted for in the rule. The SAB recommends that the EPA:

- consider substantial increases in the stringency of the proposed rule to align the outcomes with the Administration's goals and develop the ability to rapidly and realistically assess a wide variety of alternative measures and innovative technologies;

- incorporate a more accurate understanding of methane emissions from natural-gas value chains into future benefit analyses, in accordance with provisions in EPA's proposed rule titled, *Greenhouse Gas Reporting Rule: Revisions and Confidentiality Determinations for Petroleum and Natural Gas Systems* (RIN 2060-AV83); and

- form a working group that will regularly update the definition of low-GHG hydrogen as technological and industrial capabilities evolve.

Additional recommendations are provided in the enclosed report. The SAB appreciates the opportunity to provide comments on the science supporting the proposed rule. We look forward to receiving the Agency’s response.

Sincerely,

/s/

Kimberly L. Jones, Ph.D.
Chair
EPA Science Advisory Board

## NOTICE

This report has been written as part of the activities of the EPA Science Advisory Board, a public advisory committee providing extramural scientific information and advice to the Administrator and other officials of the Environmental Protection Agency. The Board is structured to provide balanced, expert assessment of scientific matters related to problems facing the Agency. This report has not been reviewed for approval by the Agency and, hence, the contents of this report do not represent the views and policies of the Environmental Protection Agency, nor of other agencies in the Executive Branch of the Federal government, nor does mention of trade names or commercial products constitute a recommendation for use. Reports of the EPA Science Advisory Board are posted on the EPA website at https://sab.epa.gov.

The SAB is a chartered federal advisory committee, operating under the Federal Advisory Committee Act (FACA; 5 U.S.C. 10). The committee provides advice to the Administrator of the U.S. Environmental Protection Agency on the scientific and technical underpinnings of the EPA's decisions. The findings and recommendations of the Committee do not represent the views of the Agency, and this document does not represent information approved or disseminated by EPA.

**U.S. Environmental Protection Agency**
**Science Advisory Board**

**CHAIR**
**Dr. Kimberly L. Jones**, Associate Provost and Professor of Civil and Environmental Engineering, Department of Civil and Environmental Engineering, Howard University, Washington, DC

**MEMBERS**
**Dr. C. Marjorie Aelion**, Dean Emerita and Professor Emerita, University of Massachusetts Amherst, Amherst, MA

**Dr. David T. Allen**, Gertz Regents Professor of Chemical Engineering and Director of the Center for Energy and Environmental Resources, Department of Chemical Engineering, The University of Texas, Austin, TX

**Dr. Susan Anenberg**, Chair, Department of Environmental and Occupational Health, Milken Institute School of Public Health, George Washington University, Washington, DC

**Dr. Florence Anoruo**, Assistant Professor of Plant and Environmental Science and Associate Research Scientist, Department of Biological and Physical Sciences, South Carolina State University, Orangeburg, SC

**Dr. Joseph Arvai**, Director, Wrigley Institute for Environment and Sustainability and Dana and David Dornsife Professor of Psychology, Department of Psychology and Biological Sciences, University of Southern California, Los Angeles, CA

**Dr. Barbara D. Beck**, Principal, Gradient, Boston, MA

**Dr. Roland Benke**, Director, Renaissance Code Development, LLC, Austin, TX

**Dr. Veronica J. Berrocal**, Professor, Department of Statistics, University of California Irvine (UCI), Irvine, CA

**Dr. Tami Bond**, Scott Presidential Chair in Energy, Environment and Health, Department of Mechanical Engineering, Colorado State University, Fort Collins, CO

**Dr. Mark Borsuk**, Professor of Civil and Environmental Engineering, Pratt School of Engineering, Duke University, Durham, NC

**Dr. Sylvie M. Brouder**, Professor and Wickersham Chair of Excellence in Agricultural Research, Department of Agronomy, Purdue University, West Lafayette, IN

**Dr. Jayajit Chakraborty**, Professor and Mellichamp Chair in Racial Environmental Justice, Bren School of Environmental Science & Management, University of California, Santa Barbara, Santa Barbara, CA

**Dr. Aimin Chen**, Professor of Epidemiology, Department of Biostatistics, Epidemiology and Informatics, Perelman School of Medicine, University of Pennsylvania, Philadelphia, PA

**Dr. John DiGiovanni**, Professor and Coulter R. Sublett Chair in Pharmacy, Division of Pharmacology and Toxicology and Department of Nutritional Sciences, Dell Pediatric Research Institute, The University of Texas at Austin, Austin, TX

**Dr. Ryan Emanuel**, Associate Professor, Nicholas School of the Environment, Duke University, Durham, NC

**Mr. Earl W. Fordham**, Deputy Director, Office of Radiation Protection, Division of Environmental Public Health, Washington Department of Health, Richland, WA

**Dr. Rebecca Fry**, Professor, Department of Environmental Sciences and Engineering, School of Global Public Health, University of North Carolina, Chapel Hill, Chapel Hill, NC

**Dr. John Guckenheimer**, Professor and Bullis Chair of Mathematics, Emeritus, Department of Mathematics, Center for Applied Mathematics, Cornell University, Ithaca, NY

**Dr. Steven P. Hamburg**, Chief Scientist, Environmental Defense Fund, Providence, RI

**Dr. Selene Hernandez-Ruiz**, Director, Laboratory and Analytical Services Division, Water Resources Mission Area, U.S. Geological Survey, Lakewood, CO

**Dr. Elena G. Irwin**, Distinguished Professor of Food, Agricultural and Environmental Sciences in Economics and Sustainability and Faculty Director for the Sustainability Institute, Department of Agricultural, Environmental, and Development Economics, The Ohio State University, Columbus, OH

**Dr. David Keiser**, Professor, Department of Resource Economics, University of Massachusetts Amherst, Amherst, MA

**Dr. Mark W. LeChevallier**, Principal, Dr. Water Consulting, LLC, Morrison, CO

**Dr. Angela M. Leung**, Clinical Associate Professor of Medicine, Department of Medicine, Division of Endocrinology, Diabetes, and Metabolism, David Geffen School of Medicine; VA Greater Los Angeles Healthcare System, University of California Los Angeles, Los Angeles, CA

**Director Lisa Lone Fight**, Science, Technology, and Research Department, MHA Nation, Three Affiliated Tribes, New Town, ND

**Dr. Lala Ma**, Associate Professor, Department of Economics, Gatton College of Business and Economics, University of Kentucky, Lexington, KY

**Dr. Enid Neptune**, Associate Professor of Medicine, Department of Medicine, Division of Pulmonary and Critical Care Medicine, Johns Hopkins University, Baltimore, MD

**Dr. Sheila Olmstead**, Dean Rusk Chair and Professor of Public Affairs, Lyndon B. Johnson School of Public Affairs, The University of Texas at Austin, Austin, TX

**Dr. Austin Omer**, Sustainable Systems Agronomist, Crop Science Commercial, Bayer U.S., Morton, IL

**Dr. Gloria Post**, Research Scientist, Division of Science and Research, New Jersey Department of Environmental Protection, Trenton, NJ

**Dr. Amanda D. Rodewald**, Garvin Professor and Senior Director of Center for Avian Population Studies, Department of Natural Resources and the Environment, Cornell Lab of Ornithology, Cornell University, Ithaca, NY

**Dr. Jonathan M. Samet**, Professor, Departments of Epidemiology and Environmental and Occupational Health, Colorado School of Public Health, Aurora, CO

**Dr. Elizabeth A. (Lianne) Sheppard**, Rohm and Haas Professor in Public Health Sciences, Department of Environmental & Occupational Health Sciences and Department of Biostatistics, Hans Rosling Center for Population Health, University of Washington, Seattle, WA

**Dr. Drew Shindell**, Nicholas Distinguished Professor of Earth Science, Duke Global Health Initiative, Nicholas School of the Environment, Duke University, Durham, NC

**Dr. Genee Smith**, Assistant Professor, Department of Environmental Health and Engineering, Bloomberg School of Public Health, Johns Hopkins University, Baltimore, MD

**Dr. Daniel O. Stram**, Professor, Department of Population and Public Health Sciences, Keck School of Medicine, University of Southern California, Los Angeles, CA

**Dr. Peter S. Thorne**, University of Iowa Distinguished Chair and Professor, Department of Occupational & Environmental Health, College of Public Health, Director of Human Toxicology Program, University of Iowa, Iowa City, IA

**Dr. Godfrey Arinze Uzochukwu**, Senior Professor, Waste Management Institute, North Carolina Agricultural and Technical State University, Greensboro, NC

**Dr. Dominique van der Mensbrugghe**, Research Professor and Director of the Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University, West Lafayette, IN

**Dr. Wei-Hsung Wang**, Professor, Center for Energy Studies and Director of the Radiation Safety Office, Louisiana State University, Baton Rouge, LA

**Dr. June Weintraub**, Deputy Director, Center for Environmental Health, California Department of Public Health, Sacramento, CA

**Dr. Sacoby Wilson**, Professor and Director of the Center for Community Engagement, Environmental Justice, and Health (CEEJH), Maryland Institute for Applied Environmental Health, School of Public Health, University of Maryland-College Park, College Park, MD

**Dr. Douglas Wolf**, Independent Consultant, Pittsboro, NC

**Dr. Yiliang Zhu**, Professor, Division of Epidemiology, Biostatistics, and Preventive Medicine Department of Internal Medicine, School of Medicine, University of New Mexico, Albuquerque, NM

**SCIENCE ADVISORY BOARD STAFF**

**Dr. Thomas Armitage**, Designated Federal Officer, U.S. Environmental Protection Agency, Science Advisory Board Staff Office, Washington, DC

**Final Science Advisory Board Report:** ***Review of the Science Supporting the Proposed Rule Titled, New Source Performance Standards for Greenhouse Gas Emissions from New, Modified, and Reconstructed Fossil Fuel-Fired Electric Generating Units; Emission Guidelines for Greenhouse Gas Emissions from Existing Fossil Fuel-Fired Electric Generating Units; and Repeal of the Affordable Clean Energy Rule (RIN 2060–AV09)***

## TABLE OF CONTENTS

## ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| ACS | American Community Survey |
| BENMAP-CE | Environmental Benefits Mapping and Analysis Program-Community Edition |
| BSER | Best System of Emission Reduction |
| CAA | Clean Air Act |
| CAMx | Comprehensive Air Quality Model with Extensions |
| CCS | carbon capture and sequestration |
| CASAC | Clean Air Scientific Advisory Committee |
| $CH_4$ | methane |
| $CO_2$ | carbon dioxide |
| DoE | U.S. Department of Energy |
| EGU | Electricity Generating Unit |
| EJ | Environmental Justice |
| EPA | U.S. Environmental Protection Agency |
| ERDDAA | Environmental Research, Development, and Demonstration Authorization Act of 1978 |
| GHG | greenhouse gas |
| GHGRP | Greenhouse Gas Reporting Program |
| GHG Reporting Rule | Greenhouse Gas Reporting Rule: Revisions and Confidentiality Determinations for Petroleum and Natural Gas Systems |
| Gt | Gigatonne |
| GW | Gigawatt |
| GWP | Global Warming Potential |
| $H_2$ | hydrogen |
| HAP | Hazardous Air Pollutant |
| IPCC | Intergovernmental Panel on Climate Change |
| ISA | Integrated Science Assessment |
| IWG | Greenhouse Gas Monitoring and Measurement Interagency Working Group |
| kg | kilogram |
| kg/h | kilogram per hour |
| MMT | million metric tons |
| MOE | margin of error |
| MW | Megawatt |
| NAAQS | National Ambient Air Quality Standards |
| NASEM | National Academies of Science, Engineering and Medicine |
| NDC | Nationally Determined Contribution (of greenhouse gas reductions) |
| NSPS | New Source Performance Standards |
| PM | Particulate Matter |
| RIA | Regulatory Impact Assessment |
| SAB | EPA Science Advisory Board |
| SC-GHG | Social Cost of Greenhouse Gases |

| | |
|---|---|
| TCEQ | Texas Commission on Environmental Quality |
| TRL | Technology Readiness Level |
| TWh | Terawatt-hours |
| UNFCCC | United Nations Framework Convention on Climate Change |
| USGCRP | U.S. Global Change Research Program |
| VOC | volatile organic compound |

# 1. INTRODUCTION

As part of its statutory duties, the EPA Science Advisory Board (SAB) may provide advice and comments on the scientific and technical basis of planned EPA regulatory actions pursuant to the Environmental Research, Development, and Demonstration Authorization Act of 1978 (ERDDAA). ERDDAA requires the EPA to make available to the SAB proposed criteria documents, standards, limitations, or regulations, together with the relevant scientific and technical information on which the proposed action is based. Based on this information, the SAB may provide advice and comments. Thus, the SAB has reviewed the scientific and technical basis of the proposed rule titled *New Source Performance Standards for Greenhouse Gas Emissions From New, Modified, and Reconstructed Fossil Fuel-Fired Electric Generating Units; Emission Guidelines for Greenhouse Gas Emissions from Existing Fossil Fuel-Fired Electric Generating Units; and Repeal of the Affordable Clean Energy Rule (RIN 2060–AV09)* (GHG Power Plant Rule or "proposed rule") published in the Federal Register on May 23, 2023.[1]

In 2009, EPA concluded that the emission of greenhouse gases (GHGs), including carbon dioxide, endangers public health and welfare. This conclusion is consistent with the international scientific consensus and is strongly supported by a growing body of scientific evidence. By establishing performance standards and providing emission guidelines in the proposed rule reviewed here, the EPA is attempting to reduce a significant quantity of GHG emissions from new and existing fossil-fuel fired electricity generating units. The EPA under the authority granted by section 111 of the Clean Air Act evaluated the scientific and technological feasibility of several emission reduction approaches, and considered other factors, such as cost, to develop the proposal being reviewed.

In conducting this review, the SAB followed the engagement process for review of science supporting EPA decisions outlined in the memo of February 28, 2022, signed by the Associate Administrator in the Office of Policy, the Deputy Assistant Administrator for Science Policy in the Office of Research and Development, and the Director of the Science Advisory Board Staff Office. The SAB met on June 23, 2023, and elected to review the scientific and technical basis of the proposed rule. A workgroup of SAB members was assembled to review the proposed rule, and a subset of workgroup members responded to charge questions developed by the group on topics of interest in the proposed rule. The SAB Workgroup consisted of Drs. David Allen (chair of the Workgroup), Susan Anenberg, Tami Bond, Jayajit Chakraborty, Steven Hamburg, David Keiser, Jonathan Samet, and Drew Shindell. The workgroup took the lead in SAB deliberations on the science supporting the proposed rule at a public meeting of the Chartered SAB held on February 29, 2024.

[1] New Source Performance Standards for Greenhouse Gas Emissions from New, Modified, and Reconstructed Fossil Fuel-Fired Electric Generating Units: Emission Guidelines for Greenhouse Gas Emissions from Existing Fossil Fuel-Fired Electric Generating Units; and Repeal of the Affordable Clean Energy Rule, Federal Register, Vol. 88, No. 99, page 33240, Tuesday, May 23, 2023. [Available at: https://www.federalregister.gov/documents/2023/05/23/2023-10141/new-source-performance-standards-for-greenhouse-gas-emissions-from-new-modified-and-reconstructed]

# 2. SAB ADVICE AND COMMENTS ON THE PROPOSED RULE

## 2.1. Overview and Relevance.

*2.1.1 Charge Question 1: Comment on the United States' commitment to limiting climate change, how cumulative greenhouse gas (GHG) emissions affect climate, the pace needed for greenhouse gas reductions, and the role of the electric-power generating system in achieving those reductions.*

*United States commitments*

The United States is a party to the United Nations Framework Convention on Climate Change (UNFCCC); the objective of the UNFCCC is to stabilize "greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."[2] The United States is also a party to the Paris Agreement, which identifies the levels to be achieved:

> Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;

These temperature targets are aligned with EPA's commitment to protecting the health and well-being of Americans.[3] Within both the UNFCCC and the Paris Agreement, the nation has committed to the principle of "common but differentiated responsibilities and respective capabilities," in which countries possessing advanced technology lead in combating climate change. As do all parties to the Paris Agreement, the United States produced its own Nationally Determined Contribution (NDC), or intended actions to mitigate climate impacts, in April 2021.

*Earth-system considerations*

Cumulative historical emissions of carbon dioxide ($CO_2$) are closely linked to global temperature change, and the carbon budget, consistent with a given warming level, is readily estimated. Through 2019, the world emitted around 2,560 gigatonnes (Gt) $CO_2$ (IPCC, 2022). The total worldwide remaining carbon budget for allowable emissions from 2020 onwards to meet 2 °C or 1.5 °C Paris targets is quite limited: just 500 Gt $CO_2$ for a 50% probability of keeping below 1.5 °C (IPCC, 2022). Global emissions are currently around 40 Gt $CO_2$ per year (IPCC, 2022), meaning that between 2020-2022 alone, humanity used around 120 Gt $CO_2$ of the small remaining budget. Large portions of the remaining carbon budget are emitted each year, so the time frame for emission reductions to near-zero becomes shorter. After updating contributions

---

[2] United Nations Framework Convention on Climate Change, United Nations, 1992; [Available at: https://unfccc.int/sites/default/files/convention_text_with_annexes_english_for_posting.pdf]
[3] FY 2022 – 2026 EPA Strategic Plan [Available at: https://www.epa.gov/system/files/documents/2022-03/fy-2022-2026-epa-strategic-plan.pdf]

from non-$CO_2$ drivers of climate change, such as methane, and accounting for the last few years of emissions, the carbon budget remaining after January 2023 is only about 250 Gt $CO_2$ for a 50% probability of keeping below 1.5 °C (Lamboll et al., 2023). Such a small budget would be exhausted by the end of 2028 if emissions remain at current levels. The share of the allowable future carbon budget allocated to the United States is small if the worldwide total is divided according to current emission levels, current population, or a combination of those (Raupach et al., 2014; Tavoni et al., 2015). The United States share becomes even smaller or vanishes entirely if historical emissions are taken into account.

No single timeframe can be assigned to any specific transition in any single country, as future climate will be set by total emissions from all sectors and all countries. However, specific timelines are widely reported in the scientific literature for many of the main features of the energy transition. The electricity generation sector plays an important role in keeping emissions within carbon budgets. It is the easiest sector to decarbonize based on the availability of low or zero carbon technology, societal acceptance of alternatives, and cost considerations (de Coninck et al., 2018). Scenarios in which emissions are successfully kept within carbon budgets generally decarbonize this sector rapidly and completely (Clarke et al., 2022). Scenarios that keep warming within the Paris Agreement's ambitious 1.5 °C target include a virtually complete phaseout of unabated coal-fired power by 2030 and achievement of net-zero emissions throughout the electricity sector by 2035 in developed countries.

In the United States, the electricity generation sector was responsible for about 31% of $CO_2$ emissions in 2022 (DoE, 2022). For several reasons, rapid and deep reductions in emissions from this sector are critical to meet climate goals. Reductions in emissions from the electricity generation sector are critical because of: (1) this sector's substantial current emissions, (2) the availability of existing options to eliminate emissions from the sector, many of which have lower costs than maintaining current systems, and (3) the need to electrify the bulk of current non-power sector fossil fuel end uses, such as transport and heating, that will increase electricity demand and would therefore otherwise increase the share of the electricity generation sector's $CO_2$ emissions (Clarke et al., 2022).

*Energy-system considerations*

Fossil fuels serve three purposes in today's energy system: they are sources of available energy; they store energy and release power when needed; and they serve as carriers that transport stored energy to the location of end-use. This combustion and subsequent release of products increases carbon dioxide in the atmosphere when carbon is a component of the fuel. The system of energy provision entails selecting not only energy sources but also the storage and conveyance of useful energy. An energy source may be extracted in one place (e.g., a coal mine); processed to a suitable quality in another location and combusted in yet another (a power plant). Each transformation, and each transportation, entails some losses of energy and fuel mass. Notably, the simple combustion of any fuel to produce electricity is a transformation with typical efficiencies of 35-50%. GHG emissions from an energy system are set by choices of source, storage, and carrier; and the end-use to which they are matched. System efficiency is optimized by minimizing the number of transformations and the distance over which carriers are distributed.

In the current United States regulatory environment, the EPA does not have jurisdiction over the entire energy system. Specifically, in *West Virginia vs. EPA* (U.S. Supreme Court Docket 20-1530, February 2022),[4] the United States Supreme Court ruled that Congress did not task the EPA with "balancing the many vital considerations of national policy implicated in the basic regulation of how Americans get their energy." The Court specifically addressed the issue of generation-shifting, averring that the mix of energy sources was not within the EPA's purview. In *West Virginia*, the Court stopped short of limiting the EPA to "measures that improve the pollution performance of <u>individual sources</u>, such that all other actions are ineligible to qualify as the [Best System of Emission Reductions]." But the Court encouraged such a focus and pointed out that "EPA has acted consistent with such a limitation for the first four decades of the [Clean Air Act]'s existence."

An implication of the *West Virginia* ruling is that in developing New Source Performance Standards under the authority of the Clean Air Act, the EPA is precluded from taking advantage of energy-system features external to individual electricity generating units (EGUs), including generation shifting as well as other energy innovations being spurred by the threat of climate change. The SAB infers that the limited authority granted to EPA also carries with it a limited responsibility for certain outcomes. In meeting national GHG emission goals and climate commitments, the EPA must be viewed as just one partner among federal agencies, States, industrial concerns, and the American public. Specifically, debating the projections of technological advance provided by the Department of Energy and other relevant agencies is likely not within the EPA's jurisdiction. Measures to reduce costs might occur within regional markets or an entire grid system, but participation in such cost optimization is not expected to be addressed in individual rules promulgated by the EPA. EGU operators have freedom of choice with regard to energy generation, storage, and distribution options outside the boundaries of their facilities. However, these factors are exogenous to EPA's rulemaking for power plants.

The SAB finds that the regulatory focus on individual facilities limits the EPA to three technological options for reducing GHG emissions from EGUs: (1) improving plant efficiency so that less fuel is required per kilowatt-hour output, known as heat rate improvements; (2) combusting the same fuel, but removing carbon from the exhaust with carbon capture and sequestration (CCS); or (3) using fuels with a lower carbon content, accomplished by emphasizing natural gas or firing or co-firing with low-carbon fuels such as hydrogen, or changing fuels entirely to a zero carbon option. Many efficiency gains have already been realized (Memorandum included in the proposed rule docket authored by Sargent and Lundy Chicago, IL dated March 2023[5]), and the proposed rule assumes that the Best System of Emission Reduction (BSER) includes all possible heat rate improvements. The proposed rule introduces the latter two options as alternatives to complete the BSER.

[4] https://www.supremecourt.gov/docket/docketfiles/html/public/20-1530.html

[5] Document can be accessed at https://www.regulations.gov/document/EPA-HQ-OAR-2023-0072-0018

## **2.2. Overview of the Regulatory Impact Analysis**

*2.2.1 Charge Question 2: Comment on the modeling framework employed by EPA for the overall analysis of costs, impacts, and benefits.*

The SAB reviewed the tools used by EPA to estimate changes in emissions, the costs of those changes, and the impacts of emissions and reduced emissions as presented in the Regulatory Impact Assessment conducted for the proposed rule. These tools are listed in Table 1. Overall, the SAB finds that the tools EPA selected for the analysis have been peer reviewed and are the best models available to the EPA. In the case of the computational general equilibrium model called SAGE, a new tool was developed and peer reviewed by the SAB (U.S. EPA SAB. 2020). The SAB previously recommended that the EPA develop such a model for use in regulation (U.S. EPA SAB, 2017). A novel aspect of the SAGE model analysis, which had not yet emerged at the time of the SAB peer review in 2020, is the addition of hydrogen as an energy carrier and storage medium.

The SAB commends the EPA for transparency in modeling and in sharing intermediate results, such as required electricity and hydrogen consumption within the power sector provided in the supplemental Regulatory Impact Assessment published on November 20, 2023, (88 FR 80682[6]). Such intermediate results aid public understanding in addition to the SAB's review.

Table 1: EPA Tools Used in the Estimation of Costs and Health Benefits

| EPA Tool | Use | Peer-Review |
|---|---|---|
| SAGE Computational General Equilibrium Model | Simulates inputs and outputs in nationwide economy by sector | Peer review conducted in 2020 |
| Integrated Planning Model (IPM) | Estimate emission reductions from individual electrical generating units based on policy changes; linked to SAGE | Peer review conducted in 2019 with EPA response in 2022[7] |
| CAMx version 7.10 | Model changes in ozone and $PM_{2.5}$ concentrations from the rule | Peer review in 1997 when developed[8] |
| Particulate Matter Source Apportionment Technology (PSAT) tool | Estimate contributions to $PM_{2.5}$ from groups of emission sources | Component of CAMx |

[6] Available at: https://www.federalregister.gov/documents/2023/11/20/2023-25580/new-source-performance-standards-for-greenhouse-gas-emissions-from-new-modified-and-reconstructed

[7] Available at: https://www.epa.gov/system/files/documents/2022-04/epas-response-to-ipm-v6-peer-review-report-4-18-2022.pdf

[8] Available at: https://gaftp.epa.gov/Air/aqmg/SCRAM/conferences/2000_7th_Conference_On_Air_Quality_Modeling/Review_Material/camx.pdf

| EPA Tool | Use | Peer-Review |
|---|---|---|
| Anthropogenic Precursor Culpability Assessment (APCA) tool | Estimate contributions to ozone from groups of emission sources | Component of CAMx |
| BENMAP-CE (Sacks et al., 2018) | Estimate counts of mortality and morbidity events; Monetize the benefits of reducing the numbers of morbidity and mortality events | Previous peer review and SAB review (U.S. EPA SAB, 2024) |

## 2.3. Achieving Greenhouse Gas Reduction Targets

*2.3.1 Charge Question 3. Comment on whether the proposed rule is likely to achieve greenhouse gas reduction targets from the power generation sector that are consistent with national commitments and international goals and treaties.*

*Magnitude and pace of reductions*

The United States' NDC, communicated under Article 4 of the Paris Agreement, commits to reduce economy-wide GHG emissions by 50-52% by 2030. Recognizing that the electricity sector is the most amenable sector for rapid decarbonization, the Biden Administration set forth a goal of net zero electricity sector emissions by 2035 as a critical component of meeting the 2030 NDC and a longer-term transition to net-zero $CO_2$ emissions (The White House, 2021).

The United States' NDC and electricity sector emission goals are consistent with analyses of the global transition required to keep planetary temperatures below low warming targets. For example, the United Nations Climate Solidarity Pact calls for the electricity sector to reach net zero emissions by 2035 and for coal-fired power to be phased out by 2030 in developed countries (UN, 2023). Similarly, the electricity sector achieves net zero emissions in advanced economies by 2035 in the Net Zero Emissions scenario from the International Energy Agency (IEA, 2022).

These transitions are clearly much faster than the proposed timelines for net zero electricity and $CO_2$ emission reductions from coal-fired EGUs in the proposed rule. The requirement of 40% natural gas co-firing for coal plants, starting in 2030, results in a 16% decrease in $CO_2$ intensity; an alternative is operating through December 31, 2034, with no reduction in $CO_2$ emissions if run with a capacity factor of no more than 20%, or operating through December 31, 2031, with no reduction of $CO_2$ emissions at any capacity factor. By capacity, more than half, 118 gigawatts (GW), of the United States' coal EGUs (212 GW) have announced plans for retirement by 2040, implying that those units would be permitted to release 84-100% of current emissions through the end of their operations, which could be as late as 2039.

Similarly, for power plants using natural gas, nearly complete co-firing with $H_2$ is required only by 2038 for large and frequently-operating plants, while intermediate-load gas EGUs are required to co-fire with only 30% co-firing from 2032 onwards. Smaller, frequently-used gas fired power plants, and large but infrequently-used gas plants, are not covered by the existing rule and hence could contribute substantial emissions in the future. In the absence of negative emission deployment within the electricity sector, the continued emissions permitted by the proposed rule from coal- and especially gas-fired power plants past 2035 are inconsistent with the 100% carbon-free electricity goal in the United States' NDC.

EPA's analysis[9] shows that the proposed rule would make a very modest contribution toward the NDC's proposed elimination of GHG emissions from this sector. The baseline projection does show a decrease in EGU emissions of more than 50% by 2035-2040 relative to 2028 and by 76-81% relative to 2005. However, emissions during 2035-2040 are still projected to range from 500 to 600 million metric tons $CO_2$ per year. Compared with baseline projections, the proposal would reduce emissions from EGUs by only about 7-8% in 2035 and 2040. EPA projects a 76% decrease in GHG emissions from 2005 to 2035 in the baseline analysis, and a 78% decrease over the same time period when the proposed rule is applied.

Detailed analyses of the transitions required to meet the United States' NDC have been published in the peer-reviewed scientific literature. A "central case" deep decarbonization scenario for the United States examined by Williams et al. (2021) illustrates the pace of the energy transition required to achieve net zero $CO_2$ emissions by 2050. In that scenario, natural-gas fired electricity generation decreases from about 1,800 terawatt-hours (TWh) (about 43% of generation) in 2023 to 700-800 TWh (about 10% of generation) in 2040. In contrast, EPA's analysis of this rule projects that it would only decrease generation from unabated gas to 1,063 TWh in 2040.

Other scenarios examined by Williams et al. (2021) include low land use, delayed electrification, and 100% renewables. Those scenarios rely on even less energy from unabated natural gas in 2050 – roughly 100-300 TWh versus ~350 TWh in the central case (values in 2040 were not reported), suggesting the 2040 decrease in the central case may be on the low side across NDC consistent scenarios. Coal-fired power is phased out by 2030 across all pathways examined by Williams et al. (2021), with less than 1% of current generating capacity left in 2030, again a faster pace than the EPA's modeling of the effects of the proposed rule.

Global projections of transitions needed to meet climate goals, including those reported in the Intergovernmental Panel on Climate Change (IPCC) AR6 Synthesis Report: Climate Change 2023, (IPCC, 2023), are consistent with the Williams et al. (2021) study. Unabated coal decreases by about 70-80% worldwide by 2030 in scenarios consistent with reaching 1.5 °C (Allen et al., 2018; Clarke et al., 2022). The IPCC AR6 states that "To limit warming to 2 °C or lower, and without new builds, existing coal plants will need to retire 10 to 25 years earlier than the historical average operating lifetime" (Clarke et al., 2022). Therefore, in order to meet stated

[9] Table 3 in Memorandum on Additional Modeling Analysis EPA-HQ-OAR-2023-0072-0237 [Available at: https://www.regulations.gov/document/EPA-HQ-OAR-2023-0072-0237 last accessed February 1, 2024.]

climate goals, the U.S. would need to retire its relatively old fleet of unabated coal-fired power plants faster than planned, and faster than in other countries, to meet low warming targets and its NDC.

Another consideration is that of lock-in, or capital investments that favor generation with specific fuels. While the use of natural gas fuel can be useful in meeting moderate GHG emission reduction goals, its continued use is consistent with short-term, but not longer-term goals (e.g., Riesz et al., 2015; De Sisternes et al., 2016). IPCC AR6 states: "If investments in coal and other fossil infrastructure continue, energy systems will be locked into higher emissions, making it harder to limit warming to well below 2 °C." (Clarke et al., 2022). While GHG emissions from both coal and natural gas can be mitigated with CCS or hydrogen co-firing, investing in technologies that burn fossil fuel carries the implication that mitigation technologies, which are still emerging, will work perfectly and ultimately obtain a zero-emission power sector (Elliston et al., 2014) or that low warming targets will not be achieved.

A final concern relates to the total carbon budget, which is the quantity relevant to temperature change and risk from climate change. Although most existing scenario projections include decreases in emissions beginning in 2021 (e.g., Williams et al., 2021; Clarke et al., 2022), emissions have continued at a high rate from 2020-2023. Thus, achieving carbon targets would necessitate even faster reductions than those in most existing scenarios.

The SAB is concerned about the continuation of allowable GHG emissions under the proposed rule, since the time required to implement responsive regulations is long compared to both the required pace of transition and compared to the rate of technological development. The SAB encourages EPA to consider increases in the stringency of the proposed rule, including requirements for co-firing with hydrogen earlier than 2038 for large and frequently used gas-fired power plants; expansion of the rule to cover smaller, frequently used gas-fired power plants; and more rapid timescales for implementing emission controls for coal-fired units retiring between 2030 and 2040.

**Finding: The SAB finds that GHG emission reductions that would be achieved by the proposed rule are insufficient to align the United States electricity sector's emissions with national goals. Given the importance of this sector in leading the way towards net-zero GHG emissions, it is very likely that the proposed rule is inconsistent with Paris Agreement targets. It appears that in 2035 and 2040, the proposed rule would have a small influence on baseline electricity-sector $CO_2$ emissions. The proposed rule also lacks provisions to recognize the importance of total carbon budgets in achieving temperature targets.**

**Recommendation: The SAB recommends that the EPA consider substantial increases in the stringency of the proposed rule, to align the outcomes with the Administration's goals and the nation's Nationally Determined Contribution to meeting climate targets.**

*Value-Chain Measurement and Accounting*

Both methane, a primary component of natural gas, and hydrogen can be unintentionally released to the atmosphere during production, storage, transportation and use. Use of these gases to produce energy causes emissions not only at the point of transformation, but along the entire value chain (the chain of processes involved in production and transportation of fuel and generation of electricity). It is important to ensure that these "value-chain" emissions are considered in evaluations of climate impact.

**Methane.** Methane emissions from production are large enough in some regions to alter the net effect of electricity-generation schemes when included in analysis. For example, the apparent climate benefits of replacing fossil-fuel generated electricity with electricity generated with hydrogen produced from natural gas combined with carbon capture and storage may be offset or even eliminated (Howarth and Jacobson, 2021; Bauer, et al., 2022; Ocko and Hamburg, 2022).

Understanding this potential problem is complicated by uncertainties in quantification. Current inventories of natural gas value chain methane emissions in the United States consistently underestimate emissions when compared to empirical measurements (Alvarez et al., 2018). The Inflation Reduction Act of 2022 included a requirement to revise the Greenhouse Gas Reporting Program (subpart W) as it relates to emissions from oil and gas systems, requiring that reports be based on empirical data and be accurate.[10]

**Hydrogen.** While hydrogen is not included in the list of greenhouse gases currently considered by the EPA, its indirect effects on climate are significant. The hydrogen molecule is much smaller than other molecules and is therefore more likely to escape from pipes and other infrastructure than methane (Swain and Swain, 1992). Hydrogen is also highly reactive in the atmosphere. Its three known mechanisms of indirect impact on climate are: reacting with hydroxyl radical that reduces hydroxyl radical concentrations in the troposphere and leads to increased methane residence times; formation of tropospheric ozone; and formation of stratospheric water vapor (Paulot et al., 2021). Hydrogen is estimated to have a global warming potential (GWP) of 37 over 20 years and 12 over 100 years (IPCC, 2023; Sand et al., 2023; Derwent, 2023). For comparison, methane has a 20-year GWP of 81-83 and a 100-year GWP of 27-30 (IPCC,2023). Thus, value-chain hydrogen emissions can offset at least some of the climate benefits of shifting from fossil fuel to hydrogen energy systems, particularly during the first few decades after the switch is implemented (Ocko and Hamburg, 2022). The indirect climate impacts of methane emissions are considered in EPA's use of IPCC GWPs, and it would be inconsistent to ignore comparable impacts from hydrogen.

One of the challenges of recognizing and quantifying hydrogen emissions is the lack of empirical data on emissions from existing infrastructure. Estimates of hydrogen emissions from existing value chains vary by two orders of magnitude although no empirical data are currently available (Esquivel-Elizondo et al., 2023). Technology is emerging to make fast-response, high- precision

[10]The SAB reviewed the science supporting the EPA proposed rule titled, *Greenhouse Gas Reporting Rule: Revisions and Confidentiality Determinations for Petroleum and Natural Gas Systems* (RIN 2060-AV83) [SAB report EPA-SAB-24-004 is available at: https://sab.epa.gov/ords/sab/f?p=114:0:13875130647045:APPLICATION_PROCESS=REPORT_DOC:::REPORT_ID:1125]

measurements required to characterize value-chain emissions, but these measurements have not yet been made.

**Time horizon.** Using the 100-year GWP, which is EPA's default standard, inaccurately represents the near-term implications of fuel switching (Ocko et al., 2017) because hydrogen and methane are short-lived climate pollutants.

**Finding: The SAB finds that both methane (natural gas) and hydrogen have emissions and atmospheric consequences that are not accurately accounted for in current greenhouse analyses of climate impacts.**

**Recommendations: The SAB recommends that EPA incorporate more accurate estimates of methane emissions from natural-gas value chains into future climate benefit determinations and cost-benefit analyses. Such improvements appear to be required under the Inflation Reduction Act through improvements to the Greenhouse Gas Reporting Rule.**

**The SAB also recommends that EPA support or promote research on the air-quality, climate and health impacts of hydrogen leakage, including improvements in detection technology for hydrogen. An understanding of unintended atmospheric consequences of hydrogen usage should be incorporated into future climate benefit determinations and cost-benefit analyses.**

## 2.4. Mitigation Analysis

> *2.4.1 Charge Question 4. The Regulatory Impact Analysis (RIA) supporting the proposed rule describes two pathways to meet the Best System of Emission Reduction (BSER): carbon capture and sequestration (CCS) of 90% by 2035 or hydrogen co-firing of 30% by 2032 with an increase to 96% by 2038. Comment on whether EPA's analyses of GHG emission reduction associated with these technologies are reasonable, appropriate, and based on the most current understanding of costs and feasibility. Also comment on whether adequate consideration has been given to unintended impacts of these technologies.*

*Carbon Capture and Sequestration*

**Financial Costs.** The potential benefits and costs of the use of CCS in industry vary considerably due to the diversity of industrial processes; Kearns et al. (2021) provide a recent review. The EPA relies on current data showing that costs are high but are coming down. For example, Giannaris et al. (2020) suggest a CCS cost of 47 U.S. dollars per tonne of $CO_2$ for a 90% capture power generation plant based on insights from the Saskpower Boundary Dam pilot. The EPA relies on this work as well as an analysis by the Global CCS Institute and operating data from several operating CCS retrofits in the United States or Canada (88 FR 33254). The proposed rule acknowledges that at present only a small number of full-scale CCS power plants have been built, so that analysis of costs and cost projections rely on limited data from the energy sector. There is much more cost data from the industrial sector, which contributes to projections of cost decreases due to technological innovation and learning. The SAB notes that the EPA's 2015 final rule, *Standards of Performance for Greenhouse Gas Emissions from New, Modified, and Reconstructed Stationary Sources: Electric Generating Units* required CCS for new coal-fired EGUs, with higher cost estimates than those in the currently proposed rule.

**Storage limitations.** A challenge with all CCS strategies is construction of gathering and transport networks for $CO_2$. Transport and sequestration cost estimates included in the RIA are based on U.S. Department of Energy (DoE) reports indicating that most United States units are within 80 km of plausible storage locations (88 FR 33347). This seems to be a reasonable approach.

The United States has the potential for storage of several trillion tons of $CO_2$ (Kearns et al, 2017), as compared with emissions of about 1 billion tons per year from the power generation sector. The number of CCS storage facilities in the United States is growing rapidly, with planned projects nearly doubling between 2022 and 2023 (Global CCS Institute, 2023). Thus, use of CCS is not limited by capacity, but rather by the rate of infrastructure development and refinement.

**Finding: The SAB finds that cost estimates provided by the EPA for carbon capture and storage are reasonable given the emerging state of technology development.**

**Societal Costs.** Societal costs for CCS are discussed in the RIA in a qualitative sense as potentially important issues (section 4). Some impacts include ammonia emissions that cause air-quality degradation (Jablonka et al., 2023; Waxman et al., 2023). Data on the range of societal impacts are quite limited due to the lack of experience with CCS. Effects of CCS on drinking water are subject to separate rules, as geologic sequestration of $CO_2$ is regulated by the EPA through the Underground Injection Control Program under the Safe Drinking Water Act. Nonetheless, the Agency should include estimates of the social costs of drinking water-related impacts in the analysis of the proposed rule.

**Recommendation: Recognizing the limited history available to characterize widespread CCS operation, the SAB recommends support for monitoring societal impacts to identify risks and costs.**

*Hydrogen co-firing*

**Hydrogen cost and production capacity.** The proposed rule anticipates that the combination of the Bipartisan Infrastructure Law and the Inflation Reduction Act will help spur the development of low-GHG hydrogen. This aspiration is consistent with DoE's National Clean Hydrogen Strategy and Roadmap[11] (hereinafter Hydrogen Roadmap). Modeling for the RIA treats hydrogen as a fuel that "is available at affected sources at a delivered cost of $1/kg under the baseline, and at a delivered cost of $0.5/kg in years when the second phase of the proposed

[11] U.S. National Clean Hydrogen Strategy and Roadmap (energy.gov) [Available at: https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf]

New Source Performance Standards (NSPS) is assumed to be active." The first cost target is consistent with the Hydrogen Roadmap, which seeks "$1 per 1 kg within 1 decade" after 2021.

DoE's *Hydrogen Roadmap* production targets are 10 million metric tons (MMT) per year by 2030 and 20 MMT by 2040. One MMT of hydrogen, if combusted in a turbine of 60% efficiency, would produce about 24 TWh of electricity. Thus, EPA's projection of 42 TWh of hydrogen co-firing in 2040[12] consumes a small fraction of the projected production. This fraction in outlying years is broadly consistent with DoE's vision that hydrogen would be applied in the power generation sector as part of a "second wave" of hydrogen deployment (Fig. 41, *Hydrogen Roadmap*).

However, EPA's projection of 283 TWh co-firing in the intermediate year of 2035 is a cause for concern. This co-firing would consume almost all the projected hydrogen production capacity during a critical time when DoE's strategy might be directing hydrogen production toward other well-matched uses such as steel and cement production. In an economy-wide computable general equilibrium model, competition for this inexpensive hydrogen resource would normally have been simulated, but the limited representation of hydrogen as a fuel with a fixed cost may have allowed modeled consumption to occur without this natural limitation. The influence of this assumption might be explored with sensitivity analyses that use different, plausible costs of hydrogen.

**Recommendation: The SAB recommends that the costs of the proposed rule estimated in the RIA include realistic uncertainties in the price of available hydrogen throughout Phases I, II and III. These cost uncertainties should reflect potential competition for hydrogen as a limited resource.**

*Upstream emissions for hydrogen production*

Major pathways to producing hydrogen include reforming of carbon-based fuels and electrolysis using power from renewable sources. Essentially all hydrogen in use today is fossil-fuel derived, produced by steam reforming of methane. Carbon intensities range from 0.3-0.8 kg $CO_2$eq/kg $H_2$ for electrolysis using renewable energy to 20-25 kg $CO_2$eq/kg $H_2$ for hydrogen from reforming coal (Incer-Valverde et al, 2023; Fell et al., 2023). Thus, the origin of hydrogen fuel is an extremely important factor to consider in ensuring that net greenhouse gas reductions occur.

The EPA proposes a definition of "low-GHG hydrogen" that conforms to the lowest-emitting production identified in the United States Tax Code 45.V, which provides tax credits for clean hydrogen:

> The EPA is proposing that hydrogen qualifies as low-GHG hydrogen if it is produced through a process that results in a GHG emission rate of less than

[12] Integrated Proposal Modeling and Updated Baseline Analysis, Memo to the Docket, July 7, 2023; Table 11. [Available at: https://www.regulations.gov/docket/EPA-HQ-OAR-2023-0072/document?filter=memo%20]

0.45 kilograms of $CO_2$ equivalent per kilogram of hydrogen (kg $CO_2e$/kg $H_2$) on a well-to-gate basis[13,14].

The SAB supports the commitment to define low-GHG hydrogen, which is an important step to constrain GHG impacts arising from an increase in hydrogen production and use. The SAB also supports the emission limitation proposed by the EPA, i.e., 0.45 kg $CO_2eq$/kg $H_2$, a value that is coordinated with the envisioned national hydrogen system. The SAB further supports the definition of low-GHG hydrogen in terms of GHG emissions rather than production pathway or "color," which allows flexibility as technological pathways develop. Finally, the SAB recognizes that producers, end-users, and federal agencies will face important challenges in certifying that the hydrogen used to meet regulatory standards is indeed produced with low GHG emissions.[15]

The SAB has concerns about GHG-relevant emissions downstream of production. The "well-to-gate" definition of GHG emissions is appropriate for assessing production. However, for estimating impacts of fuel usage, a "well-to-wheels" (i.e., production to end-use) definition is more common because it includes the environmental effects of transport and delivery between locations of production and of use.

**Finding: The SAB affirms the necessity of a low-GHG hydrogen definition in the proposed rule and recommends that this definition appear before references to that term within the rule.**

**Recommendation: The SAB strongly recommends formation of a working group that will update the definition of low-GHG hydrogen regularly as technological and industrial capabilities evolve. The EPA should also support discussions about certification of low-GHG hydrogen based on a value-chain definition rather than a "well-to-gate" definition alone.**

*Readiness of turbine technology for co-firing hydrogen*

Adapting turbines to hydrogen co-firing requires addressing several issues, including the higher flame speeds of hydrogen which may require combustor redesign (Emerson et al., 2020) and additional NOx production. Manufacturers and researchers are actively working on turbine design to address these issues. Co-firing from 5% to 25% volume has been demonstrated in several projects, and there are current examples of utility companies preparing to co-fire hydrogen. Some major turbine manufacturers advertise their products as compatible for co-

---

[13] "The term "lifecycle greenhouse gas emissions" shall only include emissions through the point of production (well-to-gate), as determined under the most recent Greenhouse gases, Regulated Emissions, and Energy use in Transportation model (commonly referred to as the "GREET model") developed by Argonne National Laboratory." - USC 45V "Credit for Production of Clean Hydrogen" 45V.c.1.B

[14] The Agency writes, "We also note the model does not track upstream emissions associated with the production of the hydrogen (or any other modeled fuels such as coal and natural gas), nor any incremental electricity demand associated with its production." (3-13)

[15] See, for an example discussion the blog post from Bergman, Prest, and Palmer (2022) from Resources for the Future: https://www.resources.org/common-resources/how-can-hydrogen-producers-show-that-they-are-clean/.

firing up to 100% hydrogen by volume. Such high rates of hydrogen co-firing have been tested but do not currently appear in long-term practice.

Technology improvement and utility demonstration are necessary steps toward widespread adoption. These measures may not be sufficient to provide confidence in adopting novel technology for all EGUs, as some may be more committed to sustained and reliable operation than to pushing a technological envelope. It is not easy to assess confidence in the current state of maturity of technology from news reports and manufacturers' web sites, as these resources do not provide a complete assessment of remaining challenges and prevalence of trouble-free operation. However, Technology Readiness Levels (TRLs) are commonly employed to communicate technology maturity by other federal agencies (DoE, 2011), and advancement along the TRL scale provides confidence to other adopters as technologies begin to penetrate the user base. Without assessing the specific TRL of any technology, it is the SAB's assessment that the TRL of 25% hydrogen co-firing is far more advanced than the TRL of 96% co-firing, and that this difference may be currently acceptable as 96% co-firing is not envisioned until Phase III. To retain a commitment to the Phase III rates of co-firing, progress along a scale similar to the TRL ladder should be monitored as the eight-year revision of the NSPS approaches.

*Readiness of distribution system to transport hydrogen*

Hydrogen might be distributed through natural-gas pipelines, which require no infrastructure change because they already exist at EGUs operating natural-gas turbines. Concerns regarding hydrogen transport by pipeline include embrittlement of pipeline material, hydrogen leakage, and safety (Melaina et al., 2013; Topolski et al., 2022; Kappes and Perez, 2023). There has been practical experience delivering hydrogen content up to about 15-20% by volume. At higher fractions, both plastic pipelines, depending on the material, and steel pipelines can undergo embrittlement by reacting with hydrogen. Advanced materials are being developed but would require replacing existing infrastructure.

**Finding: The SAB finds uncertainties in the timing of hydrogen technology readiness, but recognizes these uncertainties as characteristic of a rapidly emerging technological field. As the rule is revisited and alternatives are discussed in the public domain, the SAB suggests communication of alternatives using Technology Readiness Levels.**

*Energy system considerations*

Hydrogen is envisioned to play an important role as a storage medium and carrier of energy (Figure 2). However, hydrogen is not an energy source; its chemical energy must be generated by separating it from the other elements in the molecules where it occurs, and low-GHG options for that generation are currently limited to electricity from renewable sources. The "round-trip" efficiency - from electricity to hydrogen to turbine-generated electricity - is less than 50%, sometimes much lower, depending upon the technology employed (Escamilla et al., 2022). Given this loss, the proposed co-firing with hydrogen for stationary sources is of greatest value when it provides energy storage to achieve load matching.

On a purely scientific basis, the SAB would recommend an approach to hydrogen utilization that optimized costs and end-use matching throughout the entire energy system. However, the SAB acknowledges that the proposed rule must be restricted to measures that can be deployed by individual EGUs and confirms that hydrogen co-firing is one of a limited set of such alternatives.

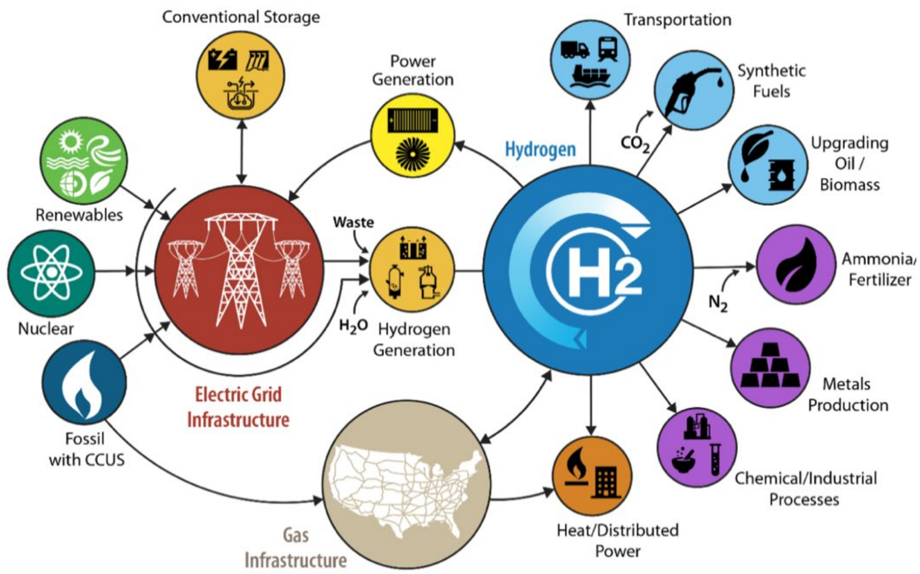


**Figure 1.** U.S. Department of Energy's "H2@scale" initiative to enable decarbonization. Reproduced from the *U.S. National Clean Strategy and Roadmap.* ([https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf](https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf) )

*Overall evaluation*

The SAB acknowledges the unprecedented nature of stipulating regulations to achieve ambitious emission targets within two decades, with available tools set by a dynamic technological and regulatory environment. The SAB affirms that this challenge should be addressed as part of the EPA's mission to protect human health and the environment. The SAB commends the EPA for its prior investment in integrated tools that aid in analysis and forecasting. Nevertheless, these tools are not yet adequate to adjust to the rapidly changing environment, leaving a gap to be filled in EPA's ability to assess alternatives with responsiveness. For example, modeling conducted for the RIA supporting the proposed rule was not yet able to represent competition for hydrogen within the economy, and it is not apparent how emerging technology, its capacity, or its readiness would be incorporated into ongoing assessments of the best system of emission reduction. The projected persistence of carbon emissions from the electricity-generating sector remains a fundamental barrier to the delivery of the United States' commitments to protecting climate and requires continual attention.

**Recommendation: The SAB strongly recommends that EPA develop, or support research to develop, the ability to rapidly and realistically assess how a wide variety of alternative measures and innovative technologies may affect overall greenhouse-gas emissions.**

**Further, the SAB strongly recommends that EPA engage in continuous use of these assessment tools to explore emerging opportunities and developing limitations. That is, EPA should conduct analysis proactively to lay a foundation for future rules, rather than reactively in response to proposed rules.**

## 2.5. Benefit Calculations

*2.5.1 Charge Question 5. Comment on whether the climate and health benefits identified in the proposed rule and associated technical support documents are appropriately estimated and bounded.*

*Social Cost of Greenhouse Gases*

To assess climate benefits associated with the proposed rule, EPA utilized Greenhouse Gas Monitoring and Measurement Interagency Working Group (IWG) estimates of the social costs of greenhouse gases (SC-GHG) in accordance with Executive Order 13990 of January 20, 2021. That order reinstated the IWG after it was disbanded in 2017 and required development of interim SC-GHGs within 30 days.[16] The estimates used in the proposed rule rely on the interim estimates of the social cost of carbon, methane, and nitrous oxide that were subsequently developed and reported by the IWG in February 2021. EPA notes that, "while likely an underestimate, [these] are the best currently available SC-GHG-estimates." [17] EPA noted that the IWG was working to update the SC-GHG estimates through a rigorous peer-review process, public comment solicitation, and review of the scientific literature.

In December 2022, EPA published a supplemental notice of proposed rulemaking, "Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review" (87 FR 74702).[18] To support this notice, EPA conducted a regulatory impact analysis (RIA). In this RIA, the Agency used the interim values of the SC-GHGs for the primary benefit-cost analysis. EPA focused on estimates of damages from methane. The Agency also included a sensitivity analysis that used draft SC-GHG estimates based on the latest available science and economics. These new estimates are

[16] https://www.federalregister.gov/documents/2021/01/25/2021-01765/protecting-public-health-and-the-environment-and-restoring-science-to-tackle-the-climate-crisis
[17] See section XIV.D. of the proposed rule.
[18]https://www.federalregister.gov/documents/2022/12/06/2022-24675/standards-of-performance-for-new-reconstructed-and-modified-sources-and-emissions-guidelines-for

described in a technical report from EPA, "Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances."[19] These updated SC-GHG values are more evidence-based and comprehensive than the IWG interim values. The EPA retained the use of the updated SC-GHG values in the EPA's final oil and gas performance standards published in December 2023.

The EPA noted, and the SAB agrees, that the IWG recommended values are likely to be underestimates. The updated values that EPA finalized in December 2023 are substantially higher, reflecting several additions and updates to the methodology to better reflect current scientific understanding, aligned with recommendations from the National Academy of Sciences, Engineering, and Medicine's "Valuing Climate Damages" report (NASEM 2017). For example, health impacts of extreme temperature are included in the updated SC-GHG estimates and not in the IWG values. A recent analysis by EPA scientists shows that adverse health impacts contribute more than any other quantified sector to damages from climate change in the United States, driven largely by mortality from climate-driven changes in extreme temperature and air quality (Hartin et al., 2023). Other changes made in the EPA's updated SC-GHG estimates include updates to the discounting approach, socioeconomic projections, climate models, damage functions, and increased transparency. While the updated estimates are not directly comparable to previous IWG estimates due to differences in the discount rate approach applied, the new value of $190 per ton $CO_2$ at a discount rate of 2% is more than three and a half times higher than the IWG's recommended value of $51 per ton $CO_2$ at a discount rate of 3%, with a rate of 2% being closest to the recommendation of the recent revisions to OMB's circular A-4.

In May 2023, an external review panel completed a final report on the methodology behind EPA's updated SC-GHG estimates. The committee reviewed the use of a modular approach to the methodological update, socioeconomic and emissions module, climate module, damages module, discounting module, and other issues including distributional impacts. While the report included only individual reviewer comments and not consensus across the panel, the reviewer comments taken together indicate the panel's assessment that the new estimates were well-designed and executed and represent a significant advance and improvement over the IWG 2021 interim values.

**Finding: The SAB finds that the analyses of climate impacts due to emission changes are scientifically sound in general.**

**Recommendation: The SAB recommends that the EPA apply its updated SC-GHG estimates to value the climate benefits of the proposed rule, acknowledging an external review panel's finding that the updated SC-GHG estimates are more comprehensive, transparent, and evidence-based.**

*Additional impacts*

[19] https://www.epa.gov/system/files/documents/2022-11/epa_scghg_report_draft_0.pdf

As with most evaluations of climate impacts, and all those relying upon the United States government's valuations for the social cost of greenhouse gases, the analyses neglect many effects of climate change that are clearly important but are difficult to quantify reliably. These neglected impacts include the economic effects of precipitation changes, the effects of extreme weather events, change in the spread of infectious diseases, and changes in ecosystem services, among many others (U.S. EPA, 2022).

Even if EPA's SC-GHG estimates were applied to estimate climate damages, the societal benefits of reducing $CO_2$ emissions would still be underestimated because even the updated SC-GHG estimates exclude many pathways by which climate change worsens public health. For example, the estimates exclude impacts of climate change on mortality and morbidity from climate-sensitive wildfire smoke, dust, ozone, and extreme weather. The scientific evidence linking climate change to these impacts is strong (Turnock et al., 2023; Hayden and Mahin, 2022, Hayden et al. 2023; West et al. 2023). If these damage pathways were included, the SC-GHG values would almost certainly be larger, leading to larger estimates of the societal benefits of this proposed rule.

In addition, the SC-GHG methodology in general cannot account for how different population subgroups would be impacted by climate change damages, often referred to as "climate injustice." Climate damages differ among individuals, communities, and population sub-groups. For example, the EPA's report, "Climate Change and Vulnerability in the United States: A Focus on Six Impacts" describes the degree to which four socially vulnerable populations – based on income, educational attainment, race and ethnicity, and age – may be disproportionately exposed and at risk to damages from climate change (U.S. EPA, 2021). Further, EPA has acknowledged the importance of climate equity as part of the overall aim of environmental justice (U.S. EPA, 2023a) and is now administering the new Environmental and Climate Justice Community Change Grants Program using funds from the Inflation Reduction Act. The current SC-GHG methodology (used to develop both the IWG recommended values in 2021 and the EPA's December 2022 values) applies a single value of damages with no geographic dimension that could potentially account for disparate impacts to certain communities or population subgroups. The external review panel for the EPA's December 2022 SC-GHG estimates did not comment extensively on the exclusion of climate injustice and disparate vulnerability to climate damages in the current SC-GHG approach.

**Recommendation: The SAB recommends that the EPA note the limitations of the SC-GHG approach and application of this approach to estimate the societal benefits of reduced greenhouse gas emissions in the proposed rule. The SAB further recommends that EPA consider how public health and equity impacts can be more appropriately and comprehensively captured in future SC-GHG updates.**

*Health Benefit Analysis*

The calculation of health benefits of the proposed rule, and the monetization of those benefits, is based on peer-reviewed assessments and models used widely by the EPA. The EPA's calculation of health benefits is based on the impact of the rule on particulate matter ($PM_{2.5}$)

and ozone, while acknowledging that emissions reductions would affect other pollutants, e.g., hazardous air pollutants. Figure 2 describes the components of the benefit analysis for $PM_{2.5}$. Three scenarios are modeled: the proposed best system of emissions reductions (BSER), a less stringent alternative, and a more stringent option. The calculations extend across the years 2024-2042 with snapshots provided for 2028, 2030, 2035, and 2040.

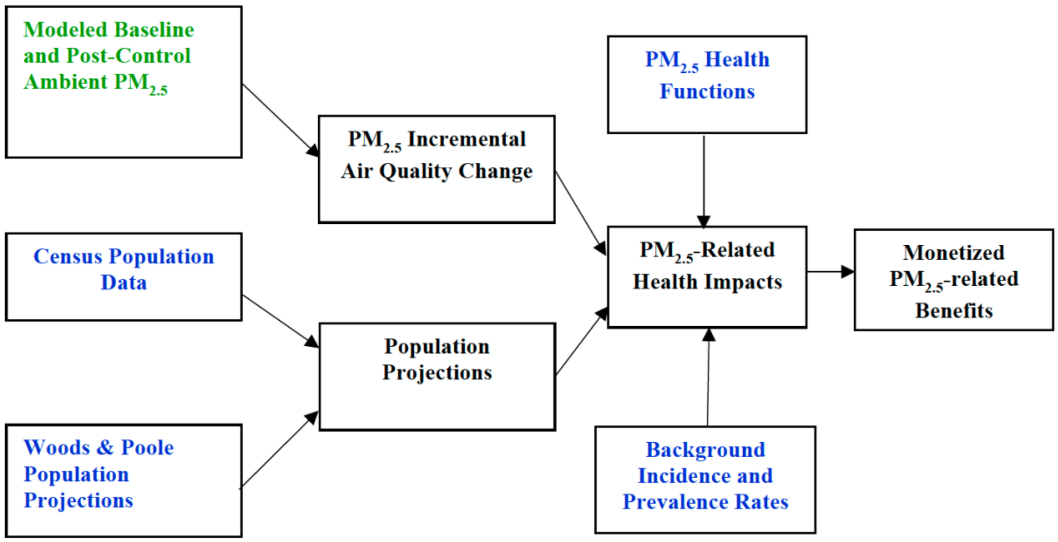


Figure 2. Data Inputs and Outputs for the BenMAP-CE Model.

The core data sets for the modeling are described in Figure 2 and their origins are well documented: the U.S. Census, population projections from Woods and Poole,[20] and the baseline incidence and mortality rates in the EPA's BENMAP-CE model,[21] which are documented in Table 12 of the Technical Support Document for the 2022 PM National Ambient Air Quality Standards (NAAQS) Reconsideration Proposal RIA (U.S. EPA 2023b).[22] The air quality changes in $PM_{2.5}$ and ozone were obtained via simulations in the Comprehensive Air Quality Model with Extensions (CAMx)[23] using scenarios of emissions reductions. Additionally, source apportionment was performed for 2026 to estimate the contributions to ozone from $NO_x$ emissions and to $PM_{2.5}$ from $NO_x$, $SO_2$, and primary $PM_{2.5}$ emissions. Initial inputs to these models were generated from the Integrated Planning Model,[24] which projects changes in emissions from electricity generating units based on policy changes.

With these inputs, BENMAP-CE was used to estimate the health impacts of the changes in modeled pollutant concentrations resulting from the rule under the three scenarios of emissions reductions. The outcomes considered in BENMAP-CE are based on Integrated Science Assessments (ISAs) for PM and ozone and include those for which the evidence was classified as either causal or likely to be causal. The Clean Air Scientific Advisory Committee (CASAC)

[20] https://www.woodsandpoole.com/our-databases/
[21] https://www.epa.gov/benmap
[22] https://www.epa.gov/system/files/documents/2023-01/Estimating%20PM2.5-%20and%20Ozone-Attributable%20Health%20Benefits%20TSD_0.pdf
[23] https://www.camx.com/
[24] https://www.epa.gov/power-sector-modeling/documentation-integrated-planning-model-ipm-base-case-v410

provides intensive peer review for the ISAs. For these outcomes, a standard health outcome function was utilized that incorporated risk coefficients from epidemiological investigations. The resulting counts were then monetized using BENMAP-CE. Sources of uncertainty and variability are listed. Monte Carlo simulation was used to characterize random sampling error and a number of assumptions made were addressed qualitatively around potential uncertainties.

The SAB assessed whether the Agency's approach to estimating health benefits of the rule followed established best practices. As a summary response, the SAB's evaluation is affirmative on the question of utilization of best practices in the context of EPA peer-reviewed tools and approaches. As shown in Figure 2, the EPA used well-documented and appropriate data inputs and peer-reviewed models for estimating the rule's effect on air pollution concentrations—$PM_{2.5}$ and ozone. In selecting health outcomes for BENMAP-CE, the EPA used the peer-reviewed ISAs for ozone and $PM_{2.5}$**.** Table 1 lists these peer-reviewed building blocks for the health benefit analysis. Additionally, as noted, the ISAs for PM and ozone were the basis for identifying the health outcomes considered in BENMAP-CE. The tools listed in the table have undergone peer review by the SAB or through other mechanisms.

One element not included in the RIA is evaluation of the health impacts of hydrogen utilization. The Agency recognizes the potential for increases nitrogen oxide, a harmful GHG and local air pollutant, from the co-firing of hydrogen.[25] However, the potential increase in nitrogen oxide, and its societal harms are not modeled in the current RIA. If hydrogen is to become a major component of the nation's energy system, health analyses will need to represent its emissions and their influence on air contaminants.

A more comprehensive description of the overall framework for estimation of the health benefits would be helpful to the reader. The descriptions are somewhat disconnected across the RIA and the Executive Summary should be revised to do a better job of describing how the various components and data sets are utilized and integrated. The handling of uncertainty should be bolstered to more fully explore the assumptions and attendant uncertainties covered on pages 4-38 and 4-39 of the RIA. An expanded discussion should address how the uncertainties covered by the assumptions made could affect the magnitude and direction of the estimates of health benefits.

With regard to sources of uncertainty, 95% confidence intervals are estimated using the Monte Carlo simulations. The qualitative description of uncertainty (pages 4-38 and 4-39 of the RIA) describes assumptions made with only brief and superficial consideration of the magnitude and direction of the resulting uncertainties.

**Finding: The SAB finds that the RIA and supporting documents adequately describe the approach taken by EPA in estimating health benefits of the proposed rule. The estimation uses peer-reviewed tools that reflect the state-of-practice for benefit estimation.**

[25] See 3-34 of the RIA and TSD for Hydrogen (https://www.regulations.gov/document/EPA-HQ-OAR-2023-0072-0059).

**Recommendation: The SAB recommends improvement of the RIA by providing a more comprehensive description of the overall framework for estimation, including how assumptions made could the affect the magnitude and direction of the estimates of health benefits.**

**The SAB further recommends that the EPA support research on the atmospheric impacts of hydrogen co-firing, with the goal of representing the influence of this change in technology on air pollutants and their impacts on health.**

While the health benefit analysis uses the EPA's standard approach to benefit quantification using BenMAP and to valuation of those benefits, the SAB has recently completed a review of both Benefits Methodology generally and BenMAP specifically (U.S. EPA SAB, 2024).[26] That review provides suggestions for improvements and updates to the health benefit analysis. Some of those suggestions relate to better characterizing the uncertainty range of future projections, for example by including a range of demographic scenarios. These changes would not be likely to greatly affect the values in the RIA but would partly address the recommendations of the SAB in response to the previous charge question.

The SAB's review of BenMap and Benefits Assessment provided other recommendations that might affect the values put forth in the RIA. The SAB recommended that the EPA: (1) expand its approach to health benefit analyses to include the use of exposure-response data from outside North America such as meta-analyses that include broader coverage, (2) include additional health impact endpoints, (3) develop more comprehensive measures by expanding its cost of illness estimates to include a wider range of averted medical and nonmedical costs and apply estimates of willingness-to-pay associated with those risks based on a criteria-driven review of the literature using the benefits transfer framework, (4) update the valuation methodology to rectify internal inconsistencies in the application of income adjustments over time, and (5) use more recent valuation of a statistical life estimates. The review also recommended that EPA include the effects of air pollution exposure on both labor productivity (a measure of economic performance that compares the amount of output with the amount of labor used to produce that output) and human capital (the economic value of worker experience and skills), which are not currently included in either climate or health benefit analyses.

**Recommendation: The SAB recommends that the Agency update the RIA for the proposed rule to incorporate the recommendations from the Benefits Methodology and BenMAP review panel, as much as possible. The SAB notes that updating the RIA would be valuable since it was only performed for parts of the proposed rule rather than for the rule in its entirety.**

*Uncertainties in Health and Climate Benefits*

[26] available at:
https://sab.epa.gov/ords/sab/f?p=114:0:14473944488630:APPLICATION_PROCESS=REPORT_DOC:::REPORT_ID:1124

Figure 2 outlines the framework for estimating the monetary benefits of reducing the adverse effect of $PM_{2.5}$ and ozone. Changes in pollutant concentrations under the three scenarios are estimated with CAMx and combined with a risk function, derived from epidemiological investigations, to calculate the changes in attributable numbers of events using BENMAP-CE. The cost estimates are based on use of willingness to pay figures derived from the literature.

The Technical Support Document for the 2022 PM NAAQS Reconsideration Proposal RIA provides the documentation for estimating monetized benefits and provides descriptions of contributors to uncertainty. Chapter 6 provides a qualitative listing of various contributors to uncertainty. Nineteen separate items are listed, some with multiple components. While the list is comprehensive, the TSD does not attempt to systematically characterize the potential directions or magnitudes of the uncertainties.

Monte Carlo simulation is used to generate 95% confidence intervals around the estimates of health benefits and also for the monetized health benefits. The RIA includes sensitivity analyses for the long-term effects of $PM_{2.5}$ on mortality, using risk estimates from two different epidemiological studies (Pope et al., 2019; Wu et al., 2020). The tables include the confidence intervals generated by the Monte Carlo simulation for both the counts of reduced (or increased) morbidity and mortality events and also monetized benefits.

This approach to defining and describing sources of uncertainty and their consequences provides an incomplete presentation of the actual ranges of values associated with the estimates of morbidity and mortality events and the cost benefits. The confidence intervals inherently understate the true range of values consistent with the uncertainties in the input data. Errors in the exposure estimates are not propagated into the calculation of health and cost benefits. The tables should provide an appropriate caveat concerning interpretation of the 95% confidence intervals, acknowledging that they capture only one contributor to uncertainty—stochastic variation.

There are also substantial uncertainties in the analysis of climate benefits, in addition to the methodological differences addressed previously between updates of the SC-GHG by the IWG and the prior estimates. One example is the role of persistent effects, by which economic damages in one year influence long-term growth. Though such impacts are difficult to constrain from empirical data, some studies attempting to incorporate such persistent effects on economic growth find much larger social cost values (e.g., Wang and Teng, 2023 and references therein). Such values could also be explored in characterizing climate damage uncertainties.

**Recommendation: The SAB recommends a more complete explication of uncertainties in the analysis of climate benefits of the proposed rule with more depth in the discussion of the qualitative analysis. The RIA could state the potential directionality of some of the sources of uncertainty, e.g., measurement error, as well as the potential magnitude of the range of uncertainty. The SAB recognizes that consideration of the aggregate consequences of the sources of uncertainty may not be possible.**

### 2.6. Distributional Issues and Environmental Justice

*2.6.1 Charge Question 6. Please comment on the scientific and technical adequacy of EPA's environmental justice analysis relating to distributed and cumulative impacts. Address both the baseline environmental justice analysis, and the analysis of projected conditions after the rule is implemented. Does the analysis support actions and future rules to achieve environmental justice?*

*Distributed costs and benefits*

The EPA's environmental justice (EJ) analysis presented in Section 6 (Environmental Justice Impacts) of this Regulatory Impact Analysis document is generally sound and adequately detailed. This EJ analysis is primarily distributional in scope and focuses on evaluating: (1) the proximity of affected facilities to potentially vulnerable populations for consideration of local pollutants affected by the proposed rule (Section 6.4 of the RIA); and (2) the distribution of $PM_{2.5}$ and ozone concentrations in the baseline and changes due to the three scenarios modeled (the proposed best system of emissions reductions, a less stringent alternative, and a more stringent option) across different socio-demographic groups based on race, ethnicity, poverty status, employment status, health insurance status, age, sex, educational attainment, and degree of linguistic isolation (Section 6.5 of the RIA). The EJ analysis does not address distributed benefits.

In its evaluation, EPA conducted a qualitative assessment of climate impacts, demographic proximity analysis, and quantitative analyses of resulting changes in $PM_{2.5}$ and ozone with respect to EJ impacts. In addition, EPA described its process for meaningful involvement in the development of the proposed rule. For health, the analyses focus on proximity to sources and exposure concentrations while not quantifying disease burden. The RIA also does not address costs and benefits in relation to specific EJ considerations.

*The qualitative assessment of climate impacts*

The qualitative assessment of climate impacts on human health is cursory and does not specifically address the consequences of the proposed rule. Instead, the RIA draws on previous reports by the Agency, including the U.S. Global Change Research Program (USGCRP) Climate and Health special report (USGCRP, 2016) and the 2021 report on Climate Change and Social Vulnerability in the United States (U.S. EPA, 2021). The RIA makes no direct connections between findings of these previous assessments of the literature and consequences of the proposed rule specifically.

The use of various discount rates as a sensitivity analysis for future cost valuations represents the state-of-the-art way to address intergenerational justice in the economics literature and is standard practice in evaluation of climate impacts using the social cost of greenhouse gases (U.S. EPA, 2022). The analyses incorporate low values of discount rate to reflect impacts on future generations. However, the lowest value used here is 3%, which is relatively high and likely undervalues cost impacts on future generations. Other discount rates should be considered that are either lower or declining over time.

*Distributional impacts*

The geographically distributed impacts of climate change are not well characterized by the methods used to value climate impacts due to the limited spatial resolution of the primary analyses supporting the development of the social cost of greenhouse gases (U.S. EPA, 2022).

**The demographic proximity analysis** was performed for all plants with at least one coal-fired unit greater than 25 MW without retirement or gas conversion plans before 2030 that would be affected by these proposed rulemakings. It also separately evaluated subsets of coal plants that are potentially subject to the proposed rule. The analysis focused on census blocks within a 10km and a 50km radius of each facility and provided descriptive statistics using census block group data from the Census' American Community Survey 5-year averages for 2016 to 2020. Demographic characteristics addressed include race, ethnicity, age, education level, poverty status, and linguistic isolation. This proximity analysis does not address health hazards or risks arising from these facilities and affecting the populations within these nearby communities.

**The quantitative analysis** of $PM_{2.5}$ and ozone was done at a 12-km resolution that might be sufficient for these pollutants and this emission sector because of tall smokestacks at the plants and the resulting dispersion of emissions. The analysis focuses on concentration impacts, but if the concentration estimates were integrated with disease rates in the populations to characterize burden, disparities could be larger than manifest in the analyses based on concentration alone because of heterogeneity of underlying disease rates across populations. Health impacts associated with these pollutants are discussed only qualitatively. The findings are presented with a variety of heat maps that summarize a great deal of data, although some of the figures, e.g., those showing data for individual states, are difficult to use because of the mass of data and small font sizes. The focus on $PM_{2.5}$ and ozone omits other important pollutants that communities are rightfully concerned about, particularly hazardous air pollutants. However, concentrations of these pollutants are more difficult to model and the RIA acknowledges their importance and also their absence from the analysis.

The geographic proximity analyses are based on census block demographic characteristics drawn from the Census' American Community Survey (ACS) data. In addition to using the census block group variables from the ACS survey, EPA could examine impacts for disadvantaged communities identified by the Climate and Economic Justice Screening Tool. This approach would provide a complementary EJ based geographical classification schema.

Overall, the analysis of potential EJ concerns is consistent with key questions and analytical approaches outlined in the EPA's *Environmental Justice Technical Guidance* (U.S. EPA, 2016). The methodology is appropriate, and results are explained with sufficient clarity. Caveats and limitations associated with proximity analysis and exposure modeling are also discussed. Some issues, however, require further clarification and consideration.

*Proximity analysis*

The proximity-based EJ analysis of proposed rule changes was based on the comparing percentages of the population in specific socio-demographic categories (i.e., race/ethnicity, low-income, education, and linguistically-isolated) residing within 10 km and 50 km radii of relevant coal plants, respectively, to their corresponding national averages. While this approach is easy to understand and interpret, it may not represent the most effective or valid approach for measuring disproportionate impacts. A more appropriate approach is to estimate and compare the percentage of each socio-demographic group inside these proximate areas (within 10 km and 50 km of relevant coal plants) to their respective percentage in areas outside (rest of the contiguous United States), as recommended in several published EJ studies. Using the overall United States percentage for comparison leads to double-counting of communities, since the national percentage for any variable includes areas both inside and outside the 10 km and 50 km radii around coal plants. The percentage difference or ratio of percentages (inside vs. outside areas proximate to coal plants) for each scenario should provide a more accurate metric for comparing or evaluating distributive EJ implications.

*Significance*

For both proximity and exposure analysis, no statistical tests of significance are included to support the numerical results. Inferences drawn from specific tables in Section 6 of the Regulatory Impact Analysis (e.g., page 6/16: "meaningful EJ exposure concerns are not likely created or exacerbated by the rule for the population groups evaluated, due to the small difference in magnitudes of $PM_{2.5}$ concentration reductions across demographic groups") are not reliable, unless appropriate statistical significance tests (e.g., two-sample tests of means or proportions) are conducted to determine if any of the observed percentage differences are significantly different from zero.

*Indigenous identification*

Although American Indians are included as a socio-demographic variable for evaluating potential EJ concerns in the proximity analysis, this classification may not be adequate to capture adverse and disproportionate impacts on Native Americans or Indigenous communities nationally. A better and more appropriate approach would be to examine the nature and extent of spatial overlap between the areas proximate to relevant power plants (i.e., within 10 km and 50 km) and boundaries of federally-designated tribal lands. Geographic boundaries of tribal areas that can be used to estimate this overlap are available in census data.[27]

*Low-income identification*

Low-income individuals are defined for this analysis as those within an annual income either equal to or twice the federal poverty line, which is not adequate for a national-scale evaluation

[27] https://www.census.gov/cgi-bin/geo/shapefiles/index.php?year=2022&layergroup=American+Indian+Area+Geography .

of potential EJ concerns. The federal poverty level measure is identical across the United States (except for Alaska and Hawaii) and does not account for the significant differences in the cost of living across and within regions. The use of a single value for the entire nation may result in a mischaracterization of income from the EJ perspective, as both upward and downward biases are possible. For example, the poverty guideline of $52,992 for a family of four living in New York compared to a small county in the Midwest or Central United States is not an equal comparison. There are alternative measures that should be considered to inform low-income measurement, including 80% of the area median income, an indicator of wealth such as home ownership rate, median home value, or a weighted income calculation. Any income-based measure deserves more scrutiny because of its impact on all aspects of a person's quality of life, from nutrition to health care to education.

*Uncertainty*

For socio-demographic variables examined in the proximity and exposure analyses (Section 6 of the RIA), data are obtained from the United States Census Bureau's American Community Survey (ACS) five-year estimates. These ACS estimates are surrounded by uncertainty, which are quantified through the margin of error (MOE). The magnitude of the MOE is typically considerable for estimates obtained at the census block group level, and particularly higher in rural areas with lower population counts. To mitigate against measurement errors and derive reliable proportional estimates, researchers have suggested removal of census enumeration units (i.e., tracts or block groups) with small population counts from their analysis, and/or using census units where MOE of the estimates are relatively low. Although the EJ analysis presented here uses census block groups and tracts, data quality problems with the ACS socio-demographic data (e.g., missing values and higher MOE) are not acknowledged and it is unclear if appropriate techniques were used to address data uncertainty and related errors.

*Procedural environmental justice*

Procedural environmental justice, also referred to as participatory environmental justice, focuses on the presence or absence of meaningful involvement of residents to influence government and industry decisions affecting their communities. In this context, meaningful involvement means that: (1) people have an opportunity to participate in decisions about activities that may affect their environment and/or health; (2) the public's contribution can influence the regulatory agency's decision; (3) community concerns are considered in the decision-making process; and (4) decision makers will seek out and facilitate the involvement of those potentially affected.

Based on the information provided in the EPA's docket (EPA–HQ–OAR–2023–0072) and the proposed rule (*Federal Register* Vol. 88, No. 99: page 33247-8), the Agency engaged adequately with EJ organizations and representatives of communities potentially impacted by various forms of pollution from the power sector, as part of its pre-proposal outreach to stakeholder. This feedback and analysis was considered by the EPA in its development of these proposals. Issues that require further clarification and consideration are:

- No details are provided about what efforts and steps were used to contact and ensure participation of all potentially affected residents, as well as underserved and vulnerable communities.

- Insufficient information is included about the criteria used to consider, evaluate, and/or address stakeholder input.

- It is unclear whether related briefings, meetings, and discussions were conducted only in English, and how or whether community residents speaking other languages were included.

*Recognition justice*

Justice as recognition is conceptualized in terms of which individuals, social groups, and communities are included, respected, and valued and which are not (Schlosberg, 2007). In the context of this analysis of potential EJ concerns, there are two vulnerable groups that were not included:

- People with disabilities, a highly disadvantaged group that has been documented to face unique barriers and challenges. President Biden's Executive Order 14096 on *Revitalizing Our Nation's Commitment to Environmental Justice for All* [28] identifies people with disabilities as a population group that should be considered as part of the definition of EJ and related analyses. In recognition of this updated definition, the EPA should consider adding disability status to the list of vulnerable and/or overburdened populations that are examined in this distributive justice analysis and for procedural justice considerations.

- Native American or Indigenous communities have not also been adequately included, despite the inclusion of American Indian as a demographic variable for proximity and exposure analyses. Specifically, the EJ analyses presented does not examine the extent to which federally-designated tribal areas will be impacted by the proposed rule.

**Finding: The SAB finds that the environmental justice evaluation accompanying the proposed rule is advanced beyond analyses of many prior rules. However, some important factors necessary for a complete analysis of environmental justice are not yet incorporated.**

**Recommendation: The SAB acknowledges that it has recently undertaken a self-initiated project on advancing environmental justice in rulemaking. The SAB recommends that the shortcomings identified here be addressed in developing the guidance that will shape future analyses.**

[28] Available at: https://www.govinfo.gov/content/pkg/FR-2023-04-26/pdf/2023-08955.pdf

## 3. SUMMARY OF FINDINGS AND RECOMMENDATIONS

The SAB finds that GHG emission reductions that would be achieved by the proposed rule are insufficient to align the United States electricity sector's emissions with national goals. Given the importance of this sector in leading the way towards net-zero GHG emissions, it is very likely that the proposed rule is inconsistent with Paris Agreement targets. It appears that in 2035 and 2040, the rule will have a small influence on baseline electricity-sector $CO_2$ emissions. The rule also lacks provisions to recognize the importance of total carbon budgets in achieving temperature targets.

The SAB finds that both methane (natural gas) and hydrogen have emissions and atmospheric consequences that are not accurately accounted for in current greenhouse analyses of climate impacts.

The SAB finds that cost estimates provided by the EPA for carbon capture and storage are reasonable given the emerging state of technology development.

The SAB affirms the necessity of a low-GHG hydrogen definition in the proposed rule and recommends that this definition be included before references to that term within the rule.

The SAB finds uncertainties in the timing of hydrogen technology readiness but recognizes that these uncertainties are characteristic of a rapidly emerging technological field. As the rule is revisited and alternatives are discussed in the public domain, the SAB suggests communication of alternatives using Technology Readiness Levels.

The SAB finds that, in general, the analyses of climate impacts due to emission changes are scientifically sound.

The SAB finds that the Regulatory Impact Analysis and supporting documents adequately describe the approach taken by EPA in estimating health benefits. In developing the estimation of health benefits, the EPA has used peer-reviewed tools that reflect the state-of-practice for benefit estimation.

The SAB finds that the environmental justice evaluation accompanying the proposed rule is advanced beyond analyses of many prior rules. However, some important factors necessary for a complete analysis of environmental justice are not yet incorporated.

*The SAB's recommendations are as follows:*

EPA should consider substantial increases in the stringency of the proposed rule, to align the outcomes with the Administration's goals and the nation's Nationally Determined Contribution to meeting climate targets.

The SAB recommends that EPA incorporate a more accurate understanding of methane emissions from natural-gas value chains into future climate benefit determinations and cost-benefit analyses. Updated emissions information is required under EPA's proposed revised Greenhouse Gas Reporting rule.

The SAB recommends that EPA support or promote research on the air-quality, climate and health impacts of hydrogen leakage, including improvements in detection technology for hydrogen. This understanding of unintended atmospheric consequences of hydrogen usage should be incorporated into future climate benefit determinations and cost-benefit analyses.

Recognizing the limited history available to characterize widespread carbon capture and storage operation, the SAB recommends support for monitoring societal impacts to identify risks and costs.

The SAB recommends that costs of the proposed rule as estimated in the RIA include realistic uncertainties in the price of available hydrogen throughout Phases I, II and III. These cost uncertainties should reflect potential competition for hydrogen as a limited resource.

The SAB strongly recommends formation of a working group to update the definition of low-GHG hydrogen regularly as technological and industrial capabilities evolve. The EPA should also support discussions about certification of low-GHG hydrogen based on a value-chain definition rather than a "well-to-gate" definition alone.

The SAB strongly recommends that EPA develop, or support research to develop, the ability to rapidly and realistically assess how a wide variety of alternative measures and innovative technologies may affect overall greenhouse-gas emissions.

The SAB strongly recommends that EPA engage in continuous use of tools to explore emerging opportunities to limit GHG emissions and developing limitations. That is, EPA should conduct analysis proactively to lay a foundation for future rules, rather than reactively in response to proposed rules.

The SAB recommends that the EPA apply the updated Social Cost of Greenhouse Gas estimates to value the climate benefits of the proposed rule, acknowledging the external review panel's finding that the updated SC-GHG estimates are more comprehensive, transparent, and evidence-based.

The SAB recommends that the EPA note the limitations of the SC-GHG approach and its application to estimate the societal benefits of reduced greenhouse gas emissions in the proposed rule. The SAB further recommends that EPA consider how public health and equity impacts can be more appropriately and comprehensively captured in future SC-GHG updates.

The SAB recommends improvement of the RIA by providing a more comprehensive description of the overall framework for estimation, including how assumptions made could the affect the magnitude and direction of the estimates of health benefits.

The SAB recommends that the EPA support research on the atmospheric impacts of hydrogen co-firing, with the goal of representing the influence of this change in technology on air pollutants and their impacts on health.

The SAB recommends that the Agency update the RIA for the proposed rule to incorporate the recommendations provided in the SAB review of BenMAP and EPA's Benefits Methodology, as much as possible. The SAB notes that updating the RIA would be valuable since it was only performed for parts of this proposed rule rather than for the rule in its entirety.

The SAB recommends a more complete explication of uncertainties in the analysis of climate benefits of the proposed rule with more depth in the discussion of the qualitative analysis. The RIA could state the potential directionality of some of the sources of uncertainty, e.g., measurement error, as well as the potential magnitude of the range of uncertainty. The SAB recognizes that consideration of the aggregate consequences of the sources of uncertainty may not be possible.

The SAB notes that it has recently undertaken a self-initiated project on advancing environmental justice in rulemaking. The SAB recommends that the shortcomings identified here be addressed in developing the guidance that will shape future environmental justice analyses.

## REFERENCES


Allen, M., O.P. Dube, W. Solecki, F. Aragón-Durand, W. Cramer, S. Humphreys and M. Kainuma, M. (2018). *Special Report: Global Warming of 1.5 C.* Intergovernmental Panel on Climate Change (IPCC).

Alvarez, R. A., D. Zavala-Araiza, D.R. Lyon, D.T. Allen, Z.R. Barkley, and A.R. Brandt et al. (2018). Assessment of methane emissions from the US oil and gas supply chain. *Science*, 361(6398), 186-188.

Bauer, C., K. Treyer, C. Antonini, J. Bergerson, M. Gazzani, and E. Gencer et al. (2022). On the climate impacts of blue hydrogen production. *Sustainable Energy & Fuels*, *6*(1), 66-75.

Clarke, L., Y.-M. Wei, A. De La Vega Navarro, A. Garg, A.N. Hahmann, S. Khennas, I.M.L. Azevedo, A. Löschel, A.K. Singh, L. Steg, G. Strbac, and K. Wada. (2022). Energy Systems. In IPCC, 2022: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.008.

de Coninck, H., A. Revi, M. Babiker, P. Bertoldi, M. Buckeridge, A. Cartwright, W. Dong, J. Ford, S. Fuss, J.C. Hourcade, D. Ley, R. Mechler, P. Newman, A. Revokatova, S. Schultz, L. Steg, and T. Sugiyama. (2018). Strengthening and implementing the global response. In: *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [V. Masson- Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA.

De Sisternes, F., J.D., Jenkins, and A. Botterud. (2016). The value of energy storage in decarbonizing the electricity sector. *Applied Energy*, *175*, 368-379.

Derwent, R.G. (2023). Global warming potential (GWP) for hydrogen: sensitivities, uncertainties and meta-analysis. *International Journal of Hydrogen Energy*, *48*(22), 8328-8341.

DoE (U.S. Department of Energy). (2011). *United States Department of Energy, Technology Readiness Assessment Guide, 2011*. Report No. DOE G 413.3-4A 9-15-2011

DoE (U.S. Department of Energy). (2022). *U.S. Energy-Related Carbon Dioxide Emission, 2022.* U.S. Department of Energy, Energy Information Administration. https://www.eia.gov/environment/emissions/carbon/pdf/2022_Emissions_Report.pdf

Elliston, B., I. MacGill, and M. Diesendorf. (2014). Comparing Least Cost Scenarios for 100% Renewable Electricity with Low Emission Fossil Fuel Scenarios in the Australian National Electricity Market. *Renewable Energy* 66: 196–204.

Emerson, B., D. Wu, T. Lieuwen, S. Sheppard, S., D. Noble, and L. Angello. (2020). Assessment of Current Capabilities and Near-Term Availability of Hydrogen-Fired Gas Turbines Considering a Low-Carbon Future, 2020. In: P*roceedings of the ASME Turbo Expo 2020: Turbomachinery Technical Conference and Exposition. Volume 6: Education; Electric Power*. https://doi.org/10.1115/GT2020-15714

Escamilla, A., D. Sánchez, D., L. García-Rodríguez. (2022). Assessment of power-to-power renewable energy storage based on the smart integration of hydrogen and micro gas turbine technologies. *International Journal of Hydrogen Energy*, 47 17505–17525. https://doi.org/https://doi.org/10.1016/j.ijhydene.2022.03.238.

Esquivel-Elizondo S., M.A. Hormaza, T. Sun, E. Shrestha, S.P. Hamburg, and I.B. Ocko. (2023). Wide range in estimates of hydrogen emissions from infrastructure. *Frontiers In Energy Research,* 11:1207208. doi: 10.3389/fenrg.2023.1207208

Fell, H., S.P. Holland, and A.J. Yates. (2023). *Optimal Subsidies for Green Hydrogen Production.* NBER Working Paper No. 31902, JEL No. D62Q58 available https://www.nber.org/system/files/working_papers/w31902/w31902.pdf

Giannaris, S., C. Bruce, B. Jacobs, W. Srisang, and D. Janowczyk. (2020). Implementing a second generation CCS facility on a coal fired power station – results of a feasibility study to retrofit SaskPower's Shand power station with CCS. *Greenhouse Gases-Science and Technology*, *10*(3), 506–518. https://doi.org/10.1002/ghg.1989

Global CCS Institute. (2023), Global Status of CCS 2023: Scaling Up Through 2030. https://res.cloudinary.com/dbtfcnfij/images/v1700717007/Global-Status-of-CCS-Report-Update-23-Nov/Global-Status-of-CCS-Report-Update-23-Nov.pdf?_i=AA. Accessed January 10, 2024.

Hartin, C., E.E. McDuffie, K. Noiva, M. Sarofim, B. Parthum, and J. Martinich et al. (2023). Advancing the estimation of future climate impacts within the United States. *Earth System Dynamics*, *14*(5), 1015-1037.

Hayden, F.G., and T.A. Mahin. (2022). Integrating the concepts of zero greenhouse-gas emissions, the precautionary principle, and environmental impact statements for climate change policy mitigation. *Journal of Economic Issues*, 56(2), 400-407.

Hayden, M.H., P.J. Schramm, C.B. Beard, J.E. Bell, A.S. Bernstein, A. Bieniek-Tobasco, N. Cooley, M. Diuk-Wasser, M.K. Dorsey, K.L. Ebi, K.C. Ernst, E. Gorris, P.D. Howe, A.S. Khan, C. Lefthand-Begay, J. Maldonado, S. Saha, F. Shafiei, A. Vaidyanathan, and O.V. Wilhelmi. (2023) Ch. 15. Human health. In: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R.

Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA.

Howarth, R. W., and M.Z. Jacobson. (2021). How green is blue hydrogen? *Energy Science & Engineering*, 9(10), 1676-1687.

IEA (International Energy Agency). (2022). *World Energy Outlook 2022*. International Energy Agency, Paris, France, 524 pp., 2022.

Incer-Vavalde, J., A. Korayem, G. Tsatsaronis, and T. Morosuk. (2023). “Colors” of hydrogen: Definitions and carbon intensity. *Energy Conversion and Management* 291, 117294. https://doi.org/https://doi.org/10.1016/j.enconman.

IPCC (Intergovernmental Panel on Climate Change). (2022). Summary for Policymakers [P.R. Shukla, J. Skea, A. Reisinger, R. Slade, R. Fradera, M. Pathak, A. Al Khourdajie, M. Belkacemi, R. van Diemen, A. Hasija, G. Lisboa, S. Luz, J. Malley, D. McCollum, S. Some, P. Vyas, (eds.)]. In: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.001.

IPCC (Intergovernmental Panel on Climate Change). (2023). *Climate Change 2023: Synthesis Report.* Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115, doi: 10.59327/IPCC/AR6-9789291691647

Jablonka, K.M., C. Charalambous, E. Sanchez Fernandez, G. Wiechers, J. Monteiro, P. Moser, B. Smit, and S. Garcia. (2023). Machine learning for industrial processes: Forecasting amine emissions from a carbon capture plant. *Science Advances*. 9 (2023) eadc9576.

Kappes, M.A., and T. Perez. (2023). Hydrogen blending in existing natural gas transmission pipelines: a review of hydrogen embrittlement, governing codes, and life prediction methods. *Corrosion Reviews*, 41 319–347. https://doi.org/doi:10.1515/corrrev-2022-0083.

Kearns, J., G. Teletzke, J. Palmer, H. Thomann, H. Kheshgi, Y.-H.H. Chen S. Paltsev, and H. Herzog. (2017). Developing a Consistent Database for Regional Geologic $CO_2$ Storage Capacity Worldwide. *Energy Procedia*, 114 4697–4709, https://doi.org/https://doi.org/10.1016/j.egypro.2017.03.1603

Kearns, D., H. Liu, and C. Consoli. (2021). Technology Readiness and Costs of CCS. Global CCS Institute. [Available at: Technology-Readiness-and-Costs-for-CCS-2021-1.pdf (scienceforsustainability.org)]

Lamboll, R., Z. Nicholls, C.J. Smith, J. Kikstra, E. Byers, and J. Rogelj. (2023). Assessing the size and uncertainty of remaining carbon budgets. *Nature Climate Change*, 13(12), 1360–1367. https://doi.org/10.1038/s41558-023-01848-5

Melaina, M.W., O. Antonia, M. and Penev. (2013). *Blending hydrogen into natural gas pipeline networks: a review of key issues*. Report No. NREL/TP-5600-51995, National Renewable Energy Laboratory, Golden, CO, March 2013.

NASEM (National Academies of Sciences, Engineering, and Medicine). (2017). Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide. Washington, DC: The National Academies Press. doi: https://doi.org/10.17226/24651.
National Academies of Sciences, Engineering, and Medicine. 2017. Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide. Washington, DC: The National Academies Press. https://doi.org/10.17226/24651.

Ocko, I. B., and S.P. Hamburg. (2022). Climate consequences of hydrogen emissions. *Atmospheric Chemistry and Physics*, *22*(14), 9349-9368.

Ocko, I.B., S.P. Hamburg, D.J. Jacob, D.W. Keith, N.O. Keohane, M. Oppenheimer, J.D. Roy-Mayhew, D.P. Schrag, and S.W. Pacala. (2017). Two-valued Global Warming Potential Effectively Captures Long- and Short-term Climate Forcing. *Science,* 356:492-493.

Paulot, F., D. Paynter, V. Naik, S. Malyshev, R. Menzel, R., and L.W. Horowitz. (2021). Global modeling of hydrogen using GFDL-AM4.1: Sensitivity of soil removal and radiative forcing, *International Journal of Hydrogen Energy*, 46, 13446–13460, https://doi.org/10.1016/j.ijhydene.2021.01.088, 2021.

Pope III, C. A., J.S. Lefler, M. Ezzati, J.D. Higbee, J.D. Marshall, and S.Y. Kim, et al. (2019). Mortality risk and fine particulate air pollution in a large, representative cohort of US adults. *Environmental Health Perspectives*, *127*(7), 077007.

Raupach, M.R., S.J. Davis, G.P. Peters, R.M. Andrew, J.G. Canadell, P. Ciais, P. Friedlingstein, F. Jotzo, D.P. Van Vuuren, and C. Le Quéré. (2014). Sharing a quota on cumulative carbon emissions. *Nature Climate Change*, 4(10), pp.873-879.

Riesz, J., P. Vithayasrichareon, and I. MacGill. (2015). Assessing “gas transition” pathways to low carbon electricity–An Australian case study. *Applied Energy*, *154*, 794-804.

Sacks J.D., J.M. Lloyd, Y. Zhu, J. Anderton, C.J. Jang, B. Hubbell, and N. Fann. (2018). The Environmental Benefits Mapping and Analysis Program - Community Edition (BenMAP-CE): A tool to estimate the health and economic benefits of reducing air pollution. *Environmental Modeling and Software.* 2018 Feb 11;104:118-129. PMID: 29962895; PMCID: PMC6022291

Sand, M., R.B. Skeie, and M. Sandstad et al. (2023). A multi-model assessment of the Global Warming Potential of hydrogen. *Communications Earth and Environment,* 4, 203 (2023). https://doi.org/10.1038/s43247-023-00857-8

Schlosberg, D. (2007). *Defining Environmental Justice: Theories, Movements, and Nature.* Oxford University Press, Oxford Academic, https://doi.org/10.1093/acprof:oso/9780199286294.001.0001]

Swain, M.R., and M.N.Swain. (1992). A comparison of $H_2$, $CH_4$ and $C_3H_8$ fuel leakage in residential settings. *International Journal of Hydrogen Energy* 17, 807–815, https://doi.org/10.1016/0360-3199(92)90025- R, 1992

Tavoni, M., E. Kriegler, K. Riahi, D.P. Van Vuuren, T. Aboumahboub, A. Bowen, K. Calvin, E. Campiglio, T. Kober, J. Jewell, and G. Luderer. (2015). Post-2020 climate agreements in the major economies assessed in the light of global models. *Nature Climate Change*, *5*(2), pp.119-126.

Topolski, K., E.P. Reznicek, B.C. Erdener, C.W. San Marchi, J.A. Ronevich, L. Fring, K. Simmons, O.I.G. Fernandez, B.-M. Hodge, and M. Chung. (2022). *Hydrogen blending into natural gas pipeline infrastructure: review of the state of technology*. Report No. NREL/TP-5400-81704, National Renewable Energy Laboratory, Golden, CO.

Turnock, S.T., C.L. Reddington, J.J. West, and F.M. O'Connor. (2023). The Air Pollution Human Health Burden in Different Future Scenarios That Involve the Mitigation of Near-Term Climate Forcers, Climate and Land-Use. *GeoHealth*, *7*(8), e2023GH000812.

UN (United Nations). (2023). *Secretary-General Calls on States to Tackle Climate Change 'Time Bomb' through New Solidarity Pact, Acceleration Agenda, at Launch of Intergovernmental Panel Report*. https://press.un.org/en/2023/sgsm21730.doc.htm

U.S. EPA (U.S. Environmental Protection Agency). (2016). *Technical Guidance for Assessing Environmental Justice in Regulatory Analysis*. https://www.epa.gov/sites/default/files/2016-06/documents/ejtg_5_6_16_v5.1.pdf

U.S. EPA (U.S. Environmental Protection Agency). (2021). *Climate Change and Social Vulnerability in the United States: A Focus on Six Impacts*. U.S. Environmental Protection Agency, EPA 430-R-21-003. [Available at: www.epa.gov/cira/social-vulnerability-report]

U.S. EPA (U.S. Environmental Protection Agency). (2022). *Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances*. National Center for Environmental Economics, U.S. EPA, Washington DC, 2022. [Available https://www.epa.gov/environmental-economics/scghg]

U.S. EPA (U.S. Environmental Protection Agency). (2023a). *Importance of Climate Equity.* https://www.epa.gov/climateimpacts/climate-equity#:~:text=EPA%20is%20committed%20to%20supporting%20communities%E2%80%94particularly%20those%20facing,in%20addressing%20systemic%20factors%20that%20impact%20climate%20equity.

U.S. EPA (U.S. Environmental Protection Agency) (2023b). Technical Support Document (TSD) for the 2022 PM NAAQS Reconsideration Proposal RIA: Estimating PM 2.5- and Ozone-Attributable Health Benefits U.S. Environmental Protection Agency. Durham, NC. Office of Air Quality Planning and Standards. January 2023. [Available at: https://www.epa.gov/system/files/documents/2023-01/Estimating%20PM2.5-%20and%20Ozone-Attributable%20Health%20Benefits%20TSD_0.pdf]

U.S. EPA SAB (U.S. Environmental Protection Agency Science Advisory Board). (2017) *SAB Advice on the Use of Economy-Wide Models in Evaluating the Social Costs, Benefits and Economic Impacts of Air Regulation.* EPA-SAB-17-012, U.S. EPA Science Advisory Board, Washington, DC

U.S. EPA SAB (U.S. EPA Science Advisory Board). (2020). Technical Review of EPA's Computable General Equilibrium Model, SAGE. EPA-SAB-20-010. U.S. Environmental Protection Agency Science Advisory Board, Washington, DC [Available at: https://sab.epa.gov/ords/sab/r/sab_apex/sab/advisoryreports?session=14452906009840 ]

U.S. EPA SAB (U.S. EPA Science Advisory Board). (2024). *Review of BenMAP and Benefits Methods.* EPA-SAB-24-003. U.S. Environmental Protection Agency Science Advisory Board, Washington, DC [Available at: https://sab.epa.gov/ords/sab/r/sab_apex/sab/advisoryreports?session=14166097266648]

USGCRP (U.S. Global Change Research Program). 2016. *The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. U.S. Global Change Research Program, Washington, DC.

Wang, T. and F. Teng. (2023). Damage function uncertainty increases the social cost of methane and nitrous oxide. *Nature Climate Change*, 1-8.

Waxman, A., H. Huber-Rodriguez, S.M. and Olmstead. (2023). What are the likely air pollution impacts of carbon capture and storage? *Social Science Research Network*. https://doi.org/10.2139/ssrn.4590320.

West, J.J., C.G. Nolte, M.L. Bell, A.M. Fiore, P.G. Georgopoulos, J.J. Hess, L.J. Mickley, S.M. O'Neill, J.R. Pierce, R.W. Pinder, S, Pusede, D.T. Shindell, and S.M. Wilson. (2023). Ch. 14. Air quality. In: Fifth National Climate Assessment. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. *U.S. Global Change Research Program*, Washington, DC, USA.

The White House. (2021). *Fact Sheet: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies.* The White House, Washington, DC, USA, https://www.whitehouse.gov/briefing-room/ statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030- greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy- technologies/.

Williams, J. H., R.A.Jones, B. Haley, G. Kwok, J. Hargreaves, J. Farbes, and M.S. Torn. (2021). Carbon-neutral pathways for the United States. *AGU advances*, *2*(1), e2020AV000284.

Wu, X, D. Braun, J. Schwartz, M. Kioumourtzoglou, and F. Dominici. (2020). Evaluating the impact of longterm exposure to fine particulate matter on mortality among the elderly. *Science Advances* 6(29).