Ontario Energy Board

EB-2022-0200

Application by Enbridge Gas Inc. for rates and other charges beginning January 1, 2024

Evidence of:

Dr. Robert W. Howarth,
Professor of Ecology & Environmental Biology, Cornell University

and

Dr. Mark Jacobson,
Professor of Civil and Environmental Engineering, Stanford University

May 11, 2023

We have been asked to provide evidence on the greenhouse gas footprint of blue hydrogen and to respond to commentary by Guidehouse Canada Inc. and Enbridge on our peer-reviewed paper: *How Green is Blue Hydrogen*? Our response is below.

Qualifications

Our qualifications are outlined in our attached *curricula vitae*.

Professor Robert Howarth is a Professor of Ecology & Environmental Biology at Cornell University and the Co-Editor in Chief of the journal of Ocean-Land-Atmosphere Research. He has published over 230 peer-reviewed papers, which have been cited more than 80,000 times in other peer-reviewed publications. He has provided invited briefings to the U.S. Congress, the U.S. Senate, the White House, and the European Parliament; is a member of the EPA Clean Air Scientific Advisory Committee' Panel on nitrogen and sulfur pollution; and has received numerous awards and appointments.

Professor Mark Jacobson is a Professor of Civil and Environmental Engineering and the Director of the Atmosphere/Energy Program at Stanford University. He has published six books and approximately 180 peer-reviewed journal articles. He has testified four times for the U.S. Congress and twice in hearings by the Environmental Protection Agency. He has sat on multiple government advisory boards and received a long list of awards and grants.

Professors Howarth and Jacobson co-authored the first peer-reviewed paper to examine the lifecycle greenhouse gas emissions of blue hydrogen accounting for emissions of both carbon dioxide and unburned fugitive methane.

The Greenhouse Gas Footprint of Blue Hydrogen

The lifecycle greenhouse gas emissions of blue hydrogen are outlined in our peer-reviewed paper entitled: *How green is blue hydrogen?* The conclusions are summarized as follows in the abstract:

> "Hydrogen is often viewed as an important energy carrier in a future decarbonized world. Currently, most hydrogen is produced by steam reforming of methane in natural gas ("gray hydrogen"), with high carbon dioxide emissions. Increasingly, many propose using carbon capture and storage to reduce these emissions, producing so-called "blue hydrogen," frequently promoted as low emissions. We undertake the first effort in a peer-reviewed paper to examine the lifecycle greenhouse gas emissions of blue hydrogen accounting for emissions of both carbon dioxide and unburned fugitive methane. Far from being low carbon, greenhouse gas emissions from the production of blue hydrogen are quite high, particularly due to the release of fugitive methane. For our default assumptions (3.5% emission rate of methane from natural gas and a 20-year global warming potential), total carbon dioxide equivalent emissions for blue hydrogen are only 9%-12% less than for gray hydrogen. While carbon dioxide emissions are lower, fugitive methane emissions for blue hydrogen are higher than for gray hydrogen

> because of an increased use of natural gas to power the carbon capture. Perhaps surprisingly, the greenhouse gas footprint of blue hydrogen is more than 20% greater than burning natural gas or coal for heat and some 60% greater than burning diesel oil for heat, again with our default assumptions. In a sensitivity analysis in which the methane emission rate from natural gas is reduced to a low value of 1.54%, greenhouse gas emissions from blue hydrogen are still greater than from simply burning natural gas, and are only 18%-25% less than for gray hydrogen. Our analysis assumes that captured carbon dioxide can be stored indefinitely, an optimistic and unproven assumption. Even if true though, the use of blue hydrogen appears difficult to justify on climate grounds."

Greenhouse gas emissions are higher from blue hydrogen than from burning natural gas mainly because approximately 1.6 to 1.7 MJ of natural gas are required to make 1 MJ of hydrogen, which results in greater upstream unburned methane emissions from natural gas production, storage, and transportation. Emissions also arise as a result of less-than-perfect rates of carbon capture and in relation to the energy needed to run the stream reforming process and the carbon capture process.

For the full details, see the attached paper, *How Green is Blue Hydrogen?*, and the attached reply to a comment on our original paper. We adopt these as part of our sworn testimony.

Response to Exhibit I.1.10-ED-58

Guidehouse Canada Ltd. provided a response to our paper an answer to an interrogatory. As discussed below, Guidehouse's critiques of our paper are unfounded.

Guidehouse stated that our paper uses 20-year global warming potential values (GWP20) and that 100-year values (GWP100) are the current Intergovernmental Panel on Climate Change (IPCC) "standard." Although we used GWP20 as our default, our paper conducted a sensitivity analysis using GWP100, which still found the emissions from blue hydrogen to be greater than burning natural gas directly. Further, although GWP100 is still used more frequently in greenhouse gas inventories by governments, this is a political decision dating back to the early 1990s when our knowledge of the critical role of methane in the climate system was quite limited, and the IPCC has noted that "there is no scientific argument for 100 years…."[1] The latest IPCC assessment concludes that for all of the time since the 1800s, methane has contributed to global warming in an amount equivalent to 67% of carbon dioxide.[2] The use of GWP100 severely understates this, leading to erroneous advice to policy makers. A 20-year time frame (i.e. GWP20) far better captures the importance of methane as a greenhouse gas and is more useful than a 100-year time frame for analyzing the impacts of blue hydrogen, because it is

[1] IPCC. 2013. Climate change 2013: the physical science basis. Contribution of working group 1 to the fifth assessment report of the intergovernmental panel on climate change. https://www.ipcc.ch/report/ar5/wg1/
[2] IPCC. 2021. Climate change 2021; the physical science basis. Contribution of working group 1 to the sixth assessment report of the intergovernmental panel on climate change. https://www.ipcc.ch/report/ar6/wg1/

crucial to eliminate substances like methane whose control can avoid catastrophic short-term damage to the climate.[3]

Guidehouse stated that our paper assumes 3.5% methane leakage from extraction to end-use, that Enbridge Inc. is targeting 1% by 2025, and Guidehouse assumed 0.4%. An estimate of 3.5% of gas consumption is a reasonable (probably conservatively low) average estimate for methane emissions from natural gas production and use not only in the United States but globally. Our methane leakage assumptions rely on "top–down" emission studies that use information such as from satellites or airplane flyovers, including estimates from 20 different studies in 10 major natural gas fields in the United States. For further details, see section 2.3 in our original paper.

In addition, we performed sensitivity analyses down to a value of 1.54%, the lowest reasonable rate supported by any independent studies. And even at 1.54%, blue hydrogen is worse than natural gas (using GWP20), or no better than natural gas (using GWP100). See Table 2 in our original paper. The 1% and 0.4% emissions rates suggested by Guidehouse do not appear to be supported by independent studies.

Guidehouse stated that our paper assumes a carbon capture and storage (CSS) rate of 85% whereas it assumes 95%. We chose 85% as our default value based on observations from actual plant operations, and giving the benefit of the doubt to industry that they can routinely fall on the high end of what has sometimes been observed in the past. A 95% capture rate has never been demonstrated.

In addition, industry has not even tried to capture carbon from the combustion of the natural gas used to power the steam methane reformer (SMR) or used to generate electricity to power the carbon capture. These capture rates are far lower than the gross capture rates from the SMR process alone. Also, capturing the flue-gas CO_2 from combustion is much more difficult than is the capture from the steam methane reformer: the CO_2 is far more dilute, the flue-gases are moving quickly, and the temperatures are very high.

Finally, we note that Guidehouse stated that our study assumed 135 gCO_2e/MJ whereas a study by CE Delft estimated 6.8 to 9.3 gCO_2e/MJ. However, the study by CE Delft did not account for unburned methane emissions, which make up the large majority of blue hydrogen emissions. It also was not peer-reviewed, unlike our study, and relied on unreasonably optimistic assumptions for CO_2 capture.

Response to Exhibit JT1.17

Enbridge provided a response to our paper in Exhibit JT1.17. Its critiques are unfounded. We have already addressed most of these same critiques above and in our attached papers. We also provide the following additional responses.

[3] IPCC. 2021. Climate change 2021; the physical science basis. Contribution of working group 1 to the sixth assessment report of the intergovernmental panel on climate change. https://www.ipcc.ch/report/ar6/wg1/; Howarth, RW. 2020. Methane emissions from fossil fuels: exploring recent changes in greenhouse-gas reporting requirements for the State of New York. *Journal of Integrative Environmental Sciences* 17: 69-81, oi.org/10.1080/1943815X.2020.17896666

Enbridge stated that we have not estimated emissions in the Canadian or Ontario context. However, gas extraction in Canada is not unique and it uses the same technologies as elsewhere. We have not seen studies showing a significant difference between emissions in Canada and the United States. Also, our paper included sensitivity analyses to address for the possibility that emissions rates are lower than we estimate in our main paper, as discussed above.

Enbridge states that the emissions in our study are higher in comparison to other peer-reviewed studies and cites three sources. We disagree.

Enbridge cited a report by EarthShift Global for natural gas production and transmission methane emission rates. This is not a peer-reviewed study, unlike ours. In any event, the EarthShift Global figure is consistent with our sensitivity analysis, with upstream emissions of 15.8 gCO_2e/MJ versus 16.8 gCO_2e/MJ in our sensitivity analysis (GWP 100-yr).

Enbridge cites a 2021 Pembina Institute Report. This also is not a peer-reviewed study, unlike ours. The leakage rates relied on in that report (0.6% and 0.16%) are not credible and not consistent with the current scientific understanding of methane emissions from gas extraction. They are far lower than even the EarthShift Global figures noted above. The Pembina report based its estimates on data that is known to be inaccurate and to greatly understate the emissions from gas extraction. It cites National Inventory figures that are based on industry self-reported bottom-up estimates. There is near scientific consensus that these self-reported bottom-up estimates are far below the actual emissions rates determined through top-down methodologies based on data collected from aircraft and satellites.

Enbridge cites a paper by Paul Balcome and others. The Balcome paper reproduces the results of previous papers that are out-of-date and therefore cannot reflect accurate top-down estimates of upstream methane emissions from gas extraction or actual verifiable data on blue hydrogen production facilities.[4] The papers cited in Balcome cannot have accounted for accurate top-down estimates of methane emissions from gas extraction and transmission because they were written before all or almost all of the top-down data became available. They were also published before verifiable data on actual blue hydrogen facilities became available. I have not reviewed the papers cited in Balcome to confirm whether they have other deficiencies. Also, note that the Balcome paper acknowledges funding from Royal Dutch Shell and Engas SA.

Finally, Enbridge makes reference to ambitious national methane reduction goals. However, these goals are presumably based on the emissions levels shown in national inventories which, as discussed above, are far below the actual levels determined from top-down aerial data. There is no evidence that the actual upstream emissions can be reduced to a level sufficient for blue hydrogen to realistically play a role in achieving net zero. In addition, there are limits to how great the emissions reductions from gas extraction and transportation can be. Some emissions are routine and purposeful, for instance to control pressure in tanks and pipelines for safety and for

[4] The publishing dates for the papers are 2004, 2005, 2011, 2012, 2012 and 2014. The most recent report, from 2014, is titled "life cycle assessment of hydrogen production via electrolysis – a review" and therefore does not seem to directly assess the life cycle emissions of blue hydrogen.

maintenance of pipelines. Other sources of emissions are extremely difficult to eliminate or cannot be eliminated with any technologies currently available today.

Received: 28 April 2021 | Revised: 16 July 2021 | Accepted: 26 July 2021

DOI: 10.1002/ese3.956

MODELLING AND ANALYSIS

Energy Science & Engineering Open Access

How green is blue hydrogen?

Robert W. Howarth[1] | **Mark Z. Jacobson**[2]

[1]Department of Ecology & Evolutionary Biology, Cornell University, Ithaca, New York, USA

[2]Department of Civil & Environmental Engineering, Stanford University, Stanford, California, USA

Correspondence
Robert W. Howarth, Department of Ecology & Evolutionary Biology, Cornell University, Ithaca, NY 14853, USA.
Email: howarth@cornell.edu

Funding information
Funding was provided by the Park Foundation and by Cornell University

Abstract

Hydrogen is often viewed as an important energy carrier in a future decarbonized world. Currently, most hydrogen is produced by steam reforming of methane in natural gas ("gray hydrogen"), with high carbon dioxide emissions. Increasingly, many propose using carbon capture and storage to reduce these emissions, producing so-called "blue hydrogen," frequently promoted as low emissions. We undertake the first effort in a peer-reviewed paper to examine the lifecycle greenhouse gas emissions of blue hydrogen accounting for emissions of both carbon dioxide and unburned fugitive methane. Far from being low carbon, greenhouse gas emissions from the production of blue hydrogen are quite high, particularly due to the release of fugitive methane. For our default assumptions (3.5% emission rate of methane from natural gas and a 20-year global warming potential), total carbon dioxide equivalent emissions for blue hydrogen are only 9%-12% less than for gray hydrogen. While carbon dioxide emissions are lower, fugitive methane emissions for blue hydrogen are higher than for gray hydrogen because of an increased use of natural gas to power the carbon capture. Perhaps surprisingly, the greenhouse gas footprint of blue hydrogen is more than 20% greater than burning natural gas or coal for heat and some 60% greater than burning diesel oil for heat, again with our default assumptions. In a sensitivity analysis in which the methane emission rate from natural gas is reduced to a low value of 1.54%, greenhouse gas emissions from blue hydrogen are still greater than from simply burning natural gas, and are only 18%-25% less than for gray hydrogen. Our analysis assumes that captured carbon dioxide can be stored indefinitely, an optimistic and unproven assumption. Even if true though, the use of blue hydrogen appears difficult to justify on climate grounds.

KEYWORDS

blue hydrogen, decarbonization, greenhouse gas footprint, hydrogen, methane, methane emissions

1 | INTRODUCTION

Hydrogen is widely viewed as an important fuel for a future energy transition. Currently, hydrogen is used mostly by industry during oil-refining and synthetic nitrogen fertilizer production, and little is used for energy because it is expensive relative to fossil fuels.[1] However, hydrogen is increasingly being promoted as a way to address climate change, as indicated by a recent article in the New York Times.[2] In this view, hydrogen is to be used not only for hard to decarbonize sectors of the economy such as long-distance transportation by trucks and airplanes but also for heating and cooking, with hydrogen blended with natural gas and distributed to homes and business through existing pipeline systems.[2] Utilities are also exploring the use of hydrogen, again blended with natural gas, to power existing electric generating facilities.[3] In Europe, a recent report from Gas for Climate, an association of natural gas pipeline companies, envisions large scale use of hydrogen in the future for heating and electricity generation.[4] The Hydrogen Council, a group established in 2017 by British Petroleum, Shell, and other oil and gas majors, has called for heating all homes with hydrogen in the future.[5]

The vast majority of hydrogen (96%) is generated from fossil fuels, particularly from steam methane reforming (SMR) of natural gas but also from coal gasification.[6] In SMR, which is responsible for approximately three quarters of all hydrogen production globally,[7] heat and pressure are used to convert the methane in natural gas to hydrogen and carbon dioxide. The hydrogen so produced is often referred to as "gray hydrogen," to contrast it with the "brown hydrogen" made from coal gasification.[8] Production of gray hydrogen is responsible for 6% of all natural gas consumption globally.[7] Hydrogen can also be generated by electrolysis of water. When such electricity is produced by a clean, renewable source, such as hydro, wind, or solar, the hydrogen is termed "green hydrogen." In 2019, green hydrogen was not cost competitive with gray hydrogen,[9] but that is changing as the cost of renewables is decreasing rapidly and electrolyzers are becoming more efficient. Still, the supply of green hydrogen in the future seems limited for at least the next several decades.[2,5]

Greenhouse gas emissions from gray hydrogen are high,[10,11] and so increasingly the natural gas industry and others are promoting "blue hydrogen".[5,8,9] Blue hydrogen is a relatively new concept and can refer to hydrogen made either through SMR of natural gas or coal gasification, but with carbon dioxide capture and storage. As of 2021, there were only two blue-hydrogen facilities globally that used natural gas to produce hydrogen at commercial scale, as far as we can ascertain, one operated by Shell in Alberta, Canada, and the other operated by Air Products in Texas, USA.[12] Often, blue hydrogen is described as having zero or low greenhouse gas emissions.[8,9] However, this is not true: not all of carbon dioxide emissions can be captured, and some carbon dioxide is emitted during the production of blue hydrogen.[1] Further, to date no peer-reviewed analysis has considered methane emissions associated with producing the natural gas needed to generate blue hydrogen.[1] Methane is a powerful greenhouse gas. Compared mass-to-mass, it is more than 100-times more powerful as a warming agent than carbon dioxide for the time both gases are in the atmosphere and causes 86-times the warming as carbon dioxide over an integrated 20-year time frame after a pulsed emission of the two gases. Approximately 25% of the net global warming that has occurred in recent decades is estimated to be due to methane.[13] In a recent report, the United Nations Environment Programme concluded that methane emissions globally from all sources need to be reduced by 40%-45% by 2030 in order to achieve the least cost pathway for limiting the increase in the Earth's temperature to 1.5°C, the target set by COP 21 in Paris in December 2015.[14]

Here, we explore the full greenhouse gas footprint of both gray and blue hydrogen, accounting for emissions of both methane and carbon dioxide. For blue hydrogen, we focus on that made from natural gas rather than coal, that is gray hydrogen combined with carbon capture and storage. In China, brown hydrogen from coal now dominates over gray hydrogen from natural gas, due to the relative prices of natural gas and coal, but globally and particular in Europe and North America, gray hydrogen dominates.[1]

2 | ESTIMATING EMISSIONS FROM PRODUCING GRAY HYDROGEN

Greenhouse gas emissions from the production of gray hydrogen can be separated into two parts: (a) the SMR process in which methane is converted to carbon dioxide and hydrogen; and (b) the energy used to generate the heat and high pressure needed for the SMR process. For blue hydrogen, which we discuss later in this paper, emissions from the generation of electricity needed to run the carbon dioxide capture equipment must also be included. In this analysis, we consider emissions of only carbon dioxide and methane, and not of other greenhouse gases such as nitrous oxide that are likely to be much smaller. For methane, we consider the major components of its lifecycle emissions associated with the mining, transport, storage, and use of the natural gas needed to produce the hydrogen and power carbon capture. Emissions are expressed per unit energy produced when combusting the hydrogen, to aid in comparing the greenhouse gas footprint with other fuels.[15,16] In this paper, we use gross calorific values.

We start by estimating how much methane is consumed and how much carbon dioxide is produced in the two aspects of production of gray hydrogen. From this information, we can subsequently below estimate emissions of unburned methane.

2.1 | Consumption of methane and production of carbon dioxide in SMR process

In the SMR process, 1 mole of carbon dioxide and 4 moles of hydrogen gas (H_2) are produced per mole of methane consumed, according to this overall reaction:

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2 \quad (1)$$

The gross caloric calorific heat content of hydrogen is 0.286 MJ per mole,[17] or inverting this value, 3.5 moles H_2 per MJ. The carbon dioxide produced during the SMR process is given by:

$$(3.5 \text{ moles } H_2/MJ) * (1 \text{ mole } CO_2/4 \text{ moles } H_2) = 0.875 \text{ moles } CO_2 \text{ per MJ} \quad (2)$$

With a molecular weight of 44.01 g per mole, the amount of carbon dioxide produced during the SMR process is 38.51 g CO_2 per MJ (Table 1). The amount of methane consumed is given by:

$$(3.5 \text{ moles } H_2/MJ) * (1 \text{ mole } CH_4/4 \text{ moles } H_2) = 0.875 \text{ moles } CH_4 \text{ per MJ} \quad (3)$$

With a molecular weight of 16.04 g per mole, 14.04 g CH_4 per MJ is consumed during the SMR process (Table 1). There is essentially no uncertainty in these estimates of how much methane is consumed, and how much carbon dioxide is produced during the SMR process: the relationship is set by the chemical stoichiometry shown in Equation (1).

2.2 | Consumption of methane and production of carbon dioxide from energy needed to drive SMR process

The production of hydrogen from methane is an endothermic reaction and requires significant input of energy, between 2.0 and 2.5 kWh per m^3 of hydrogen, to provide the necessary heat and pressure.[18] This energy comes almost entirely from natural gas when producing gray hydrogen, and therefore, also presumably when producing blue hydrogen proposed for Europe or North America.[1] Using a mean value of 2.25 kWh per m^3 of hydrogen, we estimate the energy in natural gas (methane) required to produce a mole of hydrogen as follows:

$$(2.25 \text{ kWh}/m^3 \text{ of } H_2) * (3.6 \text{ MJ/kWh}) * (1 \text{ m}^3/1000 \text{ L}) * (22.4 \text{ L/mol}) = 0.1814 \text{ MJ per mole } H_2 \quad (4)$$

That is, 0.1814 MJ of energy from burning methane is required per mole of hydrogen produced. When burning natural gas for heat, 50 g CO_2 per MJ in emissions are produced, using gross calorific values.[19] Note that higher carbon dioxide emission values are reported when using net calorific values.

Therefore,

$$(0.1814 \text{ MJ/mole } H_2) * (50 \text{ g } CO_2/MJ) = 9.07 \text{ g } CO_2 \text{ per mole } H_2. \quad (5)$$

As noted above, the gross calorific heat content of hydrogen is equivalent to 3.5 moles H_2 per MJ. Therefore,

$$(9.07 \text{ g } CO_2/\text{mole } H_2) * (3.5 \text{ moles } H_2/MJ) = 31.8 \text{ g } CO_2/MJ \quad (6)$$

So 31.8 g of carbon dioxide are produced to generate the heat and pressure to drive the SMR process per MJ of hydrogen produced (Table 1). Since one mole of methane in natural gas is burned to produce one mole of carbon dioxide emissions, we can estimate the methane consumed as follows:

$$(31.8 \text{ g } CO_2/MJ) * (1 \text{ mole } CO_2/44.01 \text{ g } CO_2) * (16.04 \text{ g } CH_4/\text{mole } CH_4) * (1 \text{ mole } CH_4/\text{mole } CO_2) = 11.6 \text{ g } CH_4/MJ \quad (7)$$

See Table 1.

2.3 | Total carbon dioxide and methane emissions for gray hydrogen

The sum of the carbon dioxide from the SMR process (38.5 g CO_2 per MJ) and from the energy used to generate the heat and electricity for the SMR (31.8 g CO_2 per MJ) is 70.3 g CO_2 per MJ. Additionally, it takes energy to produce, process, and transport the natural gas used to generate the hydrogen. Using the analysis of Santoro et al.[20] as reported in Howarth et al,[21] these indirect upstream emissions are approximately 7.5% of the direct carbon dioxide emissions for natural gas, or an additional 5.3 g CO_2 per MJ (7.5% of 70.3 g CO_2 per MJ). Therefore, the total quantity of carbon dioxide produced is 75.6 g CO_2 per MJ (Table 1).

The total quantity of methane in natural gas consumed to generate gray hydrogen is the sum of that used in the SMR process (14.04 g CH_4 per MJ) and the amount burned to generate the heat and high pressure needed for the process (11.6 g CH_4 per MJ) or 25.6 g CH_4 per MJ. It is not possible to produce and use natural gas without having some methane emitted unburned to the atmosphere, due both to leaks and to purposeful emissions including venting.[21,22] Below, we briefly discuss the recent literature that characterizes methane emissions from natural gas operations, and use a range of values in a sensitivity analysis. Here, for our default estimation of the greenhouse gas footprint of gray hydrogen, we rely on a recent synthesis on "top–down" emission studies.[16] Top–down estimates use information such as from satellites or airplane flyovers that characterize an integrated flux. The mean value of estimates from 20 different studies in 10 major natural gas fields in the United States, normalized to gas production in those fields, indicates that 2.6% of gas production is emitted to the atmosphere.[16] This is a good estimate for the upstream emissions that occur in the gas fields. Methane is also emitted from storage and transport to consumers, and the data in the top–down study of Plant et al[23] suggests this is an additional

TABLE 1 Comparison of methane that is consumed, of carbon dioxide that is produced, and of emissions of both methane and carbon dioxide for each step in the processing of methane to hydrogen for gray hydrogen, blue hydrogen with carbon dioxide capture from the SMR process but not from the exhaust flue gases created from burning natural gas to run the SMR equipment, and blue hydrogen with carbon dioxide capture from both the SMR process and from the exhaust flue gases

	Gray H_2	Blue H_2 (w/o flue-gas capture)	Blue H_2 (w/flue-gas capture)
SMR process			
CH_4 consumed (g CH_4/MJ)	14.0	14.0	14.0
CO_2 produced (g CO_2/MJ)	38.5	38.5	38.5
Fugitive CH_4 emissions (g CH_4/MJ)	0.49	0.49	0.49
Fugitive CH_4 emissions (g CO_2eq/MJ)	42.1	42.1	42.1
Direct CO_2 emissions (g CO_2/MJ)	38.5	5.8	5.8
CO_2 capture rate	0%	85%	85%
Energy to drive SMR			
CH_4 consumed (g CH_4/MJ)	11.6	11.6	11.6
CO_2 produced (g CO_2/MJ)	31.8	31.8	31.8
Fugitive CH_4 emissions (g CH_4/MJ)	0.41	0.41	0.41
Fugitive CH_4 emissions (g CO_2eq/MJ)	35.3	35.3	35.3
Direct CO_2 emissions (g CO_2/MJ)	31.8	31.8	11.1
CO_2 capture rate	0%	0%	65%
Energy to power carbon capture			
CH_4 consumed (g CH_4/MJ)	0	3.0	6.0
CO_2 produced (g CO_2/MJ)	0	8.2	16.3
Fugitive CH_4 emissions (g CH_4/MJ)	0	0.11	0.21
Fugitive CH_4 emissions (g CO_2eq/MJ)	0	9.5	1
Direct CO_2 emissions (g CO_2/MJ)	0	8.2	16.0
Indirect upstream CO_2 emissions (g CO_2/MJ)	5.3	5.9	6.5
Total CH4 consumed (g CH_4/MJ)	25.6	28.6	31.6
Total CO_2 emitted (g CO_2/MJ)	75.6	51.7	39.7
Total fugitive CH_4 emissions (g CO_2eq/MJ)	77.4	86.9	95.4
Total emissions (g CO_2eq/MJ)	153	139	135

Note: The methane leakage rate is 3.5%.

0.8%.[16,24] Combined with the 2.6% for field-level emissions, we estimate a total of 3.4% of production is emitted to the atmosphere overall. Note that in addition to some methane being lost between production and consumption due to leaks, methane is also burned by the natural gas industry to power natural gas processing and transport. This is important to consider, since we want to evaluate how much methane is emitted for the methane in natural gas that is consumed in producing hydrogen. In 2015, natural gas production in the United States was 817 billion m^3, while consumption was 771 billion m^3,[25,26] (converting cubic feet to cubic meters). Using this information, we can estimate the methane emission as a percentage of gas consumption as follows:

$$(3.4\%\text{ of production}) * (817 \times 109\ m^3 / 771 \times 109\ m^3) = 3.5\%\text{ of consumption} \quad (8)$$

With this value and the quantity of methane consumed to produce gray hydrogen, we can estimate the upstream emissions of methane:

$$(3.5\%\text{ of consumption}) * (\text{consumption of } 25.6\text{ g } CH_4\text{ per MJ}) = 0.90\text{ g } CH_4\text{ per MJ} \quad (9)$$

To compare methane emissions with carbon dioxide emissions requires a specified time frame, since the half-life of methane in the atmosphere is only 12 years or so, far less than that of carbon dioxide.[13] Greenhouse gas inventories often compare methane with carbon dioxide for an integrated period of 100 years following pulsed emissions of both gases. However, this underestimates the role of methane in global warming over shorter time periods. An increasing number of scientists have called for using a 20-year integrated time period instead of or in addition to the 100-year period.[15,21,24,27,28]

The 20-year time frame is now mandated by law in the State of New York, as part of the Climate Leadership and Community Protection Act of 2019.[24] And a 20-year period is more appropriate than a 100-year time frame given the urgency of reducing methane emissions globally over the coming decade.[14] Here, we use the 20-year time frame using the Global Warming Potential (GWP) for 20 years of 86.[13] We also consider other GWP values in a sensitivity analysis presented below. Using the 86 value, we estimate upstream methane emissions associated with the production of gray hydrogen in units of carbon dioxide equivalents (CO_2eq) thus:

$$(0.90 \text{ g } CH_4 \text{ per MJ}) * (86 \text{ g } CO_2eq/\text{g } CH_4) = 77.4 \text{ g}CO_2eq \text{ per MJ} \quad (10)$$

The sum of emissions of carbon dioxide (75.6.0 g CO_2 per MJ) and unburned methane (77.4 g CO_2eq per MJ) for the production of gray hydrogen is 153 g CO_2eq per MJ (Table 1).

There are remarkably few published peer-reviewed papers with which to compare our estimate. Many non peer-reviewed reports give estimates for carbon dioxide emission from gray hydrogen that are in the range of 10 tons carbon dioxide per ton of hydrogen,[1,7] although data in support of these values are generally absent, perhaps because they are based on confidential information.[11] Since the gross calorific heat energy content of hydrogen is 0.286 MJ per mole,[17] 10 tons of carbon dioxide per ton of hydrogen corresponds to 70 g CO_2 per MJ. This is similar to but somewhat lower than our value of 75.6 g CO_2 per MJ. Most of these non peer-reviewed reports do not include methane in their estimates,[1] or if they do, they provide no detail as to how they do so. The most thorough peer-reviewed analysis of carbon dioxide emissions for gray hydrogen is that of Sun et al[11] who obtained data on both rates of hydrogen production and emissions of carbon dioxide from many individual facilities across the United States. They concluded that on average, carbon dioxide emissions for gray hydrogen are 77.8 g CO_2 per MJ, remarkably close to our value of 75.6 g CO_2 per MJ. They did not estimate methane emissions.

3 | ESTIMATING EMISSIONS FOR BLUE HYDROGEN

Blue hydrogen differs from gray hydrogen in that, with blue hydrogen, some of the carbon dioxide released by the SMR process is captured. In another version of the blue-hydrogen process, additional carbon dioxide is removed from the flue gases created from burning natural gas to provide the heat and high pressure needed to drive the SMR process. A third set of emissions, not usually captured, is the carbon dioxide and methane from the energy used to produce the electricity for the carbon-capture equipment.

3.1 | How much carbon dioxide is emitted after carbon capture?

As noted above, only two facilities that produce blue hydrogen from natural gas are in commercial operation in 2021. Thus, only limited data are available on the percentage of carbon dioxide that can be captured. For the carbon dioxide generated during SMR, the reported capture efficiencies range from 53% to 90%.[29] Actual data from one of the two commercially operating facilities, the Shell plant in Alberta, show a capture a mean capture efficiency of 78.8%, with daily rates varying from 53% to 90% except for one outlier of 15%.[30] For our baseline analysis, we use a capture rate of 85%, roughly half way between the 78.8% for the Shell plan and the best-case of 90%. Applying 100% minus the capture efficiency to the carbon dioxide produced in SMR:

$$(15\%) * (38.5 \text{ g } CO_2 \text{ per MJ}) = 5.8 \text{ g } CO_2 \text{ per MJ} \quad (11)$$

That is, 5.8 g CO_2 per MJ are emitted from the SMR process after emissions are treated for carbon capture (Table 1).

For the blue-hydrogen facilities so far in commercial operation, carbon capture has focused only on the SMR process, and no attempt has been made to capture the carbon dioxide generated from the combustion of natural gas used to provide the heat and high pressure. If these combustion emissions are captured, the carbon dioxide capture efficiency may be lower than that from the SMR process because the carbon dioxide is more dilute in the former case. We are aware of no data on carbon-capture efficiency from any plant, including any electric power plant, that combusts natural gas, but capture efficiencies of carbon dioxide from the exhaust stream of two coal-burning power plants are reported in the range of 55%-72%.[31-33] Note that efficiencies of up to 90% have been observed in one of the plants when running at full load. However, this does not reflect long-term performance, which is evaluated at average load. Load is less than full load either when the carbon-capture equipment is down for repair or when the demand for carbon dioxide is lower than it is at full load. In this analysis, we use a value of 65% capture efficiency from flue gases for our baseline analysis. Applying 100% minus this factor for emissions from the natural gas burned to produce the heat and pressure:

$$(35\%) * (31.8 \text{ g } CO_2 \text{ per MJ}) = 11.1 \text{ g } CO_2 \text{ per MJ} \quad (12)$$

Therefore, total carbon dioxide emissions from the SMR process, including the energy used to drive the process, are in the range of 16.9 g CO_2 per MJ if the combustion flue is captured (5.8 g CO_2 per MJ plus 11.1 g CO_2 per MJ) to 37.6 g CO_2 per MJ (5.8 g CO_2 per MJ plus 31.8 g CO_2 per MJ) if the flue gases are not treated (Table 1).

3.2 | Consumption of methane and production of carbon dioxide from electricity used to capture carbon dioxide

Energy is required to capture the carbon dioxide, and often this is provided by electricity generated from burning additional natural gas.[7] The existing blue-hydrogen facilities make no effort to capture the carbon dioxide from the fuel burned to generate this electricity, nor has there been any effort to do so in the case of carbon capture from coal-burning power plants.[31] Often, an energy penalty of 25% is assumed for this additional electricity.[34-36] However, this estimate is based on very little publicly available, verifiable information and may be optimistically low. A recent analysis of carbon capture from the flue gases of a coal-burning power plant, where the electricity for carbon capture came from a dedicated natural gas plant, found that the carbon dioxide emissions from the natural gas were 39% of the carbon dioxide captured from the coal-flue gases.[31] Carbon dioxide is more concentrated in the gases produced through SMR than in the flue exhaust from combustion, suggesting that it can be captured more easily.

For this analysis, we assume that the energy used in the carbon-capture results in carbon dioxide emissions equal to 25% of the carbon dioxide captured from the stream reforming process, based on IPCC,[34] Jacobson,[35] and Sgouridi et al.[36] Therefore,

$$(25\%) * [(38.5 \text{ g CO}_2 \text{ per MJ}) - (5.8 \text{ g CO}_2 \text{ per MJ})] = 8.2 \text{ g CO}_2 \text{ per MJ} \quad (13)$$

That is, emissions from the energy used to drive the carbon captured from the SMR process are themselves an additional 8.2 g CO_2 per MJ (Table 1).

If carbon dioxide is also captured from the flue gases used to generate heat and pressure, we assume the emissions from the energy cost is equal to 39% of the emissions captured, based on Jacobson.[31] That is,

$$(39\%) * [(31.8 \text{ g CO}_2 \text{ per MJ}) - (11.1 \text{ g CO}_2 \text{ per MJ})] = 8.1 \text{ g CO}_2 \text{ per MJ} \quad (14)$$

Therefore, the carbon dioxide emissions from the energy used to drive the carbon capture is between 8.2 g CO_2 per MJ if only emissions from the SMR process are captured or an additional 8.1 g CO_2 per MJ for a total of 16.3 g CO_2 per MJ if emissions from the energy source used for heat and pressure are also captured (Table 1).

As above for Equation 7, one mole of methane is burned for every mole of carbon dioxide emitted from the burning. Therefore, we can estimate the methane burned to produce the electricity required for the carbon dioxide capture as follows, for the case where only the SMR carbon is captured:

$$(8.2 \text{ g CO}_2/\text{MJ}) * (1 \text{ mole CO}_2/44.01 \text{ g CO}_2) * (16.04 \text{ g CH}_4/\text{mole CH}_4) * (1 \text{ mole CH}_4/1 \text{ mole CO}_2) = 3.0 \text{ g CH}_4/\text{MJ} \quad (15)$$

That is, 3.0 g CH_4 per MJ are consumed to generate the electricity used for carbon capture if only the reforming process emissions are captured (Table 1). Similarly, if the emissions from the energy used for the heat and pressure are also captured,

$$(8.1 \text{ g CO}_2/\text{MJ}) * (1 \text{ mole CO}_2/44.01 \text{ g CO}_2) * (16.04 \text{ g CH}_4/\text{mole CH}_4) * (1 \text{ mole CH}_4/1 \text{ mole CO}_2) = 3.0 \text{ g CH}_4/\text{MJ} \quad (16)$$

Therefore, the quantify of methane used to drive carbon capture when the flue gases from the combustion of the gas used to generate heat and pressure for the SMR process are 3.0 g CH_4 per MJ plus 3.0 g CH_4 per MJ, for a total of 6.0 g CH_4 per MJ when carbon capture is applied both to SMR and exhaust flue gases (Table 1).

If we again assume that 3.5% of the natural gas that is consumed is emitted unburned to the atmosphere (as in Equation 9), then for the case where only carbon dioxide emissions from SMR are captured, upstream methane emissions are:

$$(3.5\%) * (3.0 \text{ g CH}_4/\text{MJ}) = 0.11 \text{g CH}_4/\text{MJ} \quad (17)$$

For the case where flue gases are also treated for carbon capture, the upstream methane emissions are:

$$(3.5\%) * (6.0 \text{ g CH}_4/\text{MJ}) = 0.21 \text{ g CH}_4/\text{MJ} \quad (18)$$

Converting these methane emissions to carbon dioxide equivalents:

$$(0.11 \text{ g CH4 per MJ}) * (86 \text{ g CO}_2\text{eq}/\text{g CH}_4) = 9.5 \text{ g CO}_2\text{eq per MJ} \quad (19)$$

And

$$(0.21 \text{ g CH}_4 \text{per MJ}) * (86 \text{ g CO}_2\text{eq}/\text{g CH}_4) = 18 \text{ g CO}_2\text{eq per MJ} \quad (20)$$

Therefore, upstream emissions of unburned methane from the energy used to drive carbon capture are between 9.5 g CO_2eq per MJ if only the SMR carbon is captured and 18 g CO_2eq per MJ if the flue-gas emissions are also captured (Table 1).

3.3 | Total carbon dioxide and methane emissions for blue hydrogen

The total emission of carbon dioxide for the production of blue hydrogen is the sum of the emissions from the SMR process after carbon capture, emissions from the energy used for heat and pressure to drive SMR, emissions from the energy used to power the carbon capture, and the indirect upstream emissions associated with producing and transporting natural gas. The indirect upstream carbon dioxide emissions result from the activity needed to provide the natural gas, and so should be applied as a percentage to the carbon dioxide produced from using natural gas, and not simply the carbon dioxide emitted after carbon capture. Using the approach of Howarth et al,[21] this is 7.5% of the carbon dioxide produced in the SMR process plus energy needed to fuel that process as for gray hydrogen (70.3 g CO_2 per MJ) plus the emissions from the energy needed to drive the carbon capture (8.2-16.3 g CO_2 per MJ depending on whether or not the flue gases from the SMR-energy source is captured). Therefore, these indirect upstream carbon dioxide emissions are between 5.9 g CO_2 per MJ and 6.5 g CO_2 per MJ depending on whether or not the flue-gas emissions are captured (Table 1). For the case where only the emissions from the SMR processes are treated for carbon capture, total emissions of carbon dioxide are:

$$(5.8 \text{ g CO2 per MJ}) + (31.8 \text{ g CO2 per MJ}) + (8.2 \text{ g } CO_2 \text{ per MJ}) + (5.90 \text{ g } CO_2 \text{ per MJ}) = 51.7 \text{ g } CO_2 \text{ per MJ} \quad (21)$$

When the emissions from exhaust flue gases are also treated for carbon capture:

$$(5.8 \text{ g } CO_2 \text{ per MJ}) + (11.1 \text{ g } CO_2 \text{ per MJ}) + (16.3 \text{ g } CO_2 \text{ per MJ}) + (6.5 \text{ g } CO_2 \text{ per MJ}) = 39.7 \text{ g } CO_2 \text{ per MJ} \quad (22)$$

To summarize, when only the carbon from the SMR process itself is captured, total emissions of carbon dioxide are 51.7 g CO_2 per MJ. When efforts are also taken to capture the carbon dioxide from the flue exhaust from the energy driving the reforming process, total carbon dioxide emissions are 39.7 g CO_2 per MJ (Table 1). Treating the exhaust flue gases for carbon capture reduces total lifecycle emissions of carbon dioxide by 23%, less than might have been expected. This is due both to a relatively low efficiency for the carbon capture of flue gases[31] and to the increased combustion of natural gas needed to provide the electricity for the carbon capture.

The methane emissions from blue hydrogen are the same as for gray hydrogen, except for those associated with the increased use of energy from natural gas to drive the carbon-capture process. The emissions for gray hydrogen are 77.4 g CO_2eq per MJ. The additional methane emissions from the gas used to drive carbon capture are given in Equations 19 and 20: 9.5 g CO_2eq per MJ when only SMR is treated for carbon capture and 18 g CO_2eq per MJ when the exhaust flue gases are also captured. Therefore, the total upstream methane emissions for the production of blue hydrogen are:

$$(77.4 \text{ g } CO_2\text{eq per MJ}) + (9.5 \text{ g } CO_2\text{eq per MJ}) = 86.9 \text{ g } CO_2\text{eq per MJ} \quad (23)$$

when only emissions from the SMR process are captured (Table 1). When flue gases are also treated, total upstream methane emissions are:

$$(77.4 \text{ g } CO_2\text{eq per MJ}) + (18 \text{ g } CO_2\text{eq per MJ}) = 95.4 \text{ g } CO_2\text{eq per MJ} \quad (24)$$

Total emissions for blue hydrogen when only the SMR process is treated are the sum of the carbon dioxide emissions and the upstream methane emissions:

$$(51.7 \text{ g } CO_2\text{per MJ}) + (86.9 \text{ g } CO_2\text{eq per J}) = 139 \text{ g } CO_2\text{eq per MJ} \quad (25)$$

See Table 1. When the exhaust flue gases are also treated for carbon dioxide capture, total emissions for producing blue hydrogen are:

$$(39.7 \text{ g } CO_2\text{per MJ}) + (95.4 \text{ g } CO_2\text{eq per MJ}) = 135 \text{ g } CO_2\text{eq per MJ} \quad (26)$$

We are aware of no previously published, peer-reviewed analyses on either total carbon dioxide or methane emissions associated with producing blue hydrogen. Several non peer-reviewed reports suggest that it may be possible to reduce carbon dioxide emissions for blue hydrogen by 56% (when only the SMR process is treated) to 90% (when exhaust flue gases are also treated) relative to gray hydrogen.[1,7] However, no data have been presented to support these estimates, and they apparently do not include emissions associated with the energy needed to drive carbon capture. Our results using a full lifecycle assessment show the 56% to 90% assumptions are too optimistic.

In Figure 1, we compare the greenhouse gas footprint of gray hydrogen with blue hydrogen where only the SMR process is captured and with blue hydrogen where carbon capture is also used for the exhaust flue gases. Because of the increased methane emissions from increased use of natural gas when flue gases are treated for carbon capture, total greenhouse gas emissions are only very slightly less than when just the carbon dioxide from the stream reforming process is treated, 135 vs 139 g CO_2eq per MJ. In both cases, total emissions from producing blue hydrogen are only 9% to 12% less than for gray hydrogen, 135 or 139 g CO_2eq per MJ compared with 153 g CO_2eq per MJ. Blue hydrogen is hardly "low emissions." The lower, but nonzero, carbon dioxide emissions from blue hydrogen compared with gray hydrogen are partially offset by the higher methane emissions. We further note that blue hydrogen as a strategy only works to the extent it is possible to store carbon dioxide long term indefinitely into the future without leakage back to the atmosphere.

4 | COMPARISON OF EMISSIONS WITH OTHER FUELS AND SENSITIVITY ANALYSES

4.1 | Emissions for fossil fuels

In Figure 1, we also compare greenhouse gas emissions from gray and blue hydrogen with those for other fuels per unit of energy produced when burned. The carbon dioxide emissions

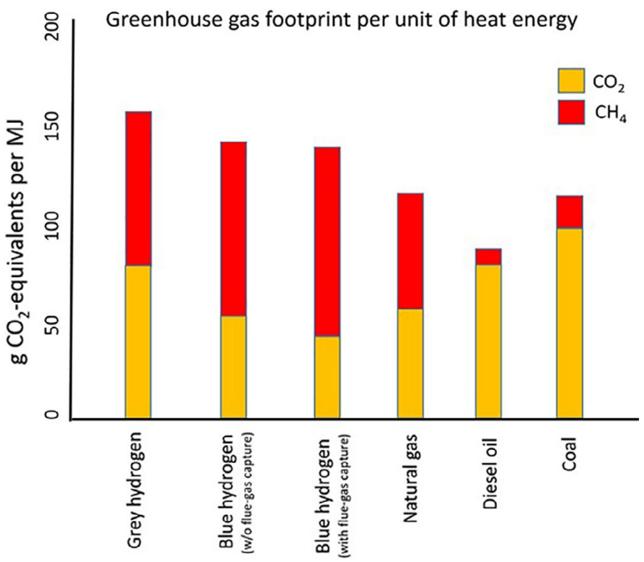


FIGURE 1 Comparison of carbon dioxide equivalent emissions from gray hydrogen, blue hydrogen with carbon dioxide capture from the SMR process but not from the exhaust flue gases created from burning natural gas to run the SMR equipment, blue hydrogen with carbon dioxide capture from both the SMR process and from the exhaust flue gases, natural gas burned for heat generation, diesel oil burned for heat, and coal burned for heat. Carbon dioxide emissions, including emissions from developing, processing, and transporting the fuels, are shown in orange. Carbon dioxide equivalent emissions of fugitive, unburned methane are shown in red. The methane leakage rate is 3.5%. See text for detailed assumptions

shown for coal, diesel oil, and natural gas include both direct and indirect emissions. The direct emissions are based on gross calorific values from EIA.[19] Indirect emissions are those required to develop and process the fuels and are based on Howarth et al.[21] These indirect carbon dioxide emissions are 4 g CO_2 per MJ for coal, 8 g CO_2 per MJ, and 3.8 g CO_2 per MJ for natural gas. Upstream fugitive emissions of unburned methane are assumed to be 3.5% for natural gas, as we have assumed for the hydrogen estimates. Methane emissions for coal and diesel oil are as presented in Howarth[24]: 0.185 g CH_4 per MJ for coal and 0.093 g CH_4 per MJ for diesel oil, corresponding to 8.0 and 15.9 4 g CO_2eq per MJ respectively based on a 20-year GWP of 86.

Combined emissions of carbon dioxide and methane are greater for gray hydrogen and for blue hydrogen (whether or not exhaust flue gases are treated for carbon capture) than for any of the fossil fuels (Figure 1). Methane emissions are a major contributor to this, and methane emissions from both gray and blue hydrogen are larger than for any of the fossil fuels. This reflects the large quantities of natural gas consumed in the production of hydrogen. Carbon dioxide emissions are less from either gray or blue hydrogen than from coal or diesel oil. Carbon dioxide emissions from blue hydrogen are also less than from using natural gas directly as a fuel, but not substantially so. Carbon dioxide emissions from gray hydrogen are somewhat larger than from natural gas (Figure 1).

4.2 | Sensitivity analyses for methane emissions

Given the importance of methane emissions to the greenhouse gas footprints of gray and blue hydrogen, we here present sensitivity analyses on our estimates. We separately consider different rates of fugitive methane emissions and different assigned GWP values.

Our default value for methane emissions used above for gray hydrogen, blue hydrogen, and natural gas is 3.5% of consumption. As noted above, this is based on top–down estimates for emissions from 20 different studies in 10 different gas fields plus a top–down estimate for emissions from gas transport and storage.[16] This is very close to an independent estimate of emissions from shale gas production and consumption estimated from global trends in the ^{13}C stable isotopic composition of methane in the atmosphere since 2005.[37] For the sensitivity analysis, we also evaluate one higher rate and two lower rates of methane emission. The higher rate is from the high-end sensitivity analysis for shale gas emissions based on the global ^{13}C data, or 4.3% of consumption.[37] The lower rates we analyze are 2.54% and 1.45% of consumption. The 2.54% value is based on Alvarez et al[22] who used "bottom–up" approaches to estimate the upstream and midstream methane emissions for natural gas in the United States as 12.7 Tg per year in 2015. This is 2.54% of consumption, based on annual gas consumption for 2015 of 771 billion m^3 of natural gas in the United States,[26] assuming methane comprises 93% of the volume of gas.[38] The bottom–up approach presented by Alvarez et al[22] likely underestimates methane emissions.[24,39,40] We also consider an even lower estimate based on Maasakkers et al.[41] Using an inverse model in combination with satellite data and the US EPA methane emissions inventory, they concluded that methane emissions from natural gas operations in the United States were 8.5 T per year in 2012. This is 1.45% of gas consumption, based on again assuming methane is 93% of gas and a national US consumption of gas of 723 billion m^3 in 2012.[26]

Our baseline analysis is based on a 20-year GWP value of 86.[13] There is uncertainty in this estimate, so here we also explore the higher 20-year GWP value of 105 presented in Shindell et al.[42] Most traditional greenhouse gas inventories use a 100-year GWP, so we explore that as well, using the latest value from the IPCC[13] synthesis report of 34. However, the IPCC[13] noted that the use of a 100-year time period is arbitrary. We prefer the use of 20-year GWP, since it better captures the role of methane as a driver of climate change over the time period of the next several decades, and the 100-year time frame discounts the importance of methane over these shorter time frames.[15,24]

In our sensitivity analyses, we substitute emission rates of 4.3%, 2.54%, and 1.54% for our baseline value of 3.5% in Equations 9, 17, and 18 for gray and blue hydrogen and in our estimate for natural gas presented in Figure 1. We also substitute a 20-year GWP value of 105 and a 100-year GWP value of 34 for the 20-year GWP of 86 used in Equations 10, 19, and 20. The sensitivity estimates are shown in Table 2. Across the full set of assumptions, both gray hydrogen and blue hydrogen without flue-gas capture (where only the carbon dioxide from SMR is captured) always have greater emissions than natural gas. The differences between the greenhouse gas footprint of blue hydrogen with or without the capture of carbon dioxide from the exhaust flue gases are generally small across all assumptions concerning fugitive methane emissions, with the total greenhouse gas emissions without the flue-gas treatment usually higher. The emissions from blue hydrogen with full carbon capture including the exhaust flue gases are higher than for natural gas across all set of assumptions except for the analysis with the 100-year GWP of 34 and low methane emissions, 2.54% or less (Table 2).

We also evaluate the sensitivity of our conclusions to the percentage of carbon dioxide that is captured from SMR and from the flue exhaust from the natural gas burned to power the SMR process. Our default values presented above are for 85% capture from the SMR process and 65% capture from the flue gases, if an effort were made to capture those. Our sensitivity analysis includes a low estimate for SMR capture of 78.8% based on actual data from one commercial blue-hydrogen plant[30] and a high estimate of 90%, the highest yet reported.[31] For capture of the flue gases, we explore carbon dioxide capture efficiencies of 55% at the low end and 90% at the high-end based on actual facility performance for flue gases from coal-burning electric plants.[31-33] Note that the 90% rate is the best ever observed and does not reflect likely actual performance under long-term commercial operations. We present the results of this sensitivity analysis in Table 3. Perhaps surprisingly, our conclusions are very insensitive to assumptions about carbon dioxide capture rates. This is because capture is very energy intensive: to capture more carbon dioxide takes more energy, and if this energy comes from natural gas, the emissions of both carbon dioxide and fugitive methane emissions from this increase in such proportion as to offset a significant amount of the reduction in carbon dioxide emission due to the carbon capture.

These sensitivity analyses show that our overall conclusion is robust: the greenhouse gas footprint of blue hydrogen, even with capture of carbon dioxide from exhaust flue gases, is as large as or larger than that of natural gas.

5 | IS THERE A PATH FOR TRULY "GREEN" BLUE HYDROGEN?

Some of the CO_2eq emissions from blue hydrogen are inherent in the extraction, processing, and use of natural gas as the feedstock source of methane for the SMR process: fugitive methane emissions and upstream emissions of carbon dioxide from the energy needed to produce, process, and transport the natural gas that is reformed into hydrogen are inescapable. On the other hand, the emissions of methane and

	Gray H_2	Blue H_2 (w/o flue-gas capture)	Blue H_2 (w/flue-gas capture)	Natural gas
Fugitive CH_4 = 3.5%				
GWP20 = 8	153	139	135	111
GWP20 = 105	170	158	155	123
GWP100 = 34	106	86	77	76
Fugitive CH_4 = 4.3%				
GWP20 = 86	171	159	156	124
GWP20 = 105	192	182	181	139
GWP100 = 34	113	94	86	81
Fugitive CH_4 = 2.54%				
GWP20 = 86	133	115	109	95
GWP20 = 105	144	129	124	104
GWP100 = 34	98	76	67	70
Fugitive CH_4 = 1.54%				
GWP20 = 86	110	90	82	79
GWP20 = 105	117	98	91	84
GWP100 = 34	89	67	57	64

TABLE 2 Sensitivity analysis for total emissions of carbon dioxide and methane (g CO_2-equivalents per MJ of heat generated in combustion) for different upstream fugitive methane leakage rates and for either 20-year or 100-year global warming potentials (GWP20, GWP100)

TABLE 3 Sensitivity analysis for combined emissions of carbon dioxide and methane (g CO_2-equivalents per MJ of heat generated in combustion) while producing blue hydrogen as a function of the percent carbon dioxide captured from the SMR process and from flue gases for the energy that drives the SMR process

	Total CO_2	Total fugitive CH_4	Total emissions
Blue H_2 w/o flue-gas capture			
85% SMR capture	51.7	86.9	139
90% SMR capture	50.2	86.9	137
78.8% SMR capture	53.5	85.7	139
Blue H_2 w/flue-gas capture			
85% SMR & 65% flue-gas capture	39.7	95.4	135
90% SMR & 90% flue-gas capture	33.3	98.9	132
78.8% SMR & 55% flue-gas capture	43.4	93.2	137

Note: The methane leakage rate is 3.5%. The first row in each case is from the baseline case in Table 1.

carbon dioxide from using natural gas to produce the heat and high pressure needed for SMR and to capture carbon dioxide could be reduced if these processes were instead driven by renewable electricity from wind, solar, or hydro. If we assume essentially zero emissions from the renewable electricity, then carbon dioxide emissions from blue hydrogen could be reduced to the 5.8 g CO_2 per MJ that is not captured from the SMR process (Equation 11) plus the indirect emissions from extracting and processing the natural gas used as feedstock for the SMR process, estimated as 2.9 g CO_2 per M (7.5% of 38.5 g CO_2 per MJ; see section on "total carbon dioxide and methane emissions for gray hydrogen"), for a total of 8.7 g CO_2 per MJ. This is a substantial reduction compared with using natural gas to power the production of blue hydrogen. However, the fugitive methane emissions associated with the natural gas that is reformed to hydrogen would remain if the process is powered by 100% renewable energy. These emissions are substantial: 3.5% of 14 g CH_4 per MJ (Equation 3). Using the 20-year GWP value of 86, these methane emissions equal 43 g CO_2eq per MJ of hydrogen produced. The total greenhouse gas emissions, then, for this scenario of blue hydrogen produced with renewable electricity are 52 g (8.7 g plus 43 g) CO_2eq per MJ. This is not a low-emissions strategy, and emissions would still be 47% of the 111 g CO_2eq per MJ for burning natural gas as a fuel, using the same methane emission estimates and GWP value (Table 1). Seemingly, the renewable electricity would be better used to produce green hydrogen through electrolysis.

This best-case scenario for producing blue hydrogen, using renewable electricity instead of natural gas to power the processes, suggests to us that there really is no role for blue hydrogen in a carbon-free future. Greenhouse gas emissions remain high, and there would also be a substantial consumption of renewable electricity, which represents an opportunity cost. We believe the renewable electricity could be better used by society in other ways, replacing the use of fossil fuels.

Similarly, we see no advantage in using blue hydrogen powered by natural gas compared with simply using the natural gas directly for heat. As we have demonstrated, far from being low emissions, blue hydrogen has emissions as large as or larger than those of natural gas used for heat (Figure 1; Table 1; Table 2). The small reduction in carbon dioxide emissions for blue hydrogen compared with natural gas are more than made up for by the larger emissions of fugitive methane. Society needs to move away from all fossil fuels as quickly as possible, and the truly green hydrogen produced by electrolysis driven by renewable electricity can play a role. Blue hydrogen, though, provides no benefit. We suggest that blue hydrogen is best viewed as a distraction, something than may delay needed action to truly decarbonize the global energy economy, in the same way that has been described for shale gas as a bridge fuel and for carbon capture and storage in general.[43] We further note that much of the push for using hydrogen for energy since 2017 has come from the Hydrogen Council, a group established by the oil and gas industry specifically to promote hydrogen, with a major emphasis on blue hydrogen.[5] From the industry perspective, switching from natural gas to blue hydrogen may be viewed as economically beneficial since even more natural gas is needed to generate the same amount of heat.

We emphasize that our analysis in this paper is a best-case scenario for blue hydrogen. It assumes that the carbon dioxide that is captured can indeed be stored indefinitely for decades and centuries into the future. In fact, there is no experience at commercial scale with storing carbon dioxide from carbon capture, and most carbon dioxide that is currently captured is used for enhanced oil recovery and is released back to the atmosphere.[44] Further, our analysis does not consider the energy cost and associated greenhouse gas emissions from transporting and storing the captured carbon dioxide. Even without these considerations, though, blue hydrogen has large climatic consequences. We see no way that blue hydrogen can be considered "green."

ACKNOWLEDGMENTS

This research was supported by a grant from the Park Foundation and by an endowment given by David R. Atkinson to Cornell University that supports Robert Howarth. We thank Dominic Eagleton, Dan Miller, and two anonymous reviewers for their valuable feedback on earlier drafts of this paper.

ORCID

Robert W. Howarth https://orcid.org/0000-0001-9531-4288

REFERENCES

1. Bartlett J, Krupnick A. *Decarbonized Hydrogen in the US Power and Industrial Sectors: Identifying and Incentivizing Opportunities to Lower Emissions*. Report 20-25. Resources for the Future; 2020. https://media.rff.org/documents/RFF_Report_20-25_Decarbonized_Hydrogen.pdf. Accessed April 1, 2021.
2. Reed S, Ewing J. *Hydrogen is One Answer to Climate Change. Getting it is the Hard Part*. New York Times; 2021. https://www.nytimes.com/2021/07/13/business/hydrogen-climate-change.html. Accessed July 15, 2021.
3. Voorhis S. *New York to Test Green Hydrogen at Long Island Power Plant*. Washington, DC: Utility Dive; 2021. https://www.utilitydive.com/news/new-york-to-test-green-hydrogen-at-long-island-power-plant/603130/. Accessed July 15, 2021.
4. Wang A, Jens J, Mavins D, Moultak M, Schimmel M, van der Leun K, Peters D, Buseman M. *Analyzing Future Demand, Supply, and Transport of Hydrogen*. European Hydrogen Backbone in cooperation with Gas for Climate; 2021. https://gasforclimate2050.eu/wp-content/uploads/2021/06/EHB_Analysing-the-future-demand-supply-and-transport-of-hydrogen_June-2021_v3.pdf. Accessed July 15, 2021.
5. Kahya D. *Unearthed Today: Why Oil Companies Want You to Love Hydrogen*. Amsterdam, the Netherlands: Unearthed; 2020. https://unearthed.greenpeace.org/2020/12/08/unearthed-today-why-oil-companies-want-you-to-love-hydrogen/. Accessed July 15, 2021.
6. World Energy Council. *New Hydrogen Economy: Hope or Hype?*. World Energy Council; 2019. https://www.worldenergy.org/assets/downloads/WEInsights-Brief-New-Hydrogen-economy-Hype-or-Hope-ExecSum.pdf. Accessed April 2, 2021.
7. IEA. *The Future of Hydrogen: Seizing Today's Opportunities*. International Energy Agency; 2019. https://www.iea.org/reports/the-future-of-hydrogen. Accessed April 1, 2021.
8. Farmer M. *What Colour is Your Hydrogen? A Power Technology Jargon-Buster*. London, UK: Power Technology; 2020. https://www.power-technology.com/features/hydrogen-power-blue-green-grey-brown-extraction-production-colour-renewable-energy-storage/. Accessed April 1, 2021.
9. van Hulst N. 2019. *The Clean Hydrogen Future has Already Begun*. IEA commentary, International Energy Agency. https://www.iea.org/commentaries/the-clean-hydrogen-future-has-already-begun. Accessed April 1, 2021.
10. Colella WG, Jacobson MZ, Golden DM. Switching to a U.S. hydrogen fuel cell vehicle fleet: the resultant change in emissions, energy use, and global warming gases. *J Power Sources*. 2005;150:150-181. https://doi.org/10.1016/j.jpowsour.2005.05.092
11. Sun P, Young B, Elgowainy A, et al. Criteria air pollutants and greenhouse gas emissions from hydrogen production in U.S. steam methane reforming facilities. *Environ Sci Technol*. 2019;53:7103-7113. https://doi.org/10.1021/acs.est.8b06197
12. Global CSS Institute. *Global Status of CCS*. The Global CSS Institute; 2020.
13. IPCC. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Intergovernmental Panel on Climate Change; 2013. https://www.ipcc.ch/report/ar5/wg1/. Accessed October 15, 2020.
14. UNEP. *Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions*. United Nations Environment Programme and Climate and Clean Air Coalition; 2021. ISBN: 978-92-807-3854-4. https://www.unep.org/resources/report/global-methane-assessment-benefits-and-costs-mitigating-methane-emissions. Accessed July 15, 2021.
15. Howarth RW. A bridge to nowhere: Methane emissions and the greenhouse gas footprint of natural gas. *Energy Sci Eng*. 2014;2:47-60. https://doi.org/10.1002/ese3.35
16. Howarth RW. Methane and climate change. In: Stolz JF, Griffin WM, Bain DJ, editors. *Environmental Impacts from Development of Unconventional Oil and Gas Reserves*. Cambridge, UK: Cambridge University Press; 2021, in press.
17. NIST. *NIST Standard Reference Database Number 69*. National Institute of Standards and Technology, U.S. Department of Commerce; 2018. https://webbook.nist.gov/chemistry/. Accessed April 1, 2021.
18. T-Raissi A, Block DL. Hydrogen: automotive fuel of the future. *IEEE Power Energ Mag*. 2004;2:40-45. https://doi.org/10.1109/MPAE.2004.1359020
19. EIA. *Carbon Dioxide Emissions Coefficients*. Energy Information Agency, U.S. Department of Energy; 2016. https://www.eia.gov/environment/emissions/co2_vol_mass.php. Accessed October 11, 2019.
20. Santoro R, Howarth RW, Ingraffea A. Indirect emissions of carbon dioxides from Marcellus shale gas development. A technical report of the Agriculture, Energy, and Environment Program at Cornell University; 2011.
21. Howarth RW, Santoro R, Ingraffea A. Methane and the greenhouse gas footprint of natural gas from shale formations. *Climatic Change Lett*. 2011;106:679-690. https://doi.org/10.1007/s10584-011-0061-5
22. Alvarez RA, Zavalao-Araiza D, Lyon DR, et al. Assessment of methane emissions from the U.S. oil and gas supply chain. *Science*. 2018;361:186-188. https://doi.org/10.1126/science.aar7204
23. Plant G, Kort EA, Floerchinger C, Gvakharia A, Vimont I, Sweeney C. Large fugitive methane emissions from urban centers along the US east coast. *Geophys Res Lett*. 2019;46:8500-8507. https://doi.org/10.1029/2019GL082635
24. Howarth RW. Methane emissions from fossil fuels: Exploring recent changes in greenhouse-gas reporting requirements for the State of New York. *J Integr Environ Sci*. 2020;17(3):69-81. https://doi.org/10.1080/1943815X.2020.1789666
25. EIA. *US Natural Gas Production Reaches Record High in 2015, Today in Energy, April 15, 2016*. Energy Information Agency, U.S. Department of Energy; 2021. https://www.eia.gov/todayinenergy/detail.php?id=25832. Accessed April 21, 2021.
26. EIA. *US Natural Gas Total Consumption*.Energy Information Agency, U.S. Department of Energy; 2021. https://www.eia.gov/dnav/ng/hist/n9140us2A.htm. Accessed April 21, 2021.
27. Ocko IB, Hamburg SP, Jacob DJ, et al. Unmask temporal trade-offs in climate policy debates. *Science*. 2017;356:492-493. https://doi.org/10.1126/science.aaj2350
28. Fesenfeld LP, Schmidt TS, Schrode A. Climate policy for short- and long-lived pollutants. *Nat Clim Change*. 2018;8:933-936. https://doi.org/10.1038/s41558-018-0328-1
29. Collodi G, Azzaro G, Ferrari N, Santos S. Techno-economic evaluation of deploying CCS in SMR based merchant H_2 production with NG as feedstock and fuel. *Energy Proc*. 2017;114:2690-2712.

30. Government of Alberta. *Quest CO_2 Capture Ratio Performance, Quest Carbon Capture and Storage (CCS) Project*. Government of Alberta; 2020. https://open.alberta.ca/dataset/f74375f3-3c73-4b9c-af2b-ef44e59b7890/resource/c36cf890-3b27-4e7e-b95b-3370cd0d9f7d/download/energy-quest-co2-capture-ratio-performance-2019.pdf. Accessed July 14, 2021.
31. Jacobson MZ. The health and climate impacts of carbon capture and direct air capture. *Energy Environ Sci*. 2019;12:3567-3574. https://doi.org/10.1039/c9ee02709b
32. Petra Nova. W.A. Parish Post-Combustion CO2 Capture and Sequestration Demonstration Project. Final Scientific/Technical Report. DOE-PNPH-03311. Petra Nova Parish Holdings LLC; 2020.
33. Schlissel D. *Boundary Dam 3 Coal Plant Achieves Goal of Capturing 4 Million Metric Tons of CO_2 but Reaches the Goal Two Years Late*. Lakewood, Ohio: Institute for Energy Economics and Financial Analysis; 2021. http://ieefa.org/wp-content/uploads/2021/04/Boundary-Dam-3-Coal-Plant-Achieves-CO2-Capture-Goal-Two-Years-Late_April-2021.pdf. Accessed July 12, 2021.
34. IPCC. *Carbon Dioxide Capture and Storage*. Intergovernmental Panel on Climate Change; 2005. https://www.ipcc.ch/report/carbon-dioxide-capture-and-storage/. Accessed April 1, 2021.
35. Jacobson MZ. Review of solutions to global warming, air pollution, and energy security. *Energy Environ Sci*. 2009;2:148-173. https://doi.org/10.1039/B809990C
36. Sgouridis S, Carbajales-Dale M, Csala D, Chiesa M, Bardi U. Comparative net energy analysis of renewable electricity and carbon capture and storage. *Nat Energy*. 2019;4:456-465. https://doi.org/10.1038/s41560-019-0365-7
37. Howarth RW. Ideas and perspectives: is shale gas a major driver of recent increase in global atmospheric methane? *Biogeosciences*. 2019;16:3033-3046. https://doi.org/10.5194/bg-16-3033-2019
38. Schneising O, Burrows JP, Dickerson RR, Buchwitz M, Reuter M, Bovensmann H. Remote sensing of fugitive emissions from oil and gas production in North American tight geological formations. *Earth's Future*. 2014;2:548-558. https://doi.org/10.1002/2014EF000265
39. Miller SM, Wofsy SC, Michalak AM, et al. Anthropogenic emissions of methane in the United States. *Proc Natl Acad Sci USA*. 2013;110:20018-20022. https://doi.org/10.1073/pnas.1314392110
40. Vaughn TL, Bella CS, Picering CK, et al. Temporal variability largely explains top-down/bottom-up difference in methane emission estimates from a natural gas production region. *Proc Natl Acad Sci USA*. 2018;115:11712-11717. https://doi.org/10.1073/pnas.1805687115
41. Maasakkers JD, Jacob DJ, Sulprizio JP, et al. 2010–2015 North American methane emissions, sectoral contributions, and trends: a high-resolution inversion of GOSAT observations of atmospheric methane. *Atmos Chem Phys*. 2021;21:4339-4356. https://doi.org/10.5194/acp-21-4339-2021
42. Shindell DT, Faluvegi G, Koch DM, Schmidt GA, Unger N, Bauer SE. Improved attribution of climate forcing to emissions. *Science*. 2009;326:716-718. https://doi.org/10.1126/science.1174760
43. Low SJ. *Climate Imagineering: Practices and Politics of Sunlight Reflection and Carbon Removal Assessment*. Ph.D. thesis, Utrecht University; 2021. https://doi.org/10.33540/668
44. Sekera J, Lichtenberger A. Assessing carbon capture: public policy, science, and societal need. *Biophys Econ Sustainability*. 2020;5:14. https://doi.org/10.1007/s41247-020-00080-5

How to cite this article: Howarth RW, Jacobson MZ. How green is blue hydrogen? *Energy Sci Eng*. 2021;9:1676–1687. https://doi.org/10.1002/ese3.956

Received: 15 March 2022 | Accepted: 31 March 2022

DOI: 10.1002/ese3.1154

COMMENTARY

Reply to comment on "How Green is Blue Hydrogen?"

Robert W. Howarth[1] | **Mark Z. Jacobson**[2]

[1]Department of Ecology and Evolutionary Biology, Cornell University, Ithaca, New York, USA

[2]Department of Civil and Environmental Engineering, Stanford University, Stanford, California, USA

Correspondence
Robert W. Howarth, Department of Ecology and Evolutionary Biology, Cornell University, Ithaca, NY 14853, USA.
Email: howarth@cornell.edu;jacobson@stanford.edu

Funding information
The Park Foundation; College of Agriculture and Life Sciences, Cornell University

Abstract

In their comment on our 2021 paper "How Green is Blue Hydrogen," Romano et al. purport to provide "a more balanced perspective on blue hydrogen, which is in line with current best available practices." We strongly disagree. First, we categorically dismiss their presentation on methane emissions. Methane dominates the greenhouse gas footprint of blue hydrogen in our analysis, and our estimates were based on very recent, peer-reviewed science. Romano et al., in sharp contrast, use only three sources: (1) a 2015 non-peer-reviewed report (which gave reasonable values, although at the low end, since based on older science, but nonetheless compatible with our paper); (2) a 2018 report from the International Energy Agency (which also gave values consistent with ours, but has been updated by the Agency in a 2022 report to give much higher values that are very consistent with ours); and (3) a value from a cartoon on a web site from an oil and gas industry trade group (i.e., not supported by any data or references and is simply wrong based on peer-reviewed science). We cannot stress enough that the Romano et al. criticism of our methane emission rates is based totally on this industry website cartoon. Beyond the methane issue, our analysis used actual data for capture of carbon dioxide from real-world operations. Romano et al. dismiss the use of real-world data, and instead rely on presentations from theoretical studies. We find this fanciful. But even if one accepts their theoretical values for carbon capture, the greenhouse gas footprint of blue hydrogen remains unacceptably high because of methane. We unequivocally stand by our analyses and conclusions: There is no room for blue hydrogen in a decarbonized energy future. The Romano et al. result derives from a cartoon and hypothetical guesses, not scientific data.

KEYWORDS
hydrogen, life cycle analysis

1 | INTRODUCTION

Globally, 96% of hydrogen is made from fossil fuels, almost entirely from natural gas in the United States and Europe.[1] Steam methane reforming (SMR) is overwhelmingly the dominant process for making hydrogen from natural gas and constitutes almost 75% of all hydrogen production globally.[2] Natural gas is mostly methane (CH_4), and this methane is the feedstock for the SMR process. Under high pressure and temperature and with the addition of steam, CH_4 is converted into hydrogen and carbon dioxide (CO_2), with some intermediate steps.

In addition to serving as the feedstock, natural gas is burned to create the heat and high pressure that drive SMR. Greenhouse gas emissions are high.[3,4] Blue hydrogen is a new concept in which an effort is made to capture CO_2 emissions from the traditional SMR process. To date, blue hydrogen has been produced in only two commercial facilities globally. The oil and gas industry heavily promotes blue hydrogen, often stating it has low or zero greenhouse gas emissions.[3,5,6] In Howarth and Jacobson,[7] we investigated this claim and provided one of the very few peer-reviewed analyses of greenhouse gas emissions from either blue hydrogen or the traditional "gray" hydrogen made by SMR, including fully accounting for CH_4 emissions in the greenhouse gas footprints. We demonstrated that while CO_2 emissions from blue hydrogen are somewhat less than for gray hydrogen, they are still substantial, and CH_4 emissions are in fact higher due to an increased use of natural gas to power the carbon capture. These results apply even before considering the leakage rate of captured carbon dioxide. Three major uncertainties arise in calculating the potential climate forcing of blue hydrogen: (1) the emission rate of CH_4 during the extraction, piping, processing, storing, and use of natural gas; (2) the emission rate of CO_2 due to the inefficiency of carbon capture equipment and due to the fact that additional energy is needed to run carbon capture equipment and to pipe CO_2, so more natural gas is burned, emitting more CO_2; and (3) the relevant time frame for looking at climate impacts, 20 or 100 years. In their comment, Romano et al.[8] mistakenly criticize our assumptions in the first of these two areas and inappropriately emphasize the 100 year time frame. Below, we respond to these misplaced criticisms one at a time.

2 | METHANE EMISSIONS

A majority of the total greenhouse gas emissions from producing blue hydrogen come from emissions of unburned CH_4 associated with using natural gas, according to Howarth and Jacobson.[7] Natural gas is composed mostly of CH_4, and it simply is not possible to develop, process, store, and transport natural gas without some CH_4 being emitted to the atmosphere. Some of these emissions are due to leaks, but significant emissions also result from the routine, purposeful operations of the natural gas industry.[9–11] For instance, for safety reasons the gas in high-pressure gas pipelines is released to the atmosphere before maintenance is performed on the pipelines. These emissions matter, since CH_4 is more than 100 times more powerful than CO_2 as an agent of global warming for the time both gases are in the atmosphere.[12] In the 2021 AR6 Working Group No. 1 synthesis report, the Intergovernmental Panel on Climate Change (IPCC) concluded that of all human-caused warming over the past century, the contribution of CH_4 is equal to 67% of that of CO_2, 0.5°C compared to 0.75°C.[13]

To estimate CH_4 emissions in Howarth and Jacobson,[7] we relied on the preponderance of the peer-reviewed literature, including very recent data in this rapidly growing area of science. We used a baseline estimate of 3.5% of gas consumption in our analysis, but also explored values as low as 1.54% and as high as 4.3%. Note that there has been an explosion in the number of new studies on CH_4 emissions from the natural gas industry over the past decade, with more than 1700 papers published over the past decade. Our 3.5% baseline estimate is based largely on 20 studies reported in 12 peer-reviewed papers for emissions as estimated from airplane flyovers and satellite data in North America between 2013 and 2020 ("top-down" estimates)[10] and a global estimate based on trends in the 13-C stable isotopic composition of atmospheric CH_4 since 2005.[14] A recent study using satellite data to examine CH_4 emissions from two of the world's largest natural gas fields, in Turkmenistan, show a rate of 4.1%, even higher than estimates based on North American data.[15] Our 4.3% estimate was based on the higher possible range calculated from the global trend in the 13-C stable isotopic composition of methane.[14] The two lower values we used, 2.54% and 1.54%, are in fact lower than we believe are representative for global average emissions but nonetheless come from solid, peer-reviewed studies.[11,16] We strongly believe that an estimate of 3.5% of gas consumption is a reasonable (probably conservatively low) average estimate for CH_4 emissions from natural gas production and use not only in the United States but globally. This was our default estimate in Howarth and Jacobson,[7] and we stand by it.

Romano et al.'s[8] estimates, on the other hand, are based on two out-of-date, non-peer-reviewed reports and a cartoon on a web page from the oil and gas industry. Of these, only the industry's cartoon gives methane emissions below the range we used in our Howarth and Jacobson analysis. Specifically, Romano et al. used:

1. A non-peer-reviewed literature review written in 2015 by the Sustainable Gas Institute at Imperial College.[17] This review reported a mean emission estimate of 2.2% from the studies they included. Despite the insinuation of the Romano et al. comment, this is well within the range we evaluated for the sensitivity analyses in our paper (1.5%–4.3%). Nonetheless, we firmly believe our baseline estimate of 3.5% better

represents global average emissions, since it is based on more data and more recently collected data.[10]

2. A 2018 report from the International Energy Agency (IEA).[18] Romano et al. interpret this report as indicating CH_4 emission rates in the range of 1.4%–2%. Again, despite the insinuation of Romano et al., this range is hardly inconsistent with our range of 1.5%–4.3%. Further, the IEA has recently issued a new report, correcting their earlier estimates used by Romano et al. The new IEA report from 2022 states that "methane emissions from the energy sector are about 70% higher than reported in official data" upon which their 2018 report relied.[18] Correcting the IEA numbers from 2018 used by Romano et al. (1.4%–2%) by this 70% factor increases the emission estimates to 2.4%–3.4%, which is very much in line with the range we used in Howarth and Jacobson (again, 1.5%–4.3%).
3. A value of 0.2% from a trade group of the oil and gas industry.[19] The citation provided by Romano et al. is simply a web site with just a few pages, and the 0.2% value comes from a cartoon that presents an industry "emission target for 2025," with no supporting data or references. We find it amazing that Romano et al. rely so heavily on this value in their criticism, as it is the only one in their comment that is below the range we used in Howarth and Jacobson. The 0.2% estimate is simply not believable, is not supported by verifiable data, and is very much at odds with almost all peer-reviewed studies on this topic.[10]

3 | CARBON DIOXIDE CAPTURE AND EMISSIONS

In their comment, Romano et al. state "a detailed reading of the paper (Howarth and Jacobson) reveals that the conclusions are inaccurate, as they were derived using an oversimplified method and a selective set of assumptions that are not representative of the technology performance and best available practices now, and especially when working in future low-carbon scenarios."[8] We reject this statement and conclude the opposite; namely Romano et al. have not carried out due diligence by using real-world data. In Howarth and Jacobson, we used the best available data for real-world performance, and explained the choices made in using these data. See sections 3.1 and 3.2 in our original paper.[7] Further, our sensitivity analyses included capture rates of 90% for CO_2 both from the steam CH_4 reforming process and from the combustion of natural gas used to drive the process, values that are higher than have ever been demonstrated in commercial plants. Even under these optimistic assumptions, blue hydrogen has a greenhouse gas footprint, larger than that from just burning natural gas (see table 2 of Howarth and Jacobson).[7]

Romano et al.[8] reject the use of data from real-world plants, stating "the regulatory and market conditions have not been sufficiently demanding to favor the deployment of commercial hydrogen plants with high CO_2 capture rate at scale yet." This admission is in contradiction to the claims often made by industry that blue hydrogen already has low or near-zero emissions of CO_2.[3,5] After dismissing the value of data from real-world facilities, Romano et al. proceed to rely on hypothetical calculations for energy use and emissions, including some highly optimistic assumptions. Specifically, they use estimates for two blue hydrogen "plants," which are so far just theoretical constructs, not physical realities subject to real-world, perhaps unexpected difficulties. To briefly summarize these two "plants:"

1. One is assumed to use conventional SMR, with an assumed postcombustion CO_2 efficiency of 90%. Romano et al.[8] state "Thanks to heat recovery, a small increase of natural gas input (+10% compared to the corresponding gray H_2 plant) is needed to self-produce the energy for CO_2 capture and compression, resulting in a blue hydrogen plant which is effectively electrically neutral."
2. The other is a "blue hydrogen plant based on an oxygen-blown autothermal reformer (ATR) and CO_2 capture from syngas with the methyl diethanoamine (MDEA) process, as proposed by Antonini et al." Antonini is the second author of the Romano et al. comment on our paper. Romano et al. state "In this plant, a target CO_2 separation efficiency of 98% was assumed in the MDEA unit, resulting in overall carbon capture rate of around 93%."[8]

Both of these case studies use highly optimistic assumptions not justified by real technologies operating continuously for one or multiple years. Whereas it is known that full-load capture rates can reach 90% or more, real carbon capture projects (e.g., Petra Nova, Boundary Dam, Gorgon) have capture rates ranging from 20% to 72% over multiple years due to equipment downtime, lack of demand for CO_2, or lower efficiency than expected.[20–23] Note that in Howarth and Jacobson, we presented this range as 55%–72% and used a value of 65% as our default. The low value of 20% we include here is from the very poor performance of the Gorgon facility.[23] For more on problems with carbon capture in real-world facilities, see the December 2021 report from the US Government Accountability Office.[24] Thus, the "assumed post-combustion CO_2 capture efficiency of 90%" used by Romano et al. in their Case no. 1 is too high, given real-world data. Further, as far as we are aware, the use of heat recovery to power the CO_2 capture in Case no. 1 has not even been tested experimentally, let alone used in commercial operation.

Regarding Case no. 2, as far as we aware, blue hydrogen based on ATR has never been attempted in commercial operation.[25] Romano et al. give no examples of actual commercial efforts to use ATR, and Kim et al.[26] note in a 2021 paper that the required need for pure oxygen has been an impediment to ATR use by industry. The "overall carbon capture rate of around 93%" used by Romano et al., then, is hypothetical and dependent upon the 98% efficiency that they "assumed in the MDEA unit," which has not been tested in any actual plant. Further, it is important to note that ATR produces less hydrogen per input of methane from natural gas than does SMR, and so at least 38% more natural gas feedstock is required for ATR.[27] This of course leads to greater methane emissions from the production, processing, storage, and transport of the needed natural gas, a fact apparently not included in the analysis of Romano et al.[8]

In support of their optimism on high efficiencies for carbon capture, Romano et al. write "As for CO_2 capture from flue gas, even though commercially immature at large scale, there is scientific and technical evidence that CO_2 capture efficiencies higher than 90% can be achieved in commercial plants. For example, the 240 MWe Petra Nova plant captured 92.4% of the CO_2 from the processed flue gas when operating at full load."[8] Note that we discussed this plant in Howarth and Jacobson, stating "that efficiencies of up to 90% have been observed in one of the plants when running at full load. However, this does not reflect long-term performance, which is evaluated at average load."[7] Our use of "a value of 65% capture efficiency from flue gases for our baseline analysis" was based in part on the data from this Petra Nova plant, viewed in its entirety. Romano should also have noted that Petra Nova shut down in 2020 because it was an economic failure, as noted in a recent report from the US Government Accountability Office.[24]

Romano et al. further write "Also, in the recent post-combustion carbon dioxide capture Best Available Techniques (BAT) UK guidelines, 95% of CO_2 capture efficiency is targeted. Therefore, under proper economic (i.e., sufficiently high CO_2 emission cost) and regulatory conditions (e.g., cap on specific emissions), it is reasonable to assume that CO_2 capture efficiencies well above 90% can be achieved in future blue hydrogen plants."[8] Reaching the UK BAT guidelines seems unlikely, based on real-world experience. Regardless, the BAT guidelines are not evidence that this high efficiency can be achieved by blue hydrogen plants.

4 | GLOBAL WARMING POTENTIAL

CH_4 is a far more potent greenhouse gas than CO_2, but its residence time in the atmosphere is less. Consequently, one must define a time frame of interest to directly compare the warming influences of the two gases. Damaging climate impacts are occurring today over periods of only a few years, and short-lived powerful global warming agents such as black carbon, CH_4, and tropospheric ozone cause much more damage over the short term than over the long term. As such, from a policy and damage-control point of view, it is crucial to eliminate substances (black carbon, CH_4, tropospheric ozone) whose control can avoid catastrophic short-term damage to the climate. With that in mind, the use of a 20-year time from for developing policies is far more useful than the use of a 100-year time frame for analyzing the impacts of blue hydrogen.[9,28]

In Howarth and Jacobson,[7] we used 20 years as the default. However, we also included the use of a 100-year global warming potential in our sensitivity analyses (see table in Howarth and Jacobson). Even under the 100-year assumption, the greenhouse gas emissions from blue hydrogen were still worse than or no better than those from simply burning natural gas. In their comment, Romano et al. use both 20- and 100-year global warming potentials but fail to emphasize the superiority of the 20-year time frame for avoiding immediate damage and tipping points for more severe long-term damage. Along those lines, Abernethy and Jackson[29] in a new 2022 paper have demonstrated that the use of a 100-year GWP is simply not compatible with reaching the climate goals set by the COP21 Paris accords in 2015.

5 | SUMMARY AND CONCLUSIONS

Nothing presented in the comment by Romano et al. has caused us to reconsider our original approach, calculations, and conclusions. Their assumptions regarding high efficiency of capture of CO_2, with very low inputs of energy, are not supported by real-world data. However, even if we fully accept the hypothetical analyses upon which they rely for carbon capture and energy requirements for blue hydrogen, greenhouse gas emissions of CH_4 will remain high. Romano et al. considered three levels of CH_4 emissions: 0.2%, 1%, and 3.5%. The two lower levels are simply not compatible with the large and growing body of literature on emissions from the natural gas industry, and in fact are lower than the range of estimates provided in the two reports Romano et al.

relied upon.[17,30] Their sole justification for using these lower values is a number on the cartoon on a web site for an oil and gas industry trade group.[19] Consequently, figures 1C, 1D, 1E, and 1F in the Romano et al. comment should be ignored. Their figures 1A and 1B, which are based on a 3.5% CH_4 emission rate using 20- and 100-year global warming potentials, demonstrate substantial greenhouse gas emissions from blue hydrogen, even under their extremely optimistic assumptions, because of the CH_4 emissions inherent in using natural gas. Similarly, the emissions shown in their figure 2 are incompatible with a decarbonized future, given the reality of CH_4 emissions, even if their technical optimism on carbon capture at low energy cost could be achieved: at a 3.5% CH_4 emission rate and 20-year global warming potential, they estimate only a 25% reduction in total greenhouse gas emissions relative to simply burning natural gas (figure 2A).[8]

We urge our engineering and science colleagues to take great care in communicating their work on greenhouse gas emissions from the production and use of hydrogen. The public and decision makers can be easily confused on these emissions, particularly in a world where the oil and gas industry is heavily engaged at messaging approaches that may be designed primarily to support their business model: to continue to sell natural gas.[31,32] Hypothetical projections of what might be possible should not be confused with what will occur in the actual world. And while we see a future for green hydrogen (hydrogen from electrolysis of 100% renewable electricity) in a decarbonized future, the greenhouse gas emissions from blue hydrogen are unacceptably high.

In their introduction to their comment, Romano et al.[8] said "Controversial statements from scientists at renowned institutions attract attention, irrespective of their basis in scientific facts or the rigor of the underpinning study." They proceeded to highlight the following set of quotes from our paper:

1. "There really is no role for blue hydrogen in a carbon-free future."
2. "There is no advantage in using blue hydrogen powered by natural gas compared with simply using the natural gas directly for heat."
3. "…blue hydrogen…is best viewed as a distraction…"
4. "There is no way that blue hydrogen can be considered 'green'."

We do not accept that our paper made "controversial statements," nor that our work lacked rigor. And we stand by these quotes selected by Romano et al. which are, in fact, supported by the best available scientific data as presented in our paper. There is nothing green about blue hydrogen.

ACKNOWLEDGEMENTS

This study is supported by a grant from the Park Foundation and by an endowment given by David R. Atkinson to Cornell University that supports Robert Howarth.

REFERENCES

1. World Energy Council. New hydrogen economy: hope or hype? World Energy Council; 2019. Accessed April 2, 2021. https://www.worldenergy.org/assets/downloads/WEInsights-Brief-New-Hydrogen-economy-Hype-or-Hope-ExecSum.pdf
2. IEA. The future of hydrogen: seizing today's opportunities. International Energy Agency; 2019. Accessed April 1, 2021. https://www.iea.org/reports/the-future-of-hydrogen
3. van Hulst N. The clean hydrogen future has already begun. IEA commentary, International Energy Agency; 2019. Accessed April 2, 2021. https://www.iea.org/commentaries/the-clean-hydrogen-future-has-already-begun
4. Colella WG, Jacobson MZ, Golden DM. Switching to a U.S. hydrogen fuel cell vehicle fleet: the resultant change in emissions, energy use, and global warming gases. *J Power Sources*. 2005;150:150-181. doi:10.1016/j.jpowsour.2005.05.092
5. Kahya D. *Unearthed Today: Why Oil Companies Want You to Love Hydrogen*. Amsterdam, The Netherlands: Unearthed; 2020. Accessed July 15, 2021. https://unearthed.greenpeace.org/2020/12/08/unearthed-today-why-oil-companies-want-you-to-love-hydrogen/
6. Farmer M. What Colour is Your Hydrogen? A Power Technology Jargon-Buster. London, UK: Power Technology; 2020. Accessed April 1, 2021. https://www.power-technology.com/features/hydrogen-power-blue-green-grey-brown-extraction-production-colour-renewable-energy-storage/
7. Howarth RW, Jacobson MZ. How green is blue hydrogen? *Energy Sci Eng*. 2021;9:1676-1687. doi:10.1002/ese3.956
8. Romano MC, Antonini C, Bardow A, et al. Comment on "how green is blue hydrogen? *Energy Sci Eng*. Forthcoming.
9. Howarth RW. A bridge to nowhere: methane emissions and the greenhouse gas footprint of natural gas. *Energy Sci Eng*. 2014;2:47-60. doi:10.1002/ese3.35
10. Howarth RW. Methane and climate change. In: Stolz JF, Griffin WM, Bain DJ, eds. *Environmental Impacts from Development of Unconventional Oil and Gas Reserves*. Cambridge University Press; 2022.
11. Alvarez RA, Zavalao-Araiza D, Lyon DR, et al. Assessment of methane emissions from the U.S. oil and gas supply chain. *Science*. 2018;361:186-188. doi:10.1126/science.aar7204
12. IPCC. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate Change; 2013. Accessed October 15, 2020. https://www.ipcc.ch/report/ar5/wg1/
13. IPCC. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Intergovernmental Panel on Climate Change; 2021. Accessed

September 14, 2021. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full_Report_smaller.pdf
14. Howarth RW. Ideas and perspectives: is shale gas a major driver of recent increase in global atmospheric methane? *Biogeosciences*. 2019;16:3033-3046. doi:10.5194/bg-16-3033-2019
15. Schneising O, Buchwitz M, Reuter M, et al. Remote sensing of methane leakage from natural gas and petroleum systems revisited. *Atmos Chem Phys*. 2020;20:9169-9182. doi:10.5194/acp-20-9169-2020
16. Maasakkers JD, Jacob DJ, Sulprizio JP, et al. 2010–2015 North American methane emissions, sectoral contributions, and trends: a high-resolution inversion of GOSAT observations of atmospheric methane. *Atmos Chem Phys*. 2021;21:4339-4356. doi:10.5194/acp-21-4339-2021
17. Balcombe P, Anderson K, Speirs J, Brandon N, et al. Methane and CO_2 Emissions from the Natural Gas Supply Chain: An Evidence Assessment; 2015. Accessed March 7, 2022. https://www.imperial.ac.uk/sustainable-gas-institute/research-themes/white-paper-series/white-paper-1-methane-and-co2-emissions-9from-the-natural-gas-supply-chain/
18. IEA. Global Methane Tracker; 2022. Accessed March 7, 2022. https://www.iea.org/reports/global-methane-tracker-2022
19. Oil and Gas Climate Initiative. Reducing Methane Emissions; 2021. Accessed March 7, 2022. https://www.ogci.com/action-and-engagement/reducing-methane-emissions/#methane-target
20. Jacobson MZ. The health and climate impacts of carbon capture and direct air capture. *Energy Environ Sci*. 2019;12:3567-3574. doi:10.1039/c9ee02709b
21. Petra Nova WA. Parish Post-Combustion CO_2 Capture and Sequestration Demonstration Project. Final Scientific/Technical Report. DOE-PNPH-03311 Petra Nova Parish Holdings LLC; 2020.
22. Schlissel D. Boundary Dam 3 Coal Plant Achieves Goal of Capturing 4 Million Metric Tons of CO_2 but Reaches the Goal Two Years Late. Lakewood, Ohio: Institute for Energy Economics and Financial Analysis; 2021. Accessed July 12, 2022. http://ieefa.org/wp-content/uploads/2021/04/Boundary-Dam-3-Coal-Plant-Achieves-CO2-Capture-Goal-Two-Years-Late_April-2021.pdf
23. Morton A. 'A shocking failure': Chevron criticized for missing carbon capture target at WA gas project; 2021. Accessed March 7, 2022. https://www.theguardian.com/environment/2021/jul/20/a-shocking-failure-chevron-criticised-for-missing-carbon-capture-target-at-wa-gas-project
24. GAO. Carbon Capture and Storage, Actions Needed to Improve DOE Management of Demonstration Projects. Report to Congressional Committees. United States Government Accountability Office; 2021. GAO-22-105111
25. Ji M, Wang J. Review and comparison of various hydrogen production methods based on costs and life cycle impact assessment indicators. *Hydrog Energy*. 2021;46:38612-38635. doi:10.1016/j.ijhydene.2021.09.142
26. Kim J, Park J, Qi M, Lee I, et al. Process integration of an autothermal reforming hydrogen production system with cryogenic air separation and carbon dioxide capture using liquefied natural gas cold energy. *Ind Eng Chem Res*. 2021;60:7257-7274. doi:10.1021/acs.iecr.0c06265
27. Chen WH, Lin MR, Lu JJ, Chao Y, Leu TS. Thermodynamic analysis of hydrogen production from methane via autothermal reforming and partial oxidation followed by water gas shift reaction. *Int J Hyd Energy*. 2010;35:11,787-11,797. doi:10.1016/j.ijhydene.2010.08.126.
28. Howarth RW. Methane emissions from fossil fuels: exploring recent changes in greenhouse-gas reporting requirements for the State of New York. *J Integr Environ Sci*. 2020;17:69-81. doi:10.1080/1943815X.2020.1789666
29. Abernethy S, Jackson RB. Global temperature goals should determine the time horizonsfor greenhouse gas emission metrics. *Environ Res Lett*. 2022;17:024019. doi:10.1088/1748-9326/ac4940
30. IEA. World Energy Outlook 2018; International Energy Agency; 2018. doi:10.1787/weo-2018-2-en
31. Szabo J. Fossil capitalism's lock-ins: the natural gas-hydrogen nexus. *Capital Nat Social*. 2021;32:91-110. doi:10.1080/10455752.2020.1843186
32. Wright A. Mapped: Europe's Fossil Fuel-Backed Hydrogen Lobby. DeSmog; 2021. Accessed March 7, 2022. https://www.desmog.com/2021/12/10/mapped-europes-fossil-fuel-backed-hydrogen-lobby/

How to cite this article: Howarth RW, Jacobson MZ. Reply to comment on "How Green is Blue Hydrogen?". *Energy Sci Eng*. 2022;10:1955-1960. doi:10.1002/ese3.1154

ROBERT W. HOWARTH

Department of Ecology & Evolutionary Biology
Corson Hall, Cornell University
Ithaca, NY 14853 USA

http://www.eeb.cornell.edu/howarth/
e-mail: howarth@cornell.edu
Tel.: (1)-607-280-9981

Education

B.A., Amherst College (*Magna cum laude*), 1974
Ph.D., Massachusetts Institute of Technology/Woods Hole Oceanographic Institution Joint Program in Biological Oceanography, 1979

Professional Experience

1993-Present	David R. Atkinson Professor of Ecology & Environmental Biology, Cornell University.
2020-Present	Member, Climate Action Council, State of New York (appointed by the Speaker of the State Assembly).
2021-Present	Co-Editor-in-Chief, *Ocean-Land-Atmosphere Research* (OLAR)
2021-Present	Member of editorial board, *Energy Science & Engineering*
2019-2020	Chair, the University Assembly, Cornell University.
2018-2019	Vice Chair, the University Assembly, Cornell University.
2014-2019	Editor-in-Chief, *Limnology & Oceanography*.
2016-Present	Distinguished Visiting Fellow, Woods Hole Research Center.
2000-Present	Adjunct Senior Scientist, Marine Biological Laboratory, Woods Hole.
1983-Present	Founding Editor, *Biogeochemistry* (Editor-in-Chief, 1983-2004).
2005-2012	Director, Agriculture, Energy, & Environment Program, Cornell University.
2000-2001	Oceans Program Director & Senior Scientist, Environmental Defense Fund.
1995-2000	Director, Program in Biogeochemistry & Environmental Change, Cornell.
1992-1995	Senior Fellow, and coordinator for Initiative in Earth, Atmospheric, & Aquatic Sciences, Center for the Environment, Cornell.
1990-1993	Professor, Section of Ecology & Systematics, Cornell University.
1988-1991	Director, Ecosystems Research Center (US EPA National Center of Excellence), Cornell University.
1985-1990	Associate Professor, Section of Ecology & Systematics, Cornell University.
1980-1985	Assistant and Associate Scientist, Marine Biological Lab, Woods Hole.
1979	Noyes Postdoctoral Fellow, Marine Biological Laboratory, Woods Hole.

Recent Awards and Honors (since 2000)

- One of the ten ever most highly cited marine biologists/aquatic scientists in the world (*PLoS Biol* 18(10): e3000918. https://doi.org/10.1371/journal.pbio)
- One of 50 "Most Influential People" driving energy policy in New York State, City & State New York magazine, three years in a row (2019, 2020, and 2021).
- Invited briefing to US Congress on the Fracking Ban Act (2020)
- Invited briefing to European Parliament on "Fueling the Fracking, Plastics, Methane Emissions and the Gas Lobby" (2020)

- ASLO John Martin Award, Association for Sciences of Limnology & Oceanography (2018).
- Moore Lecturer, University of Virginia (2017).
- ASLO Sustaining Fellow, Association for Sciences of Limnology & Oceanography (2017).
- Invited briefing on methane, shale gas development, and climate change to the Office of Science and Technology Policy, Executive Office of the White House (2016).
- Keynote speaker, Earth Day, State University of New York at Stony Brook (2014).
- Ian Morris Distinguished Scholar, Horn Point Laboratory, University of Maryland (2014).
- Featured plenary speaker, World Water Day, Michigan Technological University (2014).
- Co-Winner, 2013 Atlas Award, "honoring climate heroes worldwide"
- David Schindler Visiting Scholar, Trent University (2013)
- Pritchard Award, best physical oceanography paper published in *Estuaries & Coasts* (2013).
- One of Time Magazine's 50 "People Who Mattered," 2011 Person of the Year issue.
- Zayed International Prize for the Environment (2007), jointly with the other lead authors of the Millennium Ecosystem Assessment.
- Invited briefing on coastal water quality to the Office of Science and Technology Policy, Executive Office of the White House (2006).
- Selected by ISI Web of Science (Scientific Citation Index) as one of 250 most cited scientists globally in ecology and environmental science disciplines (every year, 2006 to the present).
- Biology Faculty of 1,000 (every year, 2005 to the present).
- Lindeman Award in Ecology, University of Minnesota (2003).
- Aldo Leopold Leadership Fellow, Ecological Society of America (2000).
- Eminent Ecologist award, Kellogg Biological Station, Michigan State Univ. (2000).

National and International Committees and Activities

2021	Delegate observer to the UN COP26 negotiations, Glasgow, Scotland.
2017-present	Member, Board of Directors, Food & Water Watch.
2017	Delegate observer to the UN COP23 negotiations, Bonn, Germany.
2017	Chair, Review Panel for Integration of Monitoring and Evaluation into Environmental Restoration Projects to Improve Outcomes in the Gulf of Mexico, National Academy of Sciences.
2015-present	Member, EPA Clean Air Scientific Advisory Committee (CASAC) Secondary National Ambient Air Quality Standards Review Panel for Oxides of Nitrogen and Sulfur, US Environmental Protection Agency.
2015	Delegate observer to the United Nations COP21 negotiations, Paris, France.
2014-2016	Member, National Estuarine Research Reserves Science Collaborative Advisory Board, National Oceanic & Atmospheric Administration.
2010-2014	Member, Working Group on Land and Soils, International Resource Panel, United Nations Environment Programme.
2007-2012	Chair, International SCOPE Biofuels Project: Environmental Consequences of Biofuels (International Council of Science).
2007-2009	President, Coastal & Estuarine Research Federation.
2008-2010	Member, Board of Directors, Council of Scientific Society Presidents.
2007-2011	Co-chair, Committee on Energy & Environment, Council of Scientific Society Presidents.

2005-2013	Representative from the State of New York to the Scientific and Technical Advisory Committee of the Chesapeake Bay Program.
2006-2008	Member, Gulf of Mexico Hypoxia Advisory Panel, US EPA.
2005-2007	Member, Steering Committee, N2007 International N Symposium, Brazil.
2004-2007	Member, Biogeochemistry Rapid Response Team, Ecological Society of America.
2003-Present	Editor, book series on Environmental Management, Springer.
2003-2008	Member, Coast and Oceans Working Group, the Heinz Center.
2003-2006	Director, North American Regional Center, International Nitrogen Initiative.
2003-2014	Member, Advisory Committee, International Nitrogen Initiative.
2002-2005	Coordinating Lead Author, chapter on responses to nutrient pollution, the Millennium Ecosystem Assessment.
2002-2004	Member, Advisory Committee, N2004 International N Symposium, China.
2002-2003	Coordinator and lead author, Working Group to Develop a Federal Interagency Research Plan for Coastal Nutrient Pollution.
2001-2002	Consultant on coastal nutrient pollution, the Pew Oceans Commission.
2000-2003	Member, US Committee for SCOPE, National Academy of Sciences.
2000-2003	Member, Scientific Advisory Board, National Center for Ecological Analysis & Synthesis, University of California at Santa Barbara.
2001-2002	Member, Committee to Evaluate the Water Programs of the US Army Corps of Engineers, National Academy of Sciences.
1992-2002	Co-Chair, International SCOPE Nitrogen Project on Nitrogen: A Regional and Global Analysis (International Council of Science).
2000-2001	Member, Advisory Committee, N2001 Symposium, Potomac, MD.
1998-2001	Member, National Climate Change Assessment (Coastal Marine Sector).
1998-2000	Chair, Committee on Causes and Management of Coastal Eutrophication, National Academy of Sciences.
2000	Chair, Panel on Coastal Nitrogen Pollution, Ecological Society of America.
1996-1998	Member, Board of Scientific Counselors, US Environmental Protection Agency
1994-1995	Member, Panel on Nitrogen Cycling in China, Committee on Scholarly Communication with China, National Academy of Sciences.
1995	Chair, Working group on Scientific Studies in Pristine Areas, National Academy of Sciences.
1994-1997	Member, Steering Committee, Sustainable Biosphere Initiative, ESA.
1994	Member, Committee on High-Priority Science to Meet National Coastal Needs, National Academy of Sciences.
1992-1998	Member, Committee on Ethics, Am. Soc. of Limnol. & Oceanography.
1990-1993	Member, Committee on Opportunities to Improve Wastewater Management for Urban Coastal Areas, National Academy of Sciences.
1991-1995	Member, Advisory Committee for the National Water-Quality Assessment Program, U.S. Geological Survey.
1989-1992	Member, Committee on the Coastal Ocean, National Academy of Sciences.
1991-1993	Member, Governing Board, Estuarine Research Federation.
1988-1990	Member, U. S. National Committee for SCOPE, National Academy of Sciences.

1985-1991 Member, Scientific Advisory Committee, the International SCOPE Sulphur Project (Moscow, USSR), International Council of Science.
1989-1990 Member, Panel on Fluxes of Trace Gases and Nutrients to and from Terrestrial Ecosystems, Committee on Global Change, National Academy of Sciences.
1986-1988 Member, Public Affairs Committee, Am. Soc. of Limnol. & Oceanography.
1981-1984 Member, Panel on Ecological Effects, Committee on Fate and Effects of Oil in the Sea, National Academy of Sciences.

Research Interests

Application of science to sustaining the biosphere; biogeochemistry and aquatic ecosystem science; global and regional nitrogen and phosphorus cycles; global methane cycle; environmental consequences of biofuels; role of trace gases in global warming and climate disruption; life-cycle analysis for greenhouse-gas footprint of energy technologies; influence of land-use, management practices, and climate change on nutrient fluxes from the landscape; atmospheric deposition of nitrogen onto the landscape; controls and consequences of eutrophication in estuaries; biotic, physical, and geochemical controls on nitrogen fixation; environmental management and the effects of pollutants on aquatic ecosystems; alternative energy systems.

Publications:

Editor of eight books and treatises. Author of one textbook: Begon, M., R.W. Howarth, and C. Townsend. 2014. *Essentials of Ecology*, 4th Edition. Wiley. ISBN-13: 978-0470909133

Author or co-author of over 230 peer-reviewed papers. These papers have been cited more than 80,000 times in other peer-reviewed publications. Fifteen of these papers have been cited more than 1,000 times each, seven have been cited more than 3,000 times each, and two have been cited more than 7,500 times each. Howarth is the first author on four of these. All publications are listed chronologically below, with those papers cited at least 1,000 times highlighted in bold.

2023 Howarth, R. W. 2023. Phosphorus in all its forms: Book review of The Devils Element. *Science.*

2022 Howarth, R.W. 2022. Methane emissions from the production and use of natural gas. *EM Magazine*, December 2022, pages 11-16.

Haviland, K. A., R. W. Howarth, R. M. Marino, and M. Hayn. 2022. Variation in sediment and seagrass characteristics reflect multiple stressors along a nitrogen-enrichment gradient in a New England lagoon. *Limnology & Oceanography* doi: 10.1002/lno.12025

Vitousek, P. M, K.K. Tresedor, R.W. Howarth, and D.N.L. Menge. 2022. A “toy model” analysis of causes of nitrogen limitation in terrestrial ecosystems. *Biogeochemistry* https://doi.org/10.1007/s10533-022-00959-z

Howarth, R. W. 2022. Nitrogen. In: Thomas Mehner and Klement Trockner (editors), *Encyclopedia of Inland Waters*, 2nd Edition. Elsevier.

Marino, R. M., and R. W. Howarth. 2022. Nitrogen fixation. In: Thomas Mehner and Klement Trockner (editors), *Encyclopedia of Inland Waters*, 2nd Edition. Elsevier.

Howarth, R. W. 2022. Methane and climate change. In: John F. Stolz, W. Michael Griffin, and Daniel J. Bain (editors), *Environmental Impacts from Development of Unconventional Oil and Gas Reserves*, Cambridge University Press.

Howarth, R. W., and M. Jacobson. 2022. Reply to comment on "how green is blue hydrogen?" *Energy Science and Engineering* doi: 10.1002/ese3.1154

2021 Howarth, R.W., and M. Jacobson. 2021. How green is blue hydrogen? *Energy Science and Engineering* 9: 1676-1687, doi: 10.1002/ese3.956

Howarth, R.W., F. Chan, D.P. Swaney, R.M. Marino, and M. Hayn. 2021. Role of external inputs of nutrients to aquatic ecosystems in determining prevalence of nitrogen vs. phosphorus limitation of net primary productivity. *Biogeochemistry* 154: 293-306, doi: 10.1007/s10533-021-00765-z

Wong, M.Y., S.D. Rathod, R. Marino, L. Li, R.W. Howarth, A. Alastuey, M.A. Alaimo, F. Barraza, M.C. Carneiro, S. Chellam, C. Yu-Cheng, D.D. Cohen, D. Connelly, G. Dongarra, D. Gomez, J. Hand, R.M. Harrison, P.K. Hopke, C. Hueglin, Y. Kuang, F. Lambert, J. Liang, R. Losno, W. Maenhaut, C. Milando, M.I.C. Monteiro, Y. Morera-Gomez, X. Querol, S. Rodriguez, P. Smichowski, D. Varrica, Y. Xiao, Y. Xu, and N.M. Mahowald. 2021. Anthropogenic perturbations to the atmospheric molybdenum cycle. *Global Biogeochemical Cycles*, doi: 10.1029/2020GB006787

2020 Howarth, R.W. 2020. Methane emissions from fossil fuels: Exploring recent changes in greenhouse-gas reporting requirements for the State of New York. *Journal of Integrative Environmental Sciences*, doi: 10.1080/1943815X.2020.1789666.

Wong, M.Y., C. Neill, R. Marino, D. Silverio, and R.W. Howarth. 2020. Molybdenum, phosphorus, and pH do not constrain nitrogen fixation in a tropical forest in the southeastern Amazon. *Ecology* doi: 10.1002/ecy.3211

Wong, M.Y., N.M. Mahowald, R. Marino, E.R. Williams, S. Chellam, and R.W. Howarth. 2020. Natural atmospheric deposition of molybdenum: a global model and implications for tropical forests. *Biogeochemistry*, doi: 10.1007/s10533-020-00671-w

2019 Howarth, R.W. 2019. Ideas and perspectives: is shale gas a major driver of recent increase in global atmospheric methane? *Biogeosciences* 16: 3033–3046, doi:10.5194/bg-16-3033-2019.

Wong, M.Y., C. Neill, R. Marino, D.V. Silvério, P.M. Brando, and R.W. Howarth. 2019. Biological nitrogen fixation does not replace nitrogen losses after forest fires in the southeastern Amazon. *Ecosystems* doi.org/10.1007/s10021-019-00453-y

Swaney, D.P., and R.W. Howarth. 2019. Phosphorus use efficiency and crop production: Patterns of regional variation in the United States, 1987-2012. *Science of the Total Environment*, 685, 174e188.https://doi.org/10.1016/j.scitotenv.2019.05.228

2018 McCrackin, M.L, B.G. Gustafsson, B. Hong, R.W. Howarth, C. Humborg, O.P. Savchuk, A. Svanbäck, and D.P. Swaney. 2018. Opportunities to reduce nutrient inputs to the Baltic Sea by improving manure use efficiency in agriculture. *Regional Environmental Change* doi.org/10.1007/s10113-018-1308-8

McCrackin, M.L, B. Muller-Karulis, B.G. Gustafsson, R.W. Howarth, C. Humborg, A. Svanback, and D.P. Swaney. 2018. A century of legacy phosphorus dynamics in a large drainage basin. *Global Biogeochemical Cycles* 32: 1107-1122. doi.org/10.1029/2018GB005914

Harada, Y., T.H. Whitlow, P.H. Templer, R.W. Howarth, M.T. Walter, N.L. Bassuk, and J. Russell-Anelli. 2018. Nitrogen biogeochemistry of an urban rooftop farm. *Frontiers in Ecology and Evolution.* doi.org/10.3389/fevo.2018.00153

Swaney, D.P., R.W. Howarth, and B. Hong. 2018. Nitrogen use efficiency and crop production: Patterns of regional variation in the United States, 1987-2012. *Science of the Total Environment* 635:498–511. doi.org/10.1016/j.scitotenv.2018.04.027

2017 Zhang, W.S., D. Swaney, B. Hong, R. Howarth, and X. Li. 2017. Influence of rapid rural-urban population migration on riverine nitrogen pollution: perspective from ammonia-nitrogen. *Environmental Science and Pollution Research*, DOI 10.1007/s11356-017-0322-6

Zhang, W.S., D. Swaney, B. Hong, and R.Howarth. 2017. Anthropogenic phosphorus inputs to a river basin and their impacts on riverine phosphorus fluxes along its upstream-downstream continuum. *J. Geophys. Res. Biogeosciences*, 122. https://doi.org/10.1002/2017JG004004

2016 Goyette, J.O., E. Bennett, R.W. Howarth, and R. Maranger. 2016. Changes in anthropogenic nitrogen and phosphorus inputs to the St. Lawrence Basin over 110 years: Impacts on riverine export. *Global Biogeochemical Cycles* 30: 1000–1014, doi:10.1002/2016GB005384.

Marino, R.M., and R.W. Howarth. 2016. Why is planktonic nitrogen fixation so rare in coastal marine ecosystems? Insights from a cross-systems approach. Pages 127-139 in P. Glibert and T. Kana (editors), *Aquatic Nutrient Biogeochemistry and Microbial Ecology: A Dual Perspective*. Springer, Dordrecht. doi: 10.1007/978-3-319-30259-1_11

Gao, W., B. Hong, D.P. Swaney, R.W. Howarth, and H. Guo. 2016. A system dynamics model for managing regional N inputs from human activities. *Ecological Modelling* 322: 82-91, doi: 10.1016/j.ecolmodel.2015.12.001

Hong, B., and R.W. Howarth. 2016. Greenhouse gas emissions from domestic hot water: heat pumps compared to most commonly used systems. *Energy Science & Engineering* 4: 123-133, doi: 10.1002/ese3.112

2015 Reynolds, L.K., R. Marino, M.F. Muth, N. McLenaghan, M. Hayn, A.C. Tyler, K.J. McGlathery, and R.W. Howarth. 2015. Evidence of grazer control on nitrogen fixation by eelgrass epiphytes in a temperate coastal bay. *Marine Ecology Progress Series* 526: 11-19, doi: 10.3354/meps11234

Zhang, W.S., D.P. Swaney, B. Hong, R.W. Howarth, H. Han, and X. Li. 2015. Net anthropogenic phosphorus inputs and riverine phosphorus fluxes in highly populated headwater watersheds in China. *Biogeochemistry* 126: 269–283, doi:10.1007/s10533-015-0145-9

Zhang, W.S., D. P. Swaney, X.Y. Li, B. Hong, R.W. Howarth, and S.H. Ding. 2015. Anthropogenic point-source and non-point-source nitrogen inputs into Huai River basin and their impacts on riverine ammonia–nitrogen flux. *Biogeosciences* 12: 4275-4289, doi:10.5194/bg-12-4275-2015

Gao, W., D. P. Swaney, B. Hong, Y. Liu, R. W. Howarth, H. C. Guo. 2015. Evaluating Anthropogenic N inputs to Diverse Lake Basins: A Case Study of Three Chinese Lakes. *Ambio*. 44: 635-646.

Gao, W., R.W. Howarth, D.P. Swaney, B. Hong, and H. Guo. 2015. Enhanced N input to Lake Dianchi Basin from 1980 to 2010: Drivers and consequences. *Science of The Total Environment* 505: 376-384, doi.org/10.1016/j.scitotenv.2014.10.016.

Howarth, R.W. 2015. Perspectives on air emissions of methane and climatic warming risk from hydraulic fracturing and shale-gas development: Implications for policy. *Energy & Emission Control Technologies* 3: 45-54.

Costello, C., X. Xue, and R.W. Howarth. 2015. Comparison of production-phase environmental impact metrics derived at the farm- and national-scale for United States agricultural commodities. *Environmental Research Letters* 10: 114004 doi:10.1088/1748-9326/10/11/114004

Butler, T., R. Marino, D. Schwede, R. Howarth, J. Sparks, and K. Sparks. 2015. Atmospheric ammonia measurements at low concentration sites in the northeastern USA: implications for total nitrogen deposition and comparison with CMAQ estimates. *Biogeochemistry* 122: 191-210.

Howarth, R.W. 2015. Editorial: Misconduct in scientific publications. *Limnology & Oceanography,* 60(#4), doi: 10.1002/lno.10131

Howarth, R.W. 2015. Editorial. *Limnology & Oceanography*, 60(#1), doi:10.1002/lno.10030

2014 Howarth, R.W. 2014. A bridge to nowhere: Methane emissions and the greenhouse gas footprint of natural gas. *Energy Science & Engineering* 2: 47-60, doi:10.1002/ese3.35

Begon, M., R.W. Howarth, and C. Townsend. 2014. *Essentials of Ecology*, 4th Edition. Wiley, Chichester. 480 pages. ISBN-13: 978-0470909133

Bringezu, S, H. Schütz, W. Pengue, M. O´Brien, F. Garcia, R. Sims, R. Howarth, L. Kauppi, M. Swilling, and J. Herrick. 2014. *Assessing Global Land Use: Balancing Consumption with Sustainable Supply.* A Report of the Working Group on Land and Soils of the International Resource Panel. United Nations Environment Program, Paris, France. ISBN: 978-92-807-3330-3

Caulton, D.R., P. B. Shepson, R.L. Santor0, J.P. Sparks, R.W. Howarth, A. Ingraffea, M.O. Camaliza, C. Sweeney, A. Karion, K.J. Davis, B.H. Stirm, S.A. Montzka, and B. Miller. 2014. Toward a better understanding and quantification of methane emissions from shale gas development. *Proceedings of the National Academy of Sciences* 111: 6237-6242. doi/10.1073/pnas.1316546111

Howarth, R.W., M. Hayn, R.M. Marino, N. Ganju, K. Foreman, K. McGlathery, A.E. Giblin, P. Berg, and D. Walker. 2014. Metabolism of a nitrogen-enriched coastal marine lagoon during the summertime. *Biogeochemistry* 118: 1-20, doi:10.1007/s10533-013-9901-x

Gao, W., R.W. Howarth, B. Hong, D.P. Swaney, and H.C. Guo. 2014. Estimating net anthropogenic nitrogen inputs (NANI) in the Lake Dianchi basin of China. *Biogeosciences* 11: 4577 – 4586, doi:10.5194/bg-11-4577-2014

Del Barrio, P., N. Ganju, A. L. Aretxabaleta, M. Hayn, A. Garcia, and R. W. Howarth. 2014. Modeling future scenarios of light attenuation and potential seagrass success in a eutrophic estuary. *Estuarine and Coastal Shelf Science* 149: 13-23, doi 10.1016/j.ecss.2014.07.005

Jacobson, M.Z., M.A. Delucchi, A.R. Ingraffea, R.W. Howarth, G. Bazouin, B. Bridgeland, K. Burkart, M. Change, N. Chowdhury, R. Cook, G. Escher, M. Galka, L. Han, C. Heavey, A. Hernandez, D.F. Jacobson, D.S. Jacobson, B. Miranda, G. Novotny, M. Pellat, P. Quach, A. Romano, D. Steward, L. Vogel, S. Wang, H. Wang, L. Willman, and T. Yeskoo. 2014. A

roadmap for repowering California for all purposes with wind, water, and sunlight. *Energy*, doi.org/10.1016/j.energy.2014.06.099

Howarth, R. W., and A. Ingraffea. 2014. Shale gas: Time to go slow. In *World Energy Monitor, World Energy Forum.* United Nations. New York, NY.

2013 Howarth, R. W., and J. Mohan (editors). 2013. *Biomes and Ecosystems*. Salem Press. 1,440 pages, ISBN 978-1-4298-3813-9

Hayn M., R.W. Howarth, R. Marino, N. Ganju, P. Berg, K. Foreman, A.E. Giblin, and K. McGlathery. 2013. Exchange of nitrogen and phosphorus between a shallow lagoon and coastal waters. *Estuaries & Coasts*, 37: 63–73, doi:10.1007/s12237-013-9699-8

Jacobson, M.Z., R.W. Howarth, M.A. Delucchi, S.R. Scobies, J.M. Barth, M.J. Dvorak, M. Klevze, H. Katkhuda, B. Miranda, N.A. Chowdhury, R. Jones, L. Plano, and A.R. Ingraffea. 2013. Examining the feasibility of converting New York State's all-purpose energy infrastructure to one using wind, water, and sunlight. *Energy Policy* 57: 585-601, doi.org/10.1016/j.enpol.2013.02.036i

Jacobson, M.Z., R.W. Howarth, M.A. Delucchi, S.R. Scobies, J.M. Barth, M.J. Dvorak, M. Klevze, H. Katkhuda, B. Miranda, N.A. Chowdhury, R. Jones, L. Plano, and A.R. Ingraffea. 2013. Response to comment on paper examining the feasibility of changing New York State's energy infrastructure to one derived from wind, water, and sunlight. *Energy Policy* 62: 1212-1215, doi.org/10.1016/j.enpol.2013.07.105i

Hong, B., D.P. Swaney, and R.W. Howarth. 2013. Estimating net anthropogenic nitrogen inputs (NANI) to US watersheds: comparison of methodologies. *Environmental Science & Technology* 47: 5199−5207

Gettel, G., A. Giblin, and R.W. Howarth. 2013. Controls of benthic nitrogen fixation and primary production from nutrient enrichment of oligotrophic, arctic lakes. *Ecosystems*, doi 10.1007/s10021-013-9701-0

Tartowski, S.L., and R. W. Howarth. 2013. Nitrogen, nitrogen cycle. *Encyclopedia of Biodiversity*, Elsevier.

Bettez, N., R. Marino, R.W. Howarth, and E.A. Davidson. 2013. Roads as nitrogen deposition hot spots. *Biogeochemistry* 114: 149-163.

Berg, P., M.H. Long, M. Huettel, J.E. Rheuban, K.J. McGlathery, R.W. Howarth, K.H. Foreman, A.E. Giblin, and R. Marino. 2013. Eddy correlation measurements of oxygen fluxes in permeable sediments exposed to varying current flow and light. *Limnology & Oceanography* 58: 1329-1343.

Howarth, R. W. 2013. Shale gas extraction. Pages 354-359 in Craig, R.K., B. Pryd, J.C. Nagle, O. Schmitz, and W. Smith (eds.), *The Berkshire Encyclopedia of Sustainability: Vol. 5, Ecosystem management and Sustainability*. Berkshire, Great Barrington, MA.

2012 Howarth, R. W., D. Swaney, G. Billen, J. Garnier, B. Hong, C. Humborg, P. Johnes, C. Morth, and R. Marino. 2012. Nitrogen fluxes from large watershed to coastal ecosystems controlled by net anthropogenic nitrogen inputs and climate. *Frontiers in Ecology & Environment* 10: 37-43.

Howarth, R. W., R. Santoro, and A. Ingraffea. 2012. Venting and leakage of methane from shale gas development: Reply to Cathles et al. *Climatic Change* 113: 537-549, doi:10.1007/s10584-012-0401-0

Howarth, R. W., D. Shindell, R. Santoro, A. Ingraffea, N. Phillips, and A. Townsend-Small. 2012. Methane emissions from natural gas systems. Background paper prepared for the National Climate Assessment, Reference # 2011-003, Office of Science & Technology Policy Assessment, Washington, DC.

Hong, B., D. P. Swaney, C. Mörth, E. Smedberg, H. E. Hägg, C. Humborg, R. W. Howarth, and F. al Bouraoui. 2012. Evaluating regional variation of net anthropogenic nitrogen and phosphorus inputs (NANI/NAPI), major drivers, nutrient retention pattern and management implications in the multinational areas of Baltic Sea basin. *Ecological Modeling*, 227: 117-135, doi:10.1016/j.ecolmodel.2011.12.002

Ganju, N.K, M. Hayn, S. Chen, R.W. Howarth, P.J. Dickhudt, A.L. Aretxabaleta, R. Marino. 2012. Tidal and groundwater fluxes to a shallow, microtidal estuary: constraining inputs through field observations and hydrodynamic modeling. *Estuaries and Coasts* 35: 1285-1298 (Winner of the Pritchard Award, Coastal & Estuarine Research Federation for best paper in physical oceanography, 2013).

Swaney, D. P., B. Hong, C. Ti, R. W. Howarth, and C. Humborg. 2012. Net anthropogenic nitrogen inputs to watersheds and a riverine N export to coastal waters: a brief overview. *Current Opinion in Environmental Sustainability* 4: 1-9.

Swaney, D.P., R.L. Santoro, R. W. Howarth, B. Hong, and K. Donaghy. 2012. Historical changes in the food and water supply systems of the New York City metropolitan area. *Regional Environmental Change*, doi 10.1007/s10113-011-0266-1

Davidson, E. A., M. B. David, J. N Galloway, C. L. Goodale, R. Haeuber, J. A. Harrison, R. W. Howarth, D. B. Jayne, R. R. Lowrance, B. T. Nolan, J. L. Peel, R. W. Pinder, E. Porder, C. S Snyder, A. R. Townsend, and M. H. Ward. 2012. Excess nitrogen in the U.S. environment: Trends, risks, and solution. *Issues in Ecology*, report #15, Ecological Society of America.

2011 Howarth, R., W., and A. Ingraffea. 2011. Should fracking stop? Yes, it is too high risk. *Nature* 477: 271-273.

Howarth, R. W., R. Santoro, and A. Ingraffea. 2011. Methane and the greenhouse gas footprint of natural gas from shale formations. *Climatic Change Letters* 106: 679–690, doi: 10.1007/s10584-011-0061-5 (Cited 1,807 times in other peer-reviewed papers as of March 14, 2023).

Santoro, R., R. W. Howarth, and A. Ingraffea. 2011. Indirect emissions of carbon dioxides from Marcellus shale gas development. A technical report of the Agriculture, Energy, and Environment Program at Cornell University.

Howarth, R. W., G. Billen, F. Chan, D. Conley, S. C. Doney, J. Garnier, and R. Marino. 2011. Coupled biogeochemical cycles: Eutrophication and hypoxia in coastal marine ecosystems. *Frontiers in Ecology & Environment* 9: 18-26.

Billen, G., M. Silvestre, B. Grizzetti, A. Leip, J. Garnier, M. Voss, R. Howarth, F. Bouraoui, H. Behrendt, A. Lepisto, P. Kortelainen, P. Johnes, C. Curtis, C. Humborg, E. Smedberg, O. Kaste, R. Ganeshram, A. Beusen, & C. Lancelot. 2011. Nitrogen flows from European regional watersheds to coastal marine waters. Pages 271 -297 in M.A. Sutton et al. (editors), *The European Nitrogen Assessment: Sources, Effects, and Policy Perspectives*. Cambridge University Press.

Grizzetti, B., F. Bouraoui, G. Billen, H. van Grinsven, A. Cardoso, V. Thieu, J. Garnier, C. Curtis, R. Howarth, and P. Johnes. 2011. Nitrogen as a threat to European water quality. Pages 379 – 404 in M.A. Sutton et al. (editors), *The European Nitrogen Assessment: Sources, Effects, and Policy Perspectives*. Cambridge University Press.

Hong, B., D. Swaney, and R. W. Howarth. 2011. A toolbox for calculating net anthropogenic nitrogen inputs (NANI). *Environmental Modeling and Software* 26: 623–33.

McLenaghan, N. A., A. C. Tyler, U. H. Mahl, R. W. Howarth, and R. M. Marino. 2011. Benthic macroinvertebrate functional diversity regulates nutrient and algal dynamics in a shallow estuary. *Mar. Ecol. Progr. Ser*. 426: 171-184.

Baojing Gu, Yimei Zhu, Jie Chang, Chanhui Peng, Dong Liu, Yong Min, Weidong Luo, R. W. Howarth, and Y. Ge. 2011. The role of technology and policy in mitigating regional nitrogen pollution. *Env. Res. Letters* 6: 014011. doi:10.1088/1748-9326/6/1/014011

2010 Townsend, A. & R. W. Howarth. 2010. Fixing the global nitrogen problem. *Scientific American* 302: 32-39

Howarth, R. W. 2010. Solutions to environmental challenges: Nitrogen cycle. *Scientific American* 302 (#4, April 2010): 38.

Johnson, P.T.J., A.R. Townsend, C.C. Cleveland, P.M. Glibert, R.W. Howarth, V.J. McKenzie, E. Rejmankova, and M.H. Ward. 2010. Linking environmental nutrient enrichment and disease emergence in humans and wildlife. *Ecological Applications* 20: 16-29.

Howarth, R. W. 2010. Celebrating 100 volumes. *Biogeochemistry* 100: 1-2.

Naijar, R., C.R. Pyke, M.B. Adams, D. Breitburg, C. Hershner, M. Kemp, R. Howarth, M.R. Mulholand, M. Paolisso, D. Secor, K. Sellner, D. Wardrop and R. Wood. 2010. Potential climate-change impacts on the Chesapeake Bay. *Estuarine and Coastal Shelf Science* 86: 1-20.

Dale, V. H., C. L. Kling, J. L. Meyer, J. Sanders, H. Stallworth, T. Armitage, D. Wangsness, T. Bianchi, A. Blumber, W. Boynton, D. J. Conley, W. Crumpton, M. David, D. Gilbert, R. W. Howarth, R. Lowrance, K. Mankin, J. Opaluch, H. Paerl, K. Reckhow, A. N. Sharpley, T. W. Simpson, C. S. Snyder, and D. Wright. 2010. *Hypoxia in the Northern Gulf of Mexico*. 284 pages. Springer, Dordrecht.

Davidson, E. A., K. E. Savage, N. D. Bettez, R. Marino, and R. W. Howarth. 2010. Nitrogen in runoff from residential roads in a coastal area. *Water Air Soil. Pollut.* 210: 3-13.

2009 **Conley, D. J, H. W. Paerl, R. W. Howarth, D. F. Boesch, S. P. Seitzinger, K. E. Havens, C. Lancelot, & G. E. Likens. 2009. Controlling eutrophication: Nitrogen and phosphorus. *Science* 323: 1014-1015 (**Cited 3,738 times in other peer-reviewed papers as of March 14, 2023).

Conley, D. J, H. W. Paerl, R. W. Howarth, D. F. Boesch, S. P. Seitzinger, K. E. Havens, C. Lancelot, & G. E. Likens. 2009. Reply to comments on "controlling eutrophication: nitrogen and phosphorus." *Science* 324: 724-725.

Boesch, D., W. Boynton, L. Crowder, R. Diaz, R. Howarth, L. Mee, S. Nixon, N. Rabalais, R. Rosenberg, J. Sanders, D. Scavia, and R. Turner. 2009. Nutrient enrichment drives Gulf of Mexico hypoxia. *Eos* 90: 117-128.

Bringezu, S., H. Schutz, M. O'Brien, L. Kauppi, R. Howarth, and J. McNeely. 2009. Towards Sustainable Production and Use of Resources: Assessing Biofuels. International Panel for Sustainable Resource Management, United Nations Environment Program, Paris, France (http://www.unep.fr/scp/rpanel/biofuels.htm).

Howarth, R. W., and S. Bringezu (eds). 2009. Biofuels: Environmental Consequences and Interactions with Changing Land Use. Proceedings of the International SCOPE Biofuels Project Rapid Assessment, International Council of Science (http://cip.cornell.edu/biofuels/)

Howarth, R.W., S. Bringezu, M. Bekunda, C. de Fraiture, L. Maene, L. Martinelli, O. Sala. 2009. Rapid assessment on biofuels and environment: Overview and key findings. Pages 1-13 in R.W. Howarth and S. Bringezu (eds), Biofuels: Environmental Consequences and Interactions with Changing Land Use. Proceedings of the International SCOPE Biofuels Project Rapid Assessment, International Council of Science (http://cip.cornell.edu/biofuels/)

Howarth, R.W., S. Bringezu, L.A. Martinelli, R. Santoro, D. Messem, O.E. Sala. 2009. Introduction: biofuels and the environment in the 21st century. Pages 15- 36, in R.W. Howarth and S. Bringezu (eds) Biofuels: Environmental Consequences and Interactions with Changing Land Use. Proceedings of the International SCOPE Biofuels Project Rapid Assessment, International Council of Science (http://cip.cornell.edu/biofuels/)

Simpson, T.W., L.A. Martinelli, A.N. Sharpley, R.W. Howarth. 2009. Impact of ethanol production on nutrient cycles and water quality: the United States and Brazil as case studies. Pages 153-167 in R.W. Howarth and S. Bringezu (eds) Biofuels: Environmental Consequences and Interactions with Changing Land Use. Proceedings of the International SCOPE Biofuels Project Rapid Assessment, International Council of Science (http://cip.cornell.edu/biofuels/)

Howarth R. 2009. Nitrogen. Pages 57-64 in Gene E. Likens (ed.), Encyclopedia of Inland Waters, Volume 2. Elsevier, Oxford.

Marino, R. & R. W. Howarth. 2009. Nitrogen fixation. Pages 65-72 in G. E. Likens (ed.), *Encyclopedia of Inland Waters*. Elsevier, Oxford.

Townsend, A. R., L. A. Martinelli, & R. W. Howarth. 2009. The global nitrogen cycle, biodiversity, and human health. Pages 159-178 in O. E. Sala, L. A Meyerson, & C. Parmeson. *Biodiversity Change and Human Health.* SCOPE #69. Island Press, Washington.

Entringer, R., and R. Howarth. 2009. Workshop on Atmospheric Deposition of Nitrogen -- Chesapeake Bay Program Science and Technical Advisory Committee. January 8, 2009. STAC Publication 09-001. (http://www.chesapeake.org/stac/Pubs/atmosphericnitrogen.report.pdf)

2008 Howarth, R. W. & H. Paerl. 2008. Coastal marine eutrophication: Control of both nitrogen and phosphorus is necessary. *Proceedings of National Academy of Sciences* 105: E104

Howarth, R. W. 2008. Coastal nitrogen pollution: A review of sources and trends globally and regionally. *Harmful Algae* 8: 14-20.

Boyer, E. W., and R. W. Howarth. 2008. Nitrogen fluxes from rivers to the coastal oceans. Pages 1565-1587 in D. Capone, D. A. Bronk, M. R. Mulholland & E. J. Carpenter (eds.), *Nitrogen in the Marine Environment*, 2nd Edition, Elsevier, Oxford.

Swaney, D. P., D. Scavia, R. W. Howarth, & R. M. Marino. 2008. Estuarine classification and response to nitrogen loading: Insights from simple ecological models. *Estuarine, Coastal & Shelf Science* 77: 253-263.

Simpson, T. W., A. N. Sharpley, R. W. Howarth, H. W. Paerl & K. R. Mankin. 2008. The new gold rush: Fueling ethanol production while protecting water quality. *Journal of Environmental Quality* 37: 318-324.

Glibert, P.A., R. Azanza, M. Burford, K. Furuya, E. Abal, A. Al-Azri, F. Al-Yamani, P. Andersen, D. Anderson, J. Beardall, G. M. Berg, L. Brand, D. Bronk, J. Brookes, J. M. Burkholder, A. Cembella, W. P. Cochlan, J. L. Collier, Y. Collos, R. Diaz, R. Doblin, T. Drennen, S. Dyhrman, Y. Fukuyo, M. Furnas, J. Galloway, E. Granéli, Dao Viet Ha, G. Hallegraeff, J. Harrison, P. J. Harrison, C. A. Heil, K. Heimann, R. Howarth, C. Jauzein, A.

Kana, T. M. Kana, H. Kim, R. Kudela, C. Legrand, M. Mallin, M. Mulholland, S. Murray, J. O'Neil, G. Pitcher, Yuzao Qi, N. Rabalais, R. Raine, S. Seitzinger, P. S. Salomon, C. Solomon, D. K. Stoecker, G. Usup, J. Wilson, Kedong Yin, Mingjiang Zhou & Mingyuan Zhu. 2008. Ocean urea fertilization for carbon credits poses high ecological risks. *Marine Pollution Bulletin* 56: 1049-1056.

Pyke, C. R., R. G. Naijar, M. B. Adams, D. Breitburg, M. Kemp, C. Hershner, R. Howarth, M. Mulholland, M. Paolisso, D. Secor, K. Sellner, D. Wardrop, and R. Wood. 2008. Climate change and the Chesapeake Bay: State-of-the-science review and recommendations. A report of the Chesapeake Bay Progam Science and Technical Advisory Committee (STAC), Annapolis, MD. 59 pages.

Howarth, R. W. 2008. How important is atmospheric deposition as a source of nitrogen to coastal marine ecosystems in the northeastern United States? Pages 47-65 in A. Desbonnet and B. A Cost-Pierce (eds.), *Science of Ecosystem-Based Management.* Springer, NY.

2007 Davidson, E. & R. W. Howarth. 2007. Nutrients in synergy. *Nature* 449: 1000-1001.

Gettel, G. M., A. E. Giblin, & R. W. Howarth. 2007. The effect of grazing by the snail, *Lymnae elodes*, on benthic N_2 fixation and primary production in oligotrophic, Arctic lakes. *Limnology & Oceanography* 52: 2398-2409.

Hambright, D., N. G. Hairston, Jr., W. R. Schaffner, & R. W. Howarth. 2007. Grazer control of nitrogen fixation: Synergisms in the feeding ecology of two freshwater crustaceans. *Fundamental and Applied Limnology/Archiv fur Hydrobiologie* 170: 89-101.

Hambright, D., N. G. Hairston, Jr., W. R. Schaffner, & R. W. Howarth. 2007. Grazer control of nitrogen fixation: Phytoplankton taxonomic composition and ecosystem functioning. *Fundamental and Applied Limnology/Archiv fur Hydrobiologie* 170: 103-124.

Turner, R. E., N. N. Rabalais, R. B. Alexander, G. McIsaac, & R. W. Howarth. 2007. Characterization of nutrient and organic matter loads from the Mississippi River into the northern Gulf of Mexico. *Estuaries & Coasts* 30: 773-790.

2006 **Howarth, R. W. & R. Marino. 2006. Nitrogen as the limiting nutrient for eutrophication in coastal marine ecosystems: Evolving views over 3 decades. *Limnol. Oceanog*r. 51: 364-376 (**Cited 1,586 times in other peer-reviewed papers as of March 14, 2023).

Martinelli, L. & R. W. Howarth (eds.). 2006. *Nitrogen Cycling in the Americas: Natural and Anthropogenic Influences and Controls*. Springer, Dordrecht. 427 pages.

Howarth, R. W., E. W. Boyer, R. Marino, D. Swaney, N. Jaworski, & C. Goodale. 2006. The influence of climate on average nitrogen export from large watersheds in the northeastern United States. *Biogeochemistry* 79: 163-186.

Chapin, F. S. III, G.M Woodwell, J. Randerson, G. Lovett, D. Baldocchi, D. A. Clark, M.E. Harmon, E. Rastetter, D. Schimel, R. Valentini, C. Wirth, J. Cole, M. Goulden, J. Harden, M. Heimann, R. Howarth, P. Matson, A.D. McGuire, J. Melillo, H. Mooney, J. Neff, R. Houghton, M. Pace, M.G. Ryan, S. Running, O. Sala, W. Schlesinger & D. Schulze. 2006. Reconciling carbon cycle concepts, terminology, and methods. *Ecosystems* 9: 1041-1050 (Cited 1,129 times in other peer-reviewed papers as of March 14, 2023).

Martinelli, L. A, R. W. Howarth, E. Cuevas, S. Filoso, A. T. Austin, L. Donos, V. Huzsar, D. Keeney, L. L. Lara, C. LLerena, G. McIssac, E. Medina. J. Ortiz-Zaya, D. Scavia, D. W. Schindler, D. Soto & A. Townsend. 2006. Sources of reactive nitrogen affecting ecosystems in Latin America and the Caribbean: Current trends and future perspectives. *Biogeochemistry* 79: 3-234.

Filoso, S., L. Martinelli, R. W. Howarth, E. W. Boyer & F. Dentener. 2006. Human activities changing the N cycle in Brazil. *Biogeochemistry* 79: 61-89.

Marino, R., F. Chan, R. W. Howarth, M. L. Pace & G. E. Likens. 2006. Experimental tests of ecological constraints on planktonic nitrogen fixation in saline estuaries: 1. Nutrient and trophic controls. *Marine Ecology Progress Series* 309: 25-39.

Chan, F., R. Marino, R., R. W. Howarth & M. L. Pace. 2006. Experimental tests of ecological constraints on planktonic nitrogen fixation in saline estuaries: 2. Mechanisms of trophic control. *Marine Ecology Progress Series* 309: 41-53.

Joye, S. B., V. H. Smith, R. W. Howarth, R. W. Bachmann, J. E. Cloern, R. E. Hecky, & D. W. Schindler (editors). 2006. Eutrophication of Freshwater and Marine Ecosystems. *Limnol. Oceanogr.* (special issue), Vol. 51, number 1, part 2.

Roberts, B. J. & R. W. Howarth. 2006. Nutrient and light availability regulate the relative contribution of autotrophs and heterotrophs to respiration in freshwater pelagic ecosystems. *Limnol. Oceanogr*. 51: 288-295.

Howarth, R. W., R. Marino, D. P. Swaney & E. W. Boyer. 2006. Wastewater and watershed influences on primary productivity and oxygen dynamics in the lower Hudson River estuary. Pages 121-139 in J. S. Levinton & J. R. Waldman (eds.), *The Hudson River Estuary,* Cambridge Univ. Press.

Howarth, R. W. 2006. Atmospheric deposition and nitrogen pollution in coastal marine ecosystems. Pages 97-116 in G. R. Visgilio & D. M. Whitelaw (eds.), *Acid in the Environment: Lessons Learned and Future Prospects.* Springer, Dordrecht.

Boyer, E. W., R. W. Howarth., J. Galloway, F. J. Dentener, P. A. Green & C. A. Vorosmarty. 2006. Riverine nitrogen export from the continents to the coasts. *Global Biogeochemical Cycles* 20, No. 1, GB1S91, 10.1029/2005GB002537

2005 Howarth, R. W., K. Ramakrishna, E. Choi, R. Elmgren, L. Martinelli, A. Mendoza, W. Moomaw, C. Palm, R. Boy, M. Scholes & Zhu Zhao-Liang. 2005. Chapter 9: Nutrient Management, Responses Assessment. Pages 295-311 in *Ecosystems and Human Well-being, Volume 3, Policy Responses, the Millennium Ecosystem Assessment.* Island Press, Washington, DC.

Howarth, R. W. 2005. The development of policy approaches for reducing nitrogen pollution to coastal waters of the USA. *Science in China,* Ser. C Life Sciences 48: 791-806

2004 Boyer, E. W., R. W. Howarth, J. N. Galloway, F. J. Dentener, C. Cleveland, G. P. Asner, P. Greene, and C. Vorosmarty. 2004. Current nitrogen inputs to world regions. Pages 221-230 in A. R. Mosier, J. K. Syers & J. R. Freney (eds.), *Agriculture and the Nitrogen Cycle.* SCOPE #65. Island Press, Washington, DC.

Galloway, J. N., F. J. Dentener, D. G. Capone, E. W. Boyer, R. W. Howarth, S. P. Seitzinger, G. P. Asner, C. Cleveland, P. A. Green, E. Holland, D. M. Karl, A. Michaels, J. H. Porter, A. Townsend & C. Vorosmarty. 2004. Nitrogen cycles: past, present, and future. *Biogeochemistry* 70: 153-226 (Cited 5,821 times in other peer-reviewed papers as of March 14, 2023).

Chan, F. M. Pace, R.W. Howarth & R. Marino. 2004. Bloom formation in heterocystic nitrogen-fixing cyanobacteria: The dependence of colony size and zooplankton grazing. *Limnol. Oceanogr.* 49: 2171-2178.

David, M. B., G. F. McIsaac, R. W. Howarth, C. L. Goodale, & L. E. Drinkwater.. 2004. Fertilizer: Complex Issue Calls for Informed Debate. *Nature* 427: 99.

2003 Howarth, R. W., R. Marino & D. Scavia. 2003. *Priority Topics for Nutrient Pollution in Coastal Waters: An Integrated National Research Program for the United States.* National Ocean Service, NOAA, Silver Spring, MD.

Townsend, A. R., R. Howarth, F. A. Bazzaz, M. S. Booth, C. C. Cleveland, S. K. Collinge, A. P. Dobson, P. R. Epstein, E. A Holland, D. R. Keeney, M. A. Mallin, C. A. Rogers, P. Wayne & A. H. Wolfe. 2003. Human health effects of a changing global nitrogen cycle. *Frontiers in Ecology & Environment* 1: 240-246.

Galloway, J. N., J. D. Aber, J. W. Erisman, S. P. Seitzinger, R. H. Howarth, E. B. Cowling & B. J. Cosby. 2003. The nitrogen cascade. *BioScience* 53: 341-356 (Cited 3,482 times in other peer-reviewed papers as of March 14, 2023).

Marino, R., R. W. Howarth, F. Chan, J. J. Cole & G. E. Likens. 2003. Sulfate inhibition of molybdenum-dependent nitrogen fixation by planktonic cyanobacteria under seawater conditions: a non-reversible effect. *Hydrobiologia* 500: 277-293.

Howarth, R. W. 2003. Human acceleration of the nitrogen cycle: Drivers, consequences, and steps towards solutions. *Water Science and Technology* 49: 7-13.

Austin, A., R. W. Howarth, J. S. Baron, F. S. Chapin, T. R. Christensen, E. A. Holland, M. V. Ivanov, A. Y. Lein, L. Z. Martinelli, J. M. Melillo, and Chao Shang. 2003. Human disruption of element interactions: Drivers, consequences, and trends for the 21st Century. Pages 15-45 in Melillo, J. M., C. B. Field & B. Moldan (eds.), *Interactions of the major Biogeochemical Cycles: Global Change and Human Impacts.* SCOPE #61. Island Press, Washington, DC.

Howarth, R. W. 2003. Coastal ecosystems. Pages 65-74 in J. C. White & J. Teninko (eds.), Acid Rain: Are the Problems Solved? *American Fisheries Society Trends in Fisheries Science and Management 2*, Bethesda, MD.

Howarth, R. W. & D. M. Rielinger. 2003. Nitrogen from the atmosphere: Understanding and reducing a major cause of degradation of our coastal waters. Science and policy bulletin #8, Waquoit Bay National Estuarine Research Reserve, NOAA.

2002 Howarth, R. W., E. W. Boyer, W. J. Pabich & J. N. Galloway. 2002. Nitrogen use in the United States from 1961-200 and potential future trends. *Ambio* 31: 88-96.

Howarth, R. W., D. Walker & A. Sharpley. 2002. Sources of nitrogen pollution to coastal waters of the United States. *Estuaries* 25: 656-676.

Howarth, R. W. 2002. Nutrient over-enrichment of coastal waters in the United States: Steps toward a solution. Pew Oceans Commission, Washington, DC.

Howarth, R. W. 2002. The nitrogen cycle. Pages 429-435 in H. A. Mooney and J. G. Canadell (eds.), *Encyclopedia of Global Environmental Change. Vol. 2, the Earth System: Biological and Ecological Dimensions of Global Environmental Change.* Wiley, Chichester.

Marino, R., F. Chan, R. Howarth, M. Pace & G. Likens. 2002. Ecological and biogeochemical interactions constrain planktonic nitrogen fixation in estuaries. *Ecosystems* 5: 719-725.

Scavia, D., J. C. Field, Boesch, R. Buddemeier, V. Burkett, D. Cayan, M. Fogarty, M. Harwell, R. W. Howarth, C. Mason, D. J. Reed, T. C. Royer, A. H. Sallenger and J. G. Titus. 2002. Climate change impacts on US coastal and marine ecosystems. *Estuaries* 25: 149-164 (Cited 1,091 times in other peer-reviewed papers as of March 14, 2023).

Boyer, E. W. & R. W. Howarth (eds,). 2002. *Global and Regional Synthesis of the Nitrogen Cycle*. Kluwer, Dordrecht. 519 pages.

Vitousek, P. M., K. Cassman, C. Cleveland, T. Crews, C. B. Field, N. B. Grimm, R. W. Howarth, R. Marino, L. Martinelli, E. B. Rastetter, and J. I. Sprent. 2002. Towards an ecological understanding of biological nitrogen fixation. *Biogeochemistry* 57&58: 1-45 (Cited 1,095 times in other peer-reviewed papers as of March 14, 2023).

Van Breemen, N., E. W. Boyer, C. L. Goodale, N. A. Jaworski, K. Paustian, S. Seitzinger, K. Lajtha, B. Mayer, D. van Dam, R. W. Howarth, K. J. Nadelhoffer, M. Eve, and G. Billen. 2002. Where did all the nitrogen go? Fate of nitrogen inputs to large watersheds in the northeastern USA. *Biogeochemistry* 57&58: 267-293.

Seitzinger, S. P., R. V. Styles, E. W. Boyer, R. Alexander, G. Billen, R. Howarth, B. Mayer, and N. van Breemen. 2002. Nitrogen retention in rivers: model development and application to watersheds in the northeastern US. *Biogeochemistry* 57&58: 199-237.

Boyer, E. W., C. L. Goodale, N. A. Jaworski, and R.W. Howarth. 2002. Anthropogenic nitrogen sources and relationships to riverine nitrogen export in the northeastern USA. *Biogeochemistry* 57&58: 137-169.

Mayer, B., E. Boyer, C. Goodale, N. Jaworski, N. van Breemen, R. Howarth, S. Seitzinger, G. Billen, K. Lajtha, K. Nadelhoffer, D. van Dam., L. J. Hetling, M. Nosal, and K. Paustian. 2002. Sources of nitrate in rivers draining sixteen watersheds in the northeastern US: Isotopic constraints. *Biogeochemistry* 57&58: 171-197.

Barron, S., C. F. Weber, R. Marino, E. A. Davidson, G. Tomasky, and R. W. Howarth. 2002. Effects of varying salinity on phytoplankton growth in a low-salinity coastal pond under two nutrient conditions. *Biological Bulletin* 203: 260-261.

Weber, C. F., S. Barron, R. Marino, R. W. Howarth, G. Tomasky, and E. A. Davidson. Nutrient limitation of phytoplankton growth in Vineyard Sound and Oyster Pond, Falmouth, Massachusetts. *Biological Bulletin* 203: 261-263.

2001 **Tilman D., J. Fargione, B. Wolff, C. D'Antonio, A. Dobson, R.W. Howarth, D. Schindler, W. Schlesinger, D. Simberloff, and D. Swackhamer. 2001. Forecasting agriculturally driven global environmental change. *Science* 292: 281-284 (**Cited 4,795 times in other peer-reviewed papers as of March 14, 2023).

Howarth, R. W. 2001. Hypoxia, fertilizer, and the Gulf of Mexico. *Science* 292: 1485-1486.

2000 Howarth, R. W., D. Anderson, J. Cloern, C. Elfring, C. Hopkinson, B. Lapointe, T. Malone, N. Marcus, K. McGlathery, A. Sharpley, and D. Walker. 2000. Nutrient pollution of coastal rivers, bays, and seas. *Issues in Ecology* 7: 1-15.

Howarth, R. W., D. Swaney, T. J. Butler, and R. Marino. 2000. Climatic control on eutrophication of the Hudson River estuary. *Ecosystems* 3: 210-215.

Tartowski, S., and R.W. Howarth. 2000. Nitrogen, nitrogen cycling. *Encyclopedia of Biodiversity*. 4: 377-388.

Sala, O., R. Jackson, H. Mooney, and R.W. Howarth (eds.). 2000. *Methods in Ecosystem Science*, Springer, NY. 430 pages.

Howarth, R.W., and A. F. Michaels. 2000. The measurement of primary production in aquatic ecosystems. Pages 72-85 in: O. Sala, R. Jackson, H. Mooney, and R. W. Howarth (eds.), *Methods in Ecosystem Science*, Springer, NY.

Howarth, R. W., N. Jaworski, D. Swaney, A. Townsend, and G. Billen. 2000. Some approaches for assessing human influences on fluxes of nitrogen and organic carbon to estuaries. Pages 17-41 in: J. E. Hobbie (ed.), *Estuarine Synthesis: The Next Decade.* Island Press, Washington, DC.

Fisher, T. R., D. Correll, R. Costanza, J. T. Hollibaugh, C. S. Hopkinson, R. W. Howarth, N. N. Rabalais, J. E. Richey, C. Vorosmarty, and R. Wiegert. 2000. Synthesizing drainage basin inputs to coastal systems. Pages 81-101 in: J. E. Hobbie (ed.), *Estuarine Synthesis: The Next Decade*. Island Press, Washington, DC.

Howarth, R. W. 2000. Review of "Estuary restoration and maintenance: the National Estuary Program" *Limnology & Oceanography*. 45: 1889.

1999 Howarth, R.W., F. Chan, and R. Marino. 1999. Do top-down and bottom-up controls interact to exclude nitrogen-fixing cyanobacteria from the plankton of estuaries: explorations with a simulation model. *Biogeochemistry* 46: 203-231.

Downing, J. A., M. McClain, R. Twilley, J. M. Melack, J. Elser, N. N. Rabalais, W. M. Lewis, R. E. Turner, J. Corredor, D. Soto, A. Yanez-Arancibia, and R. W. Howarth. 1999. The impact of accelerating land-use change on the nitrogen cycle of tropical aquatic ecosystems: Current conditions and projected changes. *Biogeochemistry* 46: 109-148.

Corredor, J.E., R.W. Howarth, R. R. Twilley, and J. M. Morell. Nitrogen cycling and anthropogenic impact in the tropical inter-American seas. *Biogeochemistry* 46: 163-178.

Howarth, R.W., and R. Marino. 1999. Oil spills: Containment and clean-up. Pages 456-458 in D. E. Alexander & R. W. Fairbridge (eds.), *Encyclopedia of Environmental Science*. Kluwer, Dordrecht.

Swaney, D. P., R.W. Howarth, and T. J. Butler. 1999. A novel approach for estimating ecosystem production and respiration in estuaries: application to the oligohaline and mesohaline Hudson River estuary. *Limnol. Oceanogr*. 44: 1509-1521.

Cleveland, C. C., A. R. Townsend, D. S. Schimel, H. Fisher, R.W. Howarth, L. O. Hedin, S. S. Perakis, E. F. Latty, J. C. von Fischer, A. Elseroad, and M. F. Wasson. 1999. Global patterns of terrestrial biological nitrogen (N_2) fixation in natural systems. *Global Biogeochemical Cycles* 13: 623-645 (Cited 1,091 times in other peer-reviewed papers as of March 14, 2023).

1998 Howarth, R.W., and R. Marino. 1998. A mechanistic approach to understanding why so many estuaries and brackish waters are nitrogen limited. In: Effects of Nitrogen in the Aquatic Environment (pages 117-136), KVA Report 1998: 1, Kungl. Vetenskapsakademien (Royal Swedish Academy of Sciences), Stockholm.

Carpenter, S. R., N. F. Caraco, D. L. Correll, R.W. Howarth, A. N. Sharpley, and V. H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications* 8: 559-568 (Cited 7,900 times in other peer-reviewed papers as of March 14, 2023).

Carpenter, S. R., N. F. Caraco, D. L. Correll, R.W. Howarth, A. N. Sharpley, and V. H. Smith. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Issues in Ecology* 3: 1-12.

Sherman, R. E., T.J. Fahey, and R.W. Howarth. 1998. Soil-plant interactions in a neotropical mangrove forest: iron, phosphorous, and sulfur dynamics. *Oecologia* 115: 553-563.

Jensen, H. S., K.J. McGlathery, R. Marino, and R.W. Howarth. 1998. Forms and availability of sediment phosphorus in carbonate sand of Bermuda seagrass beds. *Limnol. Oceanogr.* 43: 799-810.

Howarth, R.W. 1998. An assessment of human influences on inputs of nitrogen to the estuaries and continental shelves of the North Atlantic Ocean. *Nutrient Cycling in Agroecosystems* 52: 213-223.

Breitburg, D. L., J. Baxter, C. Hatfield, R.W. Howarth, C. G. Jones, G. M. Lovett, and C. Wigand. 1998. Understanding effects of multiple stressors: Ideas and challenges. Pages 416-431 in M. Pace and P. Groffman (eds.), *Success, Limitations, and Frontiers in Ecosystem Science*, Springer, NY.

1997 Vitousek, P.M., J. Aber, S. E. Bayley, R. W. Howarth, G. E. Likens, P. A. Matson, D. W. Schindler, W. H. Schlesinger, and G. D. Tilman. 1997. Human alteration of the global nitrogen cycle: Causes and consequences. *Issues in Ecology* 1: 1-15.

Vitousek, P.M., J. Aber, S. E. Bayley, R.W. Howarth, G. E. Likens, P. A. Matson, D. W. Schindler, W. H. Schlesinger, and G. D. Tilman. 1997. Human alteration of the global nitrogen cycle: Causes and consequences. *Ecological Applications* 7: 737-750 (Cited 7,761 times in other peer-reviewed papers as of March 14, 2023).

Jaworksi, N. A., R.W. Howarth, and L.J. Hetling. 1997. Atmospheric deposition of nitrogen oxides onto the landscape contributes to coastal eutrophication in the northeast US. *Environmental Science & Technology* 31: 1995-2004.

Moore, M. H., M. Pace, J. Mather , P. S. Murdoch, R.W. Howarth, C. L. Folt, C. Y. Chen, H. F. Hemond, P. A. Flebbe, and C. T. Driscoll. 1997. Potential effects of climate change on the freshwater ecosystems of the New England/mid-Atlantic region. *Water Resources* 11: 925-947.

1996 Jaworski, N. A., and R.W. Howarth. 1996. Preliminary estimates of the pollutant loads and fluxes into the northeast shelf LME. Pages 351-357 in K. Sherman, N. A. Jaworski & T. J. Smayda (eds.), *The Northeast Shelf Ecosystem: Assessment, Sustainability, and Management*. Blackwell, Cambridge, MA.

Howarth, R.W., G. Billen, D. Swaney, A. Townsend, N. Jarworski, K. Lajtha, J. A. Downing, R. Elmgren, N. Caraco, T. Jordan, F. Berendse, J. Freney, V. Kueyarov, P. Murdoch, and Zhu Zhao-liang. 1996. Riverine inputs of nitrogen to the North Atlantic Ocean: Fluxes and human influences. *Biogeochemistry* 35: 75-139 (Cited 2,062 times in other peer-reviewed papers as of March 14, 2023. Also winner of the ASLO John Martin award from the Association of the Sciences of Limnology & Oceanography, 2018, for a paper that has had a high impact on subsequent research in aquatic sciences).

Galloway, J., R.W. Howarth, J. Prospero, S. Nixon, and A. Michaels. 1996. Summary of the nitrogen cycle for the North Atlantic Ocean and its watersheds and airshed. *Biogeochemistry* 35: 3-25.

Howarth, R. W. (ed.). 1996. *Nitrogen Cycling in the North Atlantic Ocean and its Wastersheds.* Kluwer Academic, Dordrecht. 304 pages.

Howarth, R.W., R. Schneider & D. Swaney. 1996. Metabolism and organic carbon fluxes in the tidal, freshwater Hudson River. *Estuaries* 19: 848-865.

Swaney, D.P., D. Sherman & R.W. Howarth. 1996. Modeling water, sediment, and organic carbon discharges in the Hudson-Mohawk Basin: Coupling to terrestrial sources. *Estuaries* 19: 833-847.

1995 Howarth, R.W., H. Jensen, R. Marino, and H. Postma. 1995. Transport to and processing of phosphorus in near-shore and oceanic waters. Pages 323-345 in H. Tiessen (ed.), *Phosphorus in the Global Environment*, SCOPE #54. Wiley & Sons, Chichester.

Fisher, T. R., J. M. Melack, J. U. Grobbelaar, and R.W. Howarth. 1995. Nutrient limitation of phytoplankton and eutrophication of inland, estuarine, and marine waters. Pages 301-322 in H. Tiessen (ed.), *Phosphorus in the Global Environment*, SCOPE #54. Wiley & Sons, Chichester.

Howarth, R.W., D. Swaney, R. Marino, T. Butler, and C. R. Chu. 1995. Turbulence does not prevent nitrogen fixation by plankton in estuaries and coastal seas (reply to the comment of Paerl et al.). *Limnol. Oceanogr*. 40: 639-643.

1994 McGlathery, K. J., R. Marino, and R.W. Howarth. 1994. Variable rates of phosphate uptake by shallow marine sediments: Mechanisms and ecological significance. *Biogeochemistry* 25: 127-146.

Schaffner, W. R., N. G. Hairston, Jr, and R.W. Howarth. 1994. Feeding rates and filament clipping by crustacean zooplankton consuming cyanobacteria. *Verh. Internat. Verein. Limnol.* 25: 2375-2381.

1993 Howarth, R. W. Microbial processes in salt-marsh sediments. 1993. Pages 239-259 in T. E. Ford (ed.), *Aquatic Microbiology: An Ecological Approach*. Blackwell, Oxford.

Howarth, R. W. 1993. The role of nutrients in Coastal Waters. Appendix A in: *Managing Wastewater in Coastal Urban Areas* (pp. 137-158). Report of the Committee on Alternatives for Wastewater Management in Coastal Urban Areas, National Research Council, Washington, D.C.

Cole, J. J., J. M. Lane, R. Marino, and R. Howarth. 1993. Molybdenum assimilation by cyanobacteria and phytoplankton in freshwater and salt waters. *Limnol. Oceanogr*. 38: 25-35.

Howarth, R. W. 1993. River sciences: A review of the rivers handbook, vol. a, hydrological and ecological principles. *BioScience* 43: 17-21.

Howarth, R.W., R. Marino, T. Butler, K. Lunde, D. Swaney, and C. R. Chu. 1993. Turbulence and planktonic nitrogen fixation: A mesocosm experiment. *Limnol Oceanogr*. 38: 1696-1711.

Marino, R., and R.W. Howarth. 1993. Atmospheric oxygen exchange in the Hudson River: Dome measurements and comparison with other natural waters. *Estuaries* 16: 433-445.

1992 Howarth, R.W., and J.W.B. Stewart. 1992. The interactions of sulphur with other element cycles. Pages 67-79 in: R.W. Howarth, J.W.B. Stewart, and M.V. Ivanov (eds), *Sulphur Cycling on the Continents: Wetlands, Terrestrial Ecosystems, and Associated Water Bodies*. SCOPE #48. John Wiley and Sons, Chichester, U.K.

Howarth, R.W., J. W. B. Stewart, and M. V. Ivanov (editors). 1992. *Sulphur Cycling on the Continents: Wetlands, Terrestrial Ecosystems, and Associated Water Bodies*. SCOPE #48. John Wiley and Sons, Chichester, U.K. 350 pages.

McGlathery, K. J., R.W. Howarth & R. Marino. 1992. Nutrient limitation of the macroalga, *Penicillus capitatus*, associated with subtropical seagrass meadows in Bermuda. *Estuaries* 15: 18-25.

Howarth, R. W. 1992. Indirect effects of sulfur on the carbon cycle of aquatic ecosystems: Molybdenum availability, planktonic nitrogen fixation, and nitrogen limitation. In E. T .

Degens, S. Kempe, A. Lein, and Y. Soroken, (eds.) *Interactions of Biogeochemical Cycles in Aqueous Ecosystems.* Proceedings of SCOPE/UNEP workshop at Listvyanka/Irkutsk, USSR, September 2-8, 1988. University of Hamburg.

Giblin, A. E., G. E. Likens, and R.W. Howarth. 1992. The importance of reduced inorganic sulfur to the sulfur cycle of lakes. In E. T . Degens, S. Kempe, A. Lein, and Y. Soroken, (eds.) *Interactions of Biogeochemical Cycles in Aqueous Ecosystems*. Proceedings of SCOPE/UNEP workshop at Listvyanka/Irkutsk, USSR, September 2-8, 1988. University of Hamburg.

Howarth, R. W., R. Marino, R. Garritt, and D. Sherman. 1992. Ecosystem respiration in a large, tidally influenced river: The Hudson River. *Biogeochemistry* 16: 83-102.

1991 **Vitousek, P. M., and R.W. Howarth. 1991. Nitrogen limitation on land and in the sea. How can it occur? *Biogeochemistry* 13: 87-115 (**Cited 4,159 times in other peer-reviewed papers as of March 14, 2023).

Howarth, R.W., and R. Marino. 1991. Oil and water-- a bad mix. Pages 40-53 in: *Science Year*. World Book Encyclopedia, Chicago.

Howarth, R.W., J.R. Fruci, and D.M. Sherman. 1991. Inputs of sediment and carbon to an estuarine ecosystem: Influence of land use. *Ecological Applications* 1: 27-39.

Kitchell, J.F., S.R. Carpenter, S. Bayley, K.C. Ewel, R.W. Howarth, S.W. Nixon, and D.W. Schindler. 1991. Aquatic ecosystem experiments in the context of global climate change: working group report. In: H. Mooney et al. (eds.), *Ecosystem Experiments.* SCOPE, John Wiley and Sons, Chinchester, U.K.

Howarth, R.W. 1991. Assessing the ecological effects of oil pollution from outer continental shelf oil development. *Tran. of American Fisheries Society* 11: 1-8.

Howarth, R. W. 1991. Comparative responses of aquatic ecosystems to toxic chemical stress. Pages 169-195 in: J. Cole, G. Lovett, and S. Findlay (eds.), *Comparative Analyses of Ecosystems: Patterns, Mechanisms, and Theories.* Springer-Verlag, NY.

Morin, A., K.D. Hambright, N.G. Hairston, Jr., D.M. Sherman, and R.W. Howarth. 1991. Consumer control of gross primary production in replicate freshwater ponds. *Verh. Internat. Verein. Limnol.* 24: 1512-1516.

Howarth, R.W., and R. Marino. 1991. *Oil in the Oceans.* Greenpeace, London.

Giblin, A.E., G.E. Likens, G. E., and R.W. Howarth. 1991. Reply to the comments by Robert Stauffer on "Sulfur storage and alkalinity generation in New England lake sediments" by Giblin et al. *Limnol. Oceanogr*. 36: 1265.

Muramoto, J., S. Honjo, B. Fry, J. Hay, R. Howarth, and J. Cisne. 1991. Sulfur, iron, and organic carbon fluxes in the Black Sea: Sulfur isotopic evidence for origin of sulfur fluxes. *Deep Sea Research* 38: S1151-S1187.

1990 Giblin, A.E., G.E. Likens, D. White, and R.W. Howarth. 1990. Sulfur storage and alkalinity generation in New England lake sediments. *Limnol. Oceanogr*. 35: 852-869.

Marino, R., R.W. Howarth, J. Shamess, and E.E. Prepas. 1990. Molybdenum and sulfate as controls on the abundance of nitrogen-fixing cyanobacteria in saline lakes in Alberta. *Limnol. Oceanogr*. 35: 245-259

Howarth, R. W., and R. Marino. 1990. Nitrogen-fixing cyanobacteria in the plankton of lakes and estuaries: A reply to the comment by Smith. *Limnol. Oceanogr*. 35: 1859-1863.

Howarth, R.W., J. Boreman, G. Colvin, C. Decker, S. Findlay, J., Levinton, R. Malouf, J. Waldman, and P. Woodhead. 1990. Report of the working group on "ecosystems and fisheries". Pages. 24-37 in: A Research Program for the Hudson River Estuary. New York State Department of Environmental Conservation. No. 3-1990.

1989 Howarth, R. W. 1989. Determining the ecological effects of oil pollution in marine ecosystems. In S. A. Levin, M. A. Harwell, J. R. Kelly, and K. D. Kimball, (eds.) *Problems in Ecotoxicology.* Springer-Verlag, New York.

1988 Howarth, R.W., R. Marino, J. Lane, and J.J. Cole. 1988. Nitrogen fixation in freshwater, estuarine, and marine ecosystems. l. Rates and importance. *Limnol. Oceanogr*. 33: 669-687.

Howarth, R.W., R. Marino, and J.J. Cole. 1988. Nitrogen fixation in freshwater, estuarine, and marine ecosystems. 2. Biogeochemical controls. *Limnol. Oceanogr*. 33: 688-701.

Lodge, D.M., J.W. Barko, D. Strayer, R.W. Howarth, J. Melack, B. Menge, G. G. Mittelbach, and J.E. Titus. 1988. Spatial heterogeneity in lake communities: the benthos and habitat interactions. Page 181-208 in S. R. Carpenter (ed.), *Complex Interactions in Lake Communities.* Springer-Verlag, New York.

Howarth, R. W. 1988. Nutrient limitation of net primary production in marine ecosystems. *Annual Review of Ecology & Systematics* 19: 89-110 (Cited 1,345 times in other peer-reviewed papers as of March 14, 2023).

Novelli, P. C., A. R. Michelson, M. J. Scranton, G. T. Banta, J. E. Hobbie, and R.W. Howarth. 1988. Hydrogen and acetate cycling in two sulfate reducing sediments: Buzzards Bay and Town Cove, Massachusetts. *Geochem. Cosmochim. Acta* 52: 2477-2486.

1987 Peterson, B. J., and R.W. Howarth. 1987. Sulfur, carbon and nitrogen isotopes used to trace organic matter flow in the salt marsh estuaries of Sapelo Island, Georgia. *Limnol. Oceanogr.* 32: 1195-1213.

Gallagher, J. L., and R.W. Howarth. 1987. Seasonal differences in *Spartina* recoverable underground reserves in the Great Sippewissett Marsh in Massachusetts. *Estuarine, Coastal & Shelf Science* 25: 313-319.

Howarth, R. W. 1987. Potential impacts of petroleum on the biotic resources of Georges Bank. In R. Backus (ed.), *An Atlas of Georges Bank.* M.I.T. Press, Cambridge, MA.

1986 Luther, G.W., T.M. Church, A.E. Giblin, and R.W. Howarth. 1986. Speciation of dissolved sulfur in salt marshes by polarographic methods. Pages 340-355 in M. Sohn (ed.), *Organic Marine Geochemistry.* American Chemical Society, Washington, D. C.

Peterson, B.J., R.W. Howarth, and R..H. Garritt. 1986. Sulfur and carbon isotopes as tracers of salt-marsh organic matter flow. *Ecology* 67: 865-874.

Whelan, J. K., R. Oremland, M. Tarata, R. Smith, R. Howarth, and C. Lee. 1986. Evidence for sulfate reducing and methane producing microorganisms in sediments from sites 618, 619, and 622. Reports of the Deep-Sea Drilling Project.

Cole, J.J., R.W. Howarth, S.S. Nolan, and R. Marino. 1986. Sulfate inhibition of molybdate assimilation by planktonic algae and bacteria: some implications for the aquatic nitrogen cycle. *Biogeochemistry* 2: 179-196.

1985 Rowe, G., and R.W. Howarth. 1985. Early diagenesis of organic matter in sediments off the coast of Peru. *Deep-Sea Res*. 32: 43-55.

Howarth, R.W. & J.J. Cole. 1985. Molybdenum availability, nitrogen limitation, and phytoplankton growth in natural waters. *Science* 229: 653-655.

Peterson, B.J., R.W. Howarth, and R.H. Garritt. 1985. Multiple stable isotopes used to trace the flow of organic matter in estuarine food webs. *Science* 227: 1361-1363.

1984 Giblin, A., and R.W. Howarth. 1984. Pore water evidence for a dynamic sedimentary iron cycle in salt marshes. *Limnol. Oceanogr*. 29: 47-63.

Howarth, R.W. 1984. The ecological significance of sulfur in the energy dynamics of salt marsh and marine sediments. *Biogeochemistry* 1: 5-27.

Howarth, R.W. 1984. Global sulfur budgets, a review of "The Global Biogeochemical Sulfur Cycle, SCOPE 19, M. B. Ivanov & J. R. Freney (eds.)." *Ecology* 65: 1336.

Howarth, R.W., and B.B. Jorgensen. 1984. Formation of ^{35}S-labeled elemental sulfur and pyrite in coastal marine sediments (Limfjorden and Kysing Fjord, Denmark) during short-term $^{35}SO_4^{2-}$ reduction measurements. *Geochem. Cosmochim. Acta* 48: 1807-1818.

Howarth, R.W., and R. Marino. 1984. Sulfate reduction in salt marshes, with some comparisons to sulfate reduction in microbial mats. Pages 245-263 in Y. Cohen, R. W. Castenholz & H. O. Halvorson (eds.), *Microbial Mats: Stromatolites.* Alan R. Liss, Inc., NY.

Howarth, R.W., and S. Merkel. 1984. Pyrite formation and the measurement of sulfate reduction in salt marsh sediments. *Limnol. Oceanogr*. 29: 598-608.

Teal, J.M., and R.W. Howarth. 1984. Oil spill studies: a review of ecological effects. *Environmental Management* 8: 27-44.

Howarth, R.W., and A. Giblin. 1984. Sulfate reduction in the salt marshes at Sapelo Island, Georgia. *Limnol. Oceanogr*. 28: 70-82.

Howarth, R.W., A. Giblin, J. Gale, B.J. Peterson, and G.W. Luther. 1984. Reduced sulfur compounds in the pore waters of a New England salt marsh. *Ecol. Bull.* (Stockholm) 35: 135-152.

Peterson, B.J., P.A. Steudler, R.W. Howarth, A.I. Friedlander, D. Juers, and F.P. Bowles. 1984. Tidal export of reduced sulfur from a salt marsh ecosystem. *Ecol. Bull*. (Stockholm) 35: 153-165.

1982 Howarth, R.W. 1982. Debunking the myth of the "inexhaustible" ocean, a review of "The Oceans: Our Last Resource" by W. Marx. *Technolology Review* 85: 85-86.

Howarth, R.W., and J. E. Hobbie. 1982. The regulation of decomposition and heterotrophic microbial activity in salt marsh soils. Pages 183-207 in V. S. Kennedy (ed.), *Estuarine Comparisons.* Academic Press, NY.

Luther, G.W., A. Giblin, R.W. Howarth, and R.A. Ryans. 1982. Pyrite and oxidized iron mineral phases in salt marsh and estuarine sediments. *Geochem. Cosmochim. Acta* 46: 2665-2669.

Valiela, I., B.L. Howes, R.W. Howarth, A. Giblin, K. Foreman, J.M. Teal, and J.E. Hobbie. 1982. The regulation of primary production and decomposition in a salt marsh ecosystem. Pages 151-168 in B. Gopal, R. E. Turner, R. G. Wetzel, & D. F. Whigham (eds.), *Wetlands: Ecology and Management*. Proceedings of First International Wetlands Conference, New Delhi, India.

1981 Howarth, R.W. 1981. Fish versus fuel: a slippery quandary. *Technology Review* 83: 68-77.

Howarth, R.W. 1981. Oil and fish: can they coexist? Pages 49-72 in *Coast Alert: Scientists Speak Out.* Friends of the Earth Publishers, San Francisco.

Howes, B. L., R.W. Howarth, J.M. Teal, and I. Valiela. 1981. Oxidation-reduction potentials in a salt marsh: 1. Spatial patterns and interactions with primary production. *Limnol. Oceanogr*. 26: 350-360.

Teal, J.M., and R.W. Howarth. 1981. Biological effects of oil spills. Background paper, NAS Panel on Petroleum in the Marine Environment. National Academy Press, Washington, DC.

1980 Howarth, R.W., and J.M. Teal. 1980. Energy flow in a salt marsh ecosystem: the role of reduced inorganic sulfur compounds. *American Naturalist* 116: 862-872.

Lee, C.L., R.W. Howarth, and B.L. Howes. 1980. Sterols in decomposing *Spartina alterniflora* and the use of ergosterol in estimating the contribution of fungi to detrital nitrogen. *Limnol. Oceanogr*. 25: 290-303.

Peterson, B.J., R.W. Howarth, F. Lipshultz, and D. Ashendorf. 1980. Salt marsh detritus: an alternative interpretation of stable carbon isotope ratios and the fate of *Spartina alterniflora. Oikos* 34: 173-177.

1979 Howarth, R.W. 1979. The role of sulfur in salt marsh metabolism. Ph.D. thesis, MIT/WHOI Joint Program (SeaGrant publ. #WHOI 79-39).

Howarth, R.W. 1979. Pyrite: its rapid formation in a salt marsh and its importance to ecosystem metabolism. *Science* 203: 49-51.

Howarth, R.W., and J.M. Teal. 1979. Sulfate reduction in a New England salt marsh. *Limnol. Oceanogr*. 24: 999-1013.

1978 Hall, C.A.S., R.W. Howarth, B. Moore, and C.J. Vorosmarty. 1978. Environmental impacts of industrial energy systems in the coastal zone. *Annual Review of Energy* 3: 395-475.

Howarth, R.W. 1978. A rapid and precise method for determining sulfate in seawater, estuarine waters, and sediment pore waters. *Limnol. Oceanogr*. 23: 1066-1069.

Howarth, R.W., and C.A.S. Hall. 1978. What Do You Want to Do With Your Last 27,000 Gallons of Oil? *Human Ecology Forum*. 8: 2-5

1977 Connor, M. ., and R.W. Howarth. 1977. Potential effects of oil production on Georges Bank communities: A review of the draft environmental impact statement of outer continental shelf oil and gas lease sale no. 42. SeaGrant publ. #WHOI 77-1.

1976 Howarth, R.W., and S.G. Fisher. 1976. The dynamics of carbon, nitrogen, and phosphorus during leaf decomposition in stream micro-ecosystems. *Freshwater Biol*. 6: 221-228.

1975 Whitney, D., G.M. Woodwell, and R.W. Howarth. 1975. Nitrogen fixation in Flax Pond, a Long Island salt marsh. *Limnol. Oceanogr*. 20: 640-643.

CURRICULUM VITAE

Last Updated February 7, 2023

Mark Z. Jacobson
Professor of Civil and Environmental Engineering
Director, Atmosphere/Energy Program
Yang and Yamazaki Environment and Energy Building
Civil and Environmental Engineering, Mailcode 4020
473 Via Ortega, Room 397
Stanford University
Stanford, CA 94305-4020, USA
Tel: (650) 723-6836
Fax: (650) 723-7058
Email: jacobson@stanford.edu
Internet: http://www.stanford.edu/group/efmh/jacobson
Twitter: Follow @mzjacobson

Degrees and Employment

B. S., with distinction, Stanford University, Civil Engineering, 1988
B. A., with distinction, Stanford University, Economics, 1988
M. S., Stanford University, Environmental Engineering, 1988
M. S., UCLA, Atmospheric Sciences, 1991
Ph. D., UCLA, Atmospheric Sciences, 1994
Research Asst., UCLA, Atmospheric Sciences, 1989-1994
Teaching Assistant, UCLA, Atmospheric Sciences, 1989-1994
Postdoctoral Student, UCLA, Atmospheric Sciences, June-September, 1994
Assistant Professor, Civil and Environmental Engineering, Stanford University, 1994-2001.
Associate Professor, Civil and Environmental Engineering, Stanford Univ., 2001-2007
Professor, Civil and Environmental Engineering, Stanford University, 2007-present
Professor by Courtesy of Energy Resources Engineering, Stanford Univ, 2007-2010
Associate Director, Environmental Fluid Mechanics Laboratory, Stanford University, September, 1996-2004.
Director and co-founder, Atmosphere/Energy Program (link), Dept. of Civil and Environmental Engineering, Stanford University, 2004-present.
Senior Fellow, Woods Institute for the Environment (link), January 2008-present
Senior Fellow, Precourt Institute for Energy (link), January 1, 2010-present
Co-founder, The Solutions Project (link), July 10, 2011-present.

Scientific Background

Mark Z. Jacobson's career has focused on better understanding air pollution and global warming problems and developing large-scale clean, renewable energy solutions to them. Toward that end, he has developed and applied three-dimensional (3-D) atmosphere-biosphere-ocean computer models and solvers to simulate and understand air pollution, weather, climate, and renewable energy systems. He has also developed roadmaps to transition countries, states, cities, and towns to 100% clean, renewable energy for all purposes and computer models to examine grid stability in the presence of 100% renewable energy. Jacobson has been a professor at Stanford University since 1994. His research crosses two fields: Atmospheric Sciences and Energy, each discussed next.

Atmospheric Sciences

Jacobson started computer modeling in 1990. He developed over 85% of the computer code for the world's first 3-D urban air pollution model coupled, with feedback, to meteorology. He then developed the first coupled 3-D global air pollution-weather-climate model and first unified nested global-through-urban air pollution-weather-climate model, GATOR-GCMOM. Zhang (2008) calls Jacobson's unified model "the first fully-coupled online model in the history that accounts for all major feedbacks among major atmospheric processes based on first principles." Many features in GATOR-GCMOM are now mainstream in other models worldwide. For these models, he coded the world's fastest (at the time) ordinary differential equation solver in a 3-D model for a given level of accuracy (SMVGEAR). He also developed solvers for aerosol and cloud coagulation, breakup, condensation/evaporation, freezing, dissolution, chemical equilibrium, and lightning; air-sea exchange; ocean chemistry; greenhouse gas absorption; and land-surface processes. Thousands of researchers have used computer codes he has developed.

In 2000 and 2001, Jacobson applied his model to discover that black carbon, the main component of soot air pollution particles, may be the second-leading cause of global warming in terms of radiative forcing, after carbon dioxide. Several subsequent studies, including the highly-cited review by Bond et al. (2013), confirmed his finding.

Jacobson's finding about black carbon's climate effects resulted in his invitation to testify to the U.S. House of Representatives in 2007 and formed the original scientific basis for several proposed laws and policies. These included U.S. Senate Report 110-489 (Black Carbon Research Bill of 2008), U.S. House Bill 7250 (Arctic Climate Preservation Act of 2008), U.S. House Bill 1760 (Black Carbon Emissions Reduction Act of 2009), U.S. Senate Bill 849 (2009 Bill for the U.S. EPA to research black carbon), U.S. Senate Bill 3973 (Diesel Emission Reduction Act of 2010), European Parliament Resolution B7-0474/2011 (Resolution calling for black carbon controls on climate grounds), the 2012 multi-country Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants, led by Hilary Clinton, California Senate Bill 1383 (2016 Bill to reduce black carbon), and California's 2002 rule to not allow diesel vehicles to have higher particle emissions than gasoline vehicles.

For his black carbon discovery and modeling, Jacobson received the 2005 American Meteorological Society Henry G. Houghton Award, given for his "significant contributions to modeling aerosol chemistry and to understanding the role of soot and other carbon particles on climate" and a 2013 American Geophysical Union Ascent Award for "his dominating role in the development of models to identify the role of black carbon in climate change."

Jacobson's 2008 and 2010 findings that carbon dioxide domes over cities have enhanced air pollution mortality through its feedback to particles and ozone resulted in another invitation for him to testify in the U.S. House of Representatives in 2008 and to testify twice in U.S. Environmental Protection Agency (EPA) hearings. In the first EPA hearing he was called as the State of California's only expert witness to testify on how carbon dioxide can damage health locally by increasing temperatures and water vapor. This testimony served as a direct scientific basis for the EPA's 2009 approval of the first regulation in U.S. history of carbon dioxide (the California waiver).

Energy

With respect to energy, in 2001 Jacobson published a paper in Science examining the ability of the U.S. to convert a large fraction of its energy to wind. In 2005, his group developed the first world wind map based on data alone. His students and he subsequently published on the impacts of hydrogen fuel cell vehicles on air quality and climate, on reducing the variability of wind energy by interconnecting wind farms; on integrating solar, wind, geothermal, and hydroelectric power into the grid; on integrating offshore wind and wave power; on comparing ethanol with gasoline; and on mapping U.S. offshore wind resources.

In 2008, he carried out a review of proposed energy technologies to address air pollution, global warming, and energy security, concluding that wind-water-solar (WWS) technologies resulted in the greatest benefits. In 2009, he coauthored a plan, featured on the cover of Scientific American, to determine if powering the world for all purposes with WWS was possible. In 2010, he was invited to participate in a TED debate. From 2010-2012, he served on the Energy Efficiency and Renewables advisory committee to the U.S. Secretary of Energy. In 2011, he cofounded The Solutions Project non-profit, which combined science, business, culture, and community, to educate people about science-based 100% clean, renewable energy roadmaps for 100% of the people.

In 2013, 2014, and 2016, he and his students developed roadmaps to transition New York, California, and Washington State, respectively, to 100% WWS. Jacobson's New York energy roadmap resulted in an invitation for him to appear on the Late Show with David Letterman on October 9, 2013. Jacobson was then asked by the New York governor's office to provide more information about a possible transition of New York to 100% WWS. In 2016, the governor proposed and passed a 50% renewable law (the New York Clean Energy Standard). Also in 2016, and in 2018, the New York Senate proposed New York Senate Bills S5527 and S5908A, respectively, for the state to go to 100% renewable electricity. The texts of both bills state, "This bill builds upon the Jacobson wind, water and solar (WWS) study…" In 2019, New York State implemented Jacobson'd goal for the electricity sector by passing a law to go to 100% renewable electricity.

Similarly, on October 27, 2014, after the publication of Jacobson's California WWS roadmap, the California governor's office invited Jacobson to meet with the governor's policy advisors to discuss the roadmap. In January, 2015, the governor proposed and, shortly after, obtained passage of a law (SB 350) for California to move to 50% renewable electricity. In 2018, this law was updated for the state to go to 100% renewable electricity (SB 100).

In 2015, Jacobson and his group published WWS plans for all 50 states and a continental-U.S.-wide grid study assuming 100% WWS. The grid paper earned Jacobson and his coauthors a 2016 Cozzarelli Prize from the Proceedings of the National Academy of Sciences, given for "outstanding scientific excellence and originality." The plans and grid study were updated for the 50 U.S. states and individual U.S. regions in 2022. The publication of these roadmaps, together with their dissemination by the Solutions Project and dozens of other nonprofits, resulted in the widespread awareness of Jacobson's plans and the growth of the 100% renewable energy movement. Jacobson's science-based plans resulted in all three Democratic presidential candidates for the 2016 election making 100% renewable energy part of their platform. Senator Sanders included Jacobson's roadmaps on his web site and, after the election, wrote an op-ed with Jacobson in the Guardian calling for a transition to 100% renewables.

To date, activists inspired by Jacobson's plans have encouraged 16 U.S. states (NY, CA, WA, RI, CT, OR, HI, NM, IL, NV, ME, WI, VA, NJ, NC, NE), the District of Columbia, and Puerto Rico to pass laws or Executive Orders requiring a transition of up to 100% clean, renewable electricity. At the federal level, eight laws and resolutions were proposed calling for the U.S. to move to 100% renewable electricity or all energy. These included House Resolution 540 (2015), House Bill 3314 (2017), House Bill 3671 (2017), House Bill 330 (2019); Senate Resolution 632 (2019), Senate Bill 987 (2019), House Resolution 109 (2019), and Senate Resolution 59 (2019). All were inspired by Jacobson's plans. For example, the first, House Resolution 540, states: "Whereas a Stanford University study concludes that the United States energy supply could be based entirely on renewable energy by the year 2050 using current technologies."

House Resolution 109 and Senate Resolution 59 are the proposed U.S. Green New Deal. As stated by Dr. Marshall Shepherd, "Professor Mark Jacobson at Stanford University has been a longtime leader in climate science and renewable energy transition. Many of the assumptions in the Green New Deal seem to be anchored in his scholarship." The main goals of the Green New Deal, to transition the U.S. to 100% renewable energy by 2030, came from Jacobson and Delucchi's 2009 Scientific American paper.

In 2009 and 2011, Jacobson developed plans to transition the world to 100% WWS. In 2017-2018, he developed more detailed plans and grid studies for 139 individual countries. These were updated for 143 countries in 2019 and 145 countries in 2022. Not coincidentally, to date, 61 countries have enacted policies calling for 100% renewable electricity.

The Sierra Club supported the Jacobson roadmaps, and in 2013, asked him to help with a campaign to encourage cities around America to adopt 100% WWS laws. Ultimately, he and his students published plans for 53 towns and cities (2018) and 74 metropolitan areas (2020). To date, about 160 U.S. cities and over 400 cities worldwide have enacted policies to transition to 100% renewable electricity. Finally, over 380 international companies have committed to 100% renewables in their global operations.

For his research and leadership in Energy, Jacobson received the 2013 Global Green Policy Design Award for the "design of analysis and policy framework to envision a future powered by renewable energy." In 2016, he received a Cozzarelli Prize. In 2018, he received the Judi Friedman Lifetime Achievement Award "For a distinguished career dedicated to finding solutions to large-scale air pollution and climate problems." In 2019 and 2022, he was selected as "one of the world's 100 most influential people in climate policy" by Apolitical. In 2022, he was recognized as "World Visionary CleanTech Influencer of the Year" by the CleanTech Business Club.

Additional Work and Impact

To date, Jacobson has published about 180 peer-reviewed journal articles and given (since 1994) ~700 invited talks. In 2004, he founded and has ever since directed the Atmosphere/Energy Program at Stanford. Jacobson has written six textbooks, including Fundamentals of Atmospheric Modeling (1999) and Atmospheric Pollution: History, Science, and Regulation (2002). These two, plus second editions in 2005 and 2012, respectively, relate primarily to his work in Atmospheric Sciences. His last two, 100% Clean, Renewable Energy and Storage for Everything (2020) and No Miracles Needed (2023) relate to his work in Energy.

Based on the impact of his research through citations to papers, Jacobson is ranked as the most impactful scientist in the world in the field of Meteorology & Atmospheric Sciences among those with their first publication past 1985. Among scientists publishing in any year from 1788 to 2021, he is ranked #12 in that field. In the Energy field, he is ranked #6 among those with their first publication past 1980 and #16 among those with their first publication in any year. He is also ranked #1,843 among all fields, among all 10 million scientists in history.

Awards, Scholarships, and Fellowships

Yale Book award, 1982

Distinguished Scholar Award, Palo Alto Unified School District, 1983

Faculty Cup award, "Presented in recognition of outstanding academic achievement and leadership by the administration and faculty of H. M. Gunn Senior High School," 1983

National Merit scholarship, 1983

Harvard College Honorary National Scholarship,"Highest award given by Harvard University to members of incoming class, based on academic distinction and extracurricular achievement," 1983

NCAA-ITCA scholar-athlete of the year award, 1985, 1986, 1987

Division I NCAA-ITCA Academic All-American, 1987

Stanford University Tennis scholarship, Stanford University, 1986-7

Department of Civil Engineering academic fellowship, Stanford University, 1987

Second place, ASCE hazardous waste essay writing competition, 1987

Chancellor's fellowship, UCLA, 1989

Neiburger teaching award, UCLA, 1992

Dissertation Year fellowship, UCLA, 1993-4

NSF Career Early Development Award, 1995-1998

Powell Foundation Award, Stanford University, 1995-1996

Frederick Terman Fellowship, Stanford University, 1997-2000

Presidential Research Grant for Junior Faculty, Stanford University, 1998

NASA New Investigator Award, 1999-2002

Research Incentive Award, Office of Technology and Licensing Stanford Univ., 2001-2002

American Meteorological Society Henry G. Houghton Award "for significant contributions to modeling aerosol chemistry and to understanding the role of soot and other carbon particles on climate," 2005

Editors' Citation for Excellence in Refereeing, Journal of Geophysical Research-Atmospheres, 2005 (link)

Most-accessed article April-June 2007; second-most-accessed article July-September 2007, in the Journal, *Environmental Science and Technology*, "Effects of ethanol (E85) versus gasoline on cancer and mortality in the United States." (link)

Partial share of the 2007 Nobel Peace Prize as a research contributor to and reviewer of the Intergovernmental Panel on Climate Change 3rd and 4th Assessment Reports, cited for "efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change."

Editor Highlight in Geophysical Research letters for "On the causal link between carbon dioxide and air pollution mortality," February 2008. (link)

Top three most popular research news stories of 2008 published by Environmental Research Web: "Carbon dioxide increase causes air pollution deaths," a news story on "On the causal link between carbon dioxide and air pollution mortality." (link)

Top three "Most Interesting Science and Technology News of 2008", by Blogher, "Review of solutions to global warming, air pollution, and energy security," (link to story)(link to article)

Economist.com "noteworthy journal article" for January 2009, "Review of solutions to global warming, air pollution, and energy security." (link to story)(link to article)

Top-downloaded paper, "Influence of future anthropogenic emissions on climate, natural emissions, and air quality," all Journal of Geophysical Research Journals, May 2009.(link)

All-time top downloaded paper in *Energy and Environmental Science* as of June 2012, "Review of solutions to global warming, air pollution, and energy security." (link)

One of the top two science stories of 2009 according to *Science of the Times,* "A path to sustainable energy by 2030," *Scientific American,* November 2009.(link)

American Geophysical Union Research Spotlight, "Short-term effects of controlling fossil-fuel soot, biofuel soot and gases, and methane on climate, Arctic ice, and air pollution health," July 29, 2010. (link)

Top-cited first author, Stanford University School of Engineering, all departments, for first-authored papers published since Jan. 1, 1994.

Sixth all-time Science and Technology TED Talks, “Debate: Does the world need nuclear energy,” behind Stephen Hawking (1) and James Watson (5) (link)

Editors' Citation for Excellence in Refereeing, Journal of Geophysical Research-Atmospheres, 2012 (link)

American Geophysical Union Ascent Award, for “his dominating role in the development of models to identify the role of black carbon in climate change,” 2013. (link)

Atlas Award honoring climate heroes, Danville, California, November 16, 2013. (link)

Top-scoring article in Energy and Environmental Sciences: Ten Hoeve, J.E., and M.Z. Jacobson, Worldwide health effects of the Fukushima Daiichi nuclear accident, Energy and Environmental Sciences, 2012; October 28, 2013 (link)(paper)

Global Green Award, Policy Design, New York City, December 3, 2013, “Honoring the ‘design’ of analysis and policy framework to envision a future powered by renewable energy. Research and work focused on New York and California has provided an alternative path to the future,” (link)

41st highest cited climate paper out of 120,000, with 961 citations as of July 8, 2015 (Jacobson, M.Z., Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols, Nature, 409, 695-697, 2001)” (link) (spreadsheet) (paper)

Named by Grist50 as one of top 50 "Innovators, organizers, and visionaries who will lead us toward a more sustainable future, in the coming year (and beyond), January 16, 2016,” (link)

Highest-cited two papers in Energy Policy between 2011 and 2016: Jacobson and Delucchi, 2011; Delucchi and Jacobson, 2011 (link) (pdf) (pdf)

Cozzarelli Prize, Awarded February 23, 2016 “for outstanding scientific excellence and originality” to 6 out of ~3,000 papers published in 2015 in the Proceedings of the National Academy of Sciences. Each of the six papers represents an area of research. This prize was awarded in the area of “Applied Biological, Agricultural, and Environmental Sciences” for Jacobson, M.Z., M.A. Delucchi, M.A. Cameron, and B.A. Frew, A low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes (link) (paper)

American Geophysical Union, EOS Research Spotlight, “Roadmaps to transition countries to 100% clean, renewable energy for all purposes to curtail global warming, air pollution, and energy risk,” published in Earth’s Future, December 5, 2017. (link)

Judi Friedman Lifetime Achievement Award, "For a distinguished career dedicated to finding solutions to large-scale air pollution and climate problems. Professor Jacobson has carried out original and important research on the feasibility of wind, water and solar energy to meet the needs of buildings, cities, states and countries around the world. In so doing, he has given scientific rigor to a public discussion that is central to the survival of humanity. As a co-founder of the Solutions Project, he is providing a scientific basis for a collective movement to promote 100% renewable energy," presented by People's Action for Clean Energy (PACE), Hartford, Connecticut, November 8, 2018. (video)

World's 100 most influential people in climate policy for 2019, from Apolitical, March 20, 2019. (link)

World's 2nd top influencer in Environmental Sustainability, from Onalytica, June 26, 2019. (link)

All-electric showcase award, Silicon Valley Clean Energy, for being a "leader within our community who is reducing local emissions and promoting a healthier community with their advanced electric technologies and building designs," September 23, 2019. (link)

World's #1 academic influencer on Smart Grids, from Onalytica, October 23, 2019. (link)

Visionary CleanTech Influencer of the Year, World Clean Tech Awards, 2021 Edition, Dubai, UAE, March 14, 2022. (link)

Ranked as the most impactful scientist in the world in the field of Meteorology & Atmospheric Sciences among those with their first publication past 1985. Among scientists publishing in any year from 1788 to 2021, he is ranked #12 in that field. In the Energy field, he is ranked #6 among those with their first publication past 1980 and #16 among those with their first publication in any year. He is also ranked #1,843 among all fields, among all 10 million scientists in history. October 10, 2022. (link)

Grants

U.S. EPA Global Air Pollution Modeling, 1994 - 1997
U.S. EPA Urban Air Pollution, 1995-1998
National Science Foundation, Climate Modeling, 1997-2000
National Science Foundation, Climate Modeling, 2001-2004
U.S. EPA Climate Modeling, 2001-2002
U.S. EPA Climate Modeling, 2002-2003
NASA Climate Modeling, 2004-2007
Global Climate and Energy Project, Effect of hydrogen on air pollution, 2004-2007
NASA Climate and Air Pollution Modeling, 2004-2007
U.S. EPA, Climate Effects on Air Pollution, 2007-2011
NASA Effects of Aerosols on Clouds, 2007-2010
U.S. Army, Transport of Airborne and Waterborne Particles Center, 2007-2012
Federal Aviation Administration, Effects of contrails on climate, 2007-2009
U.S. Dept. of Energy, Effects of hydrogen on the atmosphere, 2007-2009
Precourt Institute for Energy Efficiency, Optimizing renewable energy, 2008-2009
Federal Aviation Administration, Effects of low-sulfur jet fuel on climate, 2008-2009
National Science Foundation, Measuring and modeling organic aerosols, 2008-2011
Federal Aviation Administration, Effects of Aviation on Climate, 2009-2013
Federal Aviation Administration, Effects of Rerouting Polar Aircraft, 2009-2010
Federal Aviation Administration, ACCRI, 2010-2012
National Science Foundation, Effects of absorbing aerosols on clouds, 2012-2014
Federal Aviation Administration, Effects of Aviation on Climate, 2011-2015
National Aeronautics and Space Administration, Megacity changes, 2012-2015 National Science Foundation, Modeling satellite correlations of cloud properties, 2015-2018
Woods Institute for the Environment, Developing 100% clean, renewable roadmaps for towns and cities, 2017-2018
Innovation Fund Denmark, RE Invest – Renewable energy investment strategies, 2017-2021
U.S. Army Corps of Engineers (USACE) Engineer Research and Development Center (ERDC), Building a self-sustaining microgrid for remote communities and military bases, 2022-2025

Courses taught
CEE 063/263C Weather and Storms
CEE 064/263D Air Pollution and Global Warming: History, Science, and Solutions
CEE 263A Air Pollution Modeling
CEE 263B Numerical Weather Prediction
CEE 176B/276B 100% Clean, Renewable Energy and Storage for Everything

Public online courses
XEIET 100 Clean, renewable energy and storage for a sustainable future
XEIET 200 Planning for a sustainable future with wind, water, and the sun

Unique Features of GATOR-GCMOM (Click here)

Ph. D. Thesis
Jacobson M. Z. (1994) *Developing, coupling, and applying a gas, aerosol, transport, and radiation model to study urban and regional air pollution*. Ph. D. Dissertation, Dept. of Atmospheric Sciences, University of California, Los Angeles, 436 pp. (pdf)

Books
Jacobson, M. Z., *Fundamentals of Atmospheric Modeling*. Cambridge University Press, New York, 656 pp., 1999. (link)

Jacobson, M. Z., *Fundamentals of Atmospheric Modeling, Second Edition*, Cambridge University Press, New York, 813 pp., 2005. (link)

Jacobson, M. Z., *Atmospheric Pollution: History, Science, and Regulation*, Cambridge University Press, New York, 399 pp., 2002. (link)

Jacobson, M. Z., *Air Pollution and Global Warming: History, Science, and Solutions*, Cambridge University Press, Cambridge, 375 pp., 2012 (link)

Jacobson, M. Z., *100% Clean, Renewable Energy and Storage for Everything*, Cambridge University Press, New York, 427 pp., 2019 (link)

Jacobson, M. Z., *No Miracles Needed*, Cambridge University Press, New York, 437 pp., 2023 (link)

Peer-Reviewed Journal Articles as First Author

1. Jacobson, M. Z., and R. P. Turco, SMVGEAR: A sparse-matrix, vectorized Gear code for atmospheric models, *Atmos. Environ., 28A*, 273-284, 1994. (link)

2. Jacobson, M. Z., R. P. Turco, E. J. Jensen, and O. B. Toon, Modeling coagulation among particles of different composition and size, *Atmos. Environ., 28A*, 1327-1338, 1994. (link)

3. Jacobson, M. Z., and R. P. Turco, Simulating condensational growth, evaporation, and coagulation of aerosols using a combined moving and stationary size grid, *Aerosol Sci. and Technol., 22*, 73-92, 1995. (link)

4. Jacobson, M. Z., Computation of global photochemistry with SMVGEAR II. *Atmos. Environ., 29A*, 2541-2546, 1995. (link)

5. Jacobson, M. Z., A. Tabazadeh, and R. P. Turco, Simulating equilibrium within aerosols and non-equilibrium between gases and aerosols, *J. Geophys. Res., 101*, 9079-9091, 1996. (link)

6. Jacobson, M. Z., R. Lu, R. P. Turco, and O. B. Toon, Development and application of a new air pollution modeling system. Part I: Gas-phase simulations, *Atmos. Environ., 30B*, 1939-1963, 1996. (link)

7. Jacobson, M. Z., Development and application of a new air pollution modeling system. Part II: Aerosol module structure and design, *Atmos. Environ., 31A*, 131-144, 1997. (link)

8. Jacobson, M. Z., Development and application of a new air pollution modeling system. Part III: Aerosol-phase simulations, *Atmos. Environ., 31A*, 587-608, 1997. (link)

9. Jacobson, M. Z., Numerical techniques to solve condensational and dissolutional growth equations when growth is coupled to reversible reactions, *Aerosol Sci. Technol., 27*, 491-498, 1997. (link)

10. Jacobson, M. Z., Improvement of SMVGEAR II on vector and scalar machines through absolute error tolerance control. *Atmos. Environ., 32*, 791-796, 1998. (link)

11. Jacobson, M. Z., Studying the effects of aerosols on vertical photolysis rate coefficient and temperature profiles over an urban airshed, *J. Geophys. Res., 103*, 10,593-10,604, 1998. (link)

12. Jacobson, M. Z., Isolating nitrated and aromatic aerosols and nitrated aromatic gases as sources of ultraviolet light absorption, *J. Geophys. Res., 104*, 3527-3542, 1999. (link)

13. Jacobson, M.Z., Effects of soil moisture on temperatures, winds, and pollutant concentrations in Los Angeles, *J. Appl. Meteorol., 38*, 607-616, 1999. (link)

14. Jacobson, M. Z., Studying the effects of calcium and magnesium on size-distributed nitrate and ammonium with EQUISOLV II, *Atmos. Environ., 33*, 3635-3649, 1999. (link)

15. Jacobson, M. Z., A physically-based treatment of elemental carbon optics: Implications for global direct forcing of aerosols, *Geophys. Res. Lett., 27*, 217-220, 2000. (link)

16. Jacobson, M. Z., Global direct radiative forcing due to multicomponent anthropogenic and natural aerosols, *J. Geophys. Res., 106*, 1551-1568, 2001. (link)

17. Jacobson, M. Z., Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols, *Nature, 409*, 695-697, 2001. (link)

18. Jacobson, M. Z., GATOR-GCMM: A global through urban scale air pollution and weather forecast model. 1. Model design and treatment of subgrid soil, vegetation, roads, rooftops, water, sea ice, and snow., *J. Geophys. Res., 106*, 5385-5402, 2001. (link)

19. Jacobson, M. Z., GATOR-GCMM: 2. A study of day- and nighttime ozone layers aloft, ozone in national parks, and weather during the SARMAP Field Campaign, *J. Geophys. Res., 106*, 5403-5420, 2001. (link)

20. Jacobson, M. Z., and G. M. Masters, Exploiting wind versus coal, *Science, 293*, 1438-1438, 2001. (link)

21. Jacobson, M. Z., Analysis of aerosol interactions with numerical techniques for solving coagulation, nucleation, condensation, dissolution, and reversible chemistry among multiple size distributions, *J. Geophys. Res., 107* (D19), 4366, doi:10.1029/2001JD002044, 2002. (link)

22. Jacobson, M. Z., Control of fossil-fuel particulate black carbon plus organic matter, possibly the most effective method of slowing global warming, *J. Geophys. Res., 107* (D19), 4410, doi:10.1029/ 2001JD001376, 2002. (link)

23. Jacobson, M. Z., Development of mixed-phase clouds from multiple aerosol size distributions and the effect of the clouds on aerosol removal, *J. Geophys. Res., 108* (D8), 425, doi:10 1029/2002JD002691, 2003. (link)

24. Jacobson, M. Z., J. H. Seinfeld, G. R. Carmichael, and D.G. Streets, The effect on photochemical smog of converting the U.S. fleet of gasoline vehicles to modern diesel vehicles, *Geophys. Res. Lett., 31*, L02116, doi:10.1029/2003GL018448, 2004. (link)

25. Jacobson, M.Z., and J.H. Seinfeld, Evolution of nanoparticle size and mixing state near the point of emission, *Atmos. Environ., 38*, 1839-1850, 2004. (link)

26. Jacobson, M. Z., The short-term cooling but long-term global warming due to biomass burning, *J. Climate, 17*, 2909-2926, 2004. (link)

27. Jacobson, M.Z., The climate response of fossil-fuel and biofuel soot, accounting for soot's feedback to snow and sea ice albedo and emissivity, *J. Geophys. Res., 109*, D21201, doi:10.1029/2004JD004945, 2004. (link)

28. Jacobson, M.Z., A solution to the problem of nonequilibrium acid/base gas-particle transfer at long time step, *Aerosol Sci. Technol, 39*, 92-103, 2005. (link)

29. Jacobson, M.Z., A refined method of parameterizing absorption coefficients among multiple gases simultaneously from line-by-line data, *J. Atmos. Sci., 62*, 506-517, 2005. (link)

30. Jacobson, M.Z., Studying ocean acidification with conservative, stable numerical schemes for nonequilibrium air-ocean exchange and ocean equilibrium chemistry, *J. Geophys. Res., 110*, D07302, doi:10.1029/2004JD005220, 2005. (link)

31. Jacobson, M.Z., W.G. Colella, and D.M. Golden, Cleaning the air and improving health with hydrogen fuel cell vehicles, *Science, 308*, 1901-1905, 2005. (link)

32. Jacobson, M.Z., D.B. Kittelson, and W.F. Watts, Enhanced coagulation due to evaporation and its effect on nanoparticle evolution, *Environmental Science and Technology, 39*, 9486-9492, 2005. (link)

33. Jacobson, M.Z., Effects of externally-through-internally-mixed soot inclusions within clouds and precipitation on global climate, *J. Phys. Chem. A, 110*, 6860-6873, 2006. (link)

34. Jacobson, M.Z., and Y.J. Kaufmann, Wind reduction by aerosol particles, *Geophys. Res. Lett., 33*, L24814, doi:10.1029/2006GL027838, 2006. (link)

35. Jacobson, M.Z., Effects of ethanol (E85) versus gasoline vehicles on cancer and mortality in the United States, *Environ. Sci. Technol., 41*, 4150-4157, 10.1021/es062085v, 2007. (link)

36. Jacobson, M.Z., Y.J. Kaufmann, Y. Rudich, Examining feedbacks of aerosols to urban climate with a model that treats 3-D clouds with aerosol inclusions, *J. Geophys. Res., 112*, D24205, doi:10.1029/2007JD008922, 2007. (link)

37. Jacobson, M.Z., On the causal link between carbon dioxide and air pollution mortality, *Geophysical Research Letters, 35*, L03809, doi:10.1029/2007GL031101, 2008. (link)

38. Jacobson, M.Z., Effects of wind-powered hydrogen fuel cell vehicles on stratospheric ozone and global climate, *Geophys. Res. Lett., 35*, L19803, doi:10.1029/2008GL035102, 2008. (link)

39. Jacobson, M.Z., The short-term effects of agriculture on air pollution and climate in California, *J. Geophys. Res., 113*, D23101, doi:10.1029/2008JD010689, 2008. (link)

40. Jacobson, M.Z., Review of solutions to global warming, air pollution, and energy security, *Energy and Environmental Science, 2*, 148-173, doi:10.1039/b809990c, 2009. (link)

41. Jacobson, M.Z., and D.G. Streets, The influence of future anthropogenic emissions on climate, natural emissions, and air quality, *J. Geophys. Res., 114*, D08118, doi:10.1029/2008JD011476, 2009. (link)

42. Jacobson, M.Z., Effects of biofuels vs. other new vehicle technologies on air pollution, global warming, land use, and water, *Int. J. Biotechnology, 11*, 14-59, 2009. (pdf)

43. Jacobson, M.Z., and M.A. Delucci, A path to sustainable energy by 2030, *Scientific American,* November 2009 (cover story). (link)

44. Jacobson, M.Z., The enhancement of local air pollution by urban CO_2 domes, *Environ. Sci. Technol., 44*, 2497-2502, doi:10.1021/es903018m, 2010. (link)

45. Jacobson, M.Z., Short-term effects of controlling fossil-fuel soot, biofuel soot and gases, and methane on climate, Arctic ice, and air pollution health, *J. Geophys.Res., 115*, D14209, doi:10.1029/2009JD013795, 2010. (link)

46. Jacobson, M.Z., and D.L. Ginnebaugh, Global-through-urban nested three-dimensional simulation of air pollution with a 13,600-reaction photochemical mechanism, *J. Geophys. Res., 115*, D14304, doi:10.1029/2009JD013289, 2010. (link)

47. Jacobson, M.Z., Numerical Solution to Drop Coalescence/Breakup With a Volume-Conserving, Positive-Definite, and Unconditionally-Stable Scheme, *J. Atmos. Sci., 68*, 334-346, doi:10.1175/2010JAS3605.1, 2011. (link)

48. Jacobson, M.Z., and M.A. Delucchi, Providing all Global Energy with Wind, Water, and Solar Power, Part I: Technologies, Energy Resources, Quantities and Areas of Infrastructure, and Materials, *Energy Policy, 39*, 1154-1169, doi:10.1016/j.enpol.2010.11.040, 2010. (link)

49. Jacobson, M.Z., J.T. Wilkerson, A.D. Naiman, and S.K. Lele, The effects of aircraft on climate and pollution. Part I: Numerical methods for treating the subgrid evolution of discrete size- and composition-resolved contrails from all commercial flights worldwide, *J. Comp. Phys., 230*, 5115-5132, doi:10.1016/j.jcp.2011.03.031, 2011. (link)

50. Jacobson, M.Z., and J.E. Ten Hoeve, Effects of urban surfaces and white roofs on global climate, *J. Climate, 25*, 1028-1044, doi:10.1175/JCLI-D-11-00032.1, 2012. (link)

51. Jacobson, M.Z., Investigating cloud absorption effects: Global absorption properties of black carbon, tar balls, and soil dust in clouds and aerosols, *J. Geophys. Res. 117*, D06205, doi:10.1029/2011JD017218, 2012. (link)

52. Jacobson, M.Z., J.T. Wilkerson, S. Balasubramanian, W.W. Cooper, Jr., and N. Mohleji, The effects of rerouting aircraft around the Arctic Circle on Arctic and global climate, *Climatic Change 115*, 709-724, doi:10.1007/s10584-012-0462-0, 2012. (link)

53. Jacobson, M.Z., and C.L. Archer, Saturation wind power potential and its implications for wind energy, *Proc. Nat. Acad. Sci. 109*, 15,679-15,684, doi:10.1073/pnas.1208993109, 2012. (link)

54. Jacobson, M.Z., R.W. Howarth, M.A. Delucchi, S.R. Scobies, J.M. Barth, M.J. Dvorak, M. Klevze, H. Katkhuda, B. Miranda, N.A. Chowdhury, R. Jones, L. Plano, and A.R. Ingraffea, Examining the feasibility of converting New York State's all-purpose energy infrastructure to one using wind, water, and sunlight, *Energy Policy 57*, 585-601, 2013. (link)

55. Jacobson, M.Z., J.T. Wilkerson, A.D. Naiman, and S.K. Lele, The effects of aircraft on climate and pollution. Part II: 20-year impacts of exhaust from all commercial aircraft worldwide treated individually at the subgrid scale, *Faraday Discussions, 165*, 369-382, doi:10.1039/C3FD00034F, 2013. (link)

56. Jacobson, M.Z., C.L. Archer, and W. Kempton, Taming hurricanes with arrays of offshore wind turbines, *Nature Climate Change, 4*, 195-200, doi:10.1038/NCLIMATE2120, 2014. (link)

57. Jacobson, M.Z., M.A. Delucchi, A.R. Ingraffea, R.W. Howarth, G. Bazouin, B. Bridgeland, K. Burkhart, M. Chang, N. Chowdhury, R. Cook, G. Escher, M. Galka, L. Han, C. Heavey, A. Hernandez, D.F. Jacobson, D.S. Jacobson, B. Miranda, G. Novotny, M. Pellat, P. Quach, A. Romano, D. Stewart, L. Vogel, S. Wang, H. Wang, L. Willman, T. Yeskoo, A roadmap for repowering California for all purposes with wind, water, and sunlight, *Energy, 73*, 875-889, doi:10.1016.j.energy.2014.06.099, 2014. (link)

58. Jacobson, M.Z., Effects of biomass burning on climate, accounting for heat and moisture fluxes, black and brown carbon, and cloud absorption effects, *J. Geophys. Res., 119*, 8980-9002, doi:10.1002/2014JD021861, 2014. (link)

59. Jacobson, M.Z., S.V. Nghiem, A. Sorichetta, and N. Whitney, Ring of impact from the mega-urbanization of Beijing between 2000 and 2009, *J. Geophys. Res., 120*, 5740-5756, doi:10.1002/2014JD023008, 2015. (link)

60. Jacobson, M.Z., M.A. Delucchi, G. Bazouin, Z.A.F. Bauer, C.C. Heavey, E. Fisher, S. B. Morris, D.J.Y. Piekutowski, T.A. Vencill, T.W. Yeskoo, 100% clean and renewable wind, water, sunlight (WWS) all-sector energy roadmaps for the 50 United States, *Energy and Environmental Sciences, 8*, 2093-2117, doi:10.1039/C5EE01283J, 2015. (link)

61. Jacobson, M.Z., M.A. Delucchi, M.A. Cameron, and B.A. Frew, A low-cost solution to the grid reliability problem with 100% penetration of intermittent wind, water, and solar for all purposes, *Proc. Nat. Acad. Sci., 112* 15,060-15,065, doi: 10.1073/pnas.1510028112, 2015. (link)

62. Jacobson, M.Z., M.A. Delucchi, G. Bazouin, M.J. Dvorak, R. Arghandeh, Z. A.F. Bauer, A. Cotte, G.M.T.H. de Moor, E.G. Goldner, C. Heier, R.T. Holmes, S.A. Hughes, L. Jin, M. Kapadia, C. Menon, S.A. Mullendore, E.M. Paris, G.A. Provost, A.R. Romano, C. Srivastava, T.A. Vencill, N.S. Whitney, and T.W. Yeskoo, A 100% wind, water, sunlight (WWS) all-sector energy plan for Washington State, *Renewable Energy, 86*, 75-88, 2016. (link)

63. Jacobson, M.Z., M.A. Delucchi, Z.A.F. Bauer, S.C. Goodman, W.E. Chapman, M.A. Cameron, Alphabetical: C. Bozonnat, L. Chobadi, H.A. Clonts, P. Enevoldsen, J.R. Erwin, S.N. Fobi, O.K. Goldstrom, E.M. Hennessy, J. Liu, J. Lo, C.B. Meyer, S.B. Morris, K.R. Moy, P.L. O'Neill, I. Petkov, S. Redfern, R. Schucker, M.A. Sontag, J. Wang, E. Weiner, A.S. Yachanin, 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for 139 countries of the world, *Joule, 1*, 1-14, doi:10.1016/j.joule.2017.07.005, 2017. (link)

64. Jacobson, M.Z., M.A. Delucchi, M.A. Cameron, and B.V, Mathiesen, Matching demand with supply at low cost among 139 countries within 20 world regions with 100% intermittent wind, water, and sunlight (WWS) for all purposes, *Renewable Energy 123*, 236-248, doi:10.1016/j.renene.2018.02.0092018, 2018 (link)

65. Jacobson, M.Z., V. Jadhav, World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels, *Solar Energy 169*, 55-66, 2018 (pdf)

66. Jacobson, M.Z., M.A. Cameron, E.M. Hennessy, I. Petkov, C.B. Meyer, T.K. Gambhir, A.T. Maki, K. Pfleeger, H. Clonts, A.L. McEvoy, M.L. Miccioli, A.-K. von Krauland, R.W. Fang, and M.A. Delucchi, 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for 53 towns and cities in North America, *Sustainable Cities and Society, 42*, 22-37, doi:10.1016/j.scs.2018.06.031, 2018 (pdf)

67. Jacobson, M.Z., S.V. Nghiem, A. Sorichetta, Short-term impacts of the mega-urbanizations of New Delhi and Los Angeles between 2000 and 2009, *J. Geophys Res. 124*, 35-56, 2019 (pdf)

68. Jacobson, M.Z., Short-term impacts of the Aliso Canyon natural gas blowout on weather, climate, air quality, and health in California and Los Angeles, *Environmental Science and Technology, 53*, 6081-6093, doi:10.1021/acs.est.9b01495, 2019 (pdf)

69. Jacobson, M.Z., The health and climate impacts of carbon capture and direct air capture, *Energy and Environmental Sciences, 12*, 3567-3574, doi:10.1039/C9EE02709B, 2019 (pdf)

70. Jacobson, M.Z., M.A. Delucchi, M.A. Cameron, S.J. Coughlin, C. Hay, I.P. Manogaran, Y. Shu, and A.-K. von Krauland, Impacts of Green New Deal energy plans on grid stability, costs, jobs, health, and climate in 143 countries, *One Earth, 1*, 449-463, doi:10.1016/j.oneear.2019.12.003, 2019 (link)

71. Jacobson, M.Z., A.-K. von Krauland, Z.F.M. Burton, S.J. Coughlin, C. Jaeggli, D. Nelli, A.J.H. Nelson, Y. Shu, M. Smith, C. Tan, C.D. Wood, and K.D. Wood, Transitioning all energy in 74 metropolitan areas, including 30 megacities, to 100% clean and renewable wind, water, and sunlight, *Energies, 13*, 4934, doi:10.3390/en13184934, 2020 (pdf)

72. Jacobson, M.Z., On the correlation between building heat demand and wind energy supply and how it helps to avoid blackouts, *Smart Energy, 1*, 100009, doi:10.1016/j.segy.2021.100009, 2021 (pdf)

73. Jacobson, M.Z., The cost of grid stability with 100% clean, renewable energy for all purposes when countries are isolated versus interconnected, *Renewable Energy, 179* , 1065-1075, 2021 (pdf)

74. Jacobson, M.Z., A.-K. von Krauland, S.J. Coughlin, F.C. Palmer, and M.M. Smith, Zero air pollution and zero carbon from all energy at low cost and without blackouts in variable weather throughout the U.S. with 100% wind-water-solar and storage, *Renewable Energy, 184*

, 430-444, doi:10.1016/j.renene.2021.11.067, 2022 (pdf)

75. Jacobson, M.Z., A.-K. von Krauland, S.J. Coughlin, E. Dukas, A.J.H. Nelson, F.C. Palmer, and K.R. Rasmussen, Low-cost solutions to global warming, air pollution, and energy insecurity for 145 countries, *Energy & Environmental Sciences, 15*, 3343-3359, doi:10.1039/d2ee00722c, 2022 (pdf)

Additional Peer-Reviewed Journal Articles (Alphabetical)

76. Archer, C. L., and M. Z. Jacobson, Spatial and temporal distributions of U.S. winds and wind power at 80 m derived from measurements, *J. Geophys. Res., 108* (*D9*) 4289, doi:10.1029/2002JD002076, 2003. (link)

77. Archer, C. L., M.Z. Jacobson, and F.L. Ludwig, The Santa Cruz eddy. Part I: Observations and statistics, *Mon. Wea. Rev., 133*, 767-782, 2005. (pdf)

78. Archer, C. L. and M.Z. Jacobson, The Santa Cruz eddy. Part II: Mechanisms of formation, *Mon. Wea. Rev* ., *133*, 767-782 , 2005. (pdf)

79. Archer, C.L., and M.Z. Jacobson, Evaluation of global wind power, *J. Geophys. Res, 110*, D12110, doi:10.1029/2004JD005462, 2005. (link)

80. Archer, C.L., and M.Z. Jacobson, Supplying baseload power and reducing transmission requirements by interconnecting wind farms, *J. Applied Meteorol. and Climatology, 46*, 1701-1717, doi:10.1175/2007JAMC1538.1, 2007. (link)

81. Archer, C.L., and M.Z. Jacobson, Geographical and seasonal variability of the global "practical" wind resources, *Applied Geography, 45*, 119-130, 2013. (link)

82. Bahadur, R., L.M. Russell, M.Z. Jacobson, K.A. Prather, A. Nenes, P.J. Adams, and J.H. Seinfeld, Importance of composition and hygroscopicity of BC particles to the effect of BC mitigation on cloud properties: application to California conditions, *J. Geophys Res. 117*, D09204 doi:10.1029/2011JD017265, 2012. (pdf)

83. Barth, M. C., S. Sillman, R. Hudman, M. Z. Jacobson, C.-H. Kim, A. Monod, and J. Liang, Summary of the cloud chemistry modeling intercomparison: Photochemical box model simulation, *J. Geophys. Res., 108* (D7) doi: 10.1029/2002JD002673, 2003. (pdf)

84. Becker, S., B.A. Frew, G.B. Andresen, T. Zeyer, S. Schramm, M Greiner, and M.Z. Jacobson, Features of a fully renewable U.S. electricity-system: Optimized mixes of wind and solar PV and transmission grid extensions, *Energy, 17,* 443-458, doi:10.1016/j.energy.2014.05.067,2014 (pdf)

85. Becker, S., B.A. Frew, G.B. Andresen, M.Z. Jacobson, S. Schramm, and M. Greiner, Renewable build-up pathways for the U.S.: Generation costs are not system costs, *Energy, 81* 437-445, 2015 (pdf)

86. Boehm, A.B., M.Z. Jacobson, M.J. O'Donnell, M. Sutula, W. Wakefield, and S.B. Weisberg, Ocean acidification science needs for resource managers and users of the North American Pacific coast, *Oceanography, 28*, 170-181, 2015 (pdf)

87. Bond, T.C., S.J. Doherty, D.W. Fahey, P.M. Forster, T. Berntsen, O. Boucher, B.J. DeAngelo, M.G. Flanner, S. Ghan, B. Karcher, D. Koch, S. Kinne, Y. Kondo, P.K. Quinn, M.C. Sarofim, M.G. Schultz, M. Schulz, C. Venkataraman, H. Zhang, S. Zhang, N. Bellouin, S.K.

Guttikunda, P.K. Hopke, M.Z. Jacobson, J.W. Kaiser, Z. Klimont, U. Lohmann, J.P. Schwarz, D. Shindell, T. Storelvmo, S.G. Warren and C.S. Zender, Bounding the role of black carbon in the climate system: A scientific assessment, *J. Geophys. Res., 118*, 5380-5552, doi:10.1002/jgrd.50171, 2013. (pdf)

88. Brasseur, G.P., M. Gupta, B.E. Anderson, S. Balasubramanian, S. Barrett, D. Duda, G. Fleming, P.M. Forster, J. Fluglestvedt, A. Gettelman, R.N. Halthore, S.D. Jacob, M.Z. Jacobson, A. Khodayari, K.-N. Liou, M.T. Lund, R.C. Miake-Lye, P. Minnis, S. Olsen, J.E. Penner, R. Prinn, U. Schumann, H.B. Selkirk, A. Sokolov, N. Unger, P. Wolfe, H.-W. Wong, D.W. Wuebbles, B. Yi, P. Yang, C. Zhou, Impact of aviation on climate: FAA's Aviation Climate Change Research Initiative, *Bulletin of the American Meteorological Society*, 561-583, doi:10.1175/BAMS-D-13-00089, April 2016. (pdf)

89. Breyer, C., S. Khalili, D. Bogdanov, M. Ram, A.S. Oyewo, A. Aghahosseini1, A. Gulagi1, A.A. Solomon, D. Keiner, G. Lopez, P.A. Østergaard, H. Lund, B.V. Mathiesen, M.Z. Jacobson, M. Victoria, S. Teske, T. Pregger, V. Fthenakis, M. Raugei, H. Holttinen, U. Bardi, A. Hoekstra, and B.K. Sovacool, On the history and future of 100% renewable energy systems research, *IEEE Access, 10*, 78,176-78,218, doi: 10.1109/ACCESS.2022.3193402, 2022. (pdf)

90. Cameron, M.A., M.Z. Jacobson, A.D. Naiman, and S.K. Lele, Effects of plume versus grid-scale treatment of aircraft exhaust photochemistry, *Geophys. Res. Lett., 40*, 5815-5820, 2013. (pdf)

91. Cameron, M.A., M.Z. Jacobson, S. R. H. Barrett, H. Bian, C.-C. Chen, S. D. Eastham, A. Gettelman, A. Khodayari, Q. Liang, H. B. Selkirk, N. Unger, D. J. Wuebbles, and X. Yue, An Inter-comparative study of the effects of aircraft emissions on surface air quality, *J. Geophys. Res. Atmos., 122*, 8325-8344, doi:10.1002/2016JD025594, 2017. (pdf)

92. Carmichael, G. R., D. Streets, G. Calori, H. Ueda, M. Amann, M. Z. Jacobson and J. E. Hansen, Changing trends in sulfur emissions in Asia: Implications for acid deposition, air pollution, and climate, *Environmental Sci. Technol., 36*, 4707-4713, 2002. (pdf)

93. Cebulla, F., and M.Z. Jacobson, Alternative renewable energy scenarios for New York, *Journal of Cleaner Production, 205*, 884-894, 2018. (pdf)

94. Chen, Y., S. Mills, J. Street, D. Golan, A. Post, M.Z. Jacobson, A. Paytan, Estimates of atmospheric dry deposition and associated input of nutrients to Gulf of Aqaba seawater, *J. Geophys. Res., 112*, D04309, doi:10.1029/2006JD007858, 2007. (pdf)

95. Colella, W.G., M.Z. Jacobson, and D.M. Golden, Switching to a U.S. hydrogen fuel cell vehicle fleet: The resultant change in emissions, energy use, and global warming gases, *J. Power Sources, 150*, 150-181, 2005. (link)

96. Corcoran, B., N. Jenkins, and M.Z. Jacobson, Effects of aggregating electric load in the United States, *Energy Policy, 46*, 399-416, doi:10.1016/j.enpol.2012.03.079, 2012. (link)

97. Creamean, J.M., A.P. Ault, J.E. Ten Hoeve, M.Z. Jacobson, G.C. Roberts, and K.A. Prather, Measurements of aerosol chemistry during new particle formation events at a remote rural mountain site, *Environ. Sci. Technol., 45*, 8208-8216, doi:10.1021/es103692f, 2011, pubs.acs.org/doi/abs/10.1021/es103692f. (pdf)

98. Delitsky, M. L., R. P. Turco, and M. Z. Jacobson, Nitrogen ion clusters in Triton's atmosphere, *Geophys. Res. Lett., 17*, 1725-1728, 1990. (pdf)

99. Delucchi, M.Z., and M.Z. Jacobson, Providing all global energy with wind, water, and solar power, Part II: Reliability, System and Transmission Costs, and Policies, *Energy Policy, 39*, 1170-1190, doi:10.1016/j.enpol.2010.11.045, 2011. (link)

100. Drdla, K., A. Tabazadeh, R. P. Turco, M. Z. Jacobson, J. E. Dye, C. Twohy, and D. Baumgardner, Analysis of the physical state of one Arctic polar stratospheric cloud based on observations, *Geophys. Res. Lett., 21*, 2475-2478, 1994. (pdf)

101. Dvorak, M., D.L. Archer, and M.Z. Jacobson, California offshore wind energy potential, *Renewable Energy,* doi:10.1016/j.renene.2009.11.022, 2009. (link)

102. Dvorak, M.J., E.D. Stoutenburg, C.L. Archer, W. Kempton, and M.Z. Jacobson, Where is the ideal location for a U.S. East Coast offshore grid, *Geophys. Res. Lett., 39*, L06804, doi:10.1029/2011GL050659, 2012. (link)

103. Dvorak, M.J., B.A. Corcoran, J.E. Ten Hoeve, N.G. McIntyre, and M.Z. Jacobson, U.S. East Coast offshore wind energy resources and their relationship to peak-time electricity demand, *Wind Energy*, doi:10.1002/we.1524, 2012. (link)

104. Edgerton, S.A., M.C. MacCracken, M.Z. Jacobson, A. Ayala, C.E. Whitman, and M.C. Trexler, Critical review discussion: Prospects for future climate change and the reasons for early action, *Journal of the Air and Waste Management Association, 58*, 1386-1400, 2008. (pdf)

105. Elliott, S., R. P. Turco, and M. Z. Jacobson, Tests on combined projection / forward differencing integration for stiff photochemical family systems at long time step, *Computers Chem., 17*, 91-102, 1993. (pdf)

106. Elliott, S., M. Shen, C. Y. J. Kao, R. P. Turco, and M. Z. Jacobson, A streamlined family photochemistry module reproduces major nonlinearities in the global tropospheric ozone system, *Computers Chem., 20*, 235-259, 1996. (pdf)

107. Elliott , S., C.-Y. J. Kao, F. Gifford, S. Barr, M. Shen, R. P. Turco, and M. Z. Jacobson, Free tropospheric ozone production after deep convection of dispersing tropical urban plumes, *Atmos. Environ., 30A*, 4263-4274, 1996. (pdf)

108. Enevoldsen, P., F.-H. Permien, I. es Bakhtaoui, A.-K. von Krauland, M.Z. Jacobson, G. Xydis, B.K. Sovacool, S.V. Valentine, D. Luecht, and G. Oxley, How much wind power potential does Europe have? Examining European wind power potential with an enhanced socio-technical Atlas, *Energy Policy, 132*, 1092-1100, 2019. (pdf)

109. Enevoldsen, P., and M.Z. Jacobson, Installed and output power densities of onshore and offshore wind turbines worldwide, *Energy for Sustainable Development, 60*, 40-51, 2021. (pdf)

110. Freedman, F. R., and M. Z. Jacobson, Transport-dissipation analytical solutions to the E-ε turbulence model and their role in predictions of the neutral ABL, *Bound.-Lay. Meteorol., 102*, 117-138, 2002. (pdf)

111. Freedman, F., and M. Z. Jacobson, Modification of the standard ε-equation for the stable ABL through enforced consistency with Monin-Obukhov similarity theory, *Bound.-Lay. Meteorol., 106*, 383-410, 2003. (pdf)

112. Frew, B.A., S. Becker, M.J. Dvorak, G. Andresen, and M.Z. Jacobson, Flexibility mechanisms and pathways to a highly renewable U.S. electricity future, *Energy, 101*, 65-78, 2016. (pdf)

113. Frew, B.A., and M.Z. Jacobson, Temporal and spatial tradeoffs in power system modeling with assumptions about storage: An application of the POWER model, *Energy, 117*, 198-213, 2016. (pdf)

114. Fridlind, A. M., and M. Z. Jacobson, A study of gas-aerosol equilibrium and aerosol pH in the remote marine boundary layer during the First Aerosol Characterization Experiment (ACE 1), *J. Geophys. Res., 105*, 17,325-17,340, 2000. (pdf)

115. Fridlind, A. M., M. Z. Jacobson, V. -M. Kerminen, R. E. Hillamo, V. Ricard, and J.-L Jaffrezo, Analysis of gas-aerosol partitioning in the Arctic: Comparison of size-resolved equilibrium model results with field data, *J. Geophys. Res., 105*, 19,891-19,904, 2000. (pdf)

116. Fridlind, A. M., and M. Z. Jacobson, Point and column aerosol radiative closure during ACE 1: Effects of particle shape and size, *J. Geophys. Res., 108* (D3) doi:10.1029/2001JD001553, 2003. (pdf)

117. Ginnebaugh, D.L., J. Liang, and M.Z. Jacobson, Examining the temperature dependence of ethanol (E85) versus gasoline emissions on air pollution with a largely-explicit chemical mechanism, *Atmos. Environ., 44,* 1192-1199, doi:10.1016/j.atmosenv.2009.12.024, 2010. (link)

118. Ginnebaugh, D.L., and M.Z. Jacobson, Coupling of highly explicit gas and aqueous chemistry mechanisms for use in 3-D, *Atmos. Environ., 62*, 408-415, 2012. (link)

119. Ginnebaugh, D.L., and M.Z. Jacobson, Examining the impacts of ethanol (E85) versus gasoline production of smog in a fog using near-explicit gas- and aqueous-chemistry mechanisms, *Environmental Research Letters*, *7*, 045901, doi:10.1088/1748-9326/7/4/045901, 2012. (link)

120. Hart, E.K., and M.Z. Jacobson, A Monte Carlo Approach to Generator Portfolio Planning and Carbon Emissions Assessments of Systems with Large Penetrations of Variable Renewables, *Renewable Energy, 36*, 2278-2286, doi:10.1016/j.renene.2011.01.015, 2012. (link)

121. Hart, E.K., E.D. Stoutenburg, and M.Z. Jacobson, The potential of intermittent renewables to meet electric power demand: A review of current analytical techniques, *Proceedings of the IEEE, 100*, 322-334, doi:10.1109/JPROC.2011.2144951, 2011. (link)

122. Hart, E.K., and M.Z. Jacobson, The carbon abatement potential of high penetration intermittent renewables, *Energy and Environmental Science,* 5, 6592-6601, doi:10.1039/c2ee03490e, 2012. (link)

123. Hou, P., P. Enevoldsen, J. Eichman, W. Hu, M.Z. Jacobson, and Z. Chen, Optimizing investments in coupled offshore wind-electrolytic hydrogen storage systems in Denmark, *J. Power Sources, 359*, 186-197, doi:10.1016/j.jpowsour.2017.05.048, 2017. (pdf)

124. Howarth, R.W., and M.Z. Jacobson, How green is blue hydrogen, *Energy Science and Engineering, 9,* 1676-1687, doi:10.1002/ese3.956, 2021 (pdf)

125. Hu, X.-M, Y. Zhang, M.Z. Jacobson, and C.K. Chan, Evaluation and improvement of gas/particle mass transfer treatments for aerosol simulation and forecast, *J. Geophys. Res*., 113, D11208, doi:10.1029/2007JD009588, 2008. (pdf)

126. Jiang, Q., J.D. Doyle, T. Haack, M.J. Dvorak, C.L. Archer, and M.Z. Jacobson, Exploring wind energy potential off the California coast, *Geophys. Res. Lett., 35*, L20819, doi:10.1029/2008GL034674, 2008. (pdf)

127. Katalenich, S.M., and M.Z. Jacobson, Renewable energy and energy storage to offset diesel generators at expeditionary contingency bases, *Journal of Defense Modeling and Simulation,* 1-15, doi:10.1177/15485129211051377, 2021. (pdf)

128. Katalenich, S.M., and M.Z. Jacobson, Toward battery electric and hydrogen fuel cell military vehicles for land, air, and sea *Energy, 254,* 124355, 2022. (pdf)

129. Kempton, W., C.L. Archer, A. Dhanju, R.W. Garvine, and M.Z. Jacobson, Large CO2 reductions via offshore wind power matched to inherent storage in energy end-uses, *Geophys. Res. Lett.,* 34, L02817, doi:10.1029/2006GL028016, 2007. (pdf)

130. Ketefian, G.S., and M.Z. Jacobson, A mass, energy, vorticity, and potential enstrophy conserving lateral fluid-land boundary scheme for the shallow water equations, *J. Comp. Phys., 228*, 1-32, doi:10.1016/j.jcp.2008.08.009, 2009. (pdf)

131. Ketefian, G.S., and M.Z. Jacobson, A mass, energy, vorticity, and potential enstrophy conserving lateral boundary scheme for the shallow water equations using piecewise linear boundary approximations, *J. Comp. Phys., 230*, 2751-2793,2011. (pdf)

132. Kreidenweis, S. M., C. Walcek, G. Feingold, W. Gong, M. Z. Jacobson, C.-H. Kim, X. Liu, J. E.Penner, A. Nenes and J. H. Seinfeld, Modification; of aerosol mass and size distribution due to aqueous-phase SO2 oxidation in clouds: Comparisons of several models, *J. Geophys. Res., 108* (D7) doi:10.1029/2002JD002697, 2003. (pdf)

133. Liang, J., and M. Z. Jacobson, A study of sulfur dioxide oxidation pathways over a range of liquid water contents, pHs, and temperatures, *J. Geophys. Res., 104*, 13,749-13,769, 1999. (pdf)

134. Liang, J., and M. Z. Jacobson, Comparison of a 4000-reaction chemical mechanism with the Carbon Bond IV and an adjusted Carbon Bond IV-EX mechanism using SMVGEAR II., *Atmos. Environ., 34*, 3015-3026, 2000. (pdf)

135. Liang, J., and M. Z. Jacobson, Effects of subgrid segregation on ozone production efficiency in a chemical model, *Atmos. Environ., 34*, 2975-2982, 2000. (pdf)

136. Liang, J., and M.Z. Jacobson, CVPS: An operator solving complex chemical and vertical processes simultaneously with sparse-matrix techniques, *Atmos. Environ.,45*, 6820-6827 doi:10.1016/j.atmosenv.2010.12.035, 2011. (pdf)

137. Lu, R., R. P. Turco, and M. Z. Jacobson, An integrated air pollution modeling system for urban and regional scales.
Part I: Structure and performance, *J. Geophys. Res., 102*, 6063-6080, 1997. (pdf)

138. Lu, R., R. P. Turco, and M. Z. Jacobson, An integrated air pollution modeling system for urban and regional scales.
Part II: Simulations for SCAQS 1987, *J. Geophys. Res., 102*, 6081-6098, 1997. (pdf)

139. Ma, Jianzhong, J. Tang, S.-M. Li, and M. Z. Jacobson, Size distributions of ionic aerosols measured at Waliguan Observatory: Implication for nitrate gas-to-particle transfer processes

in the free troposphere, *J. Geophys. Res., 108*, (D17) 4541, doi:10.1029/2002JD003356, 2003. (pdf)

140. Morrison, G.M., S.Yeh, A.R. Eggert, C. Yang, J.H. Nelson, Alphabetic: J.B. Greenblatt, R. Isaac, M.Z. Jacobson, J Johnston, D.M. Kammen, A. Mileva, J. Moore, D. Roland-Holst, M. Wei, J.P. Weyant, J.H. Williams, R. Williams, C.B. Zapata, Comparison of low-carbon pathways for California, *Climatic Change*, 131, 545-557, doi:10.1007/s10584-015-1403-5, 2015. (pdf)

141. Moya, M., S. N. Pandis, and M. Z. Jacobson, Is the size distribution of urban aerosols determined by thermodynamic equilibrium? An application to Southern California, *Atmos. Environ., 36*, 2349-2365, 2001. (pdf)

142. Naiman, A.D., S.K. Lele, J.T. Wilkerson, and M.Z. Jacobson, Parameterization of subgrid plume dilution for use in large-scale atmospheric simulations, *Atmos. Chem. Phys., 10*, 2551-2560, 2010. (link)

143. Naiman, A.D., S.K. Lele, and M.Z. Jacobson, Large eddy simulations of contrail development: Sensitivity to initial and ambient conditions over twenty minutes, *J. Geophys. Res., 116*, D21208, 2011(link)

144. Olsen, S.C., G.P. Brasseur, D.J. Wuebbles, S.R.H. Barrett, H. Dang, S.D. Eastham, M.Z. Jacobson, A. Khodayari, H. Selkirk, A. Sokolov, N. Unger, Comparison of model estimates of the effects of aviation emissions on atmospheric ozone and methane, *J. Geophys. Res. 40*, 6004-6009, 2014. (pdf)

145. Sambor, D.J., M. Wilber, E. Whitney, and M.Z. Jacobson, Development of a tool for optimizing solar and battery storage for container farming in a remote Arctic microgrid, *J. Energies 13*, 5143, doi:10.3390/en13195143, 2020. (pdf)

146. Sambor, D.J., S.C.M. Bishop, A. Dotson, S. Aggarwal, and M.Z. Jacobson, Optimizing demand response of a modular water reuse system in a remote Arctic microgrid, *J. Cleaner Production, 346*, 131110, doi.org/10.1016/j.jclepro.2022.131110, 2022. (pdf)

147. Sta. Maria, M.R.V., and M.Z. Jacobson, Investigating the effect of large wind farms on energy in the atmosphere, *Energies, 2*, 816-836, doi:10.3390/en20400816, 2009. (link)

148. Stoutenburg, E.D., N. Jenkins, and M.Z. jacobson, Power output variations of co-located offshore wind turbines and wave energy converters in California, *Renewable Energy, 35*, 2781-2791, doi:10.1016/j.renene.2010.04.033, 2010. (link)

149. Stoutenburg, E.K., and M.Z. Jacobson, Reducing offshore transmission requirements by combining offshore wind and wave farms, *IEEE Journal of Oceanic Engineering, 36*, 552-561, 2011. (link)

150. Stoutenburg, E.D., N. Jenkins, and M.Z. Jacobson, Variability and uncertainty of wind power in the California electric power system, *Wind Energy, 17,* 1411-1424, doi:10.1002/we.1640, 2013. (link)

151. Streets, D. G., K. Jiang, X. Hu, J. E. Sinton, X.-Q. Zhang, D. Xu, M. Z. Jacobson, and J. E. Hansen, Recent reductions in China's greenhouse gas emissions, *Science, 294*, 1835-1836, 2001. (pdf)

152. Stuart, A. L., and M. Z. Jacobson, A timescale investigation of volatile chemical retention during hydrometeor freezing:
Nonrime freezing and dry growth riming without spreading, *J. Geophys. Res., 108* (D6), 4178, doi:10.1029/2001JD001408, 2002. (pdf)

153. Stuart, A. L., and M. Z. Jacobson, Chemical retention during dry-growth riming: A model. *J. Geophys. Res., 109* , D07305, doi:10.1029/2003JD004197, 2004. (pdf)

154. Stuart, A.L., and M.Z. Jacobson, A numerical model of the partitioning of trace chemical solutes during drop freezing, *J. Atmos. Chem. 53*, 13-42, 2006. (pdf)

155. Tabazadeh, A., R. P. Turco, and M. Z. Jacobson, A model for studying the composition and chemical effects of stratospheric aerosols, *J. Geophys. Res., 99*, 12,897 - 12,914, 1994. (pdf)

156. Tabazadeh, A., R. P. Turco, K. Drdla, and M. Z. Jacobson, A study of Type I polar stratospheric cloud formation, *Geophys. Res. Let., 21*, 1619-1622,1994. (pdf)

157. Tabazadeh, A., M. Z. Jacobson, H. B. Singh, O. B. Toon, J. S. Lin, B. Chatfield, A. N. Thakur, R. W. Talbot, and J. E. Dibb, Nitric acid scavenging by mineral and biomass burning aerosols, *Geophys. Res. Lett., 25*, 4185-4188, 1998. (pdf)

158. Ten Hoeve, J.E., L.A. Remer, and M.Z. Jacobson, Microphysical and radiative effects of aerosols on warm clouds during the Amazon biomass burning season as observed by MODIS: impacts of water vapor and land cover, *Atmos. Chem. Phys. 11*, 3021-3036, 2011. (link)

159. Ten Hoeve, J.E., M.Z. Jacobson, and L. Remer, Comparing results from a physical model with satellite and in situ observations to determine whether biomass burning aerosols over the Amazon brighten or burn off clouds, *J. Geophys. Res., 117*, D08203, doi:10.1029/2011JD016856, 2012. (link)

160. Ten Hoeve, J.E., L.A. Remer, A.L. Correia, and M.Z. Jacobson, Recent shift from forest to savanna burning in the Amazon Basin observed by satellite, *Env. Res. Lett., 7, 117*, 024020, doi:10.1088/1748-9326/7/2/024020, 2012. (link)

161. Ten Hoeve, J.E. and M.Z. Jacobson, Worldwide health effects of the Fukushima Daiichi nuclear accident, *Energy and Environmental Science, 5*, 8743-8757, doi:10.1039/c2ee22019a, 2012. (link)

162. Von Krauland, A.-K., F.-H. Permien, P. Enevoldsen, and M.Z. Jacobson, Onshore wind energy atlas for the United States accounting for land use restrictions and wind speed thresholds, *Smart Energy, 3,* 100046, doi.org/10.1016/j.segy.2021.100046, 2021. (pdf)

163. Whitt, D.B., J.T. Wilkerson, M.Z. Jacobson, A.D. Naiman, and S.K. Lele, Vertical mixing of commercial aviation emissions from cruise altitude to the surface, *Journal of Geophysical Research., 116*, D14109, doi:1029/2010JD015532, 2011. (link)

164. Wilkerson, J.T., M.Z. Jacobson, A. Malwitz, S. Balasubramanian, R. Wayson, G. Fleming, A.D. Naiman, and S.K. Lele, Analysis of emission data from global commercial aviation: 2004 and 2006, *Atmos. Chem. Phys., 10*, 6391-6408, 2010. (link)

165. Wu, Xiawei, W. Hu, Q. Huang, C. Chen, M.Z. Jacobson, and Z. Chen, Optimizing the layout of onshore wind farms to minimize noise, *Applied Energy, 267*, 114896, 2020. (pdf)

166. Xu, X. W. Hu , D. Cao, Q Huang, W. Liu, M. Z. Jacobson, and Z. Chen, Optimal operational strategy for an offgrid hybrid hydrogen/electricity refueling station powered by solar photovoltaics, *J. Power Sources., 451*, 227810. (pdf)

167. Zamora, I.R., A. Tabazadeh, D.M. Golden, and M.Z. Jacobson, Hygroscopic growth of common organic aerosol solutes, including humic substances, as derived from water activity measurements, *J. Geophys. Res., 116*, D23207, doi:10.1029/2011JD016067, 2011. (pdf)

168. Zamora, I.R., and M.Z. Jacobson, Measuring and modeling the hygroscopic growth of two humic substances in mixed aerosol particles of atmospheric relevance, *Atmos. Chem. Phys., 13*,8973-8989, doi:10.5194/acp-13-8973-2013, 2013. (link)

169. Zhan, S., P. Hou, P. Enevoldsen, G. Yang, J. Zhu, J. Eichman, and M.Z. Jacobson, Co-optimized trading of hybrid wind power plant with retired EV batteries in energy and reserve markets under uncertainties, *Electrical Power and Energy Systems, 117*, 105631, doi:10.1016/j.ijepes.2019.105631, 2020. (pdf)

170. Zhang, Y., C. Seigneur, J. H. Seinfeld, M. Z. Jacobson, and F. Binkowski, Simulation of aerosol dynamics: A comparative review of algorithms used in air quality models, *Aerosol Sci. Technol., 31*, 487-514, 1999. (pdf)

171. Zhang, Y., C. Seigneur, J. H. Seinfeld, M. Jacobson, S. L. Clegg, and F. Binkowski, A comparative review of inorganic aerosol thermodynamic equilibrium modules: Similarities, differences, and their likely causes, *Atmos. Environ., 34*, 117-137, 2000. (pdf)

172. Zhang, Y., B. Pun, K. Vijayaraghavan, S.-Y. Wu, C. Seigneur, S. Pandis, M. Jacobson, A. Nenes, and J. H. Seinfeld, Development and application of the model of aerosol dynamics, reaction, ionization, and dissolution (MADRID), *J. Geophys. Res., 109* (D1), D01202, doi:10.1029/2003JD003501, 2004. (pdf)

173. Zhang, Y., X.-Y. Wen, K. Wang, K. Vijayaraghavan, and M.Z. Jacobson, Probing into regional O_3 and PM pollution in the U.S., 1. A 1 year CMAQ simulation and evaluation using surface and satellite data, *J. Geophys. Res., 114*, D22304, doi:10.1029/2009JD011898, 2009. (pdf)

174. Zhang, Y., X. Wen, K. Wang, K. Vijayaraghavan, and M.Z. Jacobson, Probing into regional O_3 and particulate matter pollution in the United States: 2. An examination of formation mechanisms through a process analysis technique and sensitivity study, *J. Geophys. Res., 114*, D22305, doi:1029/2009JD011900, 2009. (pdf)

175. Zhang, Y., P. Liu, X.-H. Liu, B. Pun, C. Seigneur, M. Z. Jacobson, W. Wang, Fine scale modeling of wintertime aerosol mass, number, and size distributions in Central California, *J. Geophys. Res., 115*, D15207, doi:10.1029/2009JD012950, 2010. (pdf)

176. Zhang, Y., P. Liu, X.-H. Liu, M.Z. Jacobson, P.H. McMurry, F. Yu, S. Yu, and K.L. Schere, A comparative study of homogeneous nucleation parameterizations, Part II. Three-dimensional model application and evaluation, *J. Geophys. Res., 115*, D20213, doi:10.1029/2010JD014151, 2010. (pdf)

177. Zhang, Y., P.H. McMurry, F. Yu, and M.Z. Jacobson, A comparative study of homogenous nucleation parameterizations: 1. Examination and evaluation of the formulations, *J. Geophys. Res., 115*, D20212, doi:10.1029/2010JD014150, 2010. (pdf)

Invited Keynote Talks at Conferences / Workshops and Distinguished Lectures

1. Testing the impact of interactively coupling a meteorological model to an air quality model. Measurements and Modeling in Environmental Pollution Conference, Madrid, Spain, April 22 - 24, 1997.

2. Examining the causes and effects of downward ultraviolet irradiance reductions in Los Angeles., Environsoft 98 Conference, Las Vegas, Nevada, Nov. 10-12, 1998.

3. Computational design of a global-through-urban scale air pollution / weather forecast model and application to the SARMAP field campaign, 8th Supercomputer Workshop, Tsukuba, Japan, September 18-20, 2000.

4. Control of black carbon, the most efficient method of controlling global warming, Air Pollution Modeling and Simulation conference, Paris, France, April 9-13, 2001.

5. Control of fossil-fuel particulate black carbon and organic matter, possibly the most effective method of slowing global warming, Workshop on Climate and Air Quality, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, December 3-5, 2001.

6. Current and future effects of black carbon on climate, Sixth ETH Conference on Nanoparticle Measurement, Zurich, Switzerland, August 19th-21st, 2002.

7. Addressing global warming through a large-scale wind/hydrogen program, Symposium on Environmental and Occupational Safety, University of Puerto Rico at Mayaguez, November 6-7, 2003.

8. Advances in computer modeling of air pollution and climate, Third Canadian Workshop on Air Quality, Quebec City, Canada, March 24-26, 2004.

9. The climate response of soot, accounting for its feedback to snow and sea ice albedo and emissivity, Distinguished Lecture Series, Laboratory for Atmospheres at NASA Goddard Space Flight Center, November 18, 2004.

10. Hydrogen and Wind Apollo Project, Symposium on converting existing city vehicles to utilize renewable hydrogen power, Foothill College, California, Dec. 9, 2005.

11. Effects on health and pollution of converting to hydrogen fuel cell vehicles and feasibility of wind-hydrogen, Second HyCARE symposium, Laxenburg, Austria, Dec. 19-20, 2005.

12. Global climate change: Aerosol versus greenhouse gas causes and the feasibility of a large-scale wind-energy solution, Distinguished Lecture Series, Centre for Global Change Science, Dept. of Physics, University of Toronto, February 21, 2005.

13. Fossil-fuel soot's contribution to global warming, 2nd International Conference on Global Warming and the Next Ice Age, Santa Fe, New Mexico, July 17-21, 2005.

14. The relative effects of greenhouse gases, absorbing aerosol particles, and scattering aerosol particles on global climate, Joint Session of the Atmospheric Chemistry and Atmospheric Aerosol Workshops, Telluride, Colorado, July 30-August 6, 2006.

15. Air quality impacts of biofuels, Woods Institute Biofuels Workshop, Stanford University, Dec. 5-6, 2006.

16. The role of black carbon as a factor in climate change and its impact on public health, Testimony in the U.S. House of Representatives Committee on Oversight and Government Reform, Washington, D.C, October 18, 2007.

17. Comparative effects of vehicles technologies and fuels on climate and air pollution, Plenary presentation for EnviroSymp2007, Sustainable Solutions, University of Copenhagen, Denmark, Nov. 5-6, 2007.

18. A true-renewable-energy solution to global warming, Hon. Al Gore and Mrs. Tipper Gore, and the Alliance for Climate Protection, New York City, New York, January 10, 2008.

19. Global warming health effects and energy solutions. CIRES Distinguished Lecture, CIRES, University of Colorado, Boulder, Colorado, Feb 8, 2008.

20. The relative impact of carbon dioxide on air pollution health problems in California versus the rest of the U.S., Testimony in the U.S. House of Representatives Select Committee on Energy Independence and Global Warming, Washington, D.C, April 9, 2008.

21. Briefing on the effects of carbon dioxide on air pollution mortality, American Meteorological Society, Washington, D.C., May 16, 2008.

22. Computer modeling of the atmosphere: Identifying causes and effects of and evaluating solutions to global warming, SimBuild Conference, Berkeley, California, July 30, 2008.

23. Effects of biofuels versus new vehicle technologies on air pollution, global warming, and landuse, Biofuels in the Midwest, a Discussion, Chicago, Illinois, September 5-7, 2008.

24. Biofuels in context / Energy solutions, 2008 Science for Nature Symposium, World Wildlife Fund, Washington, DC, November 19-20, 2008.

25. The effect of locally-emitted CO_2 on gases, aerosols, clouds, and health, Aerosol-Cloud-Climate Interactions Symposia, 11th Conference on Atmospheric Chemistry, American Meteorological Society, January 11-15, 2009, Phoenix, Arizona.

26. Environmental Protection Agency Hearing AMS-FRL-8772-7, California State Motor Vehicle Control Standards; Greenhouse Gas Regulations; Reconsideration of Previous Denial of a Waiver of Preemption, Arlington, Virginia, March 5, 2009.

27. Environmental Protection Agency Hearing: Endangerment and cause or contribute findings for greenhouse gases under the Clean Air Act, Arlington, Virginia, May 18, 2009.

28. Effects of fossil-fuel and biofuel soot on snow, clouds, and climate and a review of methods of solving the climate problem, German NGO consortium, Berlin, Germany, June 19, 2009.

29. The global and regional climate and air pollution health effects of fossil-fuel versus biofuel soot, 13th ETH Conference on Combustion Generated Nanoparticles, Zurich Switzerland, June 22-24, 2009.

30. Review of solutions to global warming, air pollution, and energy security, Aerosol Impacts on Climate, Energy, and the Economy, Goldschmidt 2009, Challenges to Our Volatile Planet, Davos, Switzerland, June 22-26, 2009.

31. A plan for a sustainable future, Council of Scientific Society Presidents, Washington D.C., December 3, 2009.

32. Effects of local CO_2 domes on air pollution and health, Clean Power, Health Communities Conference, Oakland, California, February 10, 2010.

33. Ranking of energy solutions to global warming, air pollution, and energy security, Ted Conference Debate with Stewart Brand, Long Beach, California, February 11, 2010.

34. A plan for a sustainable future, GeoPower America, San Francisco, California, Febreuary 16, 2010.

35. A plan for a sustainable future, Beyond Zero, Melbourne, Australia, February 21, 2010 (internet presentation).

36. A plan for a sustainable future, European Forum for Renewable Energy Sources, European Parliament Building, Brussels, Belgium, March 22, 2010.

37. A plan for a sustainable future, Press and Information Office of the Federal Government, Berlin, Germany, March 23, 2010.

38. A plan for a sustainable future, Bundestag, German Parliament Building, Berlin, Germany, March 23, 2010.

39. Presentation at 10-year anniversary for Renewable Energy Sources Act (EEG), Berlin, Germany, March 25, 2010.

40. A plan for a sustainable future using wind, water, and sun, Clean Air Forum 2010, Sydney, Australia, August 19, 2010.

41. California Air Pollution Control Officer Association's (CAPCOA's) Climate Change Forum, San Francisco, California, August 30-31, 2010.

42. 29th Annual Conference, American Association for Aerosol Research, Aerosol contribution to global warming, Arctic ice loss, and air pollution mortality and how to control it through large-scale renewable energy, Portland, Oregon, Oct. 25-29, 2010.

43. Conversion to 100% Wind, Water, and Sun, Sustainable Living Foundation, Melbourne, Australia, February 16, 2011 (via internet).

44. A plan for a sustainable future using wind, water, and sun, The Minerals, Metals, and Materials Society (TMS) Annual Meeting, San Diego, California, February 28, 2010.

45. Steering into the Storm, a Sustainability Event at the Richard Ivey School of Business, University of Western Ontario, Ontario, Canada, March 9, 2010.

46. Powering the world with wind, water, and sunlight, Singularity University Summer Program, NASA Ames Research Center, Mountain View, California, July 8, 2011.

47. A plan for a sustainable future using wind, water, and the sun, Green tech for a sustainable future with focus on smart grid, Swedish Institute & Consulate General of Sweden, Stanford, California, November 2, 2011.

48. A plan for a sustainable future using wind, water, and the sun, HEAL Utah, Salt Lake City, Utah, November 15, 2011. (link)

49. A plan for a sustainable future using wind, water, and the sun, dasHAUS, German American Chamber of Commerce, San Francisco, California, February 24, 2012.

50. A plan for a sustainable future using wind, water, and the sun, Advancing Renewables in the Midwest, Columbia, Missouri, March 26, 2012. (link)

51. A plan to power the world with wind, water, and sun, 62nd Annual Kansas University Environmental Engineering Conference, Lawrence, KS, April 18, 2012.

52. How to power New York, the U.S., and the world with wind, water, and sunlight, Barnfest, Catskills Mountains, New York, July 14, 2012. (link)

53. The case for a fully renewable, all-purpose energy system, Post Carbon Toronto/Citizen's Climate Lobby, University of Toronto, October 15, 2012. (link)

54. Planning for a sustainable future with wind, water, and the sun, Renewable Energy Conference, Selkirk College, British Columbia, October 26, 2012. (link)

55. Addressing global warming, air pollution, and energy security with wind, water, and sunlight worldwide, in the U.S., and in New York State, Inaugural lecture, Schwartz Center for Economic Policy Analysis speaker series, New School Department of Economics, New York City, New York, November 15, 2012. (video)

56. The Future of Energy, Panel discussion, Mark Z. Jacobson, Peter Byck, John Hoffmeister, moderated by Eve Troeh, IMAX theatre, Arizona State University, January 24, 2013. (link)

57. Clean energy plans for the U.S. and individual states, Presentation to politicians, business people, philanthropists, and journalists, including Sen. John Kerry, Sen Kirsten Gillibrand, Chris Matthews, Washington, D.C., February 27, 2013.

58. Powering the world, the U.S., and individual states with wind, water, and sunlight, Yale Climate and Energy Congress Annual Symposium, Yale University, New Haven, Connecticut, February 7, 2013. (link)

59. Powering individual states, the U.S., and the world with wind, water, and sunlight, Mid-America PEV Exchange, March 12, 2013.

60. Powering the world, U.S. and individual states for all purpose with wind, water, and sunlight, presentation at the White House to the Deputy Assistant to the President for Energy and Climate Change, Washington, D.C., April 2, 2013.

61. Powering the world, U.S., and individual states for all purposes with wind, water, and sun, American Meteorological Society Washington Forum, Washington, D.C., April 2, 2013. (link)

62. A plan to power the world for all purposes with wind, water, and the sun, Renewables – from vision to value, St. Gallen Forum for Management of Renewable Energies, St. Gallen, Switzerland, May 23-24, 2013. (link)

63. Roadmaps to power California and the world with wind, water, and the sun, Next 10 Forum, Napa Valley, California, June 12, 2013.

64. Powering New York with wind, water, and sunlight, New York crossroads event, Albany, New York, June 17, 2013. (link)

65. The effects of aircraft on climate and pollution, 165th Faraday Discussion meeting, Royal Society of Chemistry, Aerosols - Formation, Transformation, Fate and Impacts, Leeds, UK, July 22-24, 2013 (pdf)

66. Roadmaps for powering California, the U.S., and the world for all purposes with wind, water, and sunlight, California Energy Commission, Sacramento, California, August 5, 2013.

67. Interview, Late Show With David Letterman, New York City, October 9, 2013 (video)

68. Acceptance speech, Global Green Awards, New York City, December 3, 2013 (link)

69. 50-State plans for powering the U.S. with wind, water, and solar power for all purposes, Distinguished Speaker Series, University of Colorado, Boulder, February 20, 2014 (video)

70. Roadmaps for transitioning Washington State and all other 49 U.S. states to wind, water, and solar power for all purposes, Solutions Project, New York City, March 13, 2014.

71. Plans to convert California and the other 49 states to Wind, Water, and Solar Power, Keynote speaker, 24th Annual Clean Air Awards, San Francisco, California, April 24, 2014 (link)

72. A roadmap for transitioning California to wind, water, and solar power for all purposes, Dirty Energy/Clean Solutions conference, 350.org, San Francisco, California, May 9, 2014. (video)

73. Roadmaps for transitioning all 50 U.S. states to wind, water, and solar power for all purposes, Inaugural lecture in Prof. Michio Yanai lecture series, Department of Atmospheric Sciences, University of California at Los Angeles, May 7, 2014.

74. Roadmaps for transitioning Washington State and all other 49 U.S. states to wind, water, and solar power for all purposes, Daniel L. and Irma Evans Lecture, Department of Civil and Environmental Engineering, University of Washington, May 15, 2014 (link)

75. Roadmaps for transitioning all 50 U.S. states to wind, water, and solar power for all purposes, North American Student Energy Summit (NASES), Columbia University, New York City, New York, June 20, 2014 (link)

76. Roadmaps for transitioning the U.S. to wind, water, and solar power for all purpose, Presentation to the Vice President of the United States, Mr. Joe Biden, Washington, D.C., August 27, 2014.

77. Roadmaps for transitioning the U.S. to wind, water, and solar power for all purpose, The Economics of Sustainability Conference, San Francisco, California, October 8, 2014 (link)

78. Roadmaps for transitioning all 50 U.S. states to wind, water, and solar power for all purposes, Meeting the renewable energy challenge symposium, University of Iowa, October 16, 2014 (link)

79. Roadmaps for transitioning California to wind, water, and solar power for all purpose, Presentation to the Governor Brown's Staff, Sacramento, California October 27, 2014

80. Roadmaps for transitioning California to wind, water, and solar power for all purpose, VERGE, Palace Hotel, San Francisco, California, October 30, 2014 (video)

81. Roadmaps for transitioning the world to wind, water, and solar power for all purposes, Open Caucus, Senate of Canada, Ottawa, Canada, November 26, 2014 (audio)

82. Roadmaps for transitioning Washington State to wind, water, and solar power for all purpose, Presentation to the Governor Inslee's Staff, Olympia, Washington, December 1, 2014 (presented remotely)

83. Roadmaps for transitioning California to wind, water, and solar power for all purpose, 15th National Conference and Global Forum on Science, Policy, and the Environment, Washington, D.C., January 27, 2015 (link)

84. America can, and should, be powered by 100% renewable energy by 2050, Greentech Media debate, February 20, 2015 (link)

85. Bioethics Forum XIII: The great New York Power shift, Andy Revkin, moderator, Pace University, Pleasantville, New York, March 12, 2015 (presented remotely) (link)

86. Roadmaps for transitioning all 50 United States to wind, water, and solar power for all purposes, 6th Annual Dean's Lecture and Awards Ceremony, Physicians for Social Responsibility and the University of South Florida, Tampa, Florida, March 19, 2015 (link)

87. Wind, water, and solar power: Roadmaps to new energy future, William Issa Endowment Lecture, Siena Heights University, Adrian, Michigan, April 15, 2015 (video)

88. Roadmaps for transitioning states and countries to 100% wind, water, and solar power for all purposes, Pecha Kucha talk, Renewable cities conference, Vancouver, British Columbia, May 13, 2015 (video)

89. Roadmaps for transitioning all 50 U.S. states and 139 countries to wind, water, and solar power for all purposes, Cleantech Global Showcase 15, Los Angeles, California, October 21, 2015 (link)

90. Testimony on powering the United States 100% with wind, water, and solar, U.S. House of Representatives, Energy and Commerce Committee, Washington, D.C., November 19, 2015 (schedule) (written testimony)

91. 100% WWS plans for countries and states, UN Foundation Earth to Paris Social Good Event, UNFCC, Petit Palais, Paris, France, December 7, 2015 (link)

92. Blueprint for a carbon-free America, California State Board of Food and Agriculture, Sacramento, California, January 5, 2016 (presented remotely) (link)

93. Roadmaps for transitioning all 50 U.S. states and 139 countries to wind, water, and solar power for all purposes, 3rd Annual Symposium of Trottier Institute for Sustainability in Engineering & Design, McGill University, Montreal, Canada, March 9, 2016 video)

94. 100% Clean, renewable wind, water, and solar (WWS) roadmaps for the 50 United States and 139 countries of the world, Eastern Regional Climate Preparedness Conference, Antioch University/Environmental Protection Agency, Baltimore, Maryland, April 5, 2016 (link)

95. Roadmaps for transitioning all 50 U.S. states and 139 countries to wind, water, and solar power for all purposes, Sustainability Conference, Saint Louis University, St. Louis, Missouri, April 13, 2016 (link)

96. Distinguished Climate Lectures, Powering the Earth with 100% wind, water, and sunlight (WWS) for all purposes, von Karman Earth week lecture, Center for Climate Sciences, Jet

Propulsion Laboratory, Pasadena, California, April 18, 2016 (link)

97. Roadmaps for transitioning all 50 U.S. states and 139 countries to wind, water, and solar power for all purposes, Implementing COP21 Event Atlanta, Cleantech Open, Georgia Institute of Technology, Atlanta, Georgia, May 4, 2016 (link)

98. Transitioning the energy economy to wind, water, and solar power, Boundless, San Francisco, California, June 8, 2016.

99. Powering states, countries, and the world with 100% wind, water, and solar power for all purposes, 4th annual energy and sustainability summit, Oracle Corporation, Redwood City, California, June 30, 2016 (link)

100. Roadmaps for transitioning all 50 U.S. states and 139 countries to wind, water, and solar power for all purposes, University of Michigan Energy Institute, Ann Arbor, Michigan, September 26, 2016 (video)

101. Transitioning each country's all-purpose energy to electricity powered by wind, water, and sunlight, Distinguished Lecture Series, University of Delaware, Newark, Delaware, November 16, 2016 (video)

102. Transitioning the world to 100% wind, water, and solar for all purposes, University of British Columbia, Vancouver, British Columbia, Canada, January 30, 2017 (announcement)

103. Transitioning the energy infrastructures of states and countries to 100% wind, water, and solar for all purposes, North Carolina Climate Conference, February 4, 2017 (presented remotely).

104. How to go to 100% wind, water, solar with a stable grid at low cost 100% of the time with no coal, oil, gas, or nuclear, University of Houston, February 15, 2017 (video)

105. Realizing the 100% wind-water-solar (WWS) era, New York Climate Conference, New York University, New York City, New York, March 11, 2017.

106. 100% Renewable plan for Maryland, the 50 U.S. states, and the world, Rural America Responds to Climate Change, Easton, Maryland, April 1, 2017 (presented remotely).

107. Transitioning States and Countries to 100% Clean, Renewable Energy for all Purposes, NOAA Climate Stewards Education Project, webinar, August 7, 2017 (video)

108. Transitioning the world to 100% clean, renewable energy, CITVN/Global Ethics webinar, October 10, 2017.

109. Transitioning the world to 100% wind, water, and solar for all purposes, Fall for the Book Festival, George Mason University, Fairfax, Virginia, October 11, 2017. (link)

110. The World If? The Economist Energy Summit, London, UK, November 28, 2017 (link)

111. Transitioning countries, states, and cities to 100% clean, renewable energy for all purposes as fast as possible, Praxis Peace Institute, Sonoma, California, January 4, 2018 (link)

112. Moving the Bay Area to 100% renewable energy, Climate Reality, San Francisco, California, February 25, 2018 (video)

113. Transitioning countries, states, cities, and towns to 100% clean, renewable energy for all purposes, MIT Energy Conference 2018, March 2, 2018 (link)

114. Transitioning world energy for all purposes to stable electricity powered by 100% wind, water, and sunlight, 255th American Chemical Society Annual Meeting, New Orleans, Louisiana, March 18, 2018 (link)

115. Transitioning to clean, renewable energy for all purposes, Medical Society Consortium on Climate and Health Conference, Arlington, Virginia, April 9, 2018 (link)

116. Transitioning world energy for all purposes to stable electricity powered by 100% wind, water, and sunlight, Inaugural speaker for MS in Energy Systems Management Program, University of San Francisco, April 16, 2018 (link)

117. Transitioning homes, businesses, towns, cities, states, countries, and the world to 100% clean, renewable energy, Saratoga Rise Club Engineering a Greener World speaker event, Saratoga High School, Saratoga, California, May 18, 2018 (link)

118. Transitioning homes, cities, states, and countries to 100% clean, renewable energy for all purposes as fast as possible, Foothill College, Los Altos Hills, California, May 31, 2018. (link)

119. Transitioning buildings, cities, and countries to 100% clean, renewable energy for all purposes worldwide, Building Lasting Change 2018 Conference, Canadian Green Building Council, Toronto, Canada, June 7, 2018 (link)

120. Food and Water Watch telephone press conference on report ranking states on their renewable portfolio standards, Washington, D.C. July 24, 2018 (connected remotely) (link)

121. Getting to 100% clean, renewable energy: A roadmap to transition homes, cities, countries, and the world, Gideon Rosenbluth Memorial Lecture, Economics Department, University of British Columbia / Canadian Center for Policy Alternatives, Vancouver, Canada, October 25, 2018 (video)(pptx)

122. Transitioning buildings, cities, states, and countries to 100% clean, renewable energy for all purposes, People's Action for Clean Energy, Hartford, Connecticut, November 8, 2018 (video)

123. Transitioning towns, cities, and countries to 100% clean, renewable energy for all purposes, 4th International Conference on Smart Energy Systems and 4th Generation District Heating, Aalborg, Denmark, November 13-14, 2018 (link)(video)

124. Transitioning buildings, cities, and countries to 100% clean, renewable energy for all purposes, American Geophysical Union Annual Meeting, Washington DC, December 10-14, 2018 (link)

125. Press conference on the bailout of nuclear reactors in New York State, with Alec Baldwin, Greg Jaczko, Mark Cooper, and Joseph Magnano, Radiation and public health project, April 23, 2019 (link)

126. Why transitioning New York and the U.S. to 100% clean, renewable energy, like the Green New Deal calls for, saves money, lives, and jobs, Earth Week Expo, Jamaica, New York, April 27, 2019.

127. Transitioning countries and cities to 100% clean, renewable wind, water, and solar energy and storage for everything, Solar Canada 2019, Calgary, Canada, May 8, 2019 (presented remotely) (link)

128. Conversations about landscape: Deal or no (green new) deal, Exploratorium, San Francisco, California, May 13, 2019 (link)

129. St. Gallen Forum for Management of Renewable Energies, St. Gallen, Switzerland, May 23, 2019 (link)

130. Transitioning world energy for all purposes to stahle electricity powered by wind, water, and sun, American Society of Mass Spectrometry, Atlanta Georgia, June 2, 2019 (video)

131. Transitioning states, countries, cities, towns, and homes to 100% clean, renewable energy and storage for everything, Green Tech conference, Newburgh, New York, June 18, 2019 (presented remotely)

132. Transitioning Italy and the World to 100% Clean, Renewable Energy and Storage for Everything, Bergamo Science Festival, Padua, Italy, October 5, 2019 (video)

133. Transitioning the U.S. and the world to 100% clean, renewable energy and storage for everything, Democratic 21st Century Club, Mountain View, California, October 11, 2019

134. Bay Area Home Electrification Expo, San Jose, California, October 12, 2019

135. The present and future of global renewable energy, 2019 Global Showference, Korea Business News, Seoul, South Korea, October 15, 2019

136. 2019 Festival Albertine, New York City, New York, November 8-10, 2019 (video)

137. Transitioning the world to 100% clean, renewable energy and storage for everything. Mining Watch, Canada, Ottawa, Canada, November 14, 2019 (presented remotely) (slides)

138. Impact of Green New Deal plans on costs, jobs, health, and climate in the United States and 143 countries, Central Coast Bioneers, San Luis Obispo, California, February 1, 2020 (presented remotely) (link)

139. Politics, ethics, and economics of decarbonization policy, Rensselaer Polytechnic Institute, Troy, New York, March 5, 2020 (link)

140. Green New Deal Roadmaps for 143 Countries, Vinci (G. Bazouin) Paris, France, May 20, 2020 (presented remotely) (video)

141. Green New Deal Roadmaps for 143 Countries, 10th International 100% renewable energy conference (IRENEC), Istanbul, Turkey, June 4, 2020 (presented remotely) (link)

142. A Green New Deal for the U.S. and World, A Green Future: Race: Gender: Environment, Online Virtual Workshop by Heidi Hutner and Dennis Yerry, July 14, 2020 (presented remotely) (video)

143. 100% clean, renewable energy and storage for everything, Better Path Coalition webinar, Pennsylvania, July 15, 2020 (presented remotely) (video)

144. 100% clean, renewable energy and storage for everything, Our Changing Planet Series Event, North County Climate Change Alliance, California, August 13, 2020 (presented remotely) (video)

145. Green New Deals to address economic growth and climate change, 1st Global Emerging Network in Economy Forum, Jeonju, Jeollabuk, South Korea, September 1, 2020 (presented remotely).

146. Impacts of 100% wind-water-solar roadmaps for cities, states, and countries on grid stability, costs, jobs, health, and climate, Mobilize California, Sacramento, California, September 9, 2020 (presented remotely).

147. Impacts of 100% wind-water-solar roadmaps for the United States on grid stability, costs, jobs, health, and climate, National Renewable Energy Laboratory (NREL) On Demand Webinar: Wind Workforce Development, September 15, 2020 (presented remotely) (link)

148. Climate Emergency Mobilization Summit, September 25, 2020 (presented remotely) (link)

149. Data needs for transitioning the world to 100% clean, renewable energy and storage for everything. Inter-American Development Bank (IADB), September 28, 2020 (presented remotely) (link)

150. Transitioning the world to 100% clean, renewable energy, and how the U.S. election will affect the transition, Australian National University's 2020 annual Solar Oration, Canberra, ACT, November 16, 2020 (presented remotely) (video)

151. Webinar on textbook, 100% Clean, Renewable Energy and Storage for Everything, Stanford, California (presented remotely) (video)

152. How 100% clean, renewable energy and storage for everything can address global warming, air pollution, and energy insecurity, 10th Annual Empowering Capable Climate Communicators (ECCC) virtual symposium, CLEO Institute, Miami, Florida, November 21, 2020 (presented remotely) (video)

153. Wind energy and how it relates to the 100% renewable energy transition, General Electric Renewables Coffee Talk, February 19, 2021 (presented remotely).

154. 100% clean, renewable energy and storage for everything, Institute for Global Environmental Strategies (IGES), Hayama, Japan, April 12, 2021 (presented remotely)

155. Decarbonizing the energy system, European Parliament, Committee on Industry, Research, and Energy, April 13, 2021 (presented remotely) (link)

156. California Climate Action Summit, Opening remarks to students, CALPIRG, April 22, 2021 (presented remotely) (link)

157. Night with the experts, Nuclear energy information service (NEIS), April 29, 2021 (presented remotely) (video)

158. 100% Renewables for everything, EWG Network, Clubhouse, May 3, 2021 (presented remotely). (presented remotely) (link)

159. Transitioning all world energy for all purposes to 100% Wind-Water-Solar (WWS) and storage, Energy Oceania Conference, May 8, 2021 (presented remotely) (link)

160. 100% clean, renewable energy and storage for everything, Google Fireside Chat, Mountain View, California, May 17, 2021 (presented remotely)

161. How city and local governments and individuals can help in the transition to 100% clean, renewable energy, IRENEC2021, Istanbul, Turkey, May 20, 2021 (presented remotely) (video)

162. Why carbon capture and direct air capture cause more damage than good, Climate Cafes of Aberdeen Climate Action, Aberdeen, Scotland, June 1, 2021 (presented remotely) (video)

163. Transitioning Florida and the U.S. to 100% clean, renewable energy and storage for everything, Educational Webinar, Environment Florida, June 15, 2021 (presented remotely) (video)

164. Transitioning California, the U.S., and the world to 100% clean, renewable energy and storage for everything, Climate Reality Project, June 21, 2021 (presented remotely) (video)

165. Can Chile transition to 100% clean, renewable energy and storage for everything? Chilean Concentrated Solar Power Association, June 24, 2021 (presented remotely) (video)

166. Calgary Climate Hub, August 3, 202121 (presented remotely) (video)

167. 100% clean, renewable energy and storage for everything, Get off the Grid, Chattanooga, Tennessee, August 21, 2021 (link)

168. 1How green is blue hydrogen, Clean Energy Group, September 7, 2021 (video)

169. Blue versus gray hydrogen, Equity Research Department, Citigroup, September 9, 2021

170. Transitioning Italy and the world to 100% clean, renewable energy and storage for everything, 9th SISC Annual Conference on Accelerating Climate Action: A just transition in a post-Covid era, Societa Italiana per le Scienze del Clima (SISC), Venice, Italy, September 22, 2021

171. Transitioning Spain and the world to 100% clean, renewable energy and storage for everything, 2nd International Congress of the Industry for the Ecological Transition, Pamplona, Navarre, Spain, October 6-7, 2021Transitioning Spain and the world to 100% clean, renewable energy and storage for everything, 2nd International Congress of the Industry for the Ecological Transition, Pamplona, Navarre, Spain, October 6-7, 2021 (video-Password: STCITE-21)

172. Transitioning the World to 100% clean, renewable energy and storage for everything, 100% renewables is possible, From ambition to reality: Weaving the threads of net-zero delivery, Regione Emilia-Romagna and CNR, International Conference, Italy, October 27, 2021

173. The impacts of transitioning the U.S. to 100% Wind-Water-Solar and storage for everything, National Latino Farmers and Ranchers Trade Association (NLFRTA) Climate Zoom Meeting, October 29, 2021

174. Transitioning the Republic of Korea and the world to 100% clean, renewable energy and storage for everything, Asian Pacific Forum on Renewable Energy (AFORE), Jeju, Republic of Korea, November 1, 2021

175. World Built Environment Forum, RICS, Panel on Beyond net zero 2050-Fossil fuel free by 2050? November 9, 2021 (link)

176. Transitioning the U.S., Japan, and the world to 100% clean, renewable energy for all purposes as fast as possible, Renewable Energy Institute, Japan, December 7, 2021 (video)

177. Briefing of Senator Jeff Merkley (Oregon) on blue versus green hydrogen, Washington, D.C., February 2, 2022 (presented remotely).

178. Briefing of the Montpelier and Hampshire Foundations on the most effective ways to address the climate problem, London and Connecticut, February 9, 2022 (presented remotely).

179. Briefing of Daikin on how HVAC technologies can contribute to carbon neutrality, February 11, 2022 (presented remotely).

180. Transforming the world to 100% clean, renewable energy and storage for everything, 5th Clean Tech Business Club Leadership Forum, Dubai, UAE, March 13, 2022

181. National Emergency Management Association (NEMA) Emergency Management and Policy Mid-Year Forum, Alexandria, Virginia, March 29, 2022.

182. Transitioning the world to 100% clean, renewable energy and storage for everything, Oatmeal Club, Bainbridge Island, Washington, March 31, 2022 (presented remotely).

183. Transitioning the world to 100% clean, renewable energy and storage for everything, Sunnyvale Democratic Party, April 16, 2022 (presented remotely). (video)

184. A solution to global warming, air pollution, and energy insecurity for Canada and 145 countries, National Earth Day Celebration, Canada Revenue Agency, April 21, 2022 (presented remotely).

185. Transitioning Chile and the world to 100% clean, renewable energy and storage for everything, 9th Annual Renewable Energy Summit, Chilean Association for Renewable Energy and Storage (ACERA A.G), May 4, 2022 (presented remotely). (video)

186. Discussion with Biden Administration National Security Council staff member Melanie Nakagawa on how to transition Europe away from natural gas, Food and Water Watch, Sierra Club, May 6, 2022 (presented remotely).

187. Clean energy technology and disinformation, Clean Air Partnership, Bruce Nagy, May 10, 2022 (presented remotely) (video)

188. A solution to global warming, air pollution, and energy security for 145 countries, 7th Thermal and Fluid Engineering Conference, American Society of Thermal and Fluids Engineers (ASTFE), Las Vegas, Nevada, May 16, 2022 (presented remotely).

189. Transitioning the U.S. and the world to 100% clean, renewable energy and storage for everything, Bonneville Power Administration, June 6, 2022 (presented remotely).

190. A solution to global warming, air pollution, and energy insecurity for California, all 50 states, and 145 countries, Sequoia Living virtual summit, Bay Area Communities, California, June 29, 2022, (presented remotely).

191. A solution to global warming, air pollution, and energy security for 145 countries, Carbon Tracker, August 2, 2022 (presented remotely).

192. A conversation with Stanford University Professor Mark Jacobson, Webinar, Sierra Club Canada, September 28, 2022 (presented remotely) (video)

193. Debate on whether we need miracle technologies, Financial Times, October 19, 2022 (audio)

194. A Transitioning the world to 100% clean, renewable energy and storage for everything, 8th KAIST Global Strategy Institute International Forum, Seoul, South Korea, November 11, 2022 (presented remotely) (video)

195. A solution to global warming, air pollution, and energy security for the world, Vestas, November 22, 2022 (presented remotely)

196. Transitioning Michigan and the world to 100% clean, renewable energy and storage for everything. Great Lakes Renewable Energy Association Annual Year End Meeting, December 3, 2022 (presented remotely) (video)

197. Keynote speech, Transitioning Nepal and the world to 100% clean, renewable energy and storage for everything, Workshop on Research based education for renewable and sustainable energy development, Nepal, December 6, 2022 (presented remotely)

198. No miracles needed: Low-cost solutions to global warming, air pollution, and energy insecurity for 145 countries, World Affairs Council, Peninsula Chapter, Los Altos, California, December 7, 2022 (link)

199. . Distinguished speaker, Transitioning Vietnam and the world to 100% clean, renewable energy and storage for everything, Energy transition – green life design, Vin Future Prize Foundation, Hanoi, Vietnam, December 17, 2022 (video)

200. Transitioning Pennsylvania and the world to 100% clean, renewable energy and storage for everything, Climate Reality Project, Pennsylvania Chapters Coalition, January 19, 2023 (presented remotely) (video)

201. Media interview for Professor Mark Z. Jacobson, Greenpeace Taiwan, January 11, 2023 (presented remotely)

202. Transitioning the U.S. and world entirely to 100% clean, renewable energy and storage at low cost for all purposes, MIT Alumni for Climate Action webinar, February 1, 2023 (presented remotely) (video)

Other Invited Talks at Conferences / Workshops Since 1994

1. Simulating the sensitivity of trace gas concentrations to hydrocarbon emissions. American Geophysical Union 1994 Fall Meeting, San Francisco, California, December 5-9, 1994.

2. Application of a sparse-matrix, vectorized Gear-type code (SMVGEAR) in a new air pollution modeling system, Symposium on Numerical Algorithms for Air Pollution Models in the Third International Congress on Industrial and Applied Mathematics (ICIAM), Hamburg, Germany, July 3-7, 1995.

3. Chemical mechanism solver techniques and implementation of mechanism, Workshop on Modeling Chemistry in Clouds and Mesoscale Models, National Center for Atmospheric

Research, March 6-8, 2000.

4. Development of a global-through-urban scale nested and coupled air pollution and weather forecast model and application to the SARMAP field campaign, Institute for Mathematics and its Applications Annual Program, Reactive flow and Transport Phenomena, U. of Minnesota, March 15-19, 2000.

5. A study of the climate response to natural plus anthropogenic aerosols, Telluride Atmospheric Chemistry Meeting, Telluride, Colorado, August 7-11, 2000.

6. A study of the mixing state of aerosols and the effect of the mixing state on global direct forcing, Workshop on Atmospheric Composition, Biogeochemical Cycles and Climate Change, Aspen Global Change Institute, Aspen, Colorado, August 11-19, 2000.

7. A global-through-urban scale air pollution, weather forecast model and application to the SARMAP field campaign, Workshop on Atmospheric Composition, Biogeochemical Cycles and Climate Change, Aspen Global Change Institute, Aspen, Colorado, August 11-19, 2000.

8. Control of black carbon, the most effective means of slowing global warming, International Conference on Computational Science (ICCS), San Francisco, California, May 28-30, 2001.

9. Control of fossil-fuel particulate black carbon and organic matter, the most effective method slowing global warming, CIESIN/USEPA//Environment Canada workshop, Photoxidants, Particles, and Haze across the Arctic and North Atlantic: Transport, Observations, and Models, Palisades, New York, June 12-15, 2001.

10. Climate change mitigation and aerosols, Climate Change Impacts and Integrated Assessment Workshop VII, Snowmass, CO, July 30 - Aug. 10, 2001.

11. Controlling current and future diesel emissions and other sources of fossil-fuel particulate black carbon and organic matter as an effective method of slowing global warming, Air Pollution as a Climate Forcing Workshop, East-West Center, Hawaii, April 29-May 3, 2002.

12. Addressing air quality and climate through soot control, Regional Workshop on Better Air Quality in Asia and Pacific Rim Cities 2002, Hong Kong, December 16-18, 2002.

13. Global warming impact of black carbon, Greenhouse Gas Reduction International Technology Symposium, California Air Resources Board, Sacramento, California, March 11-13, 2003.

14. Climate and air pollution effects of gasoline, hybrid, and diesel vehicles (with and without a trap), Haagen-Smit Symposium, California Air Resources Board, Lake Arrowhead, California, May 6-9, 2003.

15. Causes of and Solutions to Global Warming, American Enterprise Institute Conference on Climate Change, Washington D.C., November 19, 2003.

16. Net climate effects of BC and OC 2: Consideration of multiple climatic effects. Air Quality and Climate Meeting on Black Carbon and Organic Carbon: Science, Inventory and Mitigation, U.S. EPA Office of Air Quality Planning and Standards and Office of Atmospheric Programs, Washington, D.C., December 3-4, 2003.

17. The effect of diesel on air pollution and global climate, Workshop on cruise ship operations, Cruise Terminal Environmental Advisory Committee Meeting, Port of San Francisco, San Francisco, California, January 23, 2004.

18. Black carbon effects on global warming and regional climate change, American Association for the Advancement of Science (AAAS) Annual Meeting, Seattle, Washington, February 12-16, 2004.

19. Numerical methods for treating size-resolved SOA formation and evolution among multiple size distributions in atmospheric models, Organic Speciation in Atmospheric Aerosol Research, Las Vegas, Nevada, April 5-7, 2004.

20. Black Carbon Effects on Climate with Different Emissions and Model Treatments, Aerosol Black Carbon and Climate Change: Emissions Workshop, San Diego, California, October 13-14, 2004.

21. The effect of particles on global and California climate, Interncontinental Transport and Climate Effects of Air Pollutants Workshop, Chapel Hill, NC, October 21-22, 2004.

22. The effects of aerosols on California climate, MODIS Science Team Meeting, Baltimore, Maryland, March 22-24, 2005.

23. Regional effect of aerosols on winds, precipitation, and climate, 8th International conference of the Israel Society of Ecology and Environmental Quality Sciences, Weizmann Institute of Science, Rehovot, Israel, May 30-June 1, 2005.

24. Global windpower and its potential effect on the hydrogen economy, 8th International conference of the Israel Society of Ecology and Environmental Quality Sciences, Weizmann Institute of Science, Rehovot, Israel, May 30-June 1, 2005.

25. Role of aerosols in regional climate: A research frontier, Second Annual Climate Change Research Conference, California Energy Commission and First Scientific Conference, West Coast Governor's Global Warming Initiative, Sacramento, California, Sept. 14-16, 2005.

26. Apollo Project for Wind Energy and Wind-Hydrogen, J.P. Morgan Public Power and Gas Conference, New York, May 11-12, 2005.

27. The effects of aerosols on wind speed, temperatures, and water supply in California, Atmospheric Chemistry Workshop, Telluride, Colorado, July 30-August 6, 2006.

28. Numerical study of the effects of aerosols and irrigation on snow, rain, and regional climate in California, California Energy Commission, Sept. 13-15, 2006.

29. Effects of future emissions and a changed climate on urban air quality, Environmental Protection Agency, Research Triangle Park, NC, February 20-22, 2007.

30. Effects of black carbon on climate. Symposium on protecting health and slowing global warming through reductions in non-Kyoto pollutants, Sacramento, California, March 29, 2007.

31. The Macro Perspective of Wind Power in the USA, From Local to Global: The Rhode Island Model for Harnessing Wind Power Worldwide, Roger Williams University School of Architecture, Art and Historic Preservation, April 19-20, 2007.

32. Comparing wind and other energy sources for addressing climate and air pollution, From Local to Global: The Rhode Island Model for Harnessing Wind Power Worldwide, Roger Williams University School of Architecture, Art and Historic Preservation, April 19-20, 2007.

33. Wind and rainfall reduction by aerosol particles, Aerosols - properties, processes, climate, Agapi Beach, Crete, April 22-24, 2007.

34. Potential of the wind energy sector, The Haagen-Smit Symposium, Aptos, California, May 14-17, 2007.

35. Extreme global warming and local cooling due to aerosol particles, American Geophysical Union Spring Joint Assembly, Acapulco, Mexico, May 22-25, 2007.

36. Comparative effects of vehicle fuels and technologies on air pollution and climate, Controlling Global Warming and Local Air Pollution - South Coast Air Quality Management District Technical Forum, Diamond Bar, California, June 28, 2007.

37. Effects of black carbon and other non-Kyoto pollutants on climate, Meeting of the California Air Resources Board Economic and Technology Advancement Advisory Committee (ETAAC), Bechtel Conference Center, Stanford University, September 7, 2007.

38. Energy solutions to air pollution and climate change in California (coauthors, M. Dvorak, C.L. Archer, and G. Hoste), Fourth Annual California Climate Change Conference, California Energy Commission, Sacramento, California, Sept. 10-13, 2007.

39. Effects of future emissions and a changed climate on urban air quality, Impacts of Climate Change on Air Quality in the Pacific Southwest, Environmental Protection Agency, San Francisco, California, October 11, 2007.

40. Examination of proposed strategies for addressing global warming and air pollution. Forum on Alternative Fuels for the Transportation Sector, California State Bar Association, Yosemite, California, Oct. 19-21, 2007.

41. Comparative effects of vehicle technologies and fuels on climate and air pollution. On the Road to Bali: Strengthening the Transatlantic Climate Cooperation, German Academic Exchange Service (DAAD) and the Heinrich Boell Foundation, San Francisco, California, Nov. 16, 2007.

42. The effects on health and climate of ethanol versus other vehicle technologies and fuels, Institute of Medicine’s Roundtable on Environmental Health, Sciences, Research, and Medicine workshop on Environmental Health, Energy, and Transportation: Bringing Health to the Fuel Mixture, National Academies Auditorium, Washington, D.C., Nov. 30, 2007.

43. A solution to the problem of nonequilibrium acid/base gas-particle transfer at long time step. International Aerosol Modeling Algorithms (IAMA) Conference, Davis, California, Dec. 6, 2007.

44. Comparative effects of ethanol (E85), gasoline, and wind-powered electric vehicles on cancer, mortality, climate-relevant emissions, and land requirements in the United States, American Geophysical Union Fall Meeting, San Francisco, California, Dec. 10-14, 2007.

45. Energy and Climate Change Symposium – “The Road to Renewables,” Australian Government Department of Foreign Affairs and Trade, Los Angeles, California, Jan. 18, 2008.

46. Examining the effects of aircraft emissions on contrails and global climate, FAA/PARTNER Meeting, Ottawa, Canada, Mar. 25-26, 2008.

47. Effects of local versus global carbon dioxide emissions on local air quality and health, Environmental Protection Agency Division 9 symposium, Stanford University, Stanford, California, May 6, 2008.

48. The effects of ethanol vehicles on air quality and health, Frontiers Meeting on the Co-Benefits of Climate Change Mitigation, Wellcome Trust, London, May 27, 2008 (connected remotely).

49. Air pollution effects of and a comparison of energy solutions to global warming, Critical Review panel, Air & Waste Management Association Annual Meeting, Portland, Oregon, June 25, 2008.

50. Examining the effects of aircraft emissions on contrails and global climate, FAA/PARTNER Meeting, Chicago, Illinois, Oct. 22-23, 2008.

51. Evaluation of proposed solutions to global warming, air pollution, and energy security, Session on Environmental Consequences of the Changing Global Food System, American Geophysical Union Fall Meeting, San Francisco, California, Dec. 15-19, 2008.

52. Examining effects of black carbon on climate and how to mitigate them through different transportation options, International Council on Clean Transportation, London, UK, Jan. 5-6, 2009.

53. Examining the effects of aircraft emissions on contrails and global climate, FAA/PARTNER Meeting, Palm Springs, California, Feb. 26-27, 2008.

54. Effects of hydrogen on climate and ozone, Department of Energy, Washington, DC, May 19, 2009.

55. Quantifying the effects of aircraft on climate with a model that treats the subgrid evolution of contrails from all commercial flights worldwide, Aviation Emissions Characterization Roadmap Meeting, Washington, DC, June 9, 2009.

56. Review of energy solutions to global warming, air pollution, and energy security, Microsoft Research Workshop, Redmond, Washington, July 13, 2009.

57. The comparative effects of fossil fuel soot, biofuel soot, and gasses, and methane on regional and global climate, Arctic ice, and human health, 6th Annual PIER Climate Change Conference, California Energy Commission, Sacramento, California, Sept. 9, 2009.

58. Solutions to global warming, air pollution, energy security, The true costs of coal: Health solutions for the low carbon economy, Washington DC, October 15-16, 2009.

59. Assessing the impact of aviation on climate, FAA/PARTNER Meeting, Atlanta, Georgia, Oct. 22, 2009.

60. Effects of soot on climate, National Association of Clean Air Agencies, Internet conference, November 17, 2009.

61. Development and application of algorithms that simulate the evolution of subgrid contrails from individual aircraft to quantify the global climate effects all commercial aviation, (Jacobson, M.Z., J.T. Wilkerson, A.D. Naiman, S.K. Lele), International Aerosol Modeling Algorithms (IAMA) Conference, Davis, California, Dec. 9-11, 2009.

62. Relative effects of fossil-fuel soot, biofuel soot and gases, and methane on climate, Arctic ice, and air pollution health, American Geophysical Union, Fall Meeting, San Francisco, California, Dec. 14-18, 2009.

63. Relative effects of fossil-fuel soot, biofuel soot and gases, and methane on climate, Arctic ice, and air pollution health, Environmental Protection Agency Short-Lived Climate Forcing agent workshop, Chapel Hill, North Carolina, March 3, 2010.

64. Presentation in Brussels at EEAC Energy Working Group: Scenarios and policies for decarbonization, Brussels, Belgium, March 22, 2010.

65. Assessing the impact of aviation on climate, FAA/PARTNER Meeting, Chapel Hill, North Carolina (Internet presentation), March 24, 2010.

66. The enhancement of local air pollution by urban CO2 domes, National Association of Clean Air Agencies, Internet conference, May 12, 2010.

67. A plan for a sustainable future using wind, water, and sun, 7th California Wind Energy Collaborative Forum, Davis, California, June 7, 2010.

68. A plan for a sustainable future using wind, water, and sun, High-altitude wind conference, Stanford University, September 28, 2010.

69. Effects of black carbon and CO2 domes on climate and air quality, EPA STAR Meeting, Research Triangle Park, North Carolina, October 4, 2010.

70. Assessing the impact of aviation on climate, FAA/PARTNER Meeting, Massachusetts Institute of Technology, Boston, October 19-21, 2010.

71. Effects of aircraft on climate and atmospheric composition, ACCRI Meeting, Atlanta, Georgia, November 15-17, 2010.

72. Grid integration challenges for 100% conversion to wind, water, and sun, Grid Integration of Renewable Energy Workshop, Stanford University, Jan. 13, 2011.

73. Dark Aerosol Particle Contributions to Global Warming and Air Pollution Mortality, 3rd Symposium on Aerosol-Cloud-Climate Interactions Symposia, 13th Conference on Atmospheric Chemistry, American Meteorological Society, January 23-27, 2011, Seattle, Washington.

74. Quantifying the effects of aircraft on surface air quality and climate with a model that treats the subgrid evolution of contrails from all commercial flights worldwide (Jacobson, M.Z., D. Whitt, A.D. Naiman, S.K. Lele), FAA-ACCRI Meeting, Atlanta, Georgia, February 22-24, 2011.

75. National Institute of Standards and Technology (NIST), Aerosol Meteorology for Climate Workshop, Gaithersburg, Maryland, March 16, 2012.

76. Coupling cloud and aerosol microphysical processes in a nested climate-weather-air pollution model and its implications for the cloud and climate effects of black carbon, European Geosciences Union, General Assembly, 2011, Vienna, Austria, April 3-8, 2011.

77. Assessing the impact of aviation on climate, FAA/PARTNER Meeting, Washington, D.C., April 12-14, 2011.

78. Powering the world on wind, water, and sun, National Migration Strategies to 100% Renewable Electricity, GreenPower Conferences, London, United Kingdom, June 29, 2011 (connected remotely).

79. Powering the world on wind, water, and sun, Triple Helix IX International Conference, Stanford University, July 12, 2011.

80. Aerosol particle contribution to global warming and air pollution mortality, Session on Atmospheric aerosols: chemistry, clouds and climate, Division of Environmental Chemistry, 242nd American Chemical Society Annual Meeting, Denver, Colorado, Aug. 28-Sept. 1, 2011.

81. The enhancement of local air pollution by urban carbon dioxide domes, Session on urban greenhouse gas emissions, short-lived climate forcers, and public health, 242nd American Chemical Society Annual Meeting, Denver, Colorado, Aug. 28-Sept. 1, 2011.

82. A plan for powering the world with wind, water, and sun, Department of Energy Efficiency and Renewables Advisory Committee (ERAC) Electricity subcommittee meeting, San Mateo, California, September 22, 2011.

83. A plan for powering the world for all purposes with wind, water, and sunlight, The Bottom Line on Climate Change: Transitioning to Renewable Energy, Schwartz Center for Economic Policy Analysis, The New School, New York City, September 24, 2011. (connected remotely)

84. Assessing the impact of aviation on climate, FAA/PARTNER Meeting, Washington, D.C., October 11, 2011.

85. A plan for powering the world with wind, water, and sun, Managing uncertainty: Integrating intermittent renewable energy into the power grid, Resnick Institute Workshop, California Institute of Technology, Pasadena, California, October 12, 2011.

86. Atmospheric effects of proposed solutions to climate change and air pollution, California Air Pollution Control Officer Association's (CAPCOA's) Climate Change Forum, San Diego, California, November 9-10, 2011.

87. A plan for powering the world for all purposes with wind, water, and sunlight, American Geophysical Union Fall Meeting, Session GC54, Climate Change: Challenges and Solutions, San Francisco, California, Dec. 5-9, 2011.

88. Studying the effects of aircraft exhaust on global and regional climate and atmospheric composition, FAA ACCRI meeting, Arlington, Virginia, December 13-15, 2012.

89. A plan for a sustainable future using wind, water, and the sun, The Future of Energy: A power Struggle, One World Forum, 2012, University of Warwick, UK, January 23, 2012. (connected remotely)

90. Examining the effects of aircraft emissions on contrails and global climate, FAA/PARTNER Meeting, Washington, D.C., March 27, 2012 (connected remotely).

91. Powering the world for all purposes with wind, water, and sunlight, Tri-agency (NSF, NASA, NOAA) climate-related education (CEE) programs PI meeting, Arlington, Virginia, April 20,

2012.

92. A plan for powering the world for all purposes with wind, water, and sunlight, World Renewable Energy Council (WREC) World Renewable Energy Forum 2012, Denver, Colorado, May 14, 2012.

93. World saturation wind potential and its implications for a sustainable future relying on wind, water, and sunlight producing electricity and electrolytic hydrogen, World Renewable Energy Council (WREC) World Renewable Energy Forum 2012, Denver, Colorado, May 14, 2012.

94. Testimony at Hearing in front of California Air Resources Board Chairman and Executive Officers on black carbon and methane, Sacramento, California, May 24, 2012. (link)

95. Saturation wind potential and its implications for wind energy (C.L. Archer, coauthor), American Wind Energy Conference (AWEC), Hampton, Virginia, September 11-12, 2012 (connected remotely). (link)

96. Powering the world, U.S., and New York with wind, water, and sunlight (with Mark A. Ruffalo and Marco Krapels), The Nantucket Project, Nantucket, Massachusetts, October 6, 2012. (link) (video)

97. Assessing climate impacts of aviation, FAA/PARTNER meeting, Arlington, Virginia, October 17, 2012.

98. Pushing the envelope with numerical modeling, Workshop on Integrated Meteorology and Chemistry Modeling, U.S. EPA, Research Triangle Park, NC, October 18, 2012 (connected remotely).

99. Planning for a sustainable future with wind, water, and the sun, Bond Buyer's 22nd Annual California Public Finance Conference, San Francisco, California, October 18, 2012. (link)

100. Effects of black and brown carbon on clouds and climate, EPA Region 9 Symposium on black carbon, San Francisco, California, November 14, 2012. (link)

101. How to repower the state of New York with wind, water, and sunlight, National Resources Defense Council, New York City, New York, November 17, 2012.

102. Short-term impacts on climate and air pollution of exhaust from all commercial aircraft worldwide treated at the subgrid scale, Jacobson, M.Z., M.A. Cameron, J.T. Wilkerson, A.D. Naiman, and S.K. Lele, ACCRI Symposium, Virginia Beach, Virginia, November 27-29, 2012. (link)

103. The effects of rerouting aircraft around the Arctic Circle on Arctic and global climate, Jacobson, M.Z., J.T. Wilkerson, S. Balasubramanian, W.W. Cooper, Jr., and N. Mohleji, ACCRI Symposium, Virginia Beach, Virginia, November 27-29, 2012. (link)

104. Taming hurricanes with arrays of offshore wind turbines, Wind energy symposium, University of Delaware, Newark, Delaware, February 27, 2013. (link)

105. Carbon dioxide domes, effects of cross-polar flights, and taming hurricanes with offshore wind, International opportunities in the weather and climate enterprise, American Meteorological Society Washington Forum, Washington, D.C., April 3, 2013.

106. Powering individual states, countries, and the world with WWS, Pathways to 100% Renewable Energy, Renewables100 Policy Institute, San Francisco, California, April 16, 2013. (link)

107. . Powering New York State with Wind, Water, and Sunlight for all purposes, Mount Kisco Public Library, Mount Kisco, New York, May 13, 2013 (connected remotely) (link)

108. Effects of aviation on surface air quality, Aviation Emissions Characterization Roadmap, 11th Meeting of Primary Contributors, Washington, DC, May 14, 2013 (connected remotely).

109. Effects of aviation on global climate, Aviation Emissions Characterization Roadmap, 11th Meeting of Primary Contributors, Washington, DC, May 14, 2013 (connected remotely).

110. Powering individual states and the world with wind, water, and sunlight, Increasing value through thermal energy storage, CSP Today, Las Vegas, Nevada, June 26-27, 2013. (link)

111. Roadmaps for powering the world, U.S., and individual states for all purposes with wind, water, and sunlight, 2013 Gordon Research Conference on Atmospheric Chemistry, Mt. Snow, Vermont, July 29, 2013 (link)

112. Assessing the impact of aviation on climate, FAA/PARTNER Meeting, Fairfax, Virginia, October 16, 2013 (presented remotely).

113. The natural gas goldrush and the future of renewables, Net Impacts Conference, San Jose, California, October 24-26, 2013.

114. Powering the states, the U.S., and world for all purposes with wind, water, and sunlight, Business for Social Responsibility (BSR) Debate: What does a Low-Carbon Energy Economy Look Like? San Francisco, California, November 6, 2013. (link)

115. Powering states and the U.S. with wind, water, and sunlight, California Democratic Party Executive Board Meeting, Environmental Caucus, San Francisco, California, November 23, 2013.

116. Roadmaps for powering the world, U.S., and individual states for all purposes with wind, water, and sunlight, U015. Water, Energy, and Food Security in a Changing World: Finding Solutions Through Integration of Physical and Social Sciences, American Geophysical Union Fall Meeting, San Francisco, California, December 9-13, 2013.

117. Taming hurricanes with arrays of offshore wind turbines that simultaneously reduce global warming and air pollution and provide normal electric power, GC028. Climate Change Adaptation and Mitigation, American Geophysical Union Fall Meeting, San Francisco, California, December 9-13, 2013.

118. Roadmaps for Converting California and the other 49 States to Wind, Water, and Solar (WWS) for all purposes, Solar Circle, Oakland, California, January 30, 2014.

119. Can we run the world's energy on windpower? American Association for the Advancement of Science (AAAS), Chicago, Illinois, February 13-17, 2014. (link)

120. Powering countries, states, and the world with wind, water, and sunlight, TEDx, Palo Alto, California, February 24, 2014 (video)

121. Assessing the impact of aviation on climate, FAA/PARTNER Meeting, Alexandria, Virginia, March 11, 2014 (presented remotely).

122. Plans to change the energy infrastructure of the 50 United States, Factory, San Francisco, California, March 12, 2014.

123. Powering the world with wind, water, and sunlight, Progressive Democrats of America, March 19, 2014 (presented remotely). (link)

124. Roadmaps for transitioning all 50 U.S. states to wind, water, and solar power for all purposes, Climate justice conference of solutions, Wesleyan University, April 12, 2014, Webinar (presented remotely). (link)

125. The effects of cross-polar flights on Arctic black carbon and climate, The Atmosphere Collaboration Team of the Interagency Arctic Research and Policy Committee (IARPC), Black Carbon Webinar II: Arctic Black Carbon Science Activities, April 18, 2014, Webinar (presented remotely). (link)

126. Roadmaps for transitioning U.S. states to wind, water, and solar power for all purposes, American Wind Energy Association Windpower 2014 conference, Las Vegas, Nevada, May 8, 2014.

127. Roadmaps for transitioning all 50 U.S. states to wind, water, and solar power for all purposes, Public pension fund investments and renewable energy forum opportunities and challenges, Oregon Office of the State Treasurer, Pegasus Capital, and R20 Regions of Climate Action, Portland State University, June 5, 2014. (link)

128. Effects of aircraft on atmospheric composition and contrails in 2050, AEC Roadmap, Washington, D.C., June 23, 2014 (presented remotely).

129. White roofs versus changing the energy infrastructure for solving climate and air pollution problems, Asphalt Roofing Association, August 19, 2014 (presented remotely).

130. Mega urban changes and impacts in the decade of the 2000s, NASA land cover land use change webinar, October, 7 2014 (Nghiem, S.V., M.Z. Jacobson et al., presented by Son Nghiem)

131. Studying the effects of aircraft exhaust on global and regional climate, ASCENT Aviation Sustainability Center Advisory Meeting, Alexandria, Virginia, October 14, 2014 (presented remotely).

132. Roadmaps for transitioning all 50 U.S. states to wind, water, and solar power for all purposes, Interfaith Power and Light webinar, October 23, 2014 (presented remotely).

133. Roadmaps for transitioning Pennsylvania and all 50 U.S. states to wind, water, and solar power for all purposes, Pennsylvanians against fracking, December 3, 2014 (presented remotely). (link)

134. Addressing global warming, air pollution, energy security, and jobs with roadmaps for changing the all-purpose energy infrastructure of the 50 United States, American Geophysical Union Fall Meeting, San Francisco, California, December 15-19, 2014.

135. Effects of aircraft on atmospheric composition and climate, FAA AEC Roadmap, Washington, D.C., January 29, 2015 (presented remotely).

136. Roadmaps for transitioning all 50 U.S. states to wind, water, and solar power for all purposes, North Jersey Public Policy Network, Fairleigh Dickinson University, Hackensack, New Jersey, February 19, 2015 (presented remotely) (link).

137. Roadmaps for transitioning states and countries to 100% wind, water, and solar power for all purposes, Global innovation summit, Stanford, California, February 20, 2015.

138. Coupling wind and solar energy systems with feedback to a coupled air pollution, weather, climate, and ocean model, GATOR-GCMOM. CCMM Symposium, World Meteorological Organization, Geneva, February 23-25, 2015 (presented remotely) (link).

139. Studying the effects of aircraft exhaust on global and regional climate, ASCENT Aviation Sustainability Center Advisory Meeting, Alexandria, Virginia, March 10, 2015 (presented remotely).

140. Roadmaps for transitioning states and countries to 100% wind, water, and solar power for all purposes, Zero net energy, San Jose, California, April 23, 2015 (link)

141. Climate justice leadership conference, University of the District of Columbia, Washington, D.C., May 9, 2015 (presented remotely) (link)

142. Transitioning Canada to 100% wind, water, and solar power for all purposes, Renewable cities conference, Vancouver, British Columbia, May 14, 2015 (link)

143. Surface air quality from cruise emissions, FAA AEC Roadmap, Washington, D.C., May 19, 2015 (presented remotely).

144. Commercial and future (2050) contrail impact under efficiency improvements and alternative fuel usage goals, FAA AEC Roadmap, Washington, D.C., May 19, 2015 (presented remotely).

145. Feasibility and implications of moving to a 100% renewable electrical power system in New York and the United States, IBM Research, New York, June 17, 2015 (link)

146. Studying the effects of aircraft exhaust on global and regional climate, ASCENT Aviation Sustainability Center Advisory Meeting, Seattle, Washington, October 14, 2015

147. Powering China, the United States, and 139 countries with 100% wind, water, and solar (WWS) power for all purposes, Energy transformation roundtable discussion, Beijing, China, November 2, 2015 (connected remotely)

148. Black carbon policy briefing: Short-lived climate pollutants, Center for energy efficiency and renewable technologies, Sacramento, California, November 17, 2015 (presented remotely)

149. Talk on 139 country and 50 state plans, Climate Action, Aubervilliers, France, December 5, 2015 (video)

150. 100% WWS plans for countries and states, E2 side event, Grand Palais, Paris, France, December 6, 2015 (schedule)

151. 100% WWS plans for countries and states, Superpublic, Paris, France, December 7, 2015

152. 100% clean, renewable wind, water, and solar roadmaps for 139 countries of the world, American Geophysical Union Fall Meeting, San Francisco, California, December 14-18, 2015

(link)

153. The Solutions Project: Educating the public and policy makers about solutions to global warming, air pollution, and energy security, American Geophysical Union Fall Meeting, San Francisco, California, December 14-18, 2015 (link)

154. 100% Wind, water, solar all-sector energy roadmaps for the 50 States and 139 countries, 100% Renewable Energy NGO Network, January 28, 2016 (presented remotely) (link)

155. Paris and onward, Nuclear Information and Resource Service (NIRS) briefing, February 2, 2016 (presented remotely) (link)

156. Offshore wind for New York City, New York, New York, February 19, 2016 (presented remotely) (link)

157. Webinar Canadian 100% renewable energy groups, March 23, 2016 (presented remotely)

158. 100% wind, water, solar all-sector energy roadmaps for Denton, all 50 states, and 139 countries, 100% Renewable Denton town hall meeting, Denton, Texas, March 25, 2016 (presented remotely) (link)

159. Is 100% clean energy plausible. Environment America conference call and discussion, March 30, 2016 (presented remotely) (link)

160. Community- and city-scale options for transforming energy to 100% wind, water, and solar. Eastern Regional Climate Preparedness Conference, Antioch University/Environmental Protection Agency, Baltimore, Maryland April 5, 2016 (link)

161. Roadmaps for transitioning all 50 United States and 139 countries to wind, water, and solar power for all purposes, Wood Institute retreat, Aptos, California, April 9, 2016.

162. Telephone presentation and press conference on Michigan groups call for 100% renewable energy, Michigan Climate Action Network, May 9, 2016 (presented remotely).

163. Integrated energy policy report workshop: Emerging technologies and approaches, California Energy Commission, Sacramento, California, May 25, 2016 (presented remotely) (link)

164. Transitioning, cities, states, and countries to 100% wind, water, and solar power for all purposes, North American dialogue on 100% renewable energy in cities, San Francisco, California, July 11, 2016 (link)

165. Transitioning to 100% clean, renewable energy, Documentary premiere, “Time to Choose,” Aquarius Theater, Palo Alto, California, July 13, 2016.

166. Can California get to 100 percent clean power, Climate 1, Commonwealth Club, San Francisco, California, August 23, 2016 (podcast)

167. What does it take to power California and the world with 100% clean, renewable energy, Interfaith Power and Light, Los Altos Hills, California, August 28, 2016.

168. Roadmaps for transitioning countries, states, and cities to 100% wind, water, and solar for all purposes, Clif Bar, Emeryville, California, September 14, 2016.

169. Transforming China and the 139 countries to 100% clean, renewable energy for all purposes, Energy System Transformation Workshop, Beijing, China, October 20, 2016 (presented remotely).

170. Transitioning 50 states and 139 countries to 100% clean, renewable energy for all purposes, Dallas Sierra Club, October 23, 2016 (presented remotely) (link)

171. The extent to which different 100% clean, renewable energy transition scenarios can reduce world carbon dioxide levels to 350-400 ppmv by 2100, Session ED12A-08, Climate Change Science and Solutions, American Geophysical Union Fall Meeting, San Francisco, California, December 12, 2016.

172. Is this the only hope for reversing global warming? Transitioning each country' all-purpose energy to 100% wind, water, and solar, Session U008, Earth's Future: The food-water-energy nexus, American Geophysical Union Fall Meeting, San Francisco, California, December 12-16, 2016. (video)

173. How to provide a 100% reliable grid with clean, renewable wind, water, and solar providing 100% of all raw energy for all purposes, Session U51A-03, Getting Near Zero: Decarbonizing the Last 20% of Energy-Sector CO2 Emissions, American Geophysical Union Fall Meeting, San Francisco, California, December 16, 2016. (presentation)

174. Transitioning cities, states, and countries to 100% clean, renewable energy for all purposes, Northern Texas-Northern Louisiana Synod-ELCA, Denton, Texas, February 25, 2017 (connected remotely).

175. Motivating change, UCSC Fourth Annual Climate Science and Policy Workshop, Santa Cruz, California, February 25, 2017.

176. Repowering cities, states, and countries with 100% clean, renewable energy, Silicon Valley Leadership Group, Charge Point, Campbell, California, March 24, 2017.

177. Transitioning states and countries to 100% clean, renewable energy for all purposes, Channing House, Palo Alto, California, April 5, 2017.

178. Transitioning cities, states, and countries to 100% clean, renewable energy for all purposes, CLEAN Network, May 2, 2017 (connected remotely).

179. Powering countries with 100% wind, water, and solar for all energy sectors to address climate, air pollution, and jobs, 100% Renewables workshop, Berlin, Germany, May 12, 2017 (connected remotely).

180. Combating air pollution and global warming with 100% wind, water, and solar plus storage and transmission for all energy sectors, ASAA14, Strasbourg, France, May 29, 2017 (presented remotely).

181. Transitioning to clean, renewable energy in the absence of federal policy, National emergency strategy call, Justice Action Mobilization Network and North Carolina Solutions Coalition, June 1, 2017 (presented remotely).

182. Grid Stability with 100% Wind, Water, Solar For All Purposes Throughout the World, Intersolar North America, San Francisco, California, July 10, 2017.

183. Powering the world with 100% clean, renewable energy. Choosing to avoid dangerous climate change: Sorting through the options, Wisconsin Energy Institute, Sept. 14, 2017 (presented remotely).

184. Jacobson, M.Z., S.V. Nghiem, and A. Sorichetta, Transient impacts of the mega-urbanizations of New Delhi and Los Angeles, Planning meeting to study land use change in Vietnam, Cambodia, and Laos, Hanoi, Vietnam, May 8, 2018 (presented remotely).

185. Powering cities, states, countries, and the world with 100% clean, renewable energy, Rotary Club, Cupertino, California, May 9, 2018. (video)

186. Powering, towns, cities, states, countries, and the world with 100% clean, renewable energy for all purposes, John Muir Series, East Bay Chapter of the Sierra Club, Berkeley Yacht Club, Berkeley, California, May 24, 2018. (video)

187. How to save the world in a hurry, Science for Peace, Toronto, Canada, May 30, 2018. (link)

188. Transitioning buildings, cities, and countries to 100% clean, renewable energy for all purposes, Vi Palo Alto, September 10, 2018.

189. Transitioning buildings, cities, states, and countries to 100% clean, renewable energy for all purposes, Transatlantic dialogues on digitalization and transformation, Delegation from Baden-Wurttemberg, Germany, Santa Clara, California, September 18, 2018.

190. Transitioning buildings, towns, cities, states, and countries to 100% clean, renewable energy for all purposes, Rockefeller Foundation, Bellagio, Italy, October 3, 2018 (remote presentation).

191. National organizing strategy call on the recent IPCC report, Justice Action Mobilization Network, September 18, 2018 (remote presentation).

192. Transitioning buildings, towns, cities, states, and countries to 100% clean, renewable energy for all purposes, City of Cupertino Sustainability Forum, October 18, 2018 (video)

193. Talk to British Columbia Energy Minister of the Environment and Climate Change Strategy, the Honourable George Heyman and Deputy Minister Bobby Plecas on transitioning British Columbia to 100% clean, renewable energy, November 9, 2018

194. Short-term impacts of the mega-urbanizations of New Delhi and Los Angeles between 2000 and 2009, Jacobson, M.Z., S.V. Nghiem, A. Sorichetta, Hanoi, Vietnam, February 20-21, 2019 (presented remotely)

195. Bio(gas) hazards: Dirty air, factory farms, and climate change, Food and Water Watch webinar, May 15, 2019 (video)

196. Nuclear versus renewables, Nuclear energy information camp, Dobein, Germany, August 16, 2019 (presented remotely)

197. 14th conference on sustainable development of energy, water, and environmental systems (SDEWES), Dubrovnik, Croatia, October 2, 2019 (presented remotely by tape) (video, starting at 19:00)

198. Impacts of Green-New-Deal Energy Plans on Grid Stability, Costs, Jobs, Health, and Climate in 143 Countries (Jacobson, M.Z., M.A. Delucchi, M.A. Cameron, S.J. Coughlin, C. Hay, I.P.

Manogaran, Y. Shu, and A.-K. von Krauland), American Geophysical Union Fall, San Francisco, California, December 9-13, 2019

199. 10 Years Since ‘A Plan for a Sustainable Future:’ How Public Education About it Paved the Way to 100% Clean, Renewable Energy Laws and Commitments by States, Cities, Businesses, and Countries and to the Green New Deal, American Geophysical Union Fall, San Francisco, California, December 9-13, 2019

200. 1Transitioning the world to 100% clean, renewable energy and storage for everything. 1st World CleanTech week eConvention, April 21, 2020 (video)

201. Impacts of 100% clean, renewable Green New Deal roadmaps on costs, jobs, health, and climate in 143 countries, Leonardo Art Science Evenings (LASERS), June 10, 2020 (presented remotely) (video)

202. Global 100% renewable energy strategy group webinar, Feb. 9, 2021 (presented remotely) (video)

203. 100% clean, renewable energy and storage for everything, Leonardo Energy webinar, Feb. 24, 2021 (presented remotely) (video)

204. Soul Café, Columbia Baptist Church, April 28, 2021 (presented remotely) (video)

205. Interview with Stacy Clark on the history of the renewable energy transition, June 16, 2021 (presented remotely) (video)

206. Getting Florida to 100% renewables, Roundtable discussion, Sierra Club, Pinellas County, Florida, June 29, 2021 (presented remotely) (video)

207. Steingraber and Jacobson on carbon capture and storage, with Dr. Sandra Steingraber, Better Path, August 11, 2021 (presented remotely) (video)

208. Transitioning Tennessee and other states to 100% clean, renewable energy and storage for everything, Workshop talk, Get off the Grid, Chattanooga, Tennessee, August 21, 2021

209. How green is blue hydrogen, with Robert Howarth, Environmental Action Germany (Deutsche Umwelthilfe), September 16, 2021 (video)

210. Carbon capture, direct air capture, and blue hydrogen, Science and Environmental Health Network, September 17, 2021 (video)

211. How to transition shipping and aircraft to 100% renewable, Pacific Environment, Los Altos, California, November 18, 2021.

212. Can we solve global warming in time, Mette Spencer, December 1, 2021 (presented remotely) (video)

213. Roundtable for world hydrogen leaders, Renewables 100 Policy Institute, Diana Moss, December 14, 2021 (presented remotely).

214. Transitioning California and the world to 100% clean, renewable energy, Promise to our planet, Acterra, March 22, 2022 (presented remotely). (video)

215. Investing in green infrastructure – Building a better future, Economist Sustainability Week panel, Washington, D.C., June 6-9, 2022 (presented remotely) (link)

216. Uniting states, for 100% renewable energy, Environment America webinar, September 21, 2022, (presented remotely) (video)

217. What works and what doesn't work in climate mitigation, Energy Watch Group webinar, September 26, 2022 (presented remotely) (video)

218. Webinar on carbon capture, Eco Justice Collaborative, Champaign, Illinois, November 15, 2022 (presented remotely) (video)

219. Why SMRs are not a fix for climate change, Institute for Energy Economics and Financial Analysis (IEEFA) Webinar, January 23, 2023 (presented remotely) (video)

220. Blue hydrogen: What you need to know, Environmental Health Project Webinar, January 25, 2023 (presented remotely) (video)

Invited Seminar Talks Outside of Stanford University Since 1994

1. A gas, aerosol, transport, and radiation model for studying urban and regional air pollution, U. C. Berkeley Environmental Engineering Seminar Series, Berkeley, California, October 7, 1994.

2. Coupling global-scale meteorological and chemical models, Stanford Research Institute Atmospheric Chemistry Group Meeting, Menlo Park, California, February 10, 1995.

3. Numerical simulations of the transport and transformations of air pollutants in an urban airshed, Dept. of Meteorology, San Jose State University, San Jose, California, March 2, 1995.

4. Simulation pollution buildup in the Los Angeles basin with a coupled air quality - meteorology model. Lawrence Livermore Nat'l Lab, May 7, 1996.

5. Coupling chemical, radiative, and meteorological models in a study of global air pollution, NASA Ames Research Center, Mountain View, California, March 22, 1995.

6. Air pollution modeling. 3-hour seminar, Dept of Meteorology, San Jose State University, May 15, 1996.

7. Studying the feedback effects of aerosols on air temperatures and gas concentrations with an air pollution model. Department of Earth and Planetary Sciences, Harvard University, March 17, 1997.

8. Effects of Aerosols and Soil Moisture on Gas Concentrations and Temperatures in Los Angeles, NASA Ames Research Center, Mountain View, California, May 1, 1997.

9. Aerosol effects on air pollution, Department of Meteorology, San Jose State University, May 1, 1997.

10. UV absorption by particles and its effects on ozone in polluted air, NASA Ames Research Center, Mountain View, California, April 16, 1998.

11. The effects of absorption by organics and other particulate components on UV irradiance and ozone in Los Angeles, Systems Applications, Inc., San Rafael, CA, August 19, 1998.

12. Global direct radiative forcing due to multicomponent anthropogenic and natural aerosols, NASA Ames Research Center, Mountain View, California, February 18, 1999.

13. Global direct radiative forcing due to multicomponent anthropogenic and natural aerosols, Department of Oceanography, University of Washington, February 25, 1999.

14. Studying the effects of soil moisture on ozone, temperatures, and winds in Los Angeles, Dept. of Meteorology, San Jose State University, March 16, 1999.

15. Examining the causes and effects of ultraviolet radiation reductions in Los Angeles, Dept. of Atmospheric Sciences, University of Illinois, April1, 1999.

16. Revised estimates of the global direct radiative forcing of aerosols due to a physically-based treatment of elemental carbon optics, Dept. of Geology & Geophysics, University of California, Berkeley, December 8, 1999.

17. Examining the climate response to anthropogenic and natural aerosols, NASA Ames Research Center, Mountain View, California, March 30, 2000.

18. Studying effects of the large scale on air pollution and weather in Northern California during SARMAP with a global-through-urban scale air pollution/weather forecast model, Environmental Engineering Seminar Series, U. C. Davis, April 10, 2000.

19. Justification for the control of black carbon, the second-leading cause of near-surface global warming, Environmental Chemistry Seminar Series, U. C. Riverside, November 21, 2000.

20. Control of black carbon, the most effective means of slowing global warming, Scripps Institute of Oceanography, La Jolla, February, 2001.

21. Control of black carbon, the most effective means of slowing global warming, NOAA Aeronomy Laboratory, Boulder, Colorado, April 18, 2001.

22. Control of fossil-fuel particulate black carbon and organic matter, possibly the most effective method of slowing global warming, Rutgers University, New Jersey, March 29, 2002.

23. Black carbon, energy, and global warming, Paul Scherrer Institute, Villigen, Switzerland, August 21, 2002.

24. Black carbon and global warming, Bay Area Air Quality Management District Advisory Council Technical Committee Meeting, San Francisco, California, August 27, 2002.

25. The short-term cooling and long-term global warming due to biomass burning, National Center for Atmospheric Research, Boulder, Colorado, November 12, 2002.

26. Addressing air quality and climate through soot control, National Institute of Standards and Technology (NIST), Gaithersburg, Maryland, March 26, 2003.

27. Climate and air pollution issues related to black carbon and modern diesel vehicles, Cummins Science and Technology Advisory Committee meeting, Indianapolis, Indiana, July 9, 2003.

28. Climate and air pollution effects of black carbon and modern diesel vehicles, Department of Chemical Engineering, University of Puerto Rico at Mayaguez, November 6, 2003.

29. Wind energy and climate, Cabrillo College, Aptos, California, November 13, 2003.

30. Climate and air pollution effects of black carbon and modern diesel vehicles, Department of Atmospheric Science, University of California, Los Angeles, February 18, 2004.

31. Climate and air pollution effects of diesel vehicles, and the impact of particle traps and NOx filters, Department of Civil and Environmental Engineering, University of California, Berkeley, March 12, 2004.

32. Effects of anthropogenic aerosol particles on California climate, California Energy Commission, Sacramento, California, October 28, 2004.

33. Diesel effects on climate and air pollution, Program in Science, Technology and Environmental Policy (STEP), Woodrow Wilson School, Princeton University, Nov. 1, 2004.

34. Enhanced coagulation due to evaporation and Van der Waals forces and its effect on nanoparticle evolution, Department of Mechanical Engineering, University of Minnesota, March 2, 2005.

35. The global and regional climate effects of black carbon and other particle components, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, April 14, 2005.

36. The effects of aerosols on global warming and regional climate, Sonoma State University, May 12, 2005.

37. The effects of aerosols on California and Los Angeles climate, North Carolina State University, October 3, 2005.

38. The relative effects of greenhouse gases, absorbing aerosol particles, and scattering aerosol particles on global climate, Environmental Protection Agency, Research Triangle Park, North Carolina, October 4, 2005.

39. Climate Change, Hurricanes, and Energy, Department of Environmental and Occupational Health, University of South Florida, College of Public Health, Tampa, Florida, Oct. 27, 2005.

40. Global warming and hurricanes, Stanford Alumni Association, Portland, Oregon, November 5, 2005.

41. Addressing climate change with wind energy, Stanford University/University of British Columbia alumni associations meeting, Palo Alto, California, February 16, 2006.

42. Cleaning the air and improving health with hydrogen fuel-cell vehicles, Stony Brook University, Stony Brook, New York, March 22, 2006.

43. New Energy, Merrill Lynch, New York City, New York, March 23, 2006.

44. Effects of E85 on air pollution in Los Angeles and the United States, California Energy Commission, Sacramento, California, July 26, 2006.

45. Causes of and a wind-energy solution to global warming, Lockheed Martin/Advanced Technology Center colloquium, Palo Alto, California, November 9, 2006.

46. University of Wyoming / Stroock Forum on Energy Futures: Global changes that challenge Wyoming, Laramie, Wyoming, November 15, 2006.

47. Comparative methods of addressing climate-relevant emissions and air pollution from vehicles, Environmental Defense, Oakland, California, May 30, 2007.

48. Evaluation of proposed solutions to global warming, Bay Area Air Quality Management District Technical Committee, San Francisco, California, Aug 6, 2007.

49. Comparative effects of vehicle technologies and fuels on climate and air pollution, Dept. of Atmospheric Sciences, Texas A&M University, College Station, Texas, Nov. 13, 2007.

50. Causes of and proposed solutions to global warming and air pollution, Hewlett-Packard Labs, Palo Alto, California, January 24, 2008.

51. A renewable-energy solution to global warming, U. Minnesota, Minneapolis, Minnesota, March 27, 2008.

52. On the causal link between carbon dioxide and air pollution mortality, Lockheed Martin/Advanced Technology Center colloquium, Palo Alto, California, May 8, 2008.

53. Evaluation of proposed energy solutions to global warming, air pollution, and energy security, Department of Chemical and Biomolecular Engineering, University of Illinois at Urbana-Champaign, February 3, 2009.

54. Review of energy solutions to global warming, air pollution, and energy security, Webcast to the National Wind Coordinating Collaborative (NWCC), February 10, 2009.

55. Evaluation of energy solutions to global warming, air pollution, and energy security, Department of Geology & Geophysics Colloquium, Yale University, February 18, 2009.

56. Evaluation of energy solutions to global warming, air polllution, and energy security, Palo Alto Research Center (PARC) colloquium, Palo Alto, California, March 5, 2009.

57. Evaluation of energy solutions to global warming, air pollution, and energy security, Department of Civil and Environmental Engineering Graduate Symposium in Environmental and Water Resources Engineering, University of California at Los Angeles, April 21, 2009.

58. Evaluation of energy solutions to global warming, air pollution, and energy security, IEEE Power Electronics Society, Santa Clara, California, April 23, 2009.

59. Review of energy solutions to global warming, air pollution, and energy security, Singularity University, NASA Ames Research Center, Mountain View, CA, July 15, 2009.

60. Evaluation of energy solutions to global warming, air pollution, and energy security, Electric Auto Association, Palo Alto, California, July 18, 2009.

61. Review of energy solutions to global warming, air pollution, and energy security, Earth and Ocean Sciences Seminar Series, Duke University, November 6, 2009.

62. Review of energy solutions to global warming, air pollution, and energy security, Environmental Engineering Fall 2009 Seminar Series, Dept. of Civil and Environmental Engineering, U.C. Berkeley, November 13, 2009.

63. A plan for a sustainable future, Clean Tech Forum, Campbell, California, December 8, 2009.

64. The enhancement of local air pollution by CO2 domes and the effects of black carbon, the second-leading cause of global warming, Environmental Protection Agency Region 9, San Francisco, California, May 24, 2010.

65. Powering the world with wind, water, and sun, Singularity University, NASA Ames Research Center, Mountain View, California, July 12, 2010.

66. A plan for a sustainable future using wind, water, and sun, DECCW Department, Sydney, Australia, August 18, 2010.

67. Causes of and energy solutions to global warming and air pollution mortality, Modesto Area Partners in Science, Modesto, California, November 19, 2010.

68. Powering the world with wind, water, and sun, College of Engineering, Systems Engineering Program, Cornell University, Ithaca, New York, February 4, 2011.

69. Powering the world with wind, water, and sun, Centre for Environment and Sustainability, University of Western Ontario, Ontario, Canada, March 9, 2011.

70. Aircraft effects on climate, Commonwealth Club, San Francisco, California, March 28, 2011.

71. A plan for powering the world for all purposes with wind, water, and sunlight, Silicon Valley Clean Tech Speaker Series, Santa Clara, California, April 21, 2011.

72. Global warming and air pollution, and a worldwide plan to solve both with wind, water, and the sun, Santa Clara Valley Life Member Affinity Group, IEEE, San Jose, California, June 7, 2011.

73. Powering the world with wind, water, and sunlight, 2011 International Student Energy Summit (ISES), Vancouver, British Columbia, June 10, 2011.

74. A plan for powering the world for all purposes with wind, water, and sunlight, Leonardo Energy Initiative, Webinar, June 16, 2011.

75. Global warming and air pollution: A worldwide plan to solve both with wind, water, and the sun, Hewlett-Packard Labs, Palo Alto, California, July 14, 2011.

76. A plan for powering the world for all purposes with wind, water, and sunlight, Harvard Engineering and Applied Sciences Atmospheric Sciences Seminar Series, Harvard University, September 9, 2011.

77. A plan for powering the world for all purposes with wind, water, and sunlight, Citizen's Climate Lobby, telephone conference speaker, October 2, 2011.

78. A plan to power the world for all purposes with wind, water, and sunlight, ENGINEER-2011 video conference, National Institute of Technology Karnataka (NITK), Surathkal, India, October 27, 2011.

79. Effects of black carbon on clouds and climate. Department of Meteorology, San Jose State University, February 1, 2012.

80. A plan to power the world for all purposes with wind, water, and sunlight, San Jose State University, April 11, 2012.

81. Powering the world with wind, water, and sunlight, Rotory Club, Cupertino, California, April 25, 2012. (video)

82. Effects of climate change on future air quality, Environmental Protection Agency, webinar, May 9, 2012 (connected remotely). (link)

83. Powering the world with wind, water, and sunlight, Stanford Alumni Association, Minneapolis, Minnesota, May 15, 2012.

84. Can the world be powered on renewable energy? Stanford Alumni Association, San Francisco, California, May 18, 2012.

85. A plan to power the world with wind, water, and sunlight, Ruffalo, M.A., M. Krapels, and M.Z. Jacobson, Talks at Google, Google, Inc., Mountain View, California, June 20, 2012. (video)

86. A plan to power the world for all purposes with wind, water, and the sun, Leonardo Art Science Evenings (LASERS), University of San Francisco, San Francisco, California, July 9, 2012. (video) (slides)

87. The effects of black and brown carbon on clouds and global climate, NASA/University of Alabama at Huntsville, National Space Science and Technology Center, Huntsville, Alabama, September 5, 2012. (link)

88. Planning for a sustainable future with wind, water, and the sun, Leonardo Art Science Evenings (LASERS), Stanford University, Stanford, California, October 9, 2012. (link)

89. A plan to power 100 percent of the planet with renewables, University College, Toronto, Ontario, October 15, 2012. (video)

90. Planning for a sustainable future for states, countries, and the world with wind, water, and the sun, Department of Earth and Environmental Engineering, Columbia University, November 16, 2012.

91. A plan to power the world, U.S., and California for all purposes with wind, water, and the sun, Friends of Hopkins, Pacific Grove, California, January 8, 2013.

92. Powering the world, U.S., and individual states for all purposes with wind, water, and sun, NOAA Chemical Sciences Division Seminar, Boulder, Colorado, January 25, 2013. (link)

93. Black carbon effects on climate, National Association of Clean Air Agencies (NACAA) presentation by conference call, February 13, 2013.

94. Technical and economic plans to power the world, U.S., and individual states for all purposes with wind, water, and sunlight, Climate Science Program, California State University, Northridge (CSUN), Northridge, California, February 20, 2013. (link)

95. Technical briefing about state and national clean energy plans, Sierra Club, April 9, 2013 (by conference call).

96. Powering individual states, the U.S., and the world with wind, water, and sunlight, Climate change symposium, West Valley College, California, Saratoga, California, April 23, 2013. (link)

97. Powering California and other states with wind, water, and sunlight, Presentation to energy group, Berkeley, California, June 24, 2013.

98. Powering states and countries with wind, water, and sunlight, Kleiner Perkins Caufield Byers, Palo Alto, California, July 11, 2013.

99. Powering states and countries with wind, water, and sunlight, Sierra Club Clean Tech webinar, July 12, 2013.

100. Roadmaps for powering states and countries for all purposes with wind, water, and sunlight, Energy Resources Group (ERG), U.C. Berkeley, Berkeley, California, September 11, 2013. (pdf)

101. 100% Renewable: Roadmaps for powering states, countries, and the world for all purposes with wind, water, and sunlight, British Columbia Sustainable Energy Association, Vancouver, British Columbia, September 17, 2013, webinar. (link)

102. How to power the world, U.S., and individual states for all purposes with wind, water, and sunlight, Vi Palo Alto Residents' Retirement Community, Palo Alto, California, October 22, 2013.

103. Transitioning to 100% clean energy, Connecticut Climate Justice Coalition, November 14, 2013 (remote presentation) (link)

104. Powering states, countries, and the world with wind, water, and solar power, Atlas Awards, Danville, California, November 16, 2013.

105. Powering states, countries, and the world with wind, water, and solar power, Hudson Valley, New York, November 20, 2013 (connected remotely). (link)

106. Powering countries, states, and the world with wind, water, and sunlight, University of Calgary, Alberta, Canada, December 6, 2013 (connected remotely). (link)

107. Roadmaps for transitioning California and the other 49 U.S. states to wind, water, and solar power for all purposes, Bay Area Air Quality Management District, February 13, 2014. (link)

108. Plans for transitioning all 50 U.S. states to wind, water, and solar power for all purposes, Acterra Speaker Series 2014, Mountain View, California, March 5, 2014. (link)

109. Plan for converting Massachusetts to wind, water, and solar power for all purposes, conference call seminar, March 24, 2014.

110. Roadmaps for transitioning all 50 U.S. states to wind, water, and solar power for all purposes, NIEHS Center, University of Southern California, April 4, 2014.

111. Roadmaps for transitioning all 50 U.S. states to wind, water, and solar power for all purposes, Youngstown State University, Youngstown, Ohio, April 23, 2014 (presented remotely). (link)

112. Roadmaps for transitioning all 50 U.S. states to wind, water, and solar power for all purposes, Henry M. Gunn Senior High School, Palo Alto, California, April 29, 2014. (link)

113. Roadmaps for transitioning all 50 U.S. states to wind, water, and solar power for all purposes, Barr Foundation, Boston, MA, May 30, 2014, (presented remotely).

114. Roadmaps for transitioning all 50 U.S. states to wind, water, and solar power for all purposes, Director's colloquium Summer Series, NASA Ames Research Center, Mountain View, California, July 8, 2014. (link)

115. Roadmaps for transitioning all 50 U.S. states to wind, water, and solar power for all purposes, Stanford Research Institute (SRI) International, Menlo Park, California, July 18, 2014.

116. Roadmaps for transitioning all 50 U.S. states to wind, water, and solar power for all purposes, Silicon Valley Leadership Group, Santa Clara, California, August 20, 2014.

117. Roadmaps for transitioning all 50 U.S. states to wind, water, and solar power for all purposes, Tech talk, Access and Energy Division, Google, Mountain View, California, August 21, 2014.

118. Roadmaps for transitioning all 50 U.S. states to wind, water, and solar power for all purposes, Apple, Inc., October 2, 2014.

119. . Roadmaps for transitioning all 50 U.S. states to wind, water and solar power for all purposes, Health and Environmental Funders Network (HEFN) Annual Meeting, Los Angeles, California, October 28, 2014 (presented remotely). (link)

120. Changing the energy infrastructure of the 50 United States to one derived from wind, water and sunlight, Northeast Ohio, January 8, 2015 (presented remotely). (link)

121. Roadmaps for transitioning all 50 U.S. states to wind, water and solar power for all purposes, Bard MBA Sustainable Business Fridays, January 30, 2015 (presented remotely). (link)

122. Roadmaps for transitioning the 50 U.S. states and 139 countries to wind, water, and solar power for all purposes, Chinese American Environmental Professionals Association, Oakland, California, March 4, 2015.

123. Roadmaps for transitioning all 50 U.S. states to wind, water and solar power for all purposes, EWRE Seminar, University of South Florida, Tampa, Florida, March 19, 2015.

124. Roadmaps for transitioning the 50 U.S. states to wind, water, and solar power for all purposes, Coloradans against fracking webinar, April 13, 2015 (presented remotely). (link)

125. Roadmaps for transitioning the U.S. and world to wind, water, and solar power for all purposes, California History Center, De Anza College, California, April 14, 2015. (link)

126. Roadmaps for transitioning 50 U.S. states and 139 countries to wind, water, and solar power for all purposes, Columbus, Ohio, April 27, 2015 (connected remotely). (video)

127. Roadmaps for transitioning all 50 U.S. states and 139 countries to wind, water, and solar power for all purposes, Lockheed Martin/Advanced Technology Center colloquium, Palo Alto, California, June 4, 2015 (link)

128. Wind energy resources accounting for feedbacks of wind turbines to the atmosphere, Harvard University, June 24-25, 2015.

129. How California Can End Fossil Fuel Extraction and Embrace 100% Wind and Solar, Center for Biological Diversity, Berkeley, California, October 29, 2015 (video)

130. What does 100% renewable energy look like, Dartmouth, New Hampshire, January 20, 2016 (presented remotely) (link)

131. Providing all energy with wind, water, and solar to states and countries, Seminar to UCLA Grand Challenge Committee, University of California at Los Angeles, February 23, 2016.

132. Powering Earth 2050: Is California's 100% renewable energy strategy globally viable, Oppenheim Lecture Series, UCLA Institute of the Environment and Sustainability, Los Angeles, California, February 23, 2016 (video)

133. Powering the Earth with 100% wind, water, and sunlight (WWS) for all purposes, De Anza College, Cupertino, California, April 27, 2016 (link)

134. Roadmaps for transitioning all 50 United States and 139 counties to 100% wind, water, and solar power for all purposes, Rotary Club of Menlo Park, Menlo Park, California, May 18, 2016 (link)

135. Roadmaps for transitioning all 50 U.S. states and 139 countries to wind, water, and solar power for all purposes, Fellowship Forum, Palo Alto, California, July 5, 2016

136. Roadmaps for transitioning all 50 states and 139 countries to wind, water, and solar power for all purposes, Antioch University/Environmental Protection Agency webinar, September 29, 2016 (presented remotely).

137. Roadmaps to transition the United States and the World to 100% Clean, Renewable Energy for all purposes, University of Minnesota, October 1, 2016 (presented remotely).

138. 100% clean, renewable energy solutions to keeping global temperatures below 1.5oC. Scripps Institute of Oceanography. La Jolla, California, October 20, 2016.

139. Roadmaps for transitioning states and countries to wind, water, and solar power for all purposes, Rotary Club of Palo Alto, Palo Alto, California, April 10, 2017.

140. Transitioning California to 100% clean, renewable energy, Solutions Project Executive Committee, April 11, 2017 (presented remotely).

141. Roadmaps for transitioning 139 countries and the 50 United States to wind, water, and solar for all purposes, Lecture Series on Energy and the Environment, Youngstown State University, Youngstown, Ohio, October 3, 2017 (presented remotely).

142. Transitioning the world to 100% wind, water, and solar for all purposes, Catholic University of America, Washington, D.C., November 16, 2017 (presented remotely). (link)

143. Transitioning to 100% clean, renewable energy buildings, Foothill College / NASA Ames Research Center, April 20, 2018.

144. Technologies needed for 100% renewable California, Public-private brainstorming event, University of California at San Diego, November 18, 2019 (presented remotely).

145. Transitioning homes, cities, states, and countries to 100% wind, water, and solar for all purposes: A worldwide Green New Deal, The Journey: Summer school for graduates and young professionals, University of Bologna, July 23, 2020 (presented remotely).

146. Transitioning buildings, cities, and countries to 100% clean, renewable energy and storage for everything, Aberdeen Business School, Robert Gordon University, PhD seminar series, Aberdeen, Scotland, March 3, 2021 (presented remotely).

147. Impact of 100% clean, renewable Green New Deal roadmaps on costs, jobs, health, and climate in 145 countries, J. James Woods Lecture Series, Butler University, Indianapolis, Indiana, January 18, 2022 (video)

148. Renewable Energy and Storage: technology, opportunities and bottleneck for a net-zero scenario, Eng. Giorgio Levi Cases Center for Energy Economics and Technology, University of Padua, Italy, March 30, 2022 (presented remotely)

149. . Transitioning the world to 100% clean, renewable energy and storage for everything, Palmer Lecture Series Colloquium, Department of Earth Sciences, Kent State University, April 15, 2022 (presented remotely).

150. On the use of only green hydrogen, and for limited applications, in a 100% clean, renewable energy world, Hydrogen webinar, Brunel University, London, UK, May 18, 2022 (presented remotely). (video)

151. A solution to global warming, air pollution, and energy insecurity for 145 countries, Graduate School of Environmental Studies (GSES), Tohoku University, Japan, September 5, 2022 (presented remotely).

152. A solution to global warming, air pollution, and energy insecurity for California, all 50 U.S. states, and the world, University of San Francisco, Graduate program in environmental management, Gordon Johnson, November 7, 2022 (presented remotely).

Invited Seminar Talks at Stanford University

1. Computer simulations of urban and regional air pollution, Stanford University School of Engineering Sunrise Breakfast Club, Stanford, California, March 14, 1995.

2. Similarities and differences between global and urban air pollution models, Stanford University, Institute for International Studies, Environmental Policy Forum, November 13, 1995.

3. The role and treatment of clouds in atmospheric models, EE 350 Radioscience Seminar, Stanford University, Feb. 11, 1998.

4. Optimization of a Gear solver for use in 3-D air pollution studies, Computer Information Systems Seminar Series, Department of Computer Science, Stanford University, May 10, 1999.

5. Studying ozone layers aloft and ozone in national parks with a global-through-urban-scale air pollution weather forecast model, Fluid Mechanics Seminar, Stanford University, May 8, 2001.

6. Effects of energy use on global warming, Robinson Environmental Theme House Seminar, Stanford University, Nov. 19, 2002.

7. Relative effects of diesel versus gasoline vehicles on climate and air pollution, Petroleum Engineering Seminar Series, Stanford University, Feb. 25, 2003.

8. Addressing air quality and climate through soot control, EE 350 Radioscience Seminar, Stanford University, March 5, 2003.

9. Climate, air pollution, and energy, University Corporation of Atmospheric Research (UCAR) University Relations Committee Meeting, Stanford University, April 15, 2003.

10. Reducing greenhouse gas emissions through a large-scale wind/hydrogen program. Robinson Environmental Theme House Seminar, Stanford University, February 24, 2004.

11. The climate and air pollution effects of aerosols, Carnegie Institution's Department of Global Ecology, November 10, 2004.

12. Effects on air pollution and health of switching to hydrogen fuel cells in all U.S. onroad vehicles, Global Climate and Energy Project Advisory Committee Meeting, March 28, 2005.

13. The effects on air pollution and health of converting all U.S. vehicles to hydrogen fuel cell or hybrid vehicles, Global Climate and Energy Project Technical Symposium, June 15, 2005.

14. Energy and Climate Change, Stanford Institute for the Environment Energy Committee Seminar Series, November 9, 2005.

15. Greenhouse gases versus soot causes of global warming, and a wind energy solution, Geological and Earth Science seminar series, March 16, 2006.

16. The wind factor: How to stop global warming, Engineering Day, School of Engineering and Engineering Alumni Relations Program, July 15, 2006.

17. Comparison of the health and climate impacts of using large-scale wind-hydrogen or wind-batter versus ethanol (E85), diesel, biodiesel, and gasoline in modern vehicles, Wood's Institute for the Environment Energy Seminar Series, Oct. 4, 2006.

18. Briefing on renewable energy and the environment to Assistant Secretary of Energy for Renewable Energy, Andy Karsner, Oct. 19, 2006.

19. Causes of and a solution to global warming, Energy Resources Engineering Seminar Series, Nov. 28, 2006.

20. Wind versus biofuels for addressing climate, health, and energy, SLAC Colloquium, Jan. 29, 2007.

21. Effects of ethanol (E85) versus gasoline on cancer and mortality in the United States, Management Science and Engineering Seminar Series, April 30, 2007.

22. Causes of and solutions to global warming, Intensive English and Academic Orientation program, Stanford University, July 24, 2007.

23. Global warming and its energy solutions, Classes Without Quizzes, Stanford University Reunion Homecoming, Oct. 12, 2007.

24. Air pollution impacts of and renewable energy solutions to climate change, Fluid Mechanics Seminar, Stanford University, January 29, 2008.

25. Presentation to Vestas Wind Systems, School of Engineering, Stanford University, March 20, 2008.

26. Review of proposed solutions to global warming, air pollution, and energy security, The Energy Seminar, Woods Institute for the Environment, October 1, 2008.

27. Briefing of John Fluke and energy specialists, School of Engineering, Stanford University, October 8, 2008.

28. Briefing of Senator Jeff Bingaman, chairman of the U.S. Senate Committee of Energy and Natural Resources, on "Low Carbon Energy Supplies," Stanford University, October 10, 2008.

29. Briefing of State Senator Fran Pavley, author of AB 32, California's Global Warming Solutions Act, Stanford University, Nov. 12, 2008.

30. Review of energy solutions to global warming, air pollution, and energy security, China's Environment, Forum for American/Chinese Exchange at Stanford (FACES), Stanford University, February 23, 2009.

31. Review of energy solutions to global warming, air pollution, and energy security, Discussion Series on Energy and the Environment, Trancos Lounge, February 24, 2009.

32. Predictions of bio-warfare agent dispersion, Army High Performance Computing Research Center (AHPCRC) Technical Review Meeting, Stanford University, June 10, 2009.

33. A plan for a clean and sustainable future using only wind, water, and the sun, EEES Seminar, Stanford University May 12, 2010.

34. Roundtable discussion, The communication eco-system surrounding electric vehicles and the role of web 2.0, Stanford University, June 7, 2010.

35. Powering the world for all purposes with wind, water, and sunlight, The Energy Seminar, Stanford University, May 16, 2011.

36. How to power the world with wind, water, and sunlight alone, Classes Without Quizzes, Stanford University Reunion Homecoming, Oct. 20, 2011.

37. Discussion and question/answer session about renewable energy research, Stanford Energy Club, Stanford, California, January 26, 2012.

38. A plan for clean, sustainable energy worldwide in 20-40 years, Café Scientifique, Stanford School of Medecine Blood Center, Palo Alto, California, March 29, 2012. Article in Stanford Magazine (link)

39. Global health impacts of the Fukushima Daiichi nuclear accident, Center for International Security and Cooperation (CISAC), Stanford University, Stanford, California, October 1, 2012 (link)

40. Roadmaps for transitioning all 50 U.S. states to wind, water, and solar power for all purposes, Energy Resources Engineering Seminar Series, April 21, 2014 (link)

41. Repowering the U.S. with wind, water, and solar to address price stability, pollution, climate, and hurricane damage, Stanford advanced workshop on data analytics for the electric grid, Stanford University Energy and Environment Affiliates Program, May 14, 2014 (link)

42. Roadmaps for powering all countries of the world with 100% wind, water, and solar for all purposes, Energy technology panel on China energy for Guodian Power, Huang Engineering Center, Stanford University, December 15, 2014.

43. Repowering the world with wind, water, and sunlight, Students for a Sustainable Stanford, talk ahead of Al Gore, White Plaza, October 2, 2015 (link)

44. Repowering the world's energy infrastructure country by country with wind, water, and solar power, Stanford in Government, October 8, 2015

45. Powering the world with wind, water, and solar, Stanford Reunion Classes Without Quizzes, Stanford University, October 21, 2015 (video)

46. Green versus Green: A debate on the future of U.S. renewables, Stanford Steyer-Taylor Center, Stanford, California, May 18, 2016 (video)

47. Energy efficient homes, Bone Structure event, Stanford, California, June 24, 2016.

48. Roadmaps for transitioning all 50 states and 139 countries to 100% wind, water, and solar power for all purposes, Point Energy Innovations Retreat, Stanford University, Stanford, California, August 12, 2016 (summary)

49. Transitioning cities and the world to 100% clean, renewable, reliable energy systems, Digital Cities Summit, Stanford University, Stanford, California, October 3, 2016 (video)

50. The Solutions Project and its path to 100% clean, renewable energy. Cross-campus energy open house, Stanford Energy Club, Stanford University, December 1, 2016 (summary)

51. Transitioning countries to 100% wind, water, and solar (WWS) for all purposes, CP Group, Thailand conglomerate, Stanford University, June 7, 2017.

52. Combatting air pollution and global warming with 100% wind, water, and solar plus storage and transmission in all energy sectors, SUPER Faculty Seminar, Stanford University, June 29, 2017

53. In conversation with professor Mark Jacobson, EmPower/Stanford Energy Club, Stanford University, January 23, 2019 (link)

54. Impact of 100% clean, renewable Green New Deal roadmaps on costs, jobs, health, and climate in 143 countries, School of Engineering Connects Committee talk to Engineering Staff, Stanford University, April 22, 2020 (connected remotely).

55. The path to zero net GHG emissions by 2050, Woods Institute of the Environment, April 7, 2021 (video)

56. Transitioning buildings, cities, states, and countries to 100% clean, renewable energy and storage for everything, Nanoscale Prototyping Laboratory, Stanford University, June 9, 2021.

Invited Panelist

1. Economist's Summit: The Role of Renewable Energy in California's Future, Capital Building, Sacramento, California, September 5, 2001.

2. Soot, wind, and global warming, Engineering Alumni Relations Panel Meeting, Stanford University, February 26, 2003.

3. Panel discussion on global warming, 8th International conference of the Israel Society of Ecology and Environmental Quality Sciences, Weizmann Institute of Science, Rehovot, Israel, May 30-June 1, 2005.

4. Homecoming panel, After Katrina: Global Climate and Energy Issues Hit Home, Stanford University, Thursday, October 20, 2005.

5. Hydrogen discussion panelist. Second HyCARE symposium, Laxenburg, Austria, Dec. 20, 2005.

6. Woods Institute Biofuels Workshop Energy Seminar panelist, Stanford University, Dec. 6, 2006.

7. Panel Discussion on climate change, NASA Ames Research Center, February, 23, 2007.

8. South Coast Air Quality Management District Roundtable Discussion on Controlling Global Warming and Local Air Pollution, Diamond Bar, California, June 28, 2007.

9. Climate Panelist for the International Civil Aviation Organization's Committee on Aviation Environmental Protection (CAEP) impacts workshop, Montreal, Canada, Oct. 29-31, 2007.

10. Energy and Climate Change Symposium -- "The Road to Renewables," Australian Government Department of Foreign Affairs and Trade, Los Angeles, California, Jan. 18, 2008.

11. Roundtable on Local Approaches to Climate Action, Dept. of Anthropology, Stanford University, Stanford, California, Feb. 13, 2008.

12. Panel on Advanced Energy Research, Woods/Precourt Affiliate Conference, Stanford University, September 12, 2008.

13. Press conference for Environmental Consequences of the Changing Global Food System, American Geophysical Union, San Francisco, December 18, 2008.

14. Horn Lecture panel discussion on energy, School of Earth Sciences, January 20, 2009.

15. BBC Radio debate on renewable versus nuclear energy, Steve Evans, moderator July 28, 2010.

16. DECCW Debate, "Will Technology Save Us," Sydney, Australia, August 19, 2010.

17. Debate on Proposition 23 (partner with Prof. Larry Goulder versus Anita Mangels, Miles Barber) Stanford Solar and Wind Energy Project, Stanford University, Oct. 18, 2010.

18. Discussion, with Prof. Willett Kempton, on a plan for an offshore east coast underwater transmission system, WHYY radio, Oct. 27, 2010.

19. Panel Discussion, Grid Integration of Renewable Energy Workshop, Stanford University, Jan. 13, 2011.

20. Panel Discussion, The Minerals, Metals, and Materials Society (TMS) Annual Meeting, San Diego, California, February 28, 2011.

21. Moderator of panel discussion, Future of automobiles, Stanford Energy Club, Stanford, California, March 5, 2012.

22. Panel discussion, The age of shale? Implications on energy industry, climate and policy, Stanford Energy Club, Stanford, California, May 31, 2012.

23. Panel discussion, Powering the world with wind, water, and sunlight with Jacobson, M.Z., M.A. Ruffalo, M. Krapels, and J. Wank, Stanford University, Stanford, California, June 20, 2012. (link)

24. Panel speaker, press conference on behalf of German Parliamentarian Hans-Josef Fell, San Francisco, California, July 10, 2012. (link)

25. Panel discussion on the Documentary SWITCH, Energy Seminar, Stanford, California, October 8, 2012 (link)

26. Moderator of speech by Christiana Figueres, Executive Secretary, United Nations Framework Convention on Climate Change, World Affairs Council, San Francisco, California, April 18, 2013 (link)

27. Panelist at the movie premier of Gasland 2, Tribeka Film Festival, New York City, April 22, 2013. (link)

28. Panelist at the movie screening of Gasland 2, Stanford University, Stanford, California, June 2, 2013. (link)

29. Panelist on natural gas hydrofracking, Stanford University, April 14, 2014. (link)

30. Panelist on renewable energy, climate change, and carbon management, NASES, Columbia University, June 20, 2014. (link)

31. Debate, Meeting the renewable energy challenge symposium, University of Iowa, October 15, 2014. Debate question. Should we go to 100% renewable energy. Audience vote: 68% to 25% in favor after debate. (link)

32. China air pollution panel, Freeman Spogli Institute, Stanford University, December 15, 2014.

33. Will renewables replace fossil fuels? The Energy XChange, September 28, 2015 (audio)

34. How California can switch from fossil fuels to renewable energy, Screening of Dear Governor Brown, Beverly Hills, California, November 4, 2015.

35. White House roundtable discussion on the decarbonization of the U.S. electricity sector by 2050, Washington, DC, August 25, 2016 (connected remotely).

36. Combatting climate change: the role of nuclear power, University of Michigan Energy Institute, Ann Arbor, Michigan, September 26, 2016 (video)

37. Emcee and panelist following screening of "Before the Flood," a documentary produced by Leonardo di Caprio, directed by Fisher Stevens, and distributed by National Geographic, Stanford University, October 27, 2016.

38. Panel discussion on the future of district heating, 4th International Conference on Smart Energy Systems and 4th Generation District Heating, Aalborg University, Aalborg, Denmark, November 14, 2018 (video)

Congressional Testimony

1. July 12, 2005. Written testimony on a comparison of wind with nuclear energy to the U.S. House of Representatives Subcommittee on Energy and Resource.

2. October 18, 2007. Oral and written testimony on the role of black carbon as a factor in climate change and its impact on public health. U.S. House of Representatives Committee on Oversight and Government Reform, Washington, D.C. (link)

3. April 9, 2008. Oral and written testimony on the relative impact of carbon dioxide on air pollution health problems in California versus the rest of the U.S., U.S. House of Representatives Select Committee on Energy Independence and Global Warming, Washington, D.C. (link)

4. November 19, 2015. Oral and written testimony on powering the 50 United States and 139 countries with 100% wind, water, and solar power for all purposes, U.S. House of Representatives, Energy and Commerce Committee, Washington, D.C.(schedule) (written testimony)

Environmental Protection Agency Testimony

1. March 5, 2009. Oral testimony invited by the State of California at the Environmental Protection Agency Hearing AMS-FRL-8772-7, California State Motor Vehicle Control Standards; Greenhouse Gas Regulations; Reconsideration of Previous Denial of a Waiver of Preemption, Arlington, Virginia. (link)

2. Oral testimony at the Environmental Protection Agency Hearing: Endangerment and cause or contribute findings for greenhouse gases under the Clean Air Act, Arlington, Virginia, May 18, 2009. (link)

Government Advisory Boards

1. United States Department of Energy Office of Energy Efficiency and Renewable Energy (EERE) Federal Advisory Committee (ERAC) to the United States Secretary of Energy, October 2010-August 2012.

2. City of San Francisco Task Force to Provide 100% Renewable Electricity by 2020, Jan., 2011-May, 2012.

3. United States Environmental Protection Agency Advisory Council on Clean Air Compliance Analysis, Panel to evaluate a draft EPA report to Congress on the climate and health effects of black carbon, February 9, 2011-April, 2012. (link)

Interviews for Documentaries

"Doomsday Tech," History Channel series, Modern Marvels, produced by Scott Goldie and Anthony Lacques, Dec. 28, 2004.

Science advisor, "Global Warming: Are we melting the planet," hosted by Tom Brokaw, Discovery Channel, BBC, NBC News Productions, January, 2006.

Alternative fuels and renewable energy, Discovery Channel Canada, produced by Frances Mackinnon, March 8, 2007; aired March 29, 2007.

“The Ethanol Maze,” Nebraska Public Broadcasting System (PBS), Perry Stoner, Producer, December 2007; aired June 19, 2008.

Climate change and air pollution, Public Broadcasting System (PBS), Joy Leighton and Bob Gliner, Stanford, California, June 26, 2009.

Documentary on Renewable Energy, Future Earth/MSNBC, Helen Lambourne, Boulder City, Nevada, July 13, 2009.

Dutch Television Documentary on the Plan for a Sustainable Future, February 12, 2010.

Documentary on Energy, Peter Bromley, Dec. 10, 2010.

"Renewable Energy and the Future," MBN, South Korean Television, May 21, 2011.

“Gasland 2," Josh Fox, Director; Trish Adlesic, Producer, July 12, 2011.

"Beyond the Light Switch," co-written by Ed Moore, host David Biello, Feb. 9, 2012. (link)

"Groundswell," produced by Renard Cohen, September 3, 2012.

"The Future of Energy," produced by Maximilian DeArmon, May 3, 2013.

Canadian Broadcasting Corporation, May 10, 2013. (video)

The Climate Project, Taki Oldham and Robert Kenner, 2013

Japanese television, Miho Sakai, interviewer, December 5, 2013.

Climate Solutions Center, Carbon Pollution: Costs and Cures, James Byrne and Geoff Haines-Stiles, January 1, 2014. (video)

The Venus Project, “The choice is ours,” January 9, 2014.

Converting to wind, water, and solar, Joe Keon, March 6, 2014.

“Life on wheels,” David Hodge, March 10, 2014.

“The race to save the world,” Joe Gantz, March 17, 2014.

Micro-documentary, Marc Tamo and Natasha Giraudie, producers, March 19, 2014. (video)

Interviewed for docmentary, Josh Fox, producer, April 2, 2014.

Podcast, Charles Margolis, May 28, 2014. (video)

Documentary on clean energy, Matt Renner, World Business Academy, September 15, 2014., April 2, 2014.

Interviewed for documentary on climate solutions, Leonardo di Caprio, October 29, 2014.

Green World Rising, Leonardo di Caprio, narrator, October 30, 2014. (video)

Interviewed for documentary on renewable energy, Cecile and Daniel Raimbeau, October 3, 2014.

Interviewed for documentary on Fukushima, Yoko Kubota, October 23, 2014.

Interviewed for educational film for Children's University, Marta Przywara, January 14, 2015. (video)

Interviewed for documentary on climate change, Jacob Freydont-Attie, February 6, 2015.

Interviewed for short video on energy transition, Rebecca Sansom, June 22, 2015 (video)

Jon Bowermaster, Dear Governor Brown, August 28, 2015

National Geographic with Bill Nye, Bill Nye's global meltdown, September 8, 2015 (video)

Effects of black carbon from shipping on climate, Sarah Robertson, October 1, 2015

Podcast on 100% WWS systems, Charles Margulis, January 5, 2016 (link)

A 100 percent renewable economy, Yale Climate Connections, Peter Sinclair, May 9, 2016 (video)

Documentary for ARD German TV, Stefan Tiyavorabun, editor/director, July 17, 2016 (video)

Bill Nye, Episode 1 of Bill Nye Saves the World, National Geographic, Sony Studious, Culver City, California, October 25, 2016 (video)

From the Ashes, Sidney Beaumont, Bloomberg Philanthropies, May 16, 2017.

Climate showdown, June 5, 2017 (video)

What if everyone had access to a home that was built without damaging the planet, Sarah Bielecki, Stanford University (video)

Documentary on Oceans, Julia Barnes, May 23, 2017.

Documentary on wind turbine impacts on hurricanes, Weather or Not, Phil Paul Call, June 13, 2017.

Documentary, "The race to save the world," Joe Gantz, August 3, 2017.

Podcast, Powering the world with renewables, Molly Seltzer, September 25, 2017. (video)

Podcast, Adam Woodhall, December 18, 2017.

Interviewed for science podcast, Kishore Hari, Mother Jones, February 13, 2018. (audio)

Interviewed for documentary on 1969 Santa Barbara oil spill and today's solutions, Isaac Hernandez, July 9, 2018.

Interviewed for Simulation Series with Allen Saakyan, San Francisco, California, July 10, 2018. (video)

Interviewed for the Gist on the Green New Deal with Mike Pesca, February 8, 2019

Interviewed with Andrew Revkin, February 8, 2019 (video)

Interviewed for Time Magazine with Justin Worland, March 8, 2019, aired March 21, 2019 (video)

Cleantech podcast with Mark Z. Jacobson by Zach Shahan, Cleantechnica, March 27, 2019 (audio)

Interviewed for podcast with Peter Sinclair, April 9, 2019 (video)

Should a Green New Deal include nuclear power, Peter Sinclair, April 9, 2019 (video)

Deep Background podcast, June 20, 2019

Climate Pod podcast, November 12, 2019 (video)

Climate Pod podcast, November 12, 2019 (video)

Green New Deal roadmaps for 143 countries, podcast, Michael Barnard, January 9, 2020 (podcast)

The Weather Network, Mario Picazzo, podcast, January 14, 2020 (video)

Future Hindsight podcast on 100% clean, renewable energy and storage for everything with Mila Atmos January 23, 2020, aired April 10, 2020 (podcast)

Cleantech Talk With Mark Z. Jacobson, Part 1, by Mike Barnard, Zach Shahan, Cleantechnica, February 16, 2020 (podcast)

Cleantech Talk With Mark Z. Jacobson, Part 2, by Mike Barnard, Zach Shahan, Cleantechnica (podcast)

CFuture tech finding genius podcast: Global climate models for air pollution and climate change: Dr. Jacobson explains the importance. (podcast)

The future of renewable energy, Taking Charge Podcast, Lauren Goldfarb, Silicon Valley Clean Energy, March 2, 2020 (podcast)

Podcast on "Why we still need the Green New Deal plan for 100% clean energy," Connect the dots, Alison Rose, April 29, 2020 (podcast)

Podcast on the film, "Planet of the Humans," Harvey Wasserman, April 29, 2020.

Video podcast, The Weather Network, Chris St. Clair, Dwight Arthur, Mario Picazzo, podcast May 1, 2020 (video)

Video podcast Chris Engelbrecht, South Africa, June 3, 2020 (video)

Podcast, Staying home with Josh Fox, July 24, 2020 (video)

Part 1 Podcast Forbes Books Radio, Fusion Capitalism episode, hosted by Steve Melink, August 25, 2020 (video)

Part 2 Podcast Forbes Books Radio, Fusion Capitalism episode, hosted by Steve Melink, August 25, 2020 (video)

Green hydrogen – where is it useful, where is it not? Podcast with Zach Shahan of Cleantechnica, December 26, 2020 (audio)

Podcast: Mark Jacobson discusses how the healthcare industry can reduce its carbon footprint, Bob Berenson, February 25, 2021 (audio)

The technically human podcast with Deb Doing, February 26, 2021 (audio)

Fully Charged Podcast, Robert Llewellyn, February 28, 2021 (video)

Podcast on nuclear power, Sky News, UK, March 10, 2021

Losing Earth, Eschatology, May 6, 2021 (video)

Interview with Alexis Issaharoff on mining, Episode 1, April 21, 2022 (video)

Interview with Allexis Issaharoff, on mining, Episode 2, May 18, 2022 (video)

The climate crisis with Mark Z. Jacobson, Fully Charged Plus Podcast, Robert Llewellyn, July 24, 2022 (video)

Low-cost, low-risk all-renewable energy plans for 145 countries, Climate Money Watchdog Podcast, July 28, 2022 (audio)

Unite and heal America with Matt Matern, August 14, 2022 (video)

100% renewable energy home and movement, Nova, PBS, August 23, 2022. (video TBA)

Discussion of the Inflation Reduction Act and 100% renewables, Scholar's Circle, August 25, 2022 (audio)

Transitioning the world to 100% clean, renewable energy, Rik Brooks podcast, October 17, 2022.

History behind 100% renewable energy plans, Flanigan's Ecologic Podcast, November 2, 2022. (audio)

Podcast on climate anxiety, Scott Cooney, Cleantechnica, November 8, 2022.

Documentary on renewable energy, Azam TV, Tanzania, Hassan Mhelela, Director George Santulli, U.S. Department of State, December 8, 2022.

Podcast on No Miracles Needed, The Climate Pod, January 30, 2023. (audio)

Interviews for Television

Future Talk television, Martin Wasserman, host. Palo Alto, California, September 25, 2013. (video)

Late Show With David Letterman, New York City, October 9, 2013. (video)

The Thom Hartmann Show, February 18, 2014. (video)

Breaking the Set, Abby Martin, Anya Parampil, RTTV America, Inc., October 31, 2014. (video)

A fossil-free world is possible: How to power a warming Earth without oil, coal, or nuclear, Democracy Now with Amy Goodman, June 6, 2015. (video)

From historic California drought to deadly Indian heatwave, global warming is wreaking havoc, Democracy Now with Amy Goodman, June 6, 2015. (video)

Hawaii leaving fossil fuels by 2045, The Real News Network, June 22, 2015 (video)

May the force be with you, Climate Matters, December 15, 2015 (video)

100% clean, renewable energy plans, Periscope TV with Leilani Munter, January 15, 2016 (video)

Clean energy plans for states and countries, Stony Brook University News TV with Heidi Hutner, February 9, 2016 (video)

Interview on 100% clean energy, Canadian Broadcasting Company National News TV, February 18, 2016 (video)

Interview Global News Canada, June 12, 2016 (video)

Abby Martin, Empire Files, February 28, 2017.

Interview for NHK World Renewable Energy, Direct Talk-100% renewable energy for the world, Hideharu Watanabe, March 8, 2018. (video)

The Big Picture interview show on RT America on renewable energy, September 7, 2018. 15:20 into (video)

Interview for ONET Polish television on air pollution and renewable energy in California versus Poland, Stanford University, February 15, 2019.

Interview Live on MSNBC with Katy Tur about the Green New Deal, March 12, 2019 (video)

Interview about Camp Fire, Dena Takruri, Al Jazeera, March 31, 2019 (video)

Interview about 100% clean, renewable energy transition, Skype interview, The Real News Network, May 8, 2019 (video)

Interview about carbon capture, CNBC, June 22, 2019 (video)

Interview by Greta van Susteren on Voice of America, August 14, 2019 (video)

Future Talk television, Martin Wasserman, host. Palo Alto, California, August 28, 2019 (video)

Interview for SkyTV on solutions to climate change, Antonio Bacile, Italy, June 16, 2020 (video)

WUSA9 debate on renewables versus oil and gas, October 23, 2020 (video)

DW News Germany, on Texas power outages, February 18, 2021

CNET interview about carbon capture, February 24, 2021 (video)

Interview by NHK World-Japan public broadcast on 100% renewable energy, April 5, 2021 (video)

Explaining climate change. Interview for NHK World-Japan public broadcast on 100% renewable energy, April 5, 2021 (video)

Interview about the Biden infrastructure plan, WUSA9 (CBS affiliate), Washington D.C., April 5, 2021 (video)

Interview about whether Biden's GHG goal is realistic, WUSA9 (CBS affiliate), Washington D.C., April 22, 2021 (video)

Interview: Is the extreme heat driven by climate change, WUSA9 (CBS affiliate), Washington D.C., June 29, 2021 (video)

Interview: Are hurricanes getting more intense? WUSA9 (CBS affiliate), Washington D.C., July 14, 2021 (video)

Interview on climate change and renewable energy, Anews Channel, Turkuvas media, July 23, 2021.

Carbon capture, Wisecrack you-tube channel, October 19, 2021 (video)

BBC News, on the cost of transitioning the world to 100% WWS, Christopher Pitt, January 21, 2022.

Discussion on carbon capture, Cheddar TV, interviewed by JD Durkin, February 17, 2022 (video)

Return to mark Jacobson's Home Page

FORM A

Proceeding: EB-2022-0200

ACKNOWLEDGMENT OF EXPERT'S DUTY

1. My name is Robert W. Howarth. I live at ~~Ithica~~ Ulysses, in the state of New York.

2. I have been engaged by or on behalf of Environmental Defence, without remuneration, to provide evidence in relation to the above-noted proceeding before the Ontario Energy Board.

3. I acknowledge that it is my duty to provide evidence in relation to this proceeding as follows:

   (a) to provide opinion evidence that is fair, objective and non-partisan;

   (b) to provide opinion evidence that is related only to matters that are within my area of expertise; and

   (c) to provide such additional assistance as the Board may reasonably require, to determine a matter in issue.

4. I acknowledge that the duty referred to above prevails over any obligation which I may owe to any party by whom or on whose behalf I am engaged.

Date: May 5, 2023

____
Signature

FORM A

Proceeding: EB-2022-0200

ACKNOWLEDGMENT OF EXPERT'S DUTY

1. My name is Mark Z. Jacobson. I live at Stanford, in the state of California.

2. I have been engaged by or on behalf of Environmental Defence, without remuneration, to provide evidence in relation to the above-noted proceeding before the Ontario Energy Board.

3. I acknowledge that it is my duty to provide evidence in relation to this proceeding as follows:

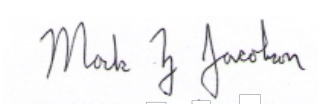
   (a) to provide opinion evidence that is fair, objective and non-partisan;

   (b) to provide opinion evidence that is related only to matters that are within my area of expertise; and

   (c) to provide such additional assistance as the Board may reasonably require, to determine a matter in issue.

4. I acknowledge that the duty referred to above prevails over any obligation which I may owe to any party by whom or on whose behalf I am engaged.

Date: May 5, 2023



Mark Z. Jacobson