BEFORE THE UNITED STATES
NUCLEAR REGULATORY COMMISSION

In the Matter of	)	
		Docket No. 50-255
Holtec Palisades LLC and Holtec Decommissioning International	)	
	)	
(Palisades Nuclear Plant		December 5, 2023
Request for Exemption)	)	

PETITION TO INTERVENE AND REQUEST FOR ADJUDICATORY HEARING BY BEYOND NUCLEAR, DON'T WASTE MICHIGAN, AND MICHIGAN SAFE ENERGY FUTURE

PETITIONERS' DECLARATION 11

Declaration of Mark Z. Jacobson, Environmental Engineer	Appendix 11

DECLARATION OF MARK Z. JACOBSON

My name is Mark Z. Jacobson. I am professor of Civil and Environmental Engineering at Stanford University. I have a B.S. with distinction in Civil Engineering from Stanford University (1988), a B.A. in Economics with distinction from Stanford University (1988), and an M.S. in Environmental Engineering from Stanford University (1988), an M.S. in Atmospheric Sciences from UCLA (1991), and a Ph.D. in Atmospheric Sciences from UCLA (1994). I started as an Assistant Professor at Stanford in 1994. I became a tenured Associate Professor in 2001 and a full Professor in 2007. Thus, I have been employed there for over 29 years.

Since 1989, I have been researching academically and professionally, the impacts of human emissions of gasses (including carbon dioxide, other greenhouse gases, and chemical air pollutants) and particles (including black and brown carbon) on air pollution, human health, weather, and climate. Starting in 1999, I began examining in detail clean, renewable energy solutions to these problems. For more details, my CV is attached.

Attached to this declaration is a section of a textbook that I wrote in 2019 regarding the evaluation of nuclear power as a viable energy source for the future. The statements made in that article are still valid and I stand by those statements.

I certify under penalty of perjury that the foregoing is true and correct to the best of my knowledge and belief.

Dated this __20th__day of ________October___________, 2023.

Mark Z Jacobson

MARK Z. JACOBSON

Evaluation of Nuclear Power as a Proposed Solution to Global Warming, Air Pollution, and Energy Security

In
Jacobson, M.Z., *100% Clean, Renewable Energy and Storage for Everything*,
Cambridge University Press, New York, 427 pp., 2020
https://web.stanford.edu/group/efmh/jacobson/WWSBook/WWSBook.html

December 22, 2019
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Summary

In evaluating solutions to global warming, air pollution, and energy security, two important questions arise are (1) should new nuclear plants be built to help solve these problems, and (2) should existing, aged nuclear plants be kept open as long as possible to help solve these problems? To answer these questions, the main risks associated with nuclear power are examined.

The risks associated with nuclear power can be broken down into two categories: (1) risks affecting its ability to reduce global warming and air pollution and (2) risks affecting its ability to provide energy and environmental (aside from climate and air pollution) security. Risks in the former category include delays between planning and operation, emissions contributing to global warming and outdoor air pollution, and costs. Risks in the latter category include weapons proliferation risk, reactor meltdown risk, radioactive waste risk, and mining cancer and land despoilment risks. These risks are discussed, in this section. Here are additional specific findings:

- New nuclear power plants cost 2.3 to 7.4 times those of onshore wind or utility solar PV per kWh, take 5 to 17 years longer between planning and operation, and produce 9 to 37 times the emissions per kWh as wind.

- As such, a fixed amount of money spent on a new nuclear plant means much less power generation, a much longer wait for power, and a much greater emission rate than the same money spent on WWS technologies.

- There is no such thing as a zero- or close-to-zero emission nuclear power plant. Even existing plants emit due to the continuous mining and refining of uranium needed for the plant. However, all plants also emit 4.4 g-CO_2e/kWh from the water vapor and heat they release. This contrasts with solar panels and wind turbines, which reduce heat or water vapor fluxes to the air by about 2.2 g-CO_2e/kWh for a net difference from this factor alone of 6.6 g-CO_2e/kWh.

- On top of that, because all nuclear reactors take 10-19 years or more between planning and operation vs. 2-5 year for utility solar or wind, nuclear causes another 64-102 g-CO_2/kWh over 100 years to be emitted from the background grid while consumers wait for it to come online or be refurbished, relative to wind or solar.

- Overall, emissions from new nuclear are 78 to 178 g-CO_2/kWh, not close to 0.

- China's investment in nuclear plants that take so long between planning and operation instead of wind or solar resulted in China's CO_2 emissions increasing 1.3 percent from 2016 to 2017 rather than declining by an estimated average of 3 percent. The resulting difference in air pollution emissions may have caused 82,000 additional air pollution deaths in China in 2016 alone, with additional deaths in years prior and since.

Table 3.5. Total 100-year CO_2e emissions from several different energy technologies. The total includes lifecycle emissions, opportunity cost emissions, anthropogenic heat and water vapor emissions, weapons and leakage risk emissions, and emissions from loss of carbon storage in land and vegetation. All units are g-CO_2e/kWh-electricity, except the last, column, which gives the ratio of total emissions of a technology to the emissions from onshore wind. CCS/U is carbon capture and storage or use.

Technology	[a]Lifecycle emissions	[b]Opportunity cost emissions due to delays	[c]Anthropogenic heat emissions	[d]Anthropogenic water vapor emissions	[e]Nuclear Weapons risk or 100-Year CCS/U leakage risk	[f]Loss of CO_2 due to covering land or clearing vegetation	**[g]Total 100-year CO_2e**	**Ratio of 100-year CO_2e to that of wind-onshore**
Solar PV-rooftop	15-34	-12 to -16	-2.2	0	0	0	**0.8-15.8**	**0.1-3.3**
Solar PV-utility	10-29	0	-2.2	0	0	0.054-0.11	**7.85-26.9**	**0.91-5.6**
CSP	8.5-24.3	0	-2.2	0 to 2.8	0	0.13-0.34	**6.43-25.2**	**0.75-5.3**
Wind-onshore	7.0-10.8	0	-1.7 to -0.7	-0.5 to -1.5	0	0.0002-0.0004	**4.8-8.6**	**1**
Wind-offshore	9-17	0	-1.7 to -0.7	-0.5 to -1.5	0	0	**6.8-14.8**	**0.79-3.1**
Geothermal	15.1-55	14-21	0	0 to 2.8	0	0.088-0.093	**29-79**	**3.4-16**
Hydroelectric	17-22	41-61	0	2.7 to 26	0	0	**61-109**	**7.1-22.7**
Wave	21.7	4-16	0	0	0	0	**26-38**	**3.0-7.9**
Tidal	10-20	4-16	0	0	0	0	**14-36**	**1.6-7.5**
Nuclear	9-70	64-102	1.6	2.8	0-1.4	0.17-0.28	**78-178**	**9.0-37**
Biomass	43-1,730	36-51	3.4	3.2	0	0.09-0.5	**86-1,788**	**10-373**
Natural gas-CCS/U	179-405	46-62	0.61	3.7	0.36-8.6	0.41-0.69	**230-481**	**27-100**
Coal-CCS/U	230-935	46-62	1.5	3.6	0.36-8.6	0.41-0.69	**282-1,011**	**33-211**

[a]Lifecycle emissions are 100-year carbon equivalent (CO_2e) emissions that result from the construction, operation, and decommissioning of a plant. They are determined as follows:

Solar PV-rooftop: The range is assumed to be the same as the solar PV-utility range, but with 5 g-CO_2/kWh added to both the low and high ends to account for the use of fixed tilt for all rooftop PV versus the use of some tracking for utility PV.

Solar PV-utility: The range is derived from Fthenakis and Raugei (2017). It is inclusive of the 17 g-CO_2/kWh mean for CdTe panels at 11 percent efficiency, the 27 g-CO_2e/kWh mean for multi-crystalline silicon panels at 13.2 percent efficiency, and the 29 gCO_2e/kWh mean for mono-crystalline silicon panels at 14 percent efficiency. The upper limit of the range is held at the mean for multi-crystalline silicon since panel efficiencies are now much higher than 13.2 percent. The lower limit is calculated by scaling the CdTe mean to 18.5 percent efficiency, its maximum in 2018.

CSP: The lower limit CSP lifecycle emission rate is from Jacobson (2009). The upper limit is from Ko et al. (2018).

Wind-onshore and wind-offshore: The range is derived from Kaldelis and Apostolou (2017).

Geothermal: The range is from Jacobson (2009) and consistent with the review of Tomasini-Montenegro et al. (2017).

Hydroelectric and wave: From Jacobson (2009).

Tidal: From Douglass et al. (2008).

Nuclear: The range of 9-70 g-CO_2e/kWh is from Jacobson (2009), which is within the Intergovernmental Panel on Climate Change (IPCC)'s range of 4-110 g-CO_2e/kWh (Bruckner et al., 2014), and conservative relative to the 68 (10-130) g-CO_2e/kWh from the review of Lenzen (2008) and the 66 (1.4-288) g-CO_2e/kWh from the review of Sovacool (2008).

Biomass: The range provided is for biomass electricity generated by forestry residues (43 gCO_2e/kWh), industry residues (46), energy crops (208), agriculture residues (291), and municipal solid waste (1730) (Kadiyala et al., 2016).

Natural gas-CCS/U: The lower bound is for the CCGT with carbon capture plant from Skone (2015), also provided in Table 3.4. The upper bound is CCGT value without carbon capture, 506 g-CO_2e/kWh from Table 3.4, multiplied by 80 percent, which is the percent of CO_2e emissions expected to be captured from the Petra Nova facility that will remain in the air over 100 years (Table 3.6).

Coal-CCS/U: The lower bound is for IGCC with carbon capture from Skone (2015). The upper bound is the coal value without carbon capture, 1,168 g-CO_2e/kWh from Table 3.6, multiplied by 80 percent, which is the percent of coal lifecycle CO_2e emissions from the Petra Nova facility that will remain in the air over 100 years (Table 3.6).

[b]Opportunity cost emissions are emissions per kWh over 100 years from the background electric power grid, calculated from Equations 3.1 and 3.2 due to (a) the longer time lag between planning and operation of one energy technology relative to another and (b) additional downtime to refurbish a technology at the end of its useful life

compared with the other technology. The planning-to-operation times of the technologies in this table are 0.5-2 years for solar PV-rooftop; 2-5 years for solar PV-utility, CSP, wind-onshore, wind-offshore, tidal, and wave; 3-6 years for geothermal; 8-16 years for hydroelectric; 10-19 years for nuclear; 4-9 years for biomass (without CCS/U), and 6-11 years for natural gas-CCS/U and coal-CCS/U (Jacobson, 2009, except rooftop PV and natural gas-CCS/U values are added and solar PV-rooftop is updated here). The refurbishment times are 0.05-1 year for solar PV-rooftop; 0.25-1 year for solar-PV-utility, CSP, wind-onshore, wind-offshore, wave, and tidal; 1-2 years for geothermal and hydroelectric; 2-4 years for nuclear, and 2-3 years for biomass, coal-CCS/U, and natural gas-CCS/U. The lifetimes before refurbishment are 15 years for tidal and wave; 30 years for solar PV-rooftop, solar PV-utility, CSP, wind-onshore, wind-offshore; 30-35 years for biomass, coal-CCS/U, and natural gas-CCS/U; 30-40 years for geothermal; 40 years for nuclear; and 80 years for hydroelectric (Jacobson, 2009). The opportunity cost emissions are calculated here relative to the utility-scale technologies with the shortest time between planning and operation (solar-PV-utility, CSP, wind-onshore, and wind-offshore). The opportunity cost emissions of the latter technologies are, by definition, zero. The opportunity cost emissions of all other technologies are calculated like in Example 3.1 while assuming a background U.S. grid emission intensity equal to 557.3 g-CO_2e/kWh in 2017. This is derived from an electricity mix from EIA (2018d) and emissions, weighted by their 100-year GWPs, of CO_2, CH_4, and N_2O from mining, transporting, processing and using fossil fuels, biomass, or uranium. The reason tidal power has opportunity cost emissions although its planning-to-operation time is the same as onshore wind is the shorter lifetime of tidal turbines than wind turbines. Thus, tidal has more down time over 100 years than do other technologies. See Section 3.2.2.1. The opportunity cost emissions of offshore and onshore wind are assumed to be the same because new projects suggest offshore wind, particularly with faster assembly techniques and with floating turbines, are easier to permit and install now than a decade ago. Although natural gas plants don't take so long as coal plants between planning and operation, natural gas combined with CCS/U is assumed to take the same time as coal with CCS/U.

[c] Anthropogenic heat emissions here include the heat released to the air from combustion (for coal or natural gas) or nuclear reaction, converted to CO_2e (see Section 3.2.2.2). For solar PV and CSP, heat emissions are negative because these three technologies reduce sunlight to the surface by converting it to electricity. The lower flux to the surface cools the ground or a building below the PV panels. For wind turbines, heat emissions are negative because turbines extract energy from wind to convert it to electricity (Section 3.2.2.3 and Example 3.6). For binary geothermal plants (low end), it is assumed all heat is re-injected back into the well. For non-binary plants, it is assumed that some heat is used to evaporate water vapor (thus the anthropogenic water vapor flux is positive) but remaining heat is injected back into the well. The electricity from all electric power generation also dissipates to heat, but this is due to the consumption rather than production of power and is the same amount per kWh for all technologies so is not included in this table.

[d] Anthropogenic water vapor emissions here include the water vapor released to the air from combustion (for coal and natural gas) or from evaporation (water-cooled CSP, water-cooled geothermal, hydroelectric, nuclear natural gas, and coal), converted to CO_2e (see Section 3.2.2.3). Air-cooled CSP and geothermal plants have zero water vapor flux, representing the low end of these technologies. The high end is assumed to be the same as for nuclear, which also uses water for cooling. The low end for hydroelectric power assumes 1.75 kg-H_2O/kWh evaporated from reservoirs at mid to high latitudes (Flury and Frischknecht, 2012). The upper end is 17.0 kg-H_2O/kWh from Jacobson (2009) for lower latitude reservoirs and assumes reservoirs serve multiple purposes. For biomass, the number is based only on the water emitted from the plant due to evaporation or combustion, not water to irrigate some energy crops. Thus, the upper estimate is low. The negative water vapor flux for onshore and offshore wind is due to the reduced water evaporation caused by wind turbines (Section 3.2.2.3 and Example 3.6).

[e] Nuclear weapons risk is the risk of emissions due to nuclear weapons use resulting from weapons proliferation caused by the spread of nuclear energy. The risk ranges from zero (no use of weapons over 100 years) to 1.4 g-CO_2e/kWh (one nuclear exchange in 100 years) (Section 3.3.2.1). The 100-year CCS/U leakage risk is the estimated rate, averaged over 100 years, that CO_2 sequestered underground leaks back to the atmosphere. Section 3.2.2.4 contains a derivation. The leakage rate from natural gas-CCS/U is assumed to be the same as for coal-CCS/U.

[f] Loss of carbon, averaged over 100 years, due to covering land or clearing vegetation is the loss of carbon sequestered in soil or in vegetation due to the covering or clearing land by an energy facility; by a mine where the fuel is extracted from (in the case of fossil fuels and uranium); by roads, railways, or pipelines needed to transport the fuel; and by waste disposal sites. No loss of carbon occurs for solar PV-rooftop, wind-offshore, wave, or tidal power. In all remaining cases, except for solar PV-utility and CSP, the energy facility is assumed to replace grassland with the organic carbon content and grass content as described in the text. For solar PV-utility and CSP, it is assumed that the organic content of both the vegetation and soil are 7 percent that of grassland because (a) most all CSP and many PV arrays are located in deserts with low carbon storage and (a) most utility PV panels and CSP mirrors are elevated above the ground. For biomass, the low value assumes the source of biomass is

industry residues or contaminated wastes. The high value assumes energy crops, agricultural residues, or forestry residues. See Section 3.2.2.5.

[g]The total column is the sum of the previous six columns.

3.3. Why Nuclear Power Represents an Opportunity Cost

In evaluating solutions to global warming, air pollution, and energy security, two important questions that arise are (1) should new nuclear plants be built to help solve these problems, and (2) should existing, aged nuclear plants be kept open as long as possible to help solve these problems? To answer these questions, the main risks associated with nuclear power are first examined.

The risks associated with nuclear power can be broken down into two categories: (1) risks affecting nuclear's ability to reduce global warming and air pollution and (2) risks affecting nuclear's ability to provide energy and environmental (aside from climate and air pollution) security. Risks under Category 1 include delays between planning and operation, emissions contributing to global warming and outdoor air pollution, and costs. Risks under Category 2 include weapons proliferation risk, reactor meltdown risk, radioactive waste risk, and mining cancer and land despoilment risks. These risks are discussed, in this section.

Nuclear fission is the process by which tiny neutrons bombard and split certain fissile heavy elements, such as **uranium-235** (**^{235}U**) or **plutonium-239** (**^{239}Pu**) in a **nuclear reactor**. The 235 and 239 refer to the isotope, or number of protons plus neutrons in the nucleus of a uranium or plutonium atom, respectively. A **fissile** element is one that can be split during fission upon neutron bombardment and whose neutrons released during splitting can split other fissile atoms in a chain reaction. Fissile elements do not spontaneously release neutrons, creating a chain reaction. Instead, they require outside neutrons bombarding them, thereby initiating a chain reaction. ^{235}U is the only fissile element found in nature. ^{239}Pu is a product of **uranium-238** (**^{238}U**) capturing a free neutron in a nuclear reactor. The resulting ^{239}U decays to ^{239}Pu, a fissile element.

When a neutron approaches ^{235}U in a nuclear reactor, the neutron may be absorbed by or pass through the atom. Fast-moving neutrons have a higher probability of passing through the atom, whereas slow-moving neutrons have a higher probability of being absorbed. If the neutron is absorbed, the uranium atom's total energy is spread among the 236 protons and neutrons now present in the atom's nucleus. The nucleus is now unstable, and some of the uranium atoms fragment into two smaller elements, whereas the remaining atoms form ^{236}U. A variety of element pairs arise from fragmentation. Two of the most common are Krypton-92 (^{92}Kr) and Barium-141 (^{141}Ba). The fragmentation, with this product pair, also produces gamma rays and three free neutrons. The overall reaction is thus

$$1\text{ neutron} + {}^{235}\text{U} \rightarrow {}^{92}\text{Kr} + {}^{141}\text{Ba} + 3\text{ neutrons} + \text{gamma rays} \qquad (3.10)$$

The new neutrons may then collide with other ^{235}U atoms or with ^{239}Pu atoms, splitting them in a chain reaction. When the fragments and the gamma rays collide with water, the collision converts kinetic energy and electromagnetic energy, respectively, to massive amounts of heat.

In a **boiling water reactor** (**BWR**) **nuclear power plant**, the heat boils water directly. The high-pressure steam turns a turbine connected to a generator to produces electricity. The steam is then re-condensed to liquid water in a condenser, and the liquid water is returned back to the reactor core. In the condenser, heat from the steam is transferred to a separate (in an enclosed pipe) stream of cooling water that originates from a lake, river, or the coastal ocean. The warmed water is then returned to where it originated from, warming the outdoor water body, creating thermal pollution. Other thermal power plants, such as those running on coal, oil, or gas, similarly warm water bodies.

In a **pressurized water reactor** (**PWR**) plant, the air pressure in the reactor is increased substantially, up to 155 bar (air pressure at Earth's surface is 1 bar). Because the boiling point of water increases with increasing atmospheric pressure, water in the reactor doesn't boil, even though the temperature in the reactor reaches 282 ^{o}C (at Earth's surface, water usually boils at 100 ^{o}C). The hot water in the reactor, which is radioactive, passes through a pipe and exchanges its heat with a different batch of water maintained at normal air pressure, causing the latter water to boil. The boiling water creates steam to run a steam turbine. The water batches are kept separate to ensure radioactive material in the high-pressure reactor does not pass through to the water vapor running through the steam turbine. BWR and PWR reactors are both **light water reactors** (**LWRs**), which are reactors that use normal water.

Uranium in a nuclear power plant is originally stored in small ceramic pellets within a metal fuel rod, often 3.7-m long. A conventional BWR or PWR nuclear reactor will go through one rod after about six years, and the rod and remaining material in it become radioactive waste. Reactors that use rods once are referred to as **once-through** reactors. The radioactive waste in the fuel rod must be stored for several hundred thousand years.

A fuel rod that has gone through a fission reactor once still has 99 percent of its uranium left over, including slightly more ^{235}U than natural uranium. This remaining uranium and its fission product, plutonium, can be extracted and reprocessed for use in a **breeder reactor**, extending the life of a given mass of uranium and reducing waste significantly. However, the reprocessing increases both the cost and the production of ^{239}Pu by the collision of ^{238}U with fast moving neutrons. Breeder reactors can thus be optimized to produce ^{239}Pu for use in nuclear weapons (Karam, 2006), so they are a concern with respect to weapons proliferation.

As of 2019, over 400 active nuclear reactors provide electric power among 31 countries. Only two of these reactors are breeder reactors. For this number of reactors, uranium mines produce about 60,000 tonnes of uranium per year (World Nuclear Association, 2019). Uranium reserves (aside from hard-to-extract uranium in seawater) as of 2015 were about 7.6 million tonnes. This suggests that about 127 years of uranium are available for current once-through fuel cycle reactors at near-current rates of uranium use. As such, even if the issues discussed below were not issues, uranium is a limited resource, and growing nuclear power will deplete uranium faster.

An alternative fuel to uranium in nuclear reactors is thorium. **Thorium**, like uranium, can be used to produce nuclear fuel in a breeder reactor. The advantage of thorium is that it produces less long-lived radioactive waste than does uranium. Its products are also more difficult to convert into nuclear weapons material. However, thorium still produces ^{232}U, which was used in one nuclear bomb core produced during the **Operation Teapot** bomb tests in 1955. Thus, thorium is not free of nuclear weapons proliferation risk. In addition, thorium reactors require the same long time lag between planning and operation as uranium reactors (Section 3.3.1.1) and most likely longer because hardly any contractors or scientists have experience building or running thorium reactors. Thus, thorium reactors will produce greater emissions from the background electric grid compared with WWS technologies, which have a shorter time lag. Finally, lifecycle emissions of carbon from a thorium reactor are similar to those from a uranium reactor.

A proposed alternative to the large once-through reactor and the breeder reactor is the **small modular reactor (SMR)**. SMRs are nuclear fission reactors that are much smaller than a traditional reactor and prefabricated in a factory. The purpose of prefabricating much of the reactor is to reduce construction time, costs, and mistakes during construction. The reactor would then be moved to its final site, where construction would be completed. Many types of SMRs have been proposed, including miniature versions of current reactors as well as new designs.

One type of new design is a **fast reactor**, in which the fuel is reformulated to allow fast-moving neutrons, rather than slow-moving neutrons, to split an atom. One way to do this is to increase ^{239}Pu, which absorbs more fast-moving neutrons than does ^{235}U. Fast reactors can be turned into breeder reactors by surrounding the core with ^{238}U, which absorbs a fast-moving neutron to become ^{239}U, which decays to ^{239}Pu.

Whereas slow reactors still produce significant radioactive waste, fast reactors produce less waste but also increase the potential for nuclear weapons proliferation by producing more ^{239}Pu. Because slow and fast SMRs are small and modular, many countries that don't currently have nuclear energy facilities could more readily purchase them, increasing the risk of nuclear weapons proliferation. Most SMRs also have meltdown risk. They also require uranium. Slow reactors have the same resource limitation, lung cancer risk, and land despoilment risk associated with uranium mining as do non-SMRs (Section 3.3.2.4). Finally, because SMRs have not been commercialized to date, their emissions, time lag between planning and operation, and cost are still not known.

Finally, **nuclear fusion** of light atomic nuclei (e.g., protium, deuterium, or tritium) could theoretically supply power indefinitely without long-lived radioactive waste because the products are isotopes of helium. However, little prospect exists for fusion to be commercially available for at least 50 to 100 years, if ever.

Nuclear power from fission first became a source of electric power in the 1950s. The first nuclear power plant to produce electricity was an experimental reactor in Arco, Idaho. On December 20, 1951, it powered four light bulbs. On June 26, 1954, a 5 MW nuclear reactor was connected to the electric power grid for industrial use in Obninsk, Russia. Subsequently, on August 27, 1956, a 50 MW reactor was connected to the grid for commercial use in Windscale, England.

Below, the risks associated with nuclear power are discussed in detail.

3.3.1. Risks Affecting the Ability of Nuclear Power to Address Global Warming and Air Pollution

The first category of risk associated with nuclear power includes risks affecting nuclear power's ability to reduce global warming and air pollution. These risks include the long lag times between planning and operating and to refurbish a nuclear reactor, nuclear's high carbon equivalent emissions relative to WWS technologies, and nuclear's high cost.

3.3.1.1. Delays Between Planning and Operation and due to Refurbishing Reactors

The longer the time lag between the planning and operation of an energy facility, the more the air pollution and climate-relevant emissions from the background electric power grid (Section 3.2.2). Similarly, the longer the time required to refurbish a plant for continued use at the end of its life, the greater the emissions from the background grid while the plant is down.

The time lag between planning and operation of a nuclear power plant includes the times to obtain a construction site, a construction permit, an operating permit, financing, and insurance; the time between construction permit approval and issue; and the construction time of the plant.

In March 2007, the United States Nuclear Regulatory Commission approved the first request for a site permit in 30 years. This process took 3.5 years. The time to review and approve a construction permit is another 2 years and the time between the construction permit approval and issue is about 0.5 years. Thus, the minimum time for preconstruction approvals (and financing) in the United States is 6 years. An estimated maximum time is 10 years. The time to construct a nuclear reactor depends significantly on regulatory requirements and costs. Although nuclear reactor **construction times** worldwide are often shorter than the 9-year median construction times in the United States since 1970 (Koomey and Hultman, 2007), they averaged 7.4 years worldwide in 2015 (Berthelemy and Rangel, 2015). As such, a reasonable estimated range for construction time is 4 to 9 years, bringing the overall time between planning and operation of a nuclear power plant worldwide to 10 to 19 years.

An examination of some recent nuclear plant developments confirms that this range is not only reasonable, but an underestimate in at least one case. The **Olkiluoto 3** reactor in Finland was proposed to the Finnish cabinet in December 2000 to be added to an existing nuclear power plant. Its latest estimated completion date is 2020, giving a **planning-to-operation** (**PTO**) time of 20 years. The **Hinkley Point** nuclear plant was planned, starting in 2008. Construction began only on December 11, 2018. It has an estimated completion year of 2025 to 2027, giving it a PTO time of 17 to 19 years. The **Vogtle 3 and 4** reactors in Georgia were first proposed in August 2006 to be added to an existing site. The anticipated completion dates are November 2021 and November 2022, respectively, given them PTO times of 15 and 16 years, respectively. Their construction times will be 8.5 and 9 years, respectively. The **Flamanville**, France, Unit 3 reactor was planned on an existing nuclear site starting in 2004. A contract was awarded in 2005. Construction started in 2007 but is not expected to be completed until 2023, for a construction time of 16 years and PTO time of 19 years. The **Haiyang 1 and 2** reactors in China were planned starting in 2005. Construction started in 2009 and 2010, respectively. Haiyang 1 began commercial operation on October 22, 2018. Haiyang 2 began operation on January 9, 2019, giving them construction times of 9 years and PTO times of 13 and 14 years, respectively. The **Taishan 1 and 2** reactors in China were bid in 2006. Construction began in 2008. Taishan 1 began commercial operation on December 13, 2018. Taishan 2 began operation on September 9, 2019, giving them construction times of 10 and 11 years and PTO times of 12 and 13 years, respectively. Planning and procurement for four reactors in **Ringhals**, Sweden started in 1965. One took 10 years, the second took 11 years, the third took 16 years, and the fourth took 18 years to complete. In sum, PTO times for both recent and historic nuclear plants have mostly been in the range of 10 to 19 years.

Some contend that France's 1974 Messmer Plan resulted in the building of its 58 reactors in 15 years. The **Messmer Plan** was a proposal, enacted without public or parliamentary debate, by the Prime Minister of France, Pierre Messmer, to build 80 nuclear reactors by 1985 and 170 by 2000. In fact, the plan had been in the works for years prior and was only proposed publicly following the international oil crisis of 1973 (Morris, 2015). For example, the Fessenheim nuclear reactor obtained its construction permit in 1967 and was planned before that. In addition, 10 of the reactors were completed only between 1991 and 2000. As such, the whole planning-to-operation time for the 58 reactors was at least 33 years, not 15. That of any individual reactor was 10 to 19 years.

Planning-to-operation delays are not the only cause of background emissions associated with nuclear power or any other energy technology. Nuclear reactors have an expected lifetime on the order of 40 years. To run longer, they need to be refurbished. An estimate of the time to refurbish a nuclear reactor is 2-4 years. Refurbishment of the Darlington 2, Ontario nuclear reactor, for example, began in October 2016 and is scheduled to take 3 years and 4 months (World Nuclear News, 2018).

Equations 3.1 and 3.2 provide an estimate of the opportunity cost CO$_2$e emissions resulting from emissions from the background due to a nuclear power plant's long PTO time and refurbishment time. Table 3.5 provides an overall estimate of this opportunity cost emissions as 64 to 102 g-CO$_2$e/kWh, which is higher than nuclear's lifecycle emissions. Opportunity cost emissions also include health-affecting air pollution emissions.

Transition highlight. Example 3.11 illustrates how China's investment in nuclear plants, which have long planning-to-operation times, instead of wind power resulted in China's CO$_2$ emissions rising 1.3 percent from 2016 to 2017 rather than declining by an estimated average of 3 percent during that period. A similar result would be found if China invested in solar instead of nuclear.

The health impacts of such delays in China are substantial. In 2016, 1.9 million people died of from air pollution particles and gases in China (Table 7.14). Assuming that air pollution emissions are proportional to CO$_2$ emissions, **82,000 (1.9 million × 4.3 percent) more people may have died in 2016 alone due to China's investment in nuclear instead of wind or solar**. Additional deaths likely occurred prior and since. Thus, opportunity-cost emissions affect both climate and health.

Example 3.11. Did construction of nuclear plants in China cause its emissions to rise between 2016 and 2017?
Between 2016 and 2017, the CO$_2$ emission rate in China (including Hong Kong) increased by 121 million metric tonnes (MT), or 1.3 percent, over its 2016 emission rate of 9,310 MT-CO$_2$ (British Petroleum, 2018). During that period, China had 14 GW of nuclear power under construction, with planning for all the plants starting before 2012. The capital cost of a new nuclear power plant ranges from \$6,500/kW to \$12,250/kW, whereas that of a new wind turbine ranges from \$1,150/kW to \$1,550/kW (Lazard, 2018). Assuming the capital for the nuclear plants had been invested in wind instead and the wind turbines had been installed prior to 2017 (because the planning to operation time of wind is 2 to 5 years versus 10 to 19 years for nuclear), estimate the 2017 CO$_2$ emissions that would have been avoided. Assume the wind turbine capacity factor ranges from 0.3 to 0.37 and that the CO$_2$ emission intensity of the grid in China is between 850 and 900 g-CO$_2$/kWh (Li et al., 2017).

Solution:
Dividing the high (and low) capital cost of nuclear per kW by the low (and high) capital cost of wind per kW and multiplying the result by 14 GW gives a range of 58.7 to 149 GW nameplate capacity of wind that could have been installed and running prior to 2017. Multiplying by the capacity factor range of wind and 8,760 hours per year and dividing by 1,000 GW per TW gives the annual energy output of the wind that could have been installed as 154 to 483 TWh/y. Multiplying this range by the CO$_2$ emission intensity that wind would have avoided, 850 to 900 g-CO$_2$/kWh, and by 10^9 kWh/TWh, and dividing by 10^{12} g/MT gives 131 to 435 MT-CO$_2$/y avoided. In other words, investing in wind instead of nuclear would have resulted in China decreasing its CO$_2$ emissions by about 1.4 to 4.7 percent (for an average of 3.0 percent) instead of increasing it by 1.3 percent. As such, investing in nuclear has caused an opportunity cost CO$_2$ emission in China.

3.3.1.2. Air Pollution and Global Warming Relevant Emissions From Nuclear

Nuclear power contributes to global warming and air pollution in the following ways: (1) emissions of air pollutants and global warming agents from the background grid due to its long planning-to-operation and refurbishment times (Section 3.2.2.1); (2) **lifecycle emissions** of air pollutants and global warming agents during construction, operation, and decommissioning of a nuclear plant; (3) heat and water vapor emissions during the operation of a nuclear plant (Sections 3.2.2.2 and 3.2.2.3); (4) carbon dioxide emissions due to covering soil or clearing vegetation during the construction of a nuclear plant, uranium mine, and waste site (Section 3.2.2.5); and (5) the emissions risk of air pollutants and global warming agents due to nuclear weapons proliferation (Section 3.3.2.1).

Every one of these categories represents an actual emission or emission risk, yet most of these emissions, except for lifecycle emissions, are incorrectly ignored in virtually all studies of nuclear energy impacts on climate. Virtually no study considers the impact of nuclear energy on air pollution mortality. By ignoring these factors, studies distort the impacts on climate and air pollution health associated with some technologies over others.

Table 3.5 summarizes the CO_2e emissions from nuclear power from each of the five categories just described. The table indicates that the opportunity cost emissions of nuclear (64 to 102 g-CO_2e/kWh) are higher than the lifecycle emissions (9 to 70 g-CO_2e/kWh). The range of lifecycle emissions estimated in Table 3.5 for nuclear power is well within the "*range of harmonized lifecycle greenhouse gas emissions reported in the literature*," 4 to 110 g-CO_2e/kWh, from the Intergovernmental Panel on Climate Change review (Bruckner et al., 2014, p. 540). It is also conservative relative to the 68 (10 to 130) g-CO_2e/kWh from the review of Lenzen (2008) and relative to the 66 (1.4 to 288) g-CO_2e/kWh from the review of Sovacool (2008).

Emissions from the heat and water vapor fluxes from nuclear (totaling 4.4 g-CO_2-kWh) alone suggest that during the life of an existing nuclear power plant, **nuclear can never be a zero-carbon-equivalent technology**, even if its lifecycle emissions from mining and refining uranium were zero. On the other hand, the emissions from nuclear due to covering and clearing soil are relatively small (0.17 to 0.28 g-CO_2e/kWh). Finally, Table 3.5 provides a low estimate (zero) and a high estimate (1.4 g-CO_2e/kWh) for the 100-year risk of CO_2e emissions associated with nuclear weapons proliferation due to nuclear energy. These numbers are derived in Section 3.3.2.1.

The total CO_2e emissions from nuclear power in Table 3.5 are 78 to 178 g-CO_2e/kWh. These emissions are 9 to 37 times the CO_2e emissions from onshore wind power. The ratio of health-affecting air pollutant emissions from nuclear relative to onshore wind is 7 to 25. This is determined by considering only the lifecycle, opportunity cost, and weapons proliferation emissions from nuclear and wind in Table 3.5.

Although the emissions from nuclear are lower than from coal or natural gas with carbon capture, nuclear power's high CO_2e emissions coupled with its long planning-to-operation time render it an opportunity cost relative to the faster-to-operate and lower-emitting alternative WWS technologies (Jacobson, 2009).

3.3.1.3. Nuclear Costs

The third risk of nuclear power related to its ability to reduce global warming and air pollution is the high cost for a new nuclear reactor relative to most WWS technologies. In addition, the cost of running existing nuclear reactors has increased significantly, and the costs of new WWS technologies have dropped so much, that many existing reactors are shutting down early due to high costs. Others have requested large subsidies to stay open. In this section, nuclear costs are discussed briefly.

The levelized cost of energy (LCOE) for a new nuclear plant in 2018, based on calculations by Lazard (2018), is $151 (112 to 189)/MWh, where $100/MWh equals 10 ¢/kWh. This compares with $43 (29 to 56)/MWh for onshore wind and $41 (36 to 46)/MWh for utility-scale solar PV from the same source (Table 7.9). A good portion of the high cost of nuclear is related to its long planning-to-operation time, which in turn is partly due to construction delays.

This nuclear LCOE is an underestimate for several reasons. First, Lazard assumes a construction time for nuclear of 5.75 years. However, the Vogtle 3 and 4 reactors, though will take at least 8.5 to 9 years to finish construction. This additional delay alone results in an estimated LCOE for nuclear of about $172 (128 to 215)/MWh, or a cost 2.3 to 7.4 times that of an onshore wind farm (or utility PV farm).

Next, the LCOE does not include the cost of the major nuclear meltdowns in history. For example, the estimated cost to clean up the damage from three Fukushima Dai-ichi nuclear reactor core meltdowns in 2011 (Section 3.3.2.2) was $460 to $640 billion (Denyer, 2019). This is equivalent to a mean of about $1.2 billion, or 10 to 18.5 percent of the capital cost, of every nuclear reactor that exists worldwide.

In addition, the LCOE does not include the cost of storing nuclear waste for hundreds of thousands of years. In the U.S. alone, about $500 million is spent yearly to safeguard nuclear waste from about 100 civilian nuclear energy plants (Garthwaite, 2018). This amount will only increase as waste continues to accumulate. After the plants retire, the spending must continue for hundreds of thousands of years with no revenue stream from electricity sales to pay for the storage.

The spiraling cost of new nuclear plants in recent years has resulted in the cancelling of several nuclear reactors under construction (e.g., two reactors in South Carolina) and in requests for subsidies to keep construction projects alive (e.g., the two Vogtle reactors in Georgia). High costs have also reduced the number of new constructions to a crawl in liberalized markets of the world. However, in some countries, such as China, nuclear reactor growth continues due to large government subsidies, albeit with a 10- to 19-year time lag between planning and operation (Section 3.3.1.1) and escalating costs.

In sum, before accounting for meltdown damage and waste storage, **a new nuclear power plant costs 2.3 to 7.4 times that of an onshore wind farm (or utility PV farm), take 5 to 17 years longer between planning and operation, and produces 9 to 37 times the emissions per unit electricity generated**. Thus, a fixed amount of money spent on a new nuclear plant means much less power generation, a much longer wait for power, and much greater emission rate than the same money spent on WWS technologies.

The Intergovernmental Panel on Climate Change similarly concluded that the economic, social, and technical feasibility of nuclear power have not improved over time,

> "*The political, economic, social and technical feasibility of solar energy, wind energy and electricity storage technologies has improved dramatically over the past few years, while that of nuclear energy and Carbon Dioxide Capture and Storage (CCS) in the electricity sector has not shown similar improvements."* (de Coninck et al., 2018, page 4-5)

Costs of existing operating nuclear plants have also escalated tremendously, forcing some plants either to shut down early or request large subsidies to stay open. Whether an existing nuclear plant should be subsidized to stay open should be evaluated on a case-by-case basis. The risk of shutting a functioning nuclear plant is that its energy may be replaced by higher-emitting fossil fuel generation. However, the risk of subsidizing the plant is that the funds could otherwise be used immediately to replace the nuclear plant with lower-cost and lower-emitting wind or solar electricity generation. Because the nuclear plant would usually need to be replaced within a decade in any case, simply incurring the cost of new renewables now will almost always be less expensive than spending the same money on renewables in ten years and paying nuclear a subsidy today.

For example, in 2016, three existing upstate New York nuclear plants requested and received subsidies to stay open using the argument that the plants were needed to keep emissions low. However, Cebulla and Jacobson (2018) found that subsidizing such plants may increase carbon emissions and costs relative to replacing the plants with wind or solar. For different nuclear plants and subsidy levels, the results could change, which is why each plant needs to be evaluated individually.

3.3.2. Risks Affecting the Ability of Nuclear Power to Address Energy and Environmental Security

The second category of risk related to nuclear power is the risk of the plant not being able to provide stable energy and environmental security. One reason for this is the risk of nuclear meltdown. Others are its risks of increasing weapons proliferation, radioactive waste exposure, and damage (cancer and land degradation) due to uranium mining. WWS technologies do not have these risks.

3.3.2.1. Weapons Proliferation Risk

The first risk of nuclear power related to energy and environmental security is weapons proliferation risk. The growth of nuclear energy has historically increased the ability of nations to obtain or harvest plutonium or enrich uranium to manufacture nuclear weapons. As stated by Fuhrmann (2009),

> "*Peaceful nuclear cooperation and nuclear weapons are related in two key respects. First, all technology and materials related to a nuclear weapons program have legitimate civilian applications. For example, uranium enrichment and plutonium reprocessing facilities are dual-use in nature because they can be used to produce fuel for power reactors or fissile material for nuclear weapons. Second, civilian nuclear cooperation builds-up a knowledge-base in nuclear matters*."

The Intergovernmental Panel on Climate Change recognizes this fact. They conclude, with "*robust evidence and high agreement*" that nuclear weapons proliferation concern is a barrier and risk to the increasing development of nuclear energy:

> "*Barriers to and risks associated with an increasing use of nuclear energy include* ***operational risks*** *and the associated safety concerns,* ***uranium mining risks****, financial and regulatory risks,* ***unresolved waste management issues, nuclear weapons proliferation concerns****, and adverse public opinion).* (Bruckner et al., 2014, Executive Summary, p. 517).

The building of a nuclear reactor for energy in a country that does not currently have a reactor increases the risk of nuclear weapons development in that country. Specifically, it allows the country to import uranium for use in the nuclear energy facility. If the country so chooses, it can secretly enrich the uranium to create weapons grade uranium as well as harvest plutonium from uranium fuel rods used in a nuclear reactor, for nuclear weapons. This does not mean any or every country will do this, but historically some have, and the risk is high, as noted by IPCC.

The next risk is whether a nuclear weapon developed in this manner is used. That risk also ranges from zero to some risk. If a weapon is used, it may kill 2 to 20 million people and burn down a megacity, releasing substantial emissions. As such, beyond the horrible risk of loss of human life, there is a risk of zero to some nonzero emission rate from nuclear weapons proliferation resulting from nuclear energy proliferation. This risk is quantified later in this section. First, the difference between weapons grade and reactor grade uranium and plutonium is described.

Uranium ore is mined in an open pit or underground and contains 0.1 to 1 percent uranium by mass. The ore is milled to concentrate the uranium in the form of a yellow power called **yellowcake**, which contains about 80 percent uranium oxide. Uranium is then processed further into uranium dioxide or uranium hexafluoride for use in nuclear reactors. However, before the uranium can be used in a reactor, it must first be enriched.

Of all uranium on Earth, 99.2745 percent is ^{238}U, 0.72 percent is ^{235}U, and 0.0055 percent is ^{234}U. Thus, less than 1 percent is ^{235}U. ^{238}U has a half-life of 4.5 billion years. Most commercial light water nuclear reactors use uranium consisting of 3 to 5 percent ^{235}U. As such, the concentration of ^{235}U in the uranium fuel rod must be increased from its ore concentration. This is done by enrichment. **Uranium enrichment** is the process of separating the isotopes of uranium to increase the percent of ^{235}U in a batch. Enriched uranium is useful for both nuclear energy and nuclear weapons.

Enrichment is done either by gas diffusion, centrifugal diffusion, or mass separation by magnetic field. Only gas diffusion and centrifugal diffusion are commercial processes, and most enrichment today is by **centrifugal diffusion** because it consumes only 2 to 2.5 percent the energy as gas diffusion. Nevertheless, centrifugal diffusion still requires many centrifuges running for long periods, thus lots of energy. Centrifugal diffusion works by spinning a cylindrical container containing uranium. The heavier ^{238}U atoms collect toward the outside edge of the cylinder and the lighter ^{235}U atoms collect toward the inside.

Uranium with less than 20 percent ^{235}U is called **low enriched uranium**. **Highly enriched uranium** contains 20 to 90 percent ^{235}U. A nuclear weapon can be made with highly enriched uranium. However, weapons increase their destructiveness with more enrichment. Thus, ninety percent or more ^{235}U is considered **weapons grade uranium** and is generally used with enriched plutonium in a nuclear bomb. An estimated 9,000 centrifuges can produce enough weapons grade ^{235}U for one nuclear weapon from natural uranium in about seven months. With 5,000 centrifuges, the process takes about one year (IranWatch, 2015). Because uranium in a fuel rod used for nuclear energy has only 3 to 5 percent ^{235}U and even less once it goes through a nuclear reactor, spent fuel rods are not considered a useful source of weapons grade uranium.

Plutonium is also used in nuclear weapons. 10 kg of ^{239}Pu was used in the bomb dropped on Nagasaki. Plutonium can be obtained from a once-through nuclear reactor running on a reactor grade uranium fuel rod. When ^{235}U decays and releases neutrons in a nuclear reactor, a neutron can bind with a ^{238}U atom to produce ^{239}U, which decays to produce ^{239}P. Plutonium that is 93 percent or more ^{239}Pu is considered weapons grade plutonium. Plutonium less than 80 percent plutonium is reactor grade. Because any plutonium can be used to make a bomb and is easier to obtain than enriching uranium (since plutonium can be harvested from a fuel rod running through a nuclear reactor), plutonium is considered the element of even greater concern than uranium with respect to nuclear weapons proliferation.

A large-scale worldwide increase in nuclear energy facilities would exacerbate the risk of nuclear weapons proliferation. In fact, producing material for a weapon requires merely operating a civilian nuclear power plant together with a sophisticated plutonium separation facility. The historic link between nuclear energy facilities and weapons is evidenced by the development or attempted development of weapons capabilities secretly under the guise of peaceful civilian nuclear energy or nuclear energy research programs in Pakistan, India, Iraq (prior to 1981), Syria (prior to 2007), Iran, and, North Korea, among other countries.

If the world's all-purpose energy were converted to electricity and electrolytic hydrogen by 2050, the ~9 trillion watts (TW) in resulting annual average end-use electric power demand would require about 12,500 850-MW nuclear reactors (31 times the number of active reactors today), or one installed every day for 34 years. Not only is this construction time impossible given the long PTO of nuclear, but it would also result in all known reserves of uranium worldwide for once-through reactors running out in about three years. As such, there is no possibility the world will run solely on once-through nuclear energy by 2050.

Even if only 6.4 percent of the world's energy were supplied with nuclear, the number of active nuclear reactors worldwide would nearly double to around 800. Many more countries would possess nuclear reactors, increasing the risk that some of these countries would use the facilities to mask the development of nuclear weapons, as has occurred historically.

If a country were to develop a weapon as a result of its acquisition of one or more nuclear energy facilities, the risk that it would use the weapons is not zero. Here, the emissions associated with a limited nuclear exchange are quantified.

The explosion of fifty 15-kilotonne nuclear devices (a total of 1.5 megatonne, or 0.1 percent of the yield of a full-scale nuclear war) during a limited nuclear exchange in a megacity would kill 2.6 to 16.7 million people from the explosion and burn 63 to 313 Tg of city infrastructure, adding 1 to 5 Tg of warming and cooling aerosol particles to the atmosphere, including much of it to the stratosphere (Jacobson, 2009). The particle emissions would cause significant short- and medium-term regional temperature changes. The CO_2 emissions would cause long-term warming. The CO_2 emissions from such a conflict are projected to be 92 to 690 Tg-CO_2.

The annual electricity production due to nuclear energy in 2017 was 2,506 TWh/y. If that doubled to 5,000 TWh/y and if one nuclear exchange, as described above, resulted during a 100 year period, the net carbon emissions due to nuclear weapons proliferation caused by the expansion of nuclear energy worldwide would be 0.2 to 1.4 g-CO_2/kWh. This calculation assumes that the total energy generation is 5,000 TWh/y multiplied by 100 years. The resulting emission rate depends on the probability of a nuclear exchange over a given period and the strengths of nuclear devices used. The probability is bounded between 0 and 1 exchange over 100 years to give the range of possible emissions for one such event as 0 to 1.4 g-CO_2e/kWh, which is the emission rate used in Table 3.5.

3.3.2.2. Meltdown Risk

The second risk of nuclear power related to energy security is meltdown risk. As stated in Section 3.3.2.1, the Intergovernmental Panel on Climate Change points to **operational risks** (meltdown) as a barrier and risk associated with nuclear power.

Through 2019, about 1.5 percent of all nuclear reactors operating in history have had a partial or significant core meltdown. To date, meltdowns at nuclear power plants have been either catastrophic (Chernobyl, Russia in 1986; three reactors at Fukushima Dai-ichi, Japan in 2011) or damaging (Three-Mile Island, Pennsylvania in 1979; Saint-Laurent France in 1980). The nuclear industry has proposed new reactor designs that they suggest are safer. However, these designs are generally untested, and there is no guarantee that the reactors will be designed, built and operated correctly or that a natural disaster or act of terrorism, such as an airplane flown into a reactor, will not cause the reactor to fail, resulting in a major disaster.

On March 11, 2011, an earthquake measuring 9.0 on the Richter scale, and the subsequent tsunami that knocked out backup power to a cooling system, caused six nuclear reactors at the **Fukushima 1 Dai-ichi plant** in northeastern Japan to shut down. Three reactors experienced a significant meltdown of nuclear fuel rods and multiple explosions of hydrogen gas that had formed during efforts to cool the rods with seawater. Uranium fuel rods in a fourth reactor also lost their cooling. As a result, cesium-137, iodine-131, and other radioactive particles and gases were released into the air. Locally, tens of thousands of people were exposed to the radiation, and 170,000 to 200,000 people were evacuated from their homes. 1,600 to 3,700 people perished during the evacuation alone (Johnson, 2015; Denyer, 2019). At least one nuclear plant worker died from lung cancer from direct radiation exposure (BBC News, 2018).

The radiation release created a dead zone around the reactors that may not be safe to inhabit for decades to centuries. The radiation also poisoned the water and food supplies in and around Tokyo. The radiation plume from the plant spread worldwide within a week. Radioactivity spread worldwide, although levels in Japan within 100 km of the plant were extremely high, those in the rest of Japan and eastern China were lower, and those in North America and Europe were even lower (Ten Hoeve and Jacobson, 2012). It is estimated that 130 (15 to 1,100) cancer related mortalities and 180 (24 to 1,800) cancer-related morbidities will occur worldwide, primarily in eastern Asia, over the next several decades due to the meltdown (Ten Hoeve and Jacobson, 2012). The cost of the cleanup of the Fukushima reactors and the surrounding area is estimated at $460 to $640 billion (Denyer, 2019), equivalent to about $1.2 billion for every nuclear reactor that exists worldwide.

The 1.5 percent risk of a catastrophe due to nuclear power plants is a high risk. Catastrophic risks with all WWS technologies aside from large hydropower (due to the risk of dam collapse) are zero. WWS roadmaps do not call for an increase in the number of large hydropower dams worldwide, only a more effective use of existing ones.

3.3.2.3. Radioactive Waste Risks

Another risk associated with nuclear power is the risk of human and animal exposure to radioactivity from fuel rods consumed by once-through nuclear reactors. Such fuel rods, once consumed, are considered **radioactive waste**. Currently, most fuel rods are stored at the same site as the reactor that consumed them. This has given rise to hundreds of radioactive waste sites in many countries that must be maintained for at least 200,000 years, far beyond the lifetimes of any nuclear power plant. Plans in the United States, which houses about one quarter of all nuclear reactors worldwide, to store the waste inside of Yucca Mountain, have not been approved. The more nuclear waste accumulates, the greater the risk of radioactive leaks, which can damage water supply, crops, animals, and humans.

3.3.2.4. Uranium Mining Health Risks and Land Degradation

The final risks discussed related to nuclear power are the risk of lung cancer by miners and land degradation due to uranium mining. Such risks continue so long as nuclear power plants continue to operate because the plants need uranium to produce electricity. WWS technologies, on the other hand, do not require the continuous mining of any material, only one-time mining to produce the WWS devices. As such, WWS technologies do not have this risk.

Uranium mining causes lung cancer in large numbers of miners because uranium mines contain natural radon gas, some of whose decay products are carcinogenic. Several studies have found a link between high radon levels and cancer (e.g., Henshaw et al., 1990; Lagarde et al., 1997). A study of 4,000 uranium miners between 1950 and 2000 (CDC, 2000) found that 405 (10 percent) died of lung cancer, a rate six times that expected based on smoking rates alone. 61 others died of mining related lung diseases, supporting the hypothesis that uranium mining is unhealthy. In fact, the combination of radon and cigarette smoking increases lung cancer risks above the normal risks associated with smoking (Hampson et al., 1998). Clean, renewable energy does not have this risk because (a) it does not require the continuous mining of any material, only one-time mining to produce the energy generators; and (b) the mining does not carry the same lung cancer risk that uranium mining does.

Radon (**Rn**) is a radioactive but chemically unreactive, colorless, tasteless, and odorless gas that forms naturally in soils. The source of radon gas is the radioactive decay of ^{238}U. Radon formation from uranium involves a long sequence of radioactive decay processes. During radioactive decay of an element, the element spontaneously emits radiation in the form of an alpha (α) particle, beta (β) particle, or gamma (γ) ray. An **alpha particle** is the nucleus of a helium atom, which is made of two neutrons and two protons. It is the least penetrating form of radiation and can be stopped by a thick piece of paper. Alpha particles are not dangerous unless the emitting substance is inhaled or ingested. A **beta particle** is a high-velocity electron. Beta particles penetrate deeper than do alpha particles, but less than do other forms of radiation, such as gamma rays. A **gamma ray** is a highly energized, deeply penetrating photon emitted from the nucleus of an atom not only during nuclear fusion (e.g., in the sun's core), but also sometimes during radioactive decay of an element.

The French physicist **Antoine Henri Becquerel** (1871 to 1937) discovered radioactive decay on March 1, 1896. Becquerel placed a uranium-containing mineral on top of a photographic plate wrapped by thin, black paper. After letting the experiment sit in a drawer for a few days, he developed the plate and found that it had become fogged by emissions, which he traced to the uranium in the mineral. He referred to the emissions as **metallic phosphorescence**. What he had discovered was the emission of some type of particle due to radioactive decay. He repeated the experiment by placing coins under the paper and found that their outlines were traced by the emissions. Two years later, the New Zealand-born, British physicist **Ernest Rutherford** (1871 to 1937) found that uranium emitted two types of particles, which he named alpha and beta particles. Rutherford later discovered the gamma ray as well.

Equation 3.11 summarizes the radioactive decay pathway of ^{238}U to ^{206}Pb. Numbers shown are half-lives of each decay process.

$$
\begin{gathered}
{}^{238}\text{U} \xrightarrow[\alpha]{4.5\text{x}10^{9}\text{ yr}} {}^{234}\text{Th} \xrightarrow[\beta]{24\text{ d}} {}^{234}\text{Pa} \xrightarrow[\beta]{1.2\text{ min}} {}^{234}\text{U} \xrightarrow[\alpha]{2.5\text{x}10^{5}\text{ yr}} {}^{230}\text{Th} \xrightarrow[\alpha]{8\text{x}10^{4}\text{ yr}} {}^{226}\text{Ra} \xrightarrow[\alpha]{1620\text{ yr}} {}^{222}\text{Rn} \xrightarrow[\alpha]{3.8\text{ d}} {}^{218}\text{Po} \\
\xrightarrow[\alpha]{3\text{ min}} {}^{214}\text{Pb} \xrightarrow[\beta]{27\text{ min}} {}^{214}\text{Bi} \xrightarrow[\beta]{30\text{ min}} {}^{214}\text{Po} \xrightarrow[\alpha]{0.00016\text{ s}} {}^{210}\text{Pb} \xrightarrow[\beta]{22\text{ yr}} {}^{210}\text{Bi} \xrightarrow[\beta]{5\text{ d}} {}^{210}\text{Po} \xrightarrow[\alpha]{138\text{ d}} {}^{206}\text{Pb}
\end{gathered}
\tag{3.11}
$$

When it decays to produce radon, ^{238}U first releases an alpha particle, producing thorium-234 (^{234}Th), which decays to protactinium-234 (^{234}Pa), releasing a beta particle. ^{234}Pa has the same number of protons and neutrons in its nucleus as does ^{234}Th, but ^{234}Pa has one less electron than does ^{234}Th, giving ^{234}Pa a positive charge. ^{234}Pa decays further to uranium-234 (^{234}U), then to thorium-230 (^{230}Th), then to radium-226 (^{226}Ra), and then to radon-222 (^{222}Rn).

Whereas radon precursors are bound in minerals, ^{222}Rn is a gas that can be breathed in. ^{222}Rn has a half-life of 3.8 days. It decays to polonium-218 (^{218}Po), which has a half-life of 3 minutes and decays to lead-214 (^{214}Pb). ^{218}Po and ^{214}Pb, referred to as **radon progeny**, are electrically charged and can be inhaled or attach to particles that are inhaled. In the lungs or in ambient air, ^{214}Pb decays to bismuth-214 (^{214}Bi), which decays to polonium-214 (^{214}Po). ^{214}Po decays almost immediately to lead-210 (^{210}Pb), which has a lifetime of 22 years and usually settles to the ground if it has not been inhaled. It decays to bismuth-210 (^{210}Bi), then to polonium-210 (^{210}Po), and then to the stable isotope, lead-206 (^{206}Pb), which does not decay further.

^{222}Rn, a gas, is not itself harmful, but its progeny, ^{218}Po and ^{214}Pb, which enter the lungs directly or on the surfaces of aerosol particles, are highly carcinogenic (Polpong and Bovornkitti, 1998). Any activity, such as uranium mining, increasing the inhalation of aerosol particles (e.g., dust) enhances the risk of inhaling radon progeny. As such, exposure of uranium miners to radon is another risk associated with nuclear energy.

Like with coal, oil, and natural gas mining, uranium mining also despoils land and reduces the carbon stored in soil. In 2017, 19 countries mined uranium. Kazakhstan, Canada, Australia, Namibia, and Niger produced the most uranium. Mines can be open pit or underground. Open pit mines cause the most land degradation. Table 3.5 provides an estimate of the effective CO_2e emissions due to clearing vegetation from land for uranium mining associated with nuclear power. The continuous mining for fuels is not needed in a 100 percent WWS world.

3.2.2. Total CO_2e Emissions of Energy Technologies

Lifecycle emissions are one component of total carbon equivalent (CO_2e) emissions. Additional components relevant to fossil fuels with carbon capture include opportunity cost emissions, anthropogenc heat emissions, anthropogenic water vapor emissions, emissions risk due to CO_2 leakage, and emissions due to covering or clearing land for energy development. These are discussed next, in turn.

3.2.2.1. Opportunity Cost Emissions

Opportunity cost emissions are emissions from the background electric power grid, averaged over a defined period of time (e.g., either 20 years or 100 years), due to two factors. The first factor is the longer time lag between planning and operation of one energy technology relative to another. The second factor is the longer downtime needed to refurbish one technology at the end of its useful life when its useful life is shorter than that of another technology (Jacobson, 2009).

For example, if Plant A takes 4 years and Plant B takes 10 years between planning and operation, the background grid will emit pollution for 6 more years out of 100 years with Plant B than with Plant A. The emissions during those additional 6 years are opportunity cost emissions. Such additional emissions include emissions of both health- and climate-affecting air pollutants.

Similarly, if Plant A and B have the same planning-to-operation time but Plant A has a useful life of 20 years and requires 2 years of refurbishing to last another 20 year and Plant B has a useful life of 30 years but takes only 1 year of refurbishing, then Plant A is down 2 y / 22 y = 9.1 percent of the time for refurbishing and Plant B is down 1 y / 31 y = 3.2 percent of the time for refurbishing. As such, Plant B is down an additional (0.091 – 0.032) × 100 y = 5.9 years out of every 100 for refurbishing. During those additional years, the background grid will emit pollution with Plant B.

Mathematically, opportunity cost emissions (E_{OC}, in g-CO_2e/kWh) are calculated as

$$E_{OC} = E_{BR,H} - E_{BR,L} \qquad (3.1)$$

where $E_{BR,H}$ are total background grid emissions over a specified number of years due to delays between planning and operation and downtime for refurbishing of the technology with the more delays. $E_{BR,L}$ is the same but for the technology with the fewer delays. Background emissions (for either technology) over the number of years of interest, Y, are calculated as

$$E_{BR} = E_G \times ([T_{PO} + (Y - T_{PO}) \times T_R / (L+T_R)] / Y \qquad (3.2)$$

where E_G is the emissions intensity of the background grid (g-CO_2e/kWh for analyses of the climate impacts and g-pollutant/kWh for analyses of health-affecting air pollutants), T_{PO} is the time lag (in years) between planning and operation of the technology, T_R is the times (years) to refurbish the technology, and L is the operating life (years) of the technology before it needs to be refurbished.

Example 3.1. Opportunity cost emissions.
What are the opportunity cost emissions (g-CO_2e/kWh) over 100 years resulting from Plant B if its planning-to-operation time is 15 years, its lifetime is 40 years, and its refurbishing time is 3 years, whereas these values for Plant A are 3 years, 30 years, and 1 year, respectively? Assume both plants produce the same number of kWh/y once operating, and the background grid emits 550 g-CO_2e/kWh.

Solution:
The opportunity cost emissions are calculated as the emissions from the background grid over 100 years of the plant with the higher background emissions (Plant B in this case) minus those from the plant with the lower background emissions (Plant A).

The background emissions from Plant B are calculated from Equation 3.2 with E_G=550 g-CO_2e/kWh, Y=100 y, T_{PO}=15 y, L=40 y, and T_R=3 y as $E_{BR,H}$=550 g-CO_2e/kWh × [15 y + (100 y – 15 y) × 3 y / 43 y)] / 100 y = 115 g-CO_2e/kWh.

Similarly, the background emissions from Plant A averaged over 100 years are $E_{BR,L}$=550 g-CO_2e/kWh × [3 y + (100 y – 3 y) × 1 y / 31 y)] / 100 y = 33.7 g-CO_2e/kWh. The difference between the two from Equation 3.1, E_{OC}= $E_{BR,H}$-$E_{BR,L}$= 81.3 g-CO_2e/kWh, is the opportunity cost emissions of Plant B over 100 years.

The time lag between planning and operation of a technology includes a development time and construction time. The development time is the time required to identify a site, obtain a site permit, purchase or lease the land, obtain a construction permit, obtain financing and insurance for construction, install transmission, negotiate a power purchase agreement, and obtain permits. The construction period is the period of building the plant, connecting it to transmission, and obtaining a final operating license.

The development phase of a coal-fired power plant without carbon capture equipment is generally 1 to 3 years, and the construction phase is another 5 to 8 years, for a total of 6 to 11 years between planning and operation (Jacobson, 2009). No coal plant has been built from scratch with carbon capture, so this could add to the planning-to-operation time. However, for a new plant, it is assumed that the carbon capture equipment can be added during the long planning-to-operation time of the coal plant itself. As such, Table 3.5 assumes the planning-to-operation time of a coal plant without carbon capture is the same as that with carbon capture. The typical lifetime of a coal plant before it needs to be refurbished is 30 to 35 years. The refurbishing time is an estimated 2 to 3 years.

No natural gas plant with carbon capture exists. The estimated planning-to-operation time of a natural gas plant without carbon capture is less than that of a coal plant. However, because of the shorter time, the addition of carbon capture equipment to a new natural gas plant is likely to extend its planning-to-operation time to that of a coal plant with or without carbon capture (6 to 11 years).

For comparison, the planning-to-operation time of a utility-scale wind or solar farm is generally 3 to 5 years, with a development period of 1 to 3 years and a construction period of 1 to 2 years (Jacobson, 2009).

This time applies to both onshore and offshore wind. For example, the 407 MW (49 turbine) Horns Rev 3 offshore wind farm, located in the North Sea off of the west coast of Denmark, required 1 year and 10 months to build (Frangoul, 2019). Wind turbines often last 30 years before refurbishing, and the refurbishing time is 0.25 to 1 year.

Table 3.5 provides the estimate opportunity cost emissions of coal and natural gas with carbon capture due to the time lag between planning and operation of those plants relative to wind or solar farms. The table indicates an investment in fossil fuels with carbon capture instead of wind and solar result in an additional 46 to 62 g-CO_2e/kWh in opportunity cost emissions from the background grid.

Table 3.5. Total 100-year CO_2e emissions from several different energy technologies. The total includes lifecycle emissions, opportunity cost emissions, anthropogenic heat and water vapor emissions, weapons and leakage risk emissions, and emissions from loss of carbon storage in land and vegetation. All units are g-CO_2e/kWh-electricity, except the last, column, which gives the ratio of total emissions of a technology to the emissions from onshore wind. CCS/U is carbon capture and storage or use.

Technology	[a]Lifecycle emissions	[b]Opportunity cost emissions due to delays	[c]Anthro-pogenic heat emissions	[d]Anthro-pogenic water vapor emissions	[e]Nuclear Weapons risk or 100-Year CCS/U leakage risk	[f]Loss of CO_2 due to covering land or clearing vegetation	**[g]Total 100-year CO_2e**	**Ratio of 100-year CO_2e to that of wind-onshore**
Solar PV-rooftop	15-34	-12 to -16	-2.2	0	0	0	**0.8-15.8**	**0.1-3.3**
Solar PV-utility	10-29	0	-2.2	0	0	0.054-0.11	**7.85-26.9**	**0.91-5.6**
CSP	8.5-24.3	0	-2.2	0 to 2.8	0	0.13-0.34	**6.43-25.2**	**0.75-5.3**
Wind-onshore	7.0-10.8	0	-1.7 to -0.7	-0.5 to -1.5	0	0.0002-0.0004	**4.8-8.6**	**1**
Wind-offshore	9-17	0	-1.7 to -0.7	-0.5 to -1.5	0	0	**6.8-14.8**	**0.79-3.1**
Geothermal	15.1-55	14-21	0	0 to 2.8	0	0.088-0.093	**29-79**	**3.4-16**
Hydroelectric	17-22	41-61	0	2.7 to 26	0	0	**61-109**	**7.1-22.7**
Wave	21.7	4-16	0	0	0	0	**26-38**	**3.0-7.9**
Tidal	10-20	4-16	0	0	0	0	**14-36**	**1.6-7.5**
Nuclear	9-70	64-102	1.6	2.8	0-1.4	0.17-0.28	**78-178**	**9.0-37**
Biomass	43-1,730	36-51	3.4	3.2	0	0.09-0.5	**86-1,788**	**10-373**
Natural gas-CCS/U	179-405	46-62	0.61	3.7	0.36-8.6	0.41-0.69	**230-481**	**27-100**
Coal-CCS/U	230-935	46-62	1.5	3.6	0.36-8.6	0.41-0.69	**282-1,011**	**33-211**

[a] Lifecycle emissions are 100-year carbon equivalent (CO_2e) emissions that result from the construction, operation, and decommissioning of a plant. They are determined as follows:

Solar PV-rooftop: The range is assumed to be the same as the solar PV-utility range, but with 5 g-CO_2/kWh added to both the low and high ends to account for the use of fixed tilt for all rooftop PV versus the use of some tracking for utility PV.

Solar PV-utility: The range is derived from Fthenakis and Raugei (2017). It is inclusive of the 17 g-CO_2/kWh mean for CdTe panels at 11 percent efficiency, the 27 g-CO_2e/kWh mean for multi-crystalline silicon panels at 13.2 percent efficiency, and the 29 gCO_2e/kWh mean for mono-crystalline silicon panels at 14 percent efficiency. The upper limit of the range is held at the mean for multi-crystalline silicon since panel efficiencies are now much higher than 13.2 percent. The lower limit is calculated by scaling the CdTe mean to 18.5 percent efficiency, its maximum in 2018.

CSP: The lower limit CSP lifecycle emission rate is from Jacobson (2009). The upper limit is from Ko et al. (2018).

Wind-onshore and wind-offshore: The range is derived from Kaldelis and Apostolou (2017).

Geothermal: The range is from Jacobson (2009) and consistent with the review of Tomasini-Montenegro et al. (2017).

Hydroelectric and wave: From Jacobson (2009).

Tidal: From Douglass et al. (2008).

Nuclear: The range of 9-70 g-CO_2e/kWh is from Jacobson (2009), which is within the Intergovernmental Panel on Climate Change (IPCC)'s range of 4-110 g-CO_2e/kWh (Bruckner et al., 2014), and conservative relative to the 68 (10-130) g-CO_2e/kWh from the review of Lenzen (2008) and the 66 (1.4-288) g-CO_2e/kWh from the review of Sovacool (2008).

<u>Biomass:</u> The range provided is for biomass electricity generated by forestry residues (43 gCO_2e/kWh), industry residues (46), energy crops (208), agriculture residues (291), and municipal solid waste (1730) (Kadiyala et al., 2016).

<u>Natural gas-CCS/U:</u> The lower bound is for the CCGT with carbon capture plant from Skone (2015), also provided in Table 3.4. The upper bound is CCGT value without carbon capture, 506 g-CO_2e/kWh from Table 3.4, multiplied by 80 percent, which is the percent of CO_2e emissions expected to be captured from the Petra Nova facility that will remain in the air over 100 years (Table 3.6).

<u>Coal-CCS/U:</u> The lower bound is for IGCC with carbon capture from Skone (2015). The upper bound is the coal value without carbon capture, 1,168 g-CO_2e/kWh from Table 3.6, multiplied by 80 percent, which is the percent of coal lifecycle CO_2e emissions from the Petra Nova facility that will remain in the air over 100 years (Table 3.6).

[b] Opportunity cost emissions are emissions per kWh over 100 years from the background electric power grid, calculated from Equations 3.1 and 3.2 due to (a) the longer time lag between planning and operation of one energy technology relative to another and (b) additional downtime to refurbish a technology at the end of its useful life compared with the other technology. The planning-to-operation times of the technologies in this table are 0.5-2 years for solar PV-rooftop; 2-5 years for solar PV-utility, CSP, wind-onshore, wind-offshore, tidal, and wave; 3-6 years for geothermal; 8-16 years for hydroelectric; 10-19 years for nuclear; 4-9 years for biomass (without CCS/U), and 6-11 years for natural gas-CCS/U and coal-CCS/U (Jacobson, 2009, except rooftop PV and natural gas-CCS/U values are added and solar PV-rooftop is updated here). The refurbishment times are 0.05-1 year for solar PV-rooftop; 0.25-1 year for solar-PV-utility, CSP, wind-onshore, wind-offshore, wave, and tidal; 1-2 years for geothermal and hydroelectric; 2-4 years for nuclear, and 2-3 years for biomass, coal-CCS/U, and natural gas-CCS/U. The lifetimes before refurbishment are 15 years for tidal and wave; 30 years for solar PV-rooftop, solar PV-utility, CSP, wind-onshore, wind-offshore; 30-35 years for biomass, coal-CCS/U, and natural gas-CCS/U; 30-40 years for geothermal; 40 years for nuclear; and 80 years for hydroelectric (Jacobson, 2009). The opportunity cost emissions are calculated here relative to the utility-scale technologies with the shortest time between planning and operation (solar-PV-utility, CSP, wind-onshore, and wind-offshore). The opportunity cost emissions of the latter technologies are, by definition, zero. The opportunity cost emissions of all other technologies are calculated like in Example 3.1 while assuming a background U.S. grid emission intensity equal to 557.3 g-CO_2e/kWh in 2017. This is derived from an electricity mix from EIA (2018d) and emissions, weighted by their 100-year GWPs, of CO_2, CH_4, and N_2O from mining, transporting, processing and using fossil fuels, biomass, or uranium. The reason tidal power has opportunity cost emissions although its planning-to-operation time is the same as onshore wind is the shorter lifetime of tidal turbines than wind turbines. Thus, tidal has more down time over 100 years than do other technologies. See Section 3.2.2.1. The opportunity cost emissions of offshore and onshore wind are assumed to be the same because new projects suggest offshore wind, particularly with faster assembly techniques and with floating turbines, are easier to permit and install now than a decade ago. Although natural gas plants don't take so long as coal plants between planning and operation, natural gas combined with CCS/U is assumed to take the same time as coal with CCS/U.

[c] Anthropogenic heat emissions here include the heat released to the air from combustion (for coal or natural gas) or nuclear reaction, converted to CO_2e (see Section 3.2.2.2). For solar PV and CSP, heat emissions are negative because these three technologies reduce sunlight to the surface by converting it to electricity. The lower flux to the surface cools the ground or a building below the PV panels. For wind turbines, heat emissions are negative because turbines extract energy from wind to convert it to electricity (Section 3.2.2.3 and Example 3.6). For binary geothermal plants (low end), it is assumed all heat is re-injected back into the well. For non-binary plants, it is assumed that some heat is used to evaporate water vapor (thus the anthropogenic water vapor flux is positive) but remaining heat is injected back into the well. The electricity from all electric power generation also dissipates to heat, but this is due to the consumption rather than production of power and is the same amount per kWh for all technologies so is not included in this table.

[d] Anthropogenic water vapor emissions here include the water vapor released to the air from combustion (for coal and natural gas) or from evaporation (water-cooled CSP, water-cooled geothermal, hydroelectric, nuclear natural gas, and coal), converted to CO_2e (see Section 3.2.2.3). Air-cooled CSP and geothermal plants have zero water vapor flux, representing the low end of these technologies. The high end is assumed to be the same as for nuclear, which also uses water for cooling. The low end for hydroelectric power assumes 1.75 kg-H_2O/kWh evaporated from reservoirs at mid to high latitudes (Flury and Frischknecht, 2012). The upper end is 17.0 kg-H_2O/kWh from Jacobson (2009) for lower latitude reservoirs and assumes reservoirs serve multiple purposes. For biomass, the number is based only on the water emitted from the plant due to evaporation or combustion, not water to irrigate some energy crops. Thus, the upper estimate is low. The negative water vapor flux for onshore and offshore wind is due to the reduced water evaporation caused by wind turbines (Section 3.2.2.3 and Example 3.6).

[e] Nuclear weapons risk is the risk of emissions due to nuclear weapons use resulting from weapons proliferation caused by the spread of nuclear energy. The risk ranges from zero (no use of weapons over 100 years) to 1.4 g-CO_2e/kWh (one nuclear exchange in 100 years) (Section 3.3.2.1). The 100-year CCS/U leakage risk is the estimated rate,

averaged over 100 years, that CO_2 sequestered underground leaks back to the atmosphere. Section 3.2.2.4 contains a derivation. The leakage rate from natural gas-CCS/U is assumed to be the same as for coal-CCS/U.

[f] Loss of carbon, averaged over 100 years, due to covering land or clearing vegetation is the loss of carbon sequestered in soil or in vegetation due to the covering or clearing land by an energy facility; by a mine where the fuel is extracted from (in the case of fossil fuels and uranium); by roads, railways, or pipelines needed to transport the fuel; and by waste disposal sites. No loss of carbon occurs for solar PV-rooftop, wind-offshore, wave, or tidal power. In all remaining cases, except for solar PV-utility and CSP, the energy facility is assumed to replace grassland with the organic carbon content and grass content as described in the text. For solar PV-utility and CSP, it is assumed that the organic content of both the vegetation and soil are 7 percent that of grassland because (a) most all CSP and many PV arrays are located in deserts with low carbon storage and (a) most utility PV panels and CSP mirrors are elevated above the ground. For biomass, the low value assumes the source of biomass is industry residues or contaminated wastes. The high value assumes energy crops, agricultural residues, or forestry residues. See Section 3.2.2.5.

[g] The total column is the sum of the previous six columns.

3.2.2.2. Anthropogenic Heat Emissions

Anthropogenic heat emissions were defined in Section 1.2.3 to include the heat released to the air from the dissipation of electricity; from the dissipation of motive energy by friction; from the combustion of fossil fuels, biofuels and biomass for energy; from nuclear reaction; and from anthropogenic biomass burning. Jacobson (2014) provide the relative contributions of different energy generating technologies to worldwide anthropogenic heat emissions.

Table 3.5 includes the g-CO_2e/kWh emissions from heat of combustion (for biomass, natural gas, and coal) and from nuclear reaction. However, because the dissipation of the resulting electricity back to heat is due to the consumption rather than production of electricity, that heat release term is not included in the table. In any case, the heat released per unit electricity produced is the same for all technologies.

Solar PV and CSP convert solar radiation to electricity, thereby reducing the flux of heat to the ground or to rooftops below PV panels. This is reflected in Table 3.5 as a negative heat flux. Wind turbines also cause a negative heat flux, discussed in Section 3.2.2.3.

The CO_2e emissions (g-CO_2e/kWh) due to the anthropogenic heat flux is calculated for all technologies (including the negative heat fluxes due to solar and wind) as follows:

$$H = E_{CO2} \times A_h / (F_{CO2} \times G_{elec}) \qquad (3.3)$$

where E_{CO2} is the equilibrium global anthropogenic emission rate of CO_2 (g-CO_2/y) that gives a specified anthropogenic mixing ratio of CO_2 in the atmosphere, F_{CO2} is the direct radiative forcing (W/m^2) of CO_2 at the specified mixing ratio, A_h is the anthropogenic heat flux (W/m^2) due to a specific electric power producing technology, and G_{elec} is the annual global energy output of the technology (kWh/y).

The idea behind this equation is that the current radiative forcing (W/m^2) in the atmosphere due to CO_2 can be maintained at an equilibrium CO_2 emission rate,

$$E_{CO2} = \chi_{CO2}C/\tau_{CO2} \qquad (3.4)$$

where χ_{CO2} (ppmv) is the specified anthropogenic mixing ratio that gives the current CO_2 radiative forcing, C is a conversion factor (8.0055×10^{15} g-CO_2/ppmv-CO_2), and τ_{CO2} is the data-constrained *e*-folding lifetime of CO_2 against loss by all processes. As of 2019, τ_{CO2} is ~50 years but increasing over time (e.g., Jacobson, 2012a).

Equation 3.4 is derived by noting that the time rate of change of the atmospheric mixing ratio of a well-mixed gas, such as CO_2 is simply, $d\chi/dt = E - \chi C/\tau$. In steady state, this simplifies to $E=\chi C/\tau$. Scaling the ratio of this equilibrium CO_2 emission rate to the radiative forcing of CO_2 by the ratio of the anthropogenic heat flux to the electricity generation per year producing that heat flux, gives Equation 3.3, the CO_2e emission rate of the heat flux.

Thus, Equation 3.3 accounts for the emission rate of CO_2 needed to maintain a mixing ratio of CO_2 in the air that gives a specific radiative forcing. It does not use the present day emission rate because that results in a much higher CO_2 mixing ratio than is currently in the atmosphere because CO_2 emissions are not in equilibrium with the CO_2 atmospheric mixing ratio. Equation 3.3 requires a constant emission rate that gives the observed mixing ratio of CO_2 for which the current direct radiative forcing applies. Similarly, the energy production rate in Equation 3.3 gives a consistent anthropogenic heat flux.

Finally, whereas radiative forcing is a top-of-the-atmosphere value (and represents changes in heat integrated over the whole atmosphere) and heat flux is added to the bottom of the atmosphere, they both represent the same amount of heat added to the atmosphere. In fact, because the anthropogenic heat flux adds heat to near-surface air, it has a slightly greater impact on surface air temperature per unit radiative forcing than does CO_2. For example, the globally averaged temperature change per unit direct radiative forcing for CO_2 is ~0.6 $K/(W/m^2)$ (Jacobson, 2002), whereas the temperature change per unit anthropogenic heat plus water vapor flux is ~0.83 $K/(W/m^2)$ (Jacobson, 2014). As such, the estimated CO_2e values for heat fluxes in particular in Table 3.5 may be slightly underestimated.

Example 3.2. Calculate the carbon equivalent heat emissions for coal and nuclear power worldwide.
In 2005, the anthropogenic flux of heat (aside from heat used to evaporate water) from all anthropogenic heat sources worldwide was A_h=0.027 W/m^2 (Jacobson, 2014). Assume the percent of all heat from coal combustion was 4.87 percent and from nuclear reaction was 1.55 percent.

Estimate the CO_2e emissions corresponding to the coal and nuclear heat fluxes given the energy generation of $G_{elec}=8.622\times10^{12}$ kWh/y from coal combustion and 2.64×10^{12} kWh/y from nuclear reaction.

Assume an anthropogenic CO_2 direct radiative forcing of F_{CO2}=1.82 W/m^2, which corresponds to an anthropogenic mixing ratio of CO_2 of χ_{CO2}=113 ppmv (Myhre et al., 2013). Also assume a CO_2 *e*-folding lifetime of τ_{CO2}=50 years.

Solution:
From Equation 3.4, the equilibrium emission rate of CO_2 giving the anthropogenic mixing ratio is

$E_{CO2}=1.809\times10^{16}$ g-CO_2/y.

Multiplying the total anthropogenic heat flux by the respective fractions of heat from coal combustion and nuclear reaction gives A_h=0.00132 W/m^2 for coal and 0.00042 W/m^2 for nuclear. Substituting these and the other given values into Equation 3.3 gives H = 1.52 g-CO_2e/kWh for coal and 1.57 g-CO_2/kWh for nuclear.

Example 3.3. Calculate the carbon-equivalent negative heat emissions of a solar PV panel.
Solar panels convert about 20 percent of the sun's energy to electricity, thereby reducing the flux of sunlight to the ground. What is the reduction in heat flux (W/m^2) per kWh/y of electricity generated by a solar panel and what is the corresponding CO_2e emission reduction? The surface area of the Earth is 5.092×10^{14} m^2.

Solution:
If a solar panel produces G_{elec}=1 kWh/y of electricity, the panel prevents exactly that much solar radiation from converting to heat compared with the sunlight otherwise hitting an equally reflective surface. Eventually, the electricity converts to heat as well (as does the electricity from all electric power generators). However, other electric power generators do not remove heat from the sun on the same timescale as solar panels do.

Multiplying the avoided heat (-1 kWh/y) by 1,000 W/kW and dividing by 8760 h/y and by the area of the Earth gives $A_h=-2.24\times10^{-16}$ W/m^2. Substituting this, G_{elec}=1 kWh/y, and E_{CO2} and F_{CO2} from Example 3.2 into Equation 3.3 gives H=-2.23 g-CO_2e/kWh.

Finally, for hydropower, evaporation of water vapor at the surface of a reservoir by the sun increases anthropogenic water vapor emissions (Section 3.2.2.3). Because evaporation requires energy, it cools the surface of the reservoir. The energy used to evaporate the water becomes embodied in latent heat carried by the water vapor. However, the water vapor eventually condenses in the air (forming clouds), releasing the heat back to the air. As a result, warming of the air offsets cooling at the surface, so hydropower causes no net anthropogenic heat flux. On the other hand, water vapor is a greenhouse gas, resulting in a net warming of the air due to evaporation. This warming is accounted for in the next section.

3.2.2.3. Anthropogenic Water Vapor Emissions

Fossil fuel, biofuel, and biomass burning release not only heat, but also water vapor. The water vapor results from chemical reaction between the hydrogen in the fuel and oxygen in the air. In addition, coal, natural gas, and nuclear plants require cool liquid water to re-condense the hot steam as it leaves a steam turbine. This process results in significant water evaporating out of a cooling tower to the sky. Many CSP turbines also use water cooling although some use air cooling. Similarly, whereas non-binary geothermal plants and some binary plants use water cooling, thus emit water vapor, binary plants that use air cooling do not emit any water vapor. Further, water evaporates from reservoirs behind hydroelectric power plant dams. Table 1.1 indicates that anthropogenic water vapor from all anthropogenic sources causes about 0.23 percent of global warming.

On the other hand, wind turbines reduce water vapor, a greenhouse gas, by reducing wind speeds (Chapter 7) (Jacobson and Archer, 2012; Jacobson et al., 2018a). Water evaporation is a function of wind speed (and temperature).

In this section, the positive or negative CO_2e emissions per unit energy (M, g-CO_2e/kWh) due to increases or decreases in water vapor fluxes resulting from an electric power source are quantified. The emissions are estimated with an equation similar to Equation, 3.3, except with the anthropogenic moisture energy flux (A_m, W/m^2) is substituted for the heat flux:

$$M = E_{CO2} \times A_m / (F_{CO2} \times G_{elec}) \tag{3.5}$$

In this equation, the globally averaged moisture energy flux can be obtained from the water vapor flux per unit energy (V, kg-H_2O/kWh) by

$$A_m = V \times L_e \times G_{elec} / (S \times A_e) \tag{3.6}$$

where $L_e=2.465\times10^6$ J/kg-H_2O is the latent heat of evaporation, $S=3.1536\times10^7$ seconds per year, and $A_e=5.092\times10^{14}$ m^2 is the surface area of the Earth. For water evaporating from a hydropower reservoir, V = 1.75 to 17 kg-H_2O/kWh (Table 3.5, footnote c).

Combining Equations 3.5 and 3.6 gives the globally averaged CO_2e emissions per unit energy due to a positive or negative water vapor flux resulting from an energy generator as

$$M = E_{CO2} \times V \times L_e / (F_{CO2} \times S \times A_e) \tag{3.7}$$

This equation is independent of the total annual energy production (G_{elec}). Examples 3.4 to 3.6 provide calculations of anthropogenic water vapor fluxes for several of the generators in Table 3.5.

Example 3.4. Calculate the carbon-equivalent anthropogenic water vapor emissions from natural gas and nuclear plants.

The global anthropogenic water vapor flux from natural gas power plants in 2005 was A_m=0.00268 W/m^2 and from nuclear power plants was A_m=0.000746 W/m^2 (Jacobson, 2014). The total energy generation from natural gas use was G_{elec}=7.208×10^{12} kWh/y and from nuclear was 2.64×10^{12} kWh/y. Calculate the CO_2e emissions associated with these fluxes.

Solution:
Substituting E_{CO2} and F_{CO2} from Example 3.2 and A_m and G_{elec} provided in the problem into Equation 3.5 gives M=3.69 g-CO_2e/kWh for natural gas and 2.81 g-CO_2e/kWh for nuclear.

Example 3.5. Calculate the carbon-equivalent anthropogenic water vapor emissions from a hydropower reservoir.
If the evaporation rate of water from a hydropower reservoir is V=1.75 kg-H_2O/kWh (Flury and Frischknecht, 2012), determine the CO_2e emissions of water vapor from the reservoir.

Solution:
Substituting V into Equation 3.7 with E_{CO2} and F_{CO2} from Example 3.2 gives the carbon equivalent emissions due to hydropower reservoir evaporation as M=2.66 g-CO_2e/kWh.

Wind turbines extract kinetic energy from the wind and convert it to electricity. **Kinetic energy** is the energy embodied in air due to its motion. For every 1 kWh of electricity produced, 1 kWh of kinetic energy is extracted. Like with all electric power generation, the 1 kWh of electricity eventually converts back to heat that is added back to the air. However, for purposes of assigning CO_2e emissions or savings, the conversion of electricity back to heat is not assigned to any particular electric power generator in Table 3.5. However, the addition or extraction of heat and water vapor by the energy technology is.

When electricity dissipates to heat, some of that heat returns to kinetic energy. Heat is **internal energy**, which is the energy associated with the random, disordered motion of molecules. Higher temperature molecules move faster than lower temperature molecules. Some of the internal energy in the air causes air to rise since warm, low-density air rises when it is surrounded by cool, high-density air. To raise the air, internal energy is converted to **gravitational potential energy (GPE)**, which is the energy required to lift an object of a given mass against gravity a certain distance. The lifted parcel is now cooler as a result of giving away some of its internal energy to GPE. Differences in GPE over horizontal distance create a pressure gradient, which recreates some kinetic energy in the form of wind (Section 6.8).

In sum, wind turbines convert kinetic energy to electricity, which dissipates to heat. Some of that heat converts to GPE, some of which converts back to kinetic energy. If a wind turbine did not extract kinetic energy from the wind, that energy would otherwise still dissipate to heat due to the wind bashing into rough surfaces, which are sources of friction. But such dissipation would occur over a longer time.

However, **wind turbines have an additional effect, which is to reduce water vapor, a greenhouse gas**. When wind from dry land blows over a lake, for example, the dry wind sweeps water vapor molecules away from the surface of the lake. More water vapor molecules must then evaporate from the lake to maintain saturation of water over the lake surface. In this way, winds increase the evaporation of water over not only lakes, but also over oceans, rivers, streams, and soils. Because a wind turbine extracts energy from the wind, it slows the wind, reducing evaporation of water.

By reducing evaporation, wind turbines warm the water or soil near the turbine because evaporation is a cooling process, so less evaporation causes warming. However, because the air now contains less water vapor, less condensation occurs in the air. Since condensation releases heat, less of it means the air cools.

In addition, because a wind turbine slows the wind in its wake, it drops the air pressure in its wake as well (Section 6.4). Lower pressure decreases temperature, as evidenced by the increased fog thickness in the wake of wind turbines at the Horns Rev offshore wind farm (Hasager et al., 2013). The increase in fog thickness results from a slight increase in the relative humidity in a turbine's wake upon a slight drop in temperature, which is due to the drop in pressure.

Thus, the surface warming due to wind turbines reducing evaporation is cancelled by the air-cooling due to both lesser atmospheric condensation and lower temperatures in the turbines wake.

However, because water vapor is a greenhouse gas, less of it in the air means that more heat radiation from the Earth's surface escapes to space, cooling the ground, reducing internal energy. Since water vapor stays in the air for days to weeks, its absence due to a wind turbine reduces heat to the surface over that time more than the one-time dissipation of electricity, created by the wind turbine, increases heat.

In sum, wind turbines allow a net escape of energy to space by reducing water vapor. A portion of the lost energy comes from the air's internal energy, resulting in lower air temperatures. The rest comes from kinetic energy, reducing wind speeds, and from gravitational potential energy, reducing air heights. As such, a new equilibrium is reached in the atmosphere. Section 6.9.1 quantifies the impacts of different numbers of turbines worldwide on temperatures and water vapor.

Thus, wind turbines reduce temperatures in the global average by reducing both heat fluxes and water vapor fluxes. Wind turbines do increase temperatures on the ground downwind of a wind farm because they reduce evaporation, but in the global average, this warming is more than offset by atmospheric cooling due to less condensation plus the loss of more heat radiation to space due to the reduction in water vapor caused by wind turbines.

The energy taken out of the atmosphere temporarily (because it is returned later as heat from dissipation of electricity) by wind turbines is 1 kWh per 1 kWh of electricity production. The maximum reduction in water vapor, based on global computer model calculations (Chapter 7), due to wind turbines ranges from -0.3 to -1 kg-H_2O/kWh, where the variation depends on the number and location of wind turbines. Example 3.6 provides an estimate of the CO_2e savings due to wind turbines from these two factors.

Example 3.6. Estimate the globally averaged CO_2e water vapor and heat emission reductions due to wind turbines. Assuming that wind turbines extract 1 kWh of the wind's kinetic energy for each 1 kWh of electricity produced, estimate the CO_2e savings per unit energy from reduced heat and water vapor fluxes due to wind turbines considering that, when the turbine is not operating, every 1 kWh of kinetic energy in the wind evaporates 0.3 to 1 kg-H_2O/kWh and the rest of the energy remains in the atmosphere. Assume the equilibrium emission rate and resulting radiative forcing of CO_2 from Example 3.2.

Solution:
Multiplying the latent heat of evaporation (L_e=2.465×10^6 J/kg) and 1 kWh/3.6×10^6 J by -0.3 to -1 kg-H_2O/kWh gives the reduction in energy available to evaporate water as -0.21 to -0.69 kWh per kWh of electricity-produced. Multiplying 1,000 W/kW and dividing by 8760 h/y and by the area of the Earth, 5.092×10^{14} m^2, gives A_m/G_{elec} = -4.6×10^{-17} to -1.53×10^{-16} (W/m^2)/(kWh/y). Substituting this and E_{CO2} and F_{CO2} from Example 3.2 into Equation 3.5 gives the anthropogenic water vapor energy flux from wind turbines as -0.46 to -1.53 g-CO_2e/kWh.

The heat flux is the difference between -1 kWh/kWh-electricity and -0.21 to -0.69 kWh/kWh-electricity, which is -0.79 to -0.31 kWh/kWh-electricity. Performing the same calculation as above gives the anthropogenic heat flux from wind turbines as -1.77 to -0.70 g-CO_2e/kWh. The total heat plus water vapor energy flux savings due to wind turbines is thus -2.23 g-CO_2e/kWh, the same as for solar panels (Example 3.3).

3.2.2.4. Leaks of CO_2 Sequestered Underground

The sequestration of carbon underground due to CCS or CCU (e.g., from injecting CO_2 during enhanced oil recovery) runs the risk of CO_2 leaking back to the atmosphere through existing fractured rock or overly porous soil or through new fractures in rock or soil resulting from an earthquake. Here, a range in the potential emission rate due to CO_2 leakage from the ground is estimated.

The ability of a geological formation to sequester CO_2 for decades to centuries varies with location and tectonic activity. IPCC (2005, p. 216) references CO_2 leakage rates for an enhanced oil recovery operation of 0.00076 percent per year, or 1 percent over 1,000 years, and CH_4 leakage from historical natural gas storage systems of 0.1 to 10 percent per 1,000 years. Thus, while some well-selected sites could theoretically sequester 99 percent of CO_2 for 1,000 years, there is no certainty of this since tectonic activity or natural leakage over 1,000 years is not possible to predict. Because liquefied CO_2 injected underground will be under high pressure, it will take advantage of horizontal and vertical fractures in rocks to escape as a gas back to the air. Because CO_2 is an acid, its low pH will also cause it to weather rocks over time. If a leak from an underground formation to the atmosphere occurs, it may or may not be detected. If a leak is detected, it may or may not be sealed, particularly if it occurs over a large area.

The time-averaged leakage rate of CO_2 from a reservoir can be calculated by first estimating how the stored mass of CO_2 changes over time. The stored mass (S) of CO_2 at any time t in a reservoir, resulting from a constant injection at rate I (mass/y) and e-folding lifetime against leakage, T (years), is

$$S(\mathrm{t}) = S(0)e^{-\mathrm{t/T}} + \mathrm{T}I(1-e^{-\mathrm{t/T}}) \qquad (3.8)$$

where S(0) is the stored mass at time t=0. The average leakage rate over t years is then simply the injection rate minus the remaining mass stored mass at time t divided by t years,

$$L(\mathrm{t}) = I - S(\mathrm{t})/\mathrm{t} \qquad (3.9)$$

Once an injection rate and lifetime against leakage are known, the average leakage rate of CO_2 from an underground storage reservoir over a specified period can be calculated from Equations 3.8 and 3.9.

Example 3.7. Estimating average leakage rates from underground storage reservoirs.
Assume a coal-fired power plant has a CO_2 emission rate before carbon capture and storage ranging from 790 to 1,017 g-CO_2/kWh. Assume also that carbon capture equipment added to the plant captures 90 and 80 percent, respectively, of the CO_2 (giving a low and high, respectively, emission rate of remaining CO_2 to the air). If the captured CO_2 is injected underground into a geological formation that has no initial CO_2 in it, calculate a low and high CO_2 emission rate from leakage averaged over 100 years, 500 years, and 1,000 years. Assume a low and high e-folding lifetime against leakage of 5,000 years and 100,000 years, respectively. The low value corresponds to 18 percent leakage over 1,000 years, close to that of some observed methane leakage rates. The high value corresponds to a 1 percent loss of CO_2 over 1,000 years (e.g., IPCC, 2005).

Solution:
The low and high injection rates are 790 × 0.9 = 711 g-CO_2/kWh and 1,017 × 0.85 = 864.5 g-CO_2/kWh, respectively. Substituting these injection rates into Equation 3.8 (using the high lifetime with the low injection rate and the low lifetime with the high injection rate) and the result into Equation 3.9 gives a leakage rate range of 0.36 to 8.6 g-CO_2/kWh over 100 years; 1.8 to 42 g-CO_2/kWh over 500 years, and 3.5 to 81 g-CO_2/kWh over 1,000 years.

Thus, the longer the averaging period, the greater the average emission rate over the period due to CO_2 leakage.

3.2.2.5. Emissions From Covering Land or Clearing Vegetation

Emissions from covering land or clearing vegetation are emissions of CO_2 itself due to (a) reducing the carbon stored in soil and in the vegetation above the soil by covering land with impervious material or (b) reducing the carbon stored in vegetation by clearing land so less vegetation grows. When soil is covered with impervious material, such as concrete or asphalt, vegetation can't grow or decay, and its remains become part of the soil. Similarly, when land is cleared of vegetation, less carbon is stored in the vegetation and below ground. Energy facilities cover land and reduce vegetation.

Estimates of the organic carbon stored in grassland and the soil under grassland are 1.15 kg-C/m^2 and 13.2 kg-C/m^2, respectively (Ni, 2002). Normally, when grass dies, the dead grass contributes to the soil organic carbon. The grass then regrows, removing carbon from the air by photosynthesis. If the soil is instead covered with concrete, the grass no longer exists to remove carbon from the air or store carbon in the soil. However, existing carbon stored underground remains. Some of this is oxidized, though, over time and carried away by ground water.

The carbon emissions due to developing land for an energy facility can be estimated simplistically by first summing the land areas covered by the facility; the mine where the fuel is extracted from (in the case of fossil fuels and uranium); the roads, railways, or pipelines needed to transport the fuel; and the waste disposal site associated with the facility. This summed area is then multiplied by the organic carbon content normally stored in vegetation per unit area that is lost plus the organic carbon content normally stored in soil under the vegetation per unit area that is lost. The latter value can be estimated as approximately one-third the original organic carbon content of the soil. The loss of carbon is then converted to a loss of carbon per unit electricity produced by the energy facility over a specified period of time. For purposes of Table 3.5, this period is 100 years. Example 3.8 provides an example calculation of CO_2e emissions from the covering land with an energy facility.

Example 3.8. Estimating the loss of carbon stored in vegetation and soil due to an energy facility.
Assume a 425 MW coal facility has a 65 percent capacity factor and has a footprint of 5.2 km^2, including the land for the coal facility, mining, railway transport, and waste disposal. Calculate the emission rate of CO_2 from the soil and vegetation, averaged over 100 years, due to this facility, assuming that it replaces grass and 34 percent of the soil carbon is lost.

Solution:
The energy generated over one year from this plant is 425 MW × 8760 h/y × 0.65 × 1,000 kW/MW = 2.42×10^9 kWh/y. Over 100 years, the energy produced is 2.42×10^{11} kWh.

The carbon lost in soil is 0.34 × 13.2 kg-C/m^2 = 4.5 kg-C/m^2 and that lost from vegetation is 1.15 kg-C/m^2, for a total of 5.64 kg-C/m^2. Multiplying by 1,000 g/kg and the molecular weight of CO_2 (44.0095 g-CO_2/mol), then dividing by the molecular weight of carbon (12.0107 g-C/mol) give 20,700 g-CO_2/m^2. Multiplying this by the land area covered by the facility and dividing by the 100-year energy use gives an emission rate from lost soil and vegetation carbon as 0.44g-CO_2/kWh, averaged over 100 years.

Because most of the carbon in soil and vegetation is lost immediately, the 100-year average loss of carbon from the soil provided in Table 3.5 underestimates the impact on climate damage of an energy facility that occupies land. Most climate impacts from the loss of carbon will begin when the emissions occur. Thus, for example, the impacts over 10 years of carbon loss in soil are 10 times those in Table 3.5. However, to maintain consistency with the other types of carbon-equivalent emissions in the table, that from soil carbon loss are also averaged over 100 years.

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Table 1.2. *E*-folding lifetimes, 20-year GWPs, and 100-year GWPs of several global warming agents.

Chemical	*E*-folding lifetime	20-Year GWP	100-Year GWP
[a]CO_2	50-90 years	1	1

[b]BC+POC in fossil fuel soot	3-7 days	2,400-3,800	1,200-1,900
[b]BC+POC in biofuel soot	3-7 days	2,100-4,000	1,060-2,020
[c]CH_4	12.4 years	86	34
[c]N_2O	121 years	268	298
[c]$CFCl_3$ (CFC-11)	45 years	7,020	5,350
[d]CF_2Cl_2 (CFC-12)	100 years	10,200	10,800
[c]CF_4 (PFC-14)	50,000 years	4,950	7,350
[d]C_2F_6 (PFC-116)	10,000 years	8,210	11,100
[e]Tropospheric O_3	23 days	--	--
[f]NO_x-N	< 2 weeks	-560	-159
[g]SO_x-S	< 2 weeks	-1,400	-394

GWP=Global Warming Potential.

[a]The low-lifetime of CO_2 is the data-constrained lifetime upon increasing CO_2 emissions from Jacobson (2012a); the high-lifetime of CO_2 is calculated from Figure 9.6, which shows CO_2 decreasing by 65 ppmv (from 400 to 335 ppmv) over 65 years upon elimination of anthropogenic CO_2 emissions. Since the natural CO_2 is 275 ppmv, the anthropogenic CO_2 = 400-275=125 ppmv, and the lifetime of anthropogenic CO_2 is ~65 y / -ln((125-65) ppmv/125 ppmv) = ~90 years. The GWP of CO_2=1 by definition.

[b]POC is primary organic carbon co-emitted with black carbon from combustion sources. In the case of diesel exhaust, it is mostly lubricating oil and unburned fuel oil. In all cases, POC includes both absorbing organic (brown) carbon (BrC) and less absorbing organic carbon. Soot particles contain both BC and POC. The lifetime is from Jacobson (2012b) and the GWP is from Jacobson (2010a, Table 4), which accounts for direct effects, optical focusing effects, semi-direct effects, indirect effects, cloud absorption effects, and snow-albedo effects. The GWPs here are the surface temperature response after 20 or 100 years per unit continuous mass emissions (STRE) of BC+POC relative to the same for CO_2. STREs are analogous to GWPs (Jacobson, 2010a, Table 4 footnote).

[c]From Myhre et al. (2013) Table 8.7. Results from Etminan et al. (2016) suggest that the 20-y GWP of CH_4 may be up to 98.

[d]From Myhre et al. (2013) Table 8.A.1.

[e]From Myhre et al. (2013), Section 8.2.3.1. Tropospheric ozone is not emitted so does not have a GWP.

[f]From Myhre et al. (2013), Table 8.A.3, including aerosol direct and indirect effects. Values are on a per kg nitrogen basis.

[g]From Streets et al. (2001) and Jacobson (2002), including aerosol direct and indirect effects. Values are on a per kg sulfur basis. These numbers are STREs, which are analogous to GWPs (Footnote b).

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Last Updated October 11, 2023

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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 radiation 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 17 U.S. states (CA, CT, HI, IL, ME, MN, NC, NE, NJ, NM, NV, NY, OR, RI, VA, WA, WI), 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. 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. Over 400 international companies have committed to 100% renewables in their global operations. In 2023, Jacobson served as an expert witness on behalf of 16 youth plaintiffs in the first climate case in U.S. history, Held v. Montana, to discuss the ability of Montana to transition to WWS. The plaintiffs prevailed.

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) ~750 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 books, plus second editions in 2005 and 2012, respectively, relate primarily to his work in Atmospheric Sciences. The 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

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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)
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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)
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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 CO2 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)

203. Should Diablo Canyon be closed? Mothers for Peace, San Luis Obispo, California February 27, 2023 (presented remotely)

204. Public book reading, “No Miracles Needed,” Books Inc., Palo Alto, California, March 1, 2023 (in person) (link)

205. No Miracles Needed, Samuel Lawrence Foundation webinar, March 3, 2023 (presented remotely) (video)

206. No Miracles Needed: How today’s technology can save our planet and clean our air, Pasadena 100: Pasadena League of Women Voters, Sierra Club, NAACP, Citizens Climate Lobby, Audubon Society California, March 8, 2023 (presented remotely) (link)

207. Good and bad uses and sources of hydrogen in a transition to 100% clean, renewable energy and storage for everything, Hydrogen Online Workshop 2023, March 22, 2023 (presented remotely) (link)

208. Transitioning California and the World to 100% Clean, Renewable Energy and Storage for Everything, Piedmont Connect and Piedmont League of Women Voters Climate Speaker Series, April 5, 2023 (presented remotely) (link)

209. Debate on carbon capture, Open to Debate, Intelligence Squared, April 10, 2023 (presented remotely - appeared May 5, 2023) (video)

210. Transitioning Connecticut and the world to 100% clean, renewable energy and storage for everything, Clean Earth Collaborative, U. Connecticut, April 11, 2023 (presented remotely) (video)

211. No miracles needed: How today's technology can save our climate and clean our air, European Energy and Climate Policy Chair of the College of Europe’s annual conference, April 12, 2023 (pre-recorded) (video)
212. Friends of the Earth Board of Directors meeting, April 18, 2023 (presented remotely)
213. No Miracles Needed: How today’s technology can save our planet and clean our air, Ontario Climate Emergency Campaign, Ontario, Canada, April 18, 2023 (presented remotely) (video)
214. Why we don’t need a miracle to solve the climate crisis, Food and Water Watch Earth Day Event, April 19, 2023 (presented remotely) (link)
215. No Miracles Needed: How today’s technology can save our climate, clean our air, Better Path Coalition and the Pennsylvania Climate Convergent Network, webinar, April 26, 2023 (presented remotely) (video)
216. No Miracles Needed: How today’s technology can save our climate and clean our air, Environment America and Explore Booksellers, Aspen, Colorado, May 11, 2023 (presented remotely) (video)
217. Can nuclear energy help meet U.S. climate goals, Congressional briefing on nuclear power, Samuel Lawrence Foundation, Washington, D.C., June 2, 2023 (presented remotely) (video)
218. Transitioning the U.S. and world to 100% clean, renewable energy and storage for everything, Jefferies Investment Company, New York, New York, June 28, 2023 (presented remotely)
219. Transitioning the U.S. and the world to 100% clean, renewable energy and storage for everything, White House Environmental Justice Advisory Council, Washington D.C., July 27, 2023 (presented remotely)
220. Accelerating the renewable era: Energy solutions for a regenerative planet, Samuel Lawrence Foundation and Blue Planet Alliance, August 4, 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)

221. Climate Capital Live 2023: From Words to Action, Financial Times, March 16, 2023 (presented remotely) (link)
222. Symposium on the decisive role of shareholders in big oil in the climate crisis, Follow This, April 19, 2023 (presented remotely) (video)
223. No Miracles Needed: How we can transition the world to 100% wind-water-solar for all energy while saving money and creating jobs, Institute for Energy Economics and Financial Analysis (IEEFA), San Francisco, California, June 21, 2021 (in person) (video)
224. Transitioning the U.S., the U.S. military, and world to 100% clean, renewable energy and storage for everything, Energy Savings Performance Contracts (ESPC)/Utility Energy Service Contracts (UESC) Workshop, Army Corps of Engineers, Huntsville, Alabama, August 1, 2023 (presented remotely) (link)

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).

153. Climate Tabletop Exercise, Department of the Navy-Stanford joint TTX event, Naval Postgraduate School, Monterey, California, April 28, 2023 (in person).

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.
57. Achieving a sustainable future with clean, renewable energy and storage, Free Stanford Webinar, Stanford Online, March 15, 2023 (link)

58. Vision 2030: Roundtable on sustainability research integrity, Scientists speak up, Stanford University, April 6, 2023 (in person) (link)
59. Transitioning California and the world to 100% clean, renewable energy and storage for everything, Environmental Health and Safety, April 11, 2023 (presented remotely)
60. Inaugural session, Climate Conversations, Stanford Theater and Performance Studies Department and Stanford Live, Harry Elam Theater, June 1, 2023 (link)

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)
39. Panel discussion with Rep. Laura Friedman about Diablo Canyon Nuclear Plant, Mothers for Peace, May 4, 2023 (presented remotely).

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)

Documentaries and Podcasts

"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.

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