

Evaluation of Coal and Natural Gas With Carbon Capture as Proposed Solutions to Global Warming, Air Pollution, and Energy Security

In

100% Clean, Renewable Energy and Storage for Everything

Textbook in press, *Cambridge University Press*

<https://web.stanford.edu/group/efmh/jacobson/WWSBook/WWSBook.html>

Mark Z. Jacobson

August 14, 2019

Contact: Jacobson@stanford.edu; Twitter @mzjacobson

Summary

Coal and natural gas with carbon capture and storage (CCS) and use (CCU) have been advertised as zero-carbon sources of electric power that should be implemented as solutions to global warming, air pollution, and energy security. Natural gas has also been proposed as a bridge fuel between coal and renewables. This section evaluates these claims.

Neither coal nor natural gas with carbon capture is remotely close to zero carbon. Based on data, they reduce only ~10.8% carbon equivalent emissions (CO₂e) over a 20-year time frame and ~20% over a 100-year time frame. At the same time, they increase air pollution and land degradation compared with no carbon capture by 25 to 50 percent. The use of the captured CO₂ for enhancing oil recovery causes even greater damage. Finally, the cost of installing carbon capture equipment is large.

Here are additional specific findings:

- There is no low-carbon, let alone zero-carbon coal or natural gas power plant with carbon capture in existence.
- In the Petra Nova coal with carbon capture plant in Texas, only 10.8 percent (rather than 90%) of the intended CO₂ emissions are reduced over a 20-year time frame and only 20 percent are reduced over a 100-year time frame.
- These emission savings may be offset fully by emissions from the oil recovered with the CO₂.
- Coal with CCS/U costs 4.2 times the energy cost of wind. Because coal-CCS increases air pollution and mining and only marginally reduces CO₂, the social (energy plus health plus climate) cost of coal+ CCS is about 65 times that of a wind turbine replacing coal over 20 years.
- New natural gas with CCS/U produces 27-100 times the 100-year CO₂e as new onshore wind.
- New coal with CCS/U produces 33-211 times the 100-year CO₂e emissions as new onshore wind.
- Without carbon capture, open cycle natural gas turbines and combined cycle natural gas turbines cause 2.8 and 2.3 times, respectively, the global warming per unit energy over a 20-year time frame as a coal plant and only 8-28 percent less warming over 100 years than a coal plant.
- The reason is the higher SO₂ and NO_x and lower CH₄ emissions from coal. The higher SO₂, NO_x, and particulate emissions from coal result in coal causing about five times the premature mortality as gas.
- As such, natural gas is not a bridge fuel.
- Instead, coal and gas are both horrendous for climate, health, and land although coal causes greater health problems.
- In comparison, wind, water, and solar power substantially address nearly all climate, health, and energy security problems.

3.1. Why Not Use Natural Gas as a Bridge Fuel?

Natural gas is a colorless, flammable gas containing a mass (mole) fraction of about 88.5 (93.9) percent methane plus smaller amounts of ethane, propane, butane, pentane, hexane, nitrogen, carbon dioxide, and oxygen (Union Gas, 2018). It is often found near petroleum deposits. It is usually either combusted in a gas turbine that is coupled with a generator to produce electricity or combusted in a burner to produce either building heat or high-temperature industrial heat.

Because natural gas is not very dense, it can be stored on its own only in a large container. As such, natural gas is often compressed or liquefied for transport and storage. **Compressed natural gas (CNG)** is natural gas compressed to less than 1 percent of its gas volume at room temperature. **Liquefied natural gas (LNG)** is natural gas that has been cooled to -162°C , the temperature at which it condenses to a liquid at ambient pressure. LNG has a volume that is $1/600^{\text{th}}$ the volume of the original gas. Both CNG and LNG can be sent through pipelines, although different pipelines are needed for each. CNG and LNG can also be stored and used directly in automobiles that are designed to run on them. CNG and LNG can further be transported by truck or bus with a special fuel tank and can be stored at a power plant for backup use when pipeline gas is not available. In addition, pipeline CNG is often converted to LNG at a marine export terminal, put on a tanker ship with super-cooled cryogenic tanks, and shipped overseas. At the import terminal, it is re-gasified and piped to its final destination -- either a power plant, industrial company, or company that transmits and distributes it to buildings for heating or other purposes.

Natural gas is obtained from underground conventional wells containing both oil and natural gas or by hydraulic fracturing. **Hydraulic fracturing (fracking)** is the process by which natural gas is extracted from shale rock formations instead of wells. **Shale** is sedimentary rock composed of a muddy mix of clay mineral flakes and small fragments of quartz and calcite. Large shale formations containing natural gas can be found in eastern North America, close to population centers, among many other locations worldwide. In the U.S., about 67 percent of natural gas in 2015 was extracted from shale rock (EIA, 2016). Extraction of natural gas from shale requires large volumes of water, laced with chemicals, forced under pressure to fracture and re-fracture the rock to increase the flow of natural gas. As the water returns to the surface over days to weeks, it is accompanied by methane that escapes to the air. As such, more methane leaks occur during fracking than during the drilling of conventional gas wells (Howarth et al., 2011, 2012; Howarth, 2019). Methane also leaks during the transmission, distribution, and processing of natural gas.

For electricity production, natural gas is usually used in either an **open cycle gas turbine (OCGT)** or a **combined cycle gas turbine (CCGT)**. In an OCGT, air is sent to a compressor, and the compressed air and natural gas are both sent to a combustion chamber, where the mixture is burned. The hot gas expands quickly, flowing through a turbine to perform work by spinning the turbine's blades. The rotating blades turn a shaft connected to a generator, which converts a portion of the rotating mechanical energy to electricity.

The main disadvantage of an OCGT is that the exhaust contains a lot of waste heat that could otherwise be used to generate more electricity. A CCGT routes that heat to a heat recovery steam generator, which boils water with the heat to create steam. The steam is then sent to a steam turbine connected to the generator to generate 50 percent more electricity than the OCGT alone. Thus, a CCGT produces about 150 percent the electricity as an OCGT with the same input mass of natural gas thus carbon dioxide emissions in each case.

On the other hand, the ramp rate of an OCGT is 20 percent per minute, which is 2 to 4 times that of a CCGT (5 to 10 percent per minute) (Table 2.1). Thus, the less efficient OCGT, which also releases more

CO₂ per unit electricity generated (Table 3.1), is more useful for filling in short-term gaps in supply on the grid than is a CCGT.

It has long been suggested that natural gas could be used as a **bridge fuel** between coal and renewables (e.g., MIT, 2011). The two main arguments for this suggestion are (1) natural gas emits less carbon dioxide equivalent emissions per unit energy produced (CO₂e – Section 1.2.3.5) than coal and (2) natural gas electric power plants are better suited to be used with intermittent renewables than coal.

However, the justifications for using gas as a bridge fuel are incorrect and insufficient. Natural gas is not recommended for use together with WWS technologies for multiple reasons. These are discussed in the following sections.

3.1.1. Climate Impacts of Natural Gas Versus Other Fossil Fuels

When used in an electric power plant, natural gas substantially increases, rather than decreases, global warming (by increasing CO₂e) compared with coal over a 20-year time frame. The difference over 100 years, while more favorable to gas, is relatively small (Table 3.1). Regardless, CO₂e emissions (and health-affecting air pollutant emissions) from both gas and coal are much larger than are those from WWS technologies, so spending money on natural gas or coal represents an opportunity cost relative to spending the same money on WWS.

Over a 20-year time frame, the CO₂e from using natural gas with a CCGT or an OCGT is **2.3 and 2.8 times**, respectively, that using coal (Table 3.1). Over a 100-year time frame, the CO₂e from a natural gas OCGT is only **8 percent less** than that of coal, and the CO₂e from a natural gas CCGT is only **28 percent less** than that of coal.

The fact that natural gas causes far more global warming than coal over a 20-year time frame is a concern because of the severe damage global warming is already causing that will only be made worse over the next two decades, including the triggering of some difficult-to-reverse impacts, such as the complete melting of the Arctic ice.

The reasons that the CO₂e of natural gas exceeds that of coal over 20 years and is close to that of coal over 100 years are as follows.

First, although natural gas combustion in an OCGT or CCGT emits only 60 or 45 percent, respectively, of the CO₂ per kilowatt-hour (kWh) of coal combustion, natural gas leaks during the mining and transport of natural gas emit similar or more CH₄ than do CH₄ leaks during coal mining. This is an issue, because CH₄ has a high, positive 20- and 100-year GWP (Table 1.2). As such, the leaked CH₄ from natural gas mining and transport contributes substantially to the CO₂e of natural gas.

Second, and more important, coal combustion emits more NO_x and SO₂ per kWh than does natural gas combustion (Table 3.1), and NO_x and SO₂ both produce cooling aerosol particles, which offset or mask much of global warming, particularly over a 20-year time frame (Figure 1.2). The cooling impacts of these particles are through their direct reflection of sunlight back to space and their enhancement of cloud thickness. Thicker clouds reflect more sunlight back to space. As such, NO_x and SO₂, which are both short-lived, have very high negative GWPs over 20 years and even over 100 years (Table 3.1).

Howarth et al. (2011, 2012) identified the importance of methane leaks, particularly natural gas fracking of shale gas on the CO₂e emissions of natural gas versus coal on a 20- versus 100-year lifetime. Wigley

(2011), for one, estimated the cooling impact of SO₂, but not NO_x, when comparing CO₂e from coal versus natural gas power plants.

Table 3.1. Comparison of 20- and 100-year lifecycle global CO₂ equivalent (CO₂e) emissions from coal versus natural gas used in either an open cycle gas turbine (OCGT) or a combined cycle gas turbine (CCGT) for electricity generation.

Chemical (X)	20-y GWP	100-y GWP	Coal			Natural Gas Open Cycle Gas Turbine			Natural Gas Combined Cycle Gas Turbine		
			Emis. factor (g-X/kWh)	20-y CO ₂ e (g-CO ₂ e/kWh)	100-y CO ₂ e (g-CO ₂ e/kWh)	Emis. factor (g-X/kWh)	20-y CO ₂ e (g-CO ₂ e/kWh)	100-y CO ₂ e (g-CO ₂ e/kWh)	Emis. factor (g-X/kWh)	20-y CO ₂ e (g-CO ₂ e/kWh)	100-y CO ₂ e (g-CO ₂ e/kWh)
^a CO ₂ -upstream				97.2	97.2		54	54		54	54
^b CH ₄ -leak	86	34	4.1	353	140	4.35	374	148	3.26	280	111
^c CO ₂ -plant	1	1	905	905	905	540	540	540	404	404	404
^d BC+OM-plant	3,100	1,550	0.045	141	70	0.0003	0.93	0.47	0.0003	0.93	0.47
^e NO _x -N-plant	-560	-159	0.23	-129	-37	0.15	-84	-24	0.015	-8.4	-2.4
^e SO ₂ -S-plant	-1,400	-394	0.75	-1,050	-393	0.005	-7	-2	0.0015	-2.1	-2
Total				317	782		878	716		728	565

All 20- and 100-year GWPs are from Table 1.2. Each CO₂e, except for upstream values, is the product of an emission factor and a GWP.

^aUpstream CO₂ emissions from coal mining, processing, and transport are 27 g-CO₂/MJ, or 97.2 g-CO₂/kWh and from natural gas are 15 g-CO₂/MJ = 54 g-CO₂/kWh (Howarth, 2014).

^bFor coal, the 100-year CO₂e from CH₄ leaks is estimated from Skone (2015), Slide 17. The emission factor in the present table is then derived from that number and the 100-year GWP of CH₄ in the present table. The 20-year CO₂e is then calculated from the emission factor and the 20-year GWP. For natural gas, the CH₄-leak emission factors in the present table are obtained by multiplying the mass of CH₄ required per kWh of electricity by L/(1-L), where L is the fractional leakage rate of methane between mining and use in a power plant. The mass of CH₄ required per kWh for a natural gas turbine is the CO₂ combustion emissions from the turbine (present table) multiplied by the ratio of the molecular weights of CH₄:CO₂ (16.04276 g/mol:44.0098 g/mol) and by the mole fraction of natural gas that consists of methane (0.939) (Union Gas, 2018). The results are 184.8 g-CH₄/kWh-electricity for open cycle and 138.3 g-CH₄/kWh-electricity for combined cycle. The overall U.S. methane leakage rate, from shale gas, which includes leaks from drilling and from pipe transmission and distribution to electric power plants, industrial facilities, homes, and other buildings, may be ~3.5 percent (Howarth, 2019). Shale gas was about 2/3 of the U.S. natural gas production in 2015 (EIA, 2016). The leakage rate all natural gas (shale gas plus conventional gas) for only drilling and transmission to large facilities may be ~2.3 percent (Alvarez et al., 2018). This number is used in this table, which is for electric power plant generation.

^cEmission factors from Figure 4 of de Gouw et al. (2014) for 2012 U.S. plants; For NO_x-N, emission factors for NO_x-NO₂ were multiplied by the ratio of the molecular weight of N to that of NO₂. For SO₂-S, emission factors for SO₂ were multiplied by the ratio of the molecular weight of S to that of SO₂.

^dThe emission factor of BC+OM for coal and natural gas were obtained from Bond et al. (2004) assuming, for coal, pulverized coal and a mix between hard and lignite coal.

Neither natural gas nor coal is recommended in a 100 percent WWS world because, among other reasons, the natural gas lifecycle 100-year CO₂e for electricity generation (565 to 716 g-CO₂e/kWh) (Table 3.1) is on the order of 56 to 72 times that of wind (~10 g-CO₂e/kWh) (Table 3.5), and the 100-year coal CO₂e (~780 g-CO₂e/kWh) is about 78 times that of wind. Similarly, both coal and gas produce much more air pollution than do WWS sources (Section 3.1.2).

The CO₂e emissions from natural gas versus other fossil fuels are higher for heating and transportation than for electricity. For building heat and industrial process heat, for example, natural gas offers less efficiency advantage over oil or coal than it does for electricity generation. As such, after accounting for all chemical emissions and their respective global warming potentials, natural gas may cause greater long-term global warming than does oil or coal for heating.

With respect to transportation fuels, the carbon dioxide equivalent emissions of natural gas may also exceed that of oil, since the efficiency of natural gas used in transportation is similar to that of oil. Thus, when methane leaks are added in, natural gas causes more overall warming than oil (Alvarez et al. 2012). In sum, in terms of climate, natural gas causes greater global warming than other fossil fuels over 20 years across all applications. Over a 100-year time frame, natural gas causes similar or less warming than coal used for electricity generation and greater warming than oil for heating and transportation over 100 years. All fossil fuels emit 1.5 to 2 orders of magnitude the CO_{2e} as WWS sources.

3.1.2. Air Pollution Impacts of Natural Gas Versus Coal and Renewables

Whereas natural gas causes more CO_{2e} emissions than coal over 20 years and a similar or slightly less level over 100 years, coal emits more health-affecting air pollutants than does natural gas, which is the main reason it has a lower CO_{2e} over 20 years than does natural gas. Nevertheless, both natural gas and coal are much worse for human health than are WWS technologies, which emit no air pollutants during their operation, only during their manufacture and decommissioning. Such WWS emissions will disappear to zero as all energy transitions to WWS since even manufacturing will be powered by WWS at that point.

Table 3.2 provides U.S. emissions from all natural gas and coal uses in the United States in 2008. The table indicates that natural gas production and use in the U.S. emitted more CO, volatile organic carbon (VOC), CH₄, and ammonia (NH₃) than coal production and use, whereas coal emitted more NO_x, SO₂, and particulate matter smaller than 2.5- and 10- μ m in diameter (PM_{2.5}, PM₁₀). Thus, both fuels resulted in significant air pollution, although the higher SO₂, NO_x, and particulate matter emissions from coal resulted in overall greater air pollution health problems from coal than natural gas.

Table 3.2. 2008 U.S emissions from natural gas and coal (metric tonnes/y). Bold indicates higher overall emissions between coal and natural gas (NG).

	Coal All Uses	NG All Uses
CO	680	900
VOC	40	1,130
CH ₄	5	310
NH ₃	11	54
NO _x	2,800	1,540
SO ₂	7,600	123
PM _{2.5}	290	61
PM ₁₀	420	71

Source: U.S. EPA (2011). VOCs exclude methane. The methane emissions from the EPA inventory are likely underestimated (e.g., Alvarez et al., 2018).

Most SO₂ and NO_x emissions evolve to sulfate and nitrate aerosol particles, respectively. Natural gas also emits NO_x, but less so than does coal (Tables 2.6 and 2.7). Natural gas, on the other hand, emits much less SO₂ than does coal (Tables 2.6 and 2.7). Aerosol particles, including those containing sulfate and nitrate formed from gases in the atmosphere, and those emitted directly, cause 90 percent of the 4 to 9 million air pollution deaths that occur annually worldwide (Section 1.1.1). As such, coal in particular, but also natural gas, causes significant health damage.

Model simulations over the United States with the emission data from Table 3.2 suggests that emissions from all natural gas sources may cause 5,000 to 10,000 premature mortalities each year in the U.S. from air pollution (Jacobson et al., 2015a). Coal-related emissions may cause 20,000 to 50,000 premature mortalities in the U.S. Many of the remaining premature mortalities are due to pollution associated with oil (e.g., traffic exhaust, oil refinery evaporation), biofuels for transportation, and wood smoke emissions from open fires, fireplaces, and cooking.

In sum, coal causes more mortalities than does natural gas, but both coal and gas cause far more mortalities than do WWS technologies. The combination of the much higher CO_{2e} emissions and premature mortalities due to natural gas than WWS technologies renders natural gas not an option as a bridge fuel.

3.1.3. Using Natural Gas for Peaking or Load Following

Another argument for using natural gas as a bridge fuel is that it can be used in a load-following or peaking plant (defined in Section 2.4), and WWS technologies will need load-following or peaking plants that use natural gas to back them up when not enough wind or solar is available.

Whereas natural gas plants can help with peaking and load following, they are not needed (Section 8.2.1). Other types of WWS electric power storage options available include CSP with storage, hydroelectric dam storage, pumped hydropower storage, stationary batteries, flywheels, compressed air energy storage, and gravitational storage with solid masses (Section 2.7). As of 2019, the cost of a system consisting of wind and solar plus batteries costs less than using natural gas. For example, a Florida utility is replacing two natural gas plants with a combined solar-battery system due the lower cost of the latter (Geuss, 2019).

More important, a 100 percent WWS world involves electrifying or providing direct heat for all energy sectors, where the electricity or heat comes from WWS. Such a transition allows heat, cold, and hydrogen storage to work together with demand response to facilitate matching electric power demand with supply on the grid while also satisfying heat, cold, and hydrogen demands minute by minute at low cost. Chapter 8 discusses this issue in detail.

3.1.4. Land Required for Natural Gas Infrastructure

The continuous use of natural gas for electricity and heat results in the cumulative degradation of land for as long as the gas use continues. Wells must be dug, and pipes laid every year to supply a world thirsty for gas. When gas wells become depleted, new wells must be drilled. Allred et al. (2015) estimate that 50,000 new natural gas wells are drilled each year in North America alone to satisfy gas demand. The land area required for the well pads, roads, and storage facilities of these 50,000 new wells amounts to 2,500 km² of additional land consumed per year (Allred et al., 2015). Once a gas well is depleted, it is sealed and abandoned, and a portion of the abandoned land cannot be used for any other purpose. The natural gas infrastructure also requires land for underground and aboveground pipes, power plants, fueling stations, and underground storage facilities. The flammability of natural gas further results in explosions in homes and urban areas that have had fatal consequences.

Table 3.3 shows the estimated land required for the entire fossil fuel and nuclear infrastructure in California and the United States. The table indicates that the fossil fuel infrastructure takes up about 1.3 percent of the United States land area and 1.2 percent of California’s land area. Whereas all fossil fuels contribute to this land area degradation, natural gas’ share is growing due to the phase out of coal and growth of gas, particularly of hydraulically fracked gas. The damage due to fracking includes damage not only to the landscape but also to nearby groundwater, in which natural gas often leaks. Additional damage occurs to roads, which much carry heavy trucks associated with natural gas development. Gas flaring is another form of local environmental degradation, as the flaring emits soot (containing black carbon) that deposits downwind.

Table 3.3. Estimated land areas required for the fossil fuel and nuclear infrastructure in California and the United States.

		California		United States	
	Area per installation	Number	Area (km ²)	Number	Area (km ²)

	(km ²)				
^a Active oil and gas wells	0.05	105,000	3,327	1.3 million	65,000
^b Abandoned oil wells	0.00005	225,000	6.6	2.6 million	128.5
^b Abandoned gas wells	0.000025	48,000	0.7	550,000	13.8
^c Coal mines	50	0	0	680	34,000
^d Oil refineries	7.28	17	124	135	983
^e Kilometers of oil pipeline	0.006	4,800	29	258,000	1,550
^e Kilometers of gas pipeline	0.006	180,000	1,080	2.62 million	15,700
^f Coal power plants	1.74	1	1.74	359	626
^f Gas power plants	0.12	37	4.5	1,820	221
^g Petroleum power plants	0.93	0	0	1,080	1,007
^f Nuclear power plants	14.9	1	14.9	61	911
^f Other power plants	0.93	0	0	41	41
^g Fueling stations	0.0018	10,200	18	156,000	275
^h Gas storage facilities	12.95	10	130	394	5,102
Total			4,736		126,000
Percent of CA or U.S.			1.2		1.3

^aNumber of active oil and gas wells, compressors, and processors from Oil and Gas (2018). The area of each is calculated from the 3 million ha of well pads, roads, and storage facilities required for 600,000 new wells from 2000 to 2012 (Allred et al., 2015).

^bThe number of abandoned U.S. oil and gas wells is from U.S. EPA (2017), slide 11. The California number is calculated as the U.S. number multiplied by the California to U.S. ratio of active wells. The area of each abandoned oil well is estimated as 50 m², and of each gas well, 25 m² from Jepsen (2018).

^cThe number of coal mines is from EIA (2018a). The area per mine is estimated from the total area among all mines from Sourcewatch (2011) divided by number of mines here.

^dThe number of oil refineries is from EIA (2018b). The area of each refinery is based on the area of the Richmond, California refinery.

^eKilometers of oil and gas pipeline for the U.S. were from BTS (2018); for California were estimated. The area needed for each 1 km of pipeline is estimated to be 6 m (3 m on each side of the pipe) multiplied by 1 km.

^fThe numbers of coal, gas, petroleum, nuclear and other power plants are from EIA (2018c). The areas for each coal, gas, and nuclear plant is derived from Strata (2017). For coal, the area includes those for the plant and waste disposal (mining is a separate line in this table). For gas, the area is just for the plant. For nuclear, the area includes the areas required for uranium mining, the plant itself, and waste disposal. The areas required for petroleum and other are an average of that for a coal and gas plant.

^gThe number of retail fueling stations in the U.S. is from AFDC (2014) for 2012 and in California, from Statistica (2017) for 2016. The area of a fueling station is estimated from the area of a typical gas station.

^hThe number of gas storage facilities is from FERC (2004). The area of a gas storage facility is estimated as that of the Aliso Canyon storage facility.

A transition to 100 percent WWS, on the other hand, eliminates the energy consumed to continuously mine, transport, and process fossil fuels and uranium, which amounts to 12.1 percent of all energy worldwide (Table 7.1). Wind, on the other hand, comes right to the turbine, and sunlight comes right to the solar panel. In other words, eliminating all fossil fuels and uranium will eliminate 12.1 percent of all energy needs worldwide immediately and will prevent the degradation of land used for the continuous mining of natural gas, coal, oil, and uranium.

3.2. Why Not Use Natural Gas or Coal with Carbon Capture?

Another proposal to help solve the climate problem is to capture the CO₂ emitted from a coal or natural gas power plant before the CO₂ is released from the exhaust stack. This would be accomplished with carbon capture and sequestration (CCS) equipment added to the plant. However, this solution is poor for four reasons: it increases emissions and health problems of all gases and particles aside from CO₂ compared with no CCS, it only marginally reduces CO₂, it increases the land degradation from the mining of fossil fuels compared with no CCS, and its high cost prevents more effective climate and pollution mitigation with lower-cost renewables.

Carbon capture and sequestration (CCS) is the separation of CO₂ from other exhaust gases after fossil fuel or biofuel combustion, followed by the transfer of the CO₂ to an underground geological formation (e.g., saline aquifer, depleted oil and gas field, or un-minable coal seam). The remaining combustion gases are emitted into the air or filtered further. Geological formations worldwide may theoretically store up to 2,000 Gt-CO₂, which compares with a fossil fuel emission rate in 2017 of about 37 Gt-CO₂/y.

Another proposed CCS method is to inject the CO₂ into the deep ocean. The addition of CO₂ to the ocean, however, results in ocean acidification. Dissolved CO₂ in the deep ocean eventually equilibrates with CO₂ in the surface ocean, reducing ocean pH and simultaneously supersaturating the surface ocean with CO₂, forcing some of it back into the air.

A third type of sequestration method is to mix captured CO₂ with concrete material, trapping the CO₂ inside the concrete (Section 2.4.8.2).

Carbon capture and use (CCU) is the same as CCS, except that the isolated CO₂ with CCU is sold to reduce the cost of the carbon capture equipment. To date, the major application of CCU has been **enhanced oil recovery**. With this process, CO₂ is pumped underground into an oil field. It binds with oil, reducing its density and allowing it to rise to the surface more readily. Once the oil rises up, the CO₂ is separated from it and sent back into the reservoir. About two additional barrels of oil can be extracted for every ton of CO₂ injected into the ground.

Another proposed use has been to create carbon-based fuels to replace gasoline and diesel. The problem with this proposal is that it allows combustion to continue in vehicles. Combustion creates air pollution, only some of which can be stopped by emission control technologies.

3.2.1. Air Pollution Increases and Only Modest Lifecycle CO₂e Decreases due to Carbon Capture

Whereas carbon capture equipment is nominally expected to capture 85 to 90 percent of the CO₂ from a fossil fuel exhaust stream, several factors cause the overall CO₂ and CO₂e savings due to carbon capture to be much smaller than this but also cause an increase in emissions of health-affecting air pollutants relative to no carbon capture. The reasons for these impacts are summarized as follows:

- 1) A fossil fuel with carbon capture power plant needs to produce 25 to 50 percent more energy, thus requires 25 to 50 percent more fuel, to run the carbon capture equipment than does a plant without the equipment (IPCC, 2005, EIA, 2017).
- 2) Carbon capture equipment does not capture the upstream CO₂e emissions resulting from mining, transporting, or processing the fossil fuel used in the plant. Instead, such emissions increase 25 to 50 percent because 25 to 50 percent more fuel is needed. These emissions offset a portion of the captured CO₂ from the plant exhaust and increase the air pollution associated with the mining, transporting, and processing of the fuel.
- 3) The carbon capture equipment does not capture any of the non-CO₂ air pollutants from the fossil fuel exhaust. Such pollutants include CO, NO_x, SO₂, organic gases, mercury, toxins, BC, BrC, fly ash, and other aerosol components, all of which affect health. Instead, those pollutants increase 25 to 50 percent because this much more fossil fuel from the plant is needed to run the CCS equipment.
- 4) The chance that CO₂ sequestered underground leaks increases over time and varies with geological formation.

One way to estimate the climate impact of carbon capture equipment attached to a fossil fuel plant is to examine the plant's lifecycle emissions before and after the equipment is added. **Lifecycle emissions** are carbon-equivalent (CO₂e) emissions of a technology per unit electric power generation (kWh or MWh), averaged over a 20- or 100-year time frame. The emissions accounted for include those during the construction, operation, and decommissioning of the plant. For a fossil fuel (or nuclear) plant, the operation phase includes mining, transporting, and processing the fuel as well as running the plant equipment, repairing the plant over its life, and disposing of waste (e.g., coal residue or nuclear waste) over its life. Lifecycle CO₂e is calculated as the lifecycle emission of CO₂ plus the lifecycle emission of each other gas or particle pollutant from the technology multiplied by its respective 20- or 100-year GWP (Table 1.2).

Table 3.4 shows theoretical estimates of 20- and 100-year lifecycle CO₂e emissions from an average U.S. coal plant, a modern **supercritical pulverized coal (SCPC)** plant, and a natural gas combined cycle gas turbine (CCGT) plant, each with and without carbon capture. An SCPC plant operates at a high temperature and pressure than a normal coal plant. As such, the efficiency of combustion (electricity production per mass of coal) is higher. The table indicates that, even after carbon capture, the coal SCPC plant still emits 50.4 percent of its CO₂e over 20 years and 28.7 percent over 100 years compared with no carbon capture. A natural gas CCGT emits 34 percent of its CO₂e over 20 years and 35.4 percent over 100 years compared with no capture. These results reflect the fact that the carbon capture equipment increases the upstream emissions of CO₂e due to increasing the fuel needed to be burned in the power plant. The results also reflect the fact that the carbon capture equipment lets 10 to 15 percent of the CO₂ emitted by the stack escape. Whereas, these estimates are theoretical, data from a real coal plant before and after carbon capture (Table 3.6) show much lesser removal of CO₂e than indicated in the Table 3.4.

Table 3.4. Theoretical lifecycle 20-year and 100-year CO₂e emissions from average U.S. coal power plants, a supercritical pulverized coal (SCPC) power plant and a natural gas combined cycle gas turbine (CCGT) plant with and without carbon capture. Compare with data from a real carbon capture facility in Table 3.6.

	Average U.S. Coal Plant			Coal SCPC Plant			Natural Gas CCGT Plant		
	No Carbon Capture	With Carbon Capture	Percent CO ₂ e Remaining	No Carbon Capture	With Carbon Capture	Percent CO ₂ e Remaining	No Carbon Capture	With Carbon Capture	Percent CO ₂ e Remaining
20-y CO ₂ e/kWh	1,316	664	50.4	1,188	599	50.4	896	305	34.0
100-y CO ₂ e/kWh	1,205	346	28.7	965	277	28.7	506	179	35.4

All values are from Skone (2015), except the percent remaining for average U.S. coal was assumed the same as from Coal SCPC, and the CO_{2e} values with carbon capture for average U.S. coal were calculated from the percent remaining and the no carbon capture values.

The results in Table 3.4 suggest that carbon capture does not come close to eliminating CO_{2e} emissions from coal or gas power plants. Data from real world projects (Section 3.2.3) indicate even less reduction in CO_{2e} emissions due to carbon capture than Table 3.4 suggests. Further, the lifecycle CO_{2e} emissions from a natural gas or coal plant with carbon capture are not the only emissions associated with a fossil fuel plant. Other important emissions include those that affect human and animal health. Lifecycle emissions can be placed in context only when all relevant climate-affecting emissions or avoided emissions associated with a plant are accounted for and compared with the same from other energy technologies, as discussed next.

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, anthropogenic heat emissions, anthropogenic water vapor emissions, emissions risk due to CO₂ 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 $2 \text{ y} / 22 \text{ y} = 9.1$ percent of the time for refurbishing and Plant B is down $1 \text{ y} / 31 \text{ y} = 3.2$ percent of the time for refurbishing. As such, Plant B is down an additional $(0.091 - 0.032) \times 100 \text{ y} = 5.9$ 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

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

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

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

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-CO₂e/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-CO₂e/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-CO₂e/kWh, $Y=100$ y, $T_{PO}=15$ y, $L=40$ y, and $T_R=3$ y as $E_{BR,H}=550$ g-CO₂e/kWh $\times [15$ y + $(100$ y – 15 y) $\times 3$ y / 43 y] / 100 y = 115 g-CO₂e/kWh.

Similarly, the background emissions from Plant A averaged over 100 years are $E_{BR,L}=550$ g-CO₂e/kWh $\times [3$ y + $(100$ y – 3 y) $\times 1$ y / 31 y] / 100 y = 33.7 g-CO₂e/kWh. The difference between the two from Equation 3.1, $E_{OC}=E_{BR,H}-E_{BR,L}=81.3$ g-CO₂e/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). 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-CO₂e/kWh in opportunity cost emissions from the background grid.

Table 3.5. Total 100-year CO₂e 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-CO₂/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 ₂ e	^h Ratio of 100-year CO ₂ e 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

^aLifecycle emissions are 100-year carbon equivalent (CO₂e) 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-CO₂/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-CO₂/kWh mean for CdTe panels at 11 percent efficiency, the 27 g-CO₂/kWh mean for multi-crystalline silicon panels at 13.2 percent efficiency, and the 29 g-CO₂/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-CO₂/kWh is from Jacobson (2009), which is within the Intergovernmental Panel on Climate Change (IPCC)'s range of 4-110 g-CO₂/kWh (Bruckner et al., 2014), and conservative relative to the 68 (10-130) g-CO₂/kWh from the review of Lenzen (2008) and the 66 (1.4-288) g-CO₂/kWh from the review of Sovacool (2008).

Biomass: The range provided is for biomass electricity generated by forestry residues (43 g-CO₂/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-CO₂/kWh from Table 3.4, multiplied by 80 percent, which is the percent of CO₂e 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-CO₂/kWh from Table 3.6, multiplied by 80 percent, which is the percent of coal lifecycle CO₂e emissions from the Petra Nova facility that will remain in the air over 100 years (Table 3.6).

^bOpportunity 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-CO₂e/kWh in 2017. This is derived from an electricity mix from EIA (2018d) and emissions, weighted by their 100-year GWPs, of CO₂, CH₄, and N₂O 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.

^cAnthropogenic heat emissions here include the heat released to the air from combustion (for coal or natural gas) or nuclear reaction, converted to CO₂e (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.

^dAnthropogenic 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 CO₂e (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-H₂O/kWh evaporated from reservoirs at mid to high latitudes (Flury and Frischknecht, 2012). The upper end is 17.0 kg-H₂O/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).

^eNuclear 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-CO₂e/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 CO₂ 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.

^fLoss 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 of 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.

^gThe 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-CO₂e/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 CO₂e emissions (g-CO₂e/kWh) due to the anthropogenic heat flux is calculated for all technologies (including the negative heat fluxes due to solar and wind) as follows:

$$H = E_{CO_2} \times A_h / (F_{CO_2} \times G_{elec}) \quad (3.3)$$

where E_{CO_2} is the equilibrium global anthropogenic emission rate of CO₂ (g-CO₂/y) that gives a specified anthropogenic mixing ratio of CO₂ in the atmosphere, F_{CO_2} is the direct radiative forcing (W/m²) of CO₂ at the specified mixing ratio, A_h is the anthropogenic heat flux (W/m²) 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/m²) in the atmosphere due to CO₂ can be maintained at an equilibrium CO₂ emission rate,

$$E_{CO_2} = \chi_{CO_2} C / \tau_{CO_2} \quad (3.4)$$

where χ_{CO_2} (ppmv) is the specified anthropogenic mixing ratio that gives the current CO₂ radiative forcing, C is a conversion factor (8.0055×10¹⁵ g-CO₂/ppmv-CO₂), and τ_{CO_2} is the data-constrained e -folding lifetime of CO₂ against loss by all processes. As of 2019, τ_{CO_2} is ~50 years but increasing over time (e.g., Jacobson, 2012a, Figure 3.12).

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 CO₂ 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 CO₂ emission rate to the radiative forcing of CO₂ by the ratio of the anthropogenic heat flux to the electricity generation per year producing that heat flux, gives Equation 3.3, the CO₂e emission rate of the heat flux.

Thus, Equation 3.3 accounts for the emission rate of CO₂ needed to maintain a mixing ratio of CO₂ 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 CO₂ mixing ratio than is currently in the atmosphere because CO₂ emissions are not in equilibrium with the CO₂ atmospheric mixing ratio. Equation 3.3 requires a constant emission rate that gives the observed mixing ratio of CO₂ 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 CO₂. For example, the globally averaged temperature change per unit direct radiative forcing for CO₂ is $\sim 0.6 \text{ K}/(\text{W}/\text{m}^2)$ (Jacobson, 2002), whereas the temperature change per unit anthropogenic heat plus water vapor flux is $\sim 0.83 \text{ K}/(\text{W}/\text{m}^2)$ (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 $A_h = 0.027 \text{ W}/\text{m}^2$ (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 $G_{\text{elec}} = 8.622 \times 10^{12} \text{ kWh}/\text{y}$ from coal combustion and $2.64 \times 10^{12} \text{ kWh}/\text{y}$ from nuclear reaction.

Assume an anthropogenic CO₂ direct radiative forcing of $F_{\text{CO}_2} = 1.82 \text{ W}/\text{m}^2$, which corresponds to an anthropogenic mixing ratio of CO₂ of $\chi_{\text{CO}_2} = 113 \text{ ppmv}$ (Myhre et al., 2013). Also assume a CO₂ e-folding lifetime of $\tau_{\text{CO}_2} = 50$ years.

Solution:

From Equation 3.4, the equilibrium emission rate of CO₂ giving the anthropogenic mixing ratio is

$$E_{\text{CO}_2} = 1.809 \times 10^{16} \text{ g-CO}_2/\text{y}.$$

Multiplying the total anthropogenic heat flux by the respective fractions of heat from coal combustion and nuclear reaction gives $A_h = 0.00132 \text{ W}/\text{m}^2$ for coal and $0.00042 \text{ W}/\text{m}^2$ for nuclear. Substituting these and the other given values into Equation 3.3 gives $H = 1.52 \text{ g-CO}_2\text{e}/\text{kWh}$ for coal and $1.57 \text{ g-CO}_2\text{e}/\text{kWh}$ 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 $5.092 \times 10^{14} \text{ m}^2$.

Solution:

If a solar panel produces $G_{\text{elec}} = 1 \text{ kWh}/\text{y}$ 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 ($-1 \text{ kWh}/\text{y}$) by $1,000 \text{ W}/\text{kWh}$ and dividing by $8760 \text{ h}/\text{y}$ and by the area of the Earth gives $A_h = -2.24 \times 10^{-16} \text{ W}/\text{m}^2$. Substituting this, $G_{\text{elec}} = 1 \text{ kWh}/\text{y}$, and E_{CO_2} and F_{CO_2} from Example 3.2 into Equation 3.3 gives $H = -2.23 \text{ g-CO}_2\text{e}/\text{kWh}$.

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, the 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 CO₂e emissions per unit energy (M , g-CO₂e/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/m²) is substituted for the heat flux:

$$M = E_{CO_2} \times A_m / (F_{CO_2} \times G_{elec}) \quad (3.5)$$

In this equation, the globally averaged moisture energy flux can be obtained from the water vapor flux per unit energy (V , kg-H₂O/kWh) by

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

where $L_e=2.465 \times 10^6$ J/kg-H₂O is the latent heat of evaporation, $S=3.1536 \times 10^7$ seconds per year, and $A_e=5.092 \times 10^{14}$ m² is the surface area of the Earth. For water evaporating from a hydropower reservoir, $V = 1.75$ to 17 kg-H₂O/kWh (Table 3.5, footnote c).

Combining Equations 3.5 and 3.6 gives the globally averaged CO₂e emissions per unit energy due to a positive or negative water vapor flux resulting from an energy generator as

$$M = E_{CO_2} \times V \times L_e / (F_{CO_2} \times S \times A_e) \quad (3.7)$$

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/m² and from nuclear power plants was $A_m=0.000746$ W/m² (Jacobson, 2014). The total energy generation from natural gas use was $G_{elec}=7.208 \times 10^{12}$ kWh/y and from nuclear was 2.64×10^{12} kWh/y. Calculate the CO₂e emissions associated with these fluxes.

Solution:

Substituting E_{CO_2} and F_{CO_2} from Example 3.2 and A_m and G_{elec} provided in the problem into Equation 3.5 gives $M=3.69$ g-CO₂e/kWh for natural gas and 2.81 g-CO₂e/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-H₂O/kWh (Flury and Frischknecht, 2012), determine the CO₂e emissions of water vapor from the reservoir.

Solution:

Substituting V into Equation 3.7 with E_{CO_2} and F_{CO_2} from Example 3.2 gives the carbon equivalent emissions due to hydropower reservoir evaporation as $M=2.66$ g-CO₂e/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 CO₂e 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-H₂O/kWh, where the variation depends on the number and location of wind turbines. Example 3.6 provides an estimate of the CO₂e savings due to wind turbines from these two factors.

Example 3.6. Estimate the globally averaged CO₂e 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 CO₂e 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-H₂O/kWh and the rest of the energy remains in the atmosphere. Assume the equilibrium emission rate and resulting radiative forcing of CO₂ from Example 3.2.

Solution:

Multiplying the latent heat of evaporation ($L_e=2.465 \times 10^6$ J/kg) and 1 kWh/ 3.6×10^6 J by -0.3 to -1 kg-H₂O/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} m², gives $A_m/G_{elec} = -4.6 \times 10^{-17}$ to -1.53×10^{-16} (W/m²)/(kWh/y). Substituting this and E_{CO_2} and F_{CO_2} 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-CO₂e/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-CO₂e/kWh. The total heat plus water vapor energy flux savings due to wind turbines is thus -2.23 g-CO₂e/kWh, the same as for solar panels (Example 3.3).

3.2.2.4. Leaks of CO₂ Sequestered Underground

The sequestration of carbon underground due to CCS or CCU (e.g., from injecting CO₂ during enhanced oil recovery) runs the risk of CO₂ 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 CO₂ leakage from the ground is estimated.

The ability of a geological formation to sequester CO₂ for decades to centuries varies with location and tectonic activity. IPCC (2005, p. 216) references CO₂ leakage rates for an enhanced oil recovery operation of 0.00076 percent per year, or 1 percent over 1,000 years, and CH₄ 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 CO₂ 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 CO₂ injected underground will be under high pressure, it will take advantage of any horizontal or vertical fractures in rocks to escape as a gas to the air. Because CO₂ is an acid, its low pH will also cause it to weather rock over time. If a leak

from an underground formation to the atmosphere occurs, it is not clear whether it will be detected. If a leak is detected, it is not clear how it will be sealed, particularly if it is occurring over a large area.

The time-averaged leakage rate of CO₂ from a reservoir can be calculated by first estimating how the stored mass of CO₂ changes over time. The stored mass (S) of CO₂ at any given time t in a reservoir, resulting from a constant injection at rate I (mass/y) and e -folding lifetime against leakage T (years) is

$$S(t) = S(0)e^{-t/T} + TI(1 - e^{-t/T}) \quad (3.8)$$

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,

$$L(t) = I - S(t)/t \quad (3.9)$$

The average leakage rate of CO₂ from an underground storage reservoir over a specified period is calculated from Equations 3.8 and 3.9 given an injection rate and a lifetime against leakage.

Example 3.7. Estimating average leakage rates from underground storage reservoirs.

Assume a coal-fired power plant has a CO₂ emission rate before carbon capture and storage ranging from 790 to 1,017 g-CO₂/kWh. Assume also that carbon capture equipment added to the plant captures 90 and 80 percent, respectively, of the CO₂ (giving a low and high, respectively, emission rate of remaining CO₂ to the air). If the captured CO₂ is injected underground into a geological formation that has no initial CO₂ in it, calculate a low and high CO₂ 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 CO₂ over 1,000 years (e.g., IPCC, 2005).

Solution:

The low and high injection rates are $790 \times 0.9 = 711$ g-CO₂/kWh and $1,017 \times 0.85 = 864.5$ g-CO₂/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-CO₂/kWh over 100 years; 1.8 to 42 g-CO₂/kWh over 500 years, and 3.5 to 81 g-CO₂/kWh over 1,000 years.

Thus, the longer the averaging period, the greater the average emission rate over the period due to CO₂ leakage.

3.2.2.5. Emissions From Covering of Land or Clearing of Vegetation

Emissions from the **covering of land or clearing of vegetation** are emissions of CO₂ itself due to (a) reducing the carbon stored in soil and in the vegetation above the soil by covering the land with impervious material or (b) reducing the carbon stored in vegetation by clearing the land so less vegetation grows. When soil is covered with impervious material, such as concrete or asphalt, vegetation can't grow in the soil or decay and 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/m² and 13.2 kg-C/m², 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 covered instead 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 (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 in 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 CO₂e emissions from 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 km², including the land for the coal facility, mining, railway transport, and waste disposal. Calculate the emission rate of CO₂ 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 $425 \text{ MW} \times 8760 \text{ h/y} \times 0.65 \times 1,000 \text{ kW/MW} = 2.42 \times 10^9 \text{ kWh/y}$. Over 100 years, the energy produced is $2.42 \times 10^{11} \text{ kWh}$.

The carbon lost in soil is $0.34 \times 13.2 \text{ kg-C/m}^2 = 4.5 \text{ kg-C/m}^2$ and that lost from vegetation is 1.15 kg-C/m^2 , for a total of 5.64 kg-C/m^2 . Multiplying by $1,000 \text{ g/kg}$ and the molecular weight of CO₂ ($44.0095 \text{ g-CO}_2/\text{mol}$), then dividing by the molecular weight of carbon (12.0107 g-C/mol) give $20,700 \text{ g-CO}_2/\text{m}^2$. 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 $0.44 \text{ g-CO}_2/\text{kWh}$, 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.

3.2.2.6. Comparison of Coal and Natural Gas with Carbon Capture with Other Energy Technologies

Table 3.5 compares the overall 100-year CO₂e emissions from coal and natural gas power plants that have carbon capture (CCS or CCSU) with emissions from other electricity generating technologies. The table indicates that coal-CCS/U results in 33 to 211 times the CO₂e emissions as onshore wind. Natural gas-CCS/U results in 27 to 100 times the emissions as onshore wind.

The reasons for the high CO₂e emissions of coal and natural gas with carbon capture, are (1) coal and gas plants need 25 to 55 percent more energy to run the carbon capture equipment, and this increases the upstream emissions (fuel mining, transport, and processing) of coal and gas by 25 to 55 percent (Example 3.9), (2) the capture equipment allows 10 to 30 percent of the CO₂ in the power plant exhaust to escape (Example 3.9), (3) CO₂e emissions from the background grid occur due to the time lag between planning and operation of a coal or gas plant with capture relative to a wind or solar farm, (4) coal and natural gas have heat and water vapor emissions associated with them, (5) some leaks of CO₂ occurs once CO₂ is sequestered, and (6) coal and gas facilities reduce the storage of carbon in the ground.

Table 3.5 provides climate-relevant emissions, but not health-relevant emissions. Air pollution emissions of coal and natural gas without carbon capture are 100 to 400 times those of onshore wind per unit energy. Adding carbon capture to a coal or gas plant increases air pollution emissions another 25 to 55 percent.

The high air pollution and climate-relevant emission rates of coal and natural gas with carbon capture suggest that spending money on them represents an opportunity cost relative to spending money on lower-emitting technologies. Another issue is that, in a future WWS system, the number of hours of fossil fuel use at any given plant decreases, making CCS equipment, which is already costly, even more uneconomical (Lund and Mathiesen, 2012).

3.2.3. Carbon Capture Projects

To date, CO₂ has been captured and separated primarily from mined natural gas or, in one case, from gasified coal. In all such cases, the CO₂ has been used to enhance oil recovery.

As of 2019, only two fossil fuel power plants have operated with carbon capture equipment. In both cases, the separated CO₂ was used for enhanced oil recovery, and the CCU equipment was installed at high cost. One project experienced equipment problems, resulting in much more CO₂ released to the air than anticipated. The other project required a natural gas plant to be built to power the CCU equipment, also resulting in much less benefit than anticipated. Future projects like these must also be in proximity to an oil and gas production field.

The first electric power plant with CCU equipment was the **Boundary Dam power station** in Estevan, Saskatchewan, Canada, which has been operating with CCU equipment on one coal boiler connected to a steam turbine since October 2014. The cost of the retrofit project was \$1.5 billion (\$13.6 million/MW for a 110 MW turbine). This cost included a \$240 million subsidy from the Canadian government and was on top of the original coal plant cost. Whereas half the captured CO₂ from the CCU equipment has been sold for enhanced oil recovery, the other half has been released to the air. In addition, since 2016, the CCU equipment has been operating only 40 percent of the time due to design problems. The energy required to run the CCU equipment also results in additional uncaptured CO₂ emissions. Mining the coal for the plant results in even more uncaptured emissions.

The second plant with CCU equipment was the **W.A. Parish coal power plant** near Thompsons, Texas. The plant was retrofitted with CCU equipment as part of the **Petra Nova** project and began using the equipment during January 2017. The CC equipment (240 MW) receives 36.7 percent of the emissions from a 654 MW boiler at the plant. The equipment requires about 0.497 kWh of electricity to run per kWh produced by the coal plant (Table 3.6, Footnote 8). A natural gas turbine with a heat recovery boiler was installed to provide this electricity. A cooling tower and water treatment facility were also added. The retrofit cost \$1 billion (\$4,200/kW) beyond the coal plant cost (Scottmadden, 2017).

The captured CO₂ is compressed and piped to an oil field, where it is used to enhance oil recovery. CO₂ from the gas turbine is not captured. Natural gas production also has upstream CO₂e emissions, including CH₄ leaks, which are not captured. Upstream CO₂ and CH₄ emissions from the coal plant are also uncaptured.

Table 3.6 indicate that, when upstream emissions are excluded, the CCU equipment captures an average of only 55.4 percent of coal combustion CO₂ and only 33.9 percent of coal plus gas combustion CO₂. Table 3.6 also shows the upstream emissions from the mining and processing of coal and natural gas. When these are accounted for, the CCU equipment reduces coal and gas combustion plus upstream CO₂ a net of only 10.8 percent over a 20-year time frame and 20 percent over a 100-year time frame. 20 years is a relevant time frame to avoid 1.5° global warming and resulting climate feedbacks (IPCC, 2018).

When wind, instead of gas, is used to power the CCU equipment, CO₂e increases compared with no CCU by 12 percent over 20 years and 6 percent over 100 years (Table 3.6). The reason is that, if wind is not used

to run the CCU equipment, it is used to replace coal at the plant, reducing emissions substantially. In fact, a third case in Table 3.6 indicates that using the wind electricity that powers the CCU equipment to replace coal electricity at the same plant reduces CO₂e by 47.9 percent compared with no CCU. This last strategy is the best for reducing CO₂e among the three cases. Using solar PV results in a similar benefit as using wind.

Because CCU equipment does not capture health-affecting air pollutants, their emissions continue from coal and rise from the new use of gas. Even when wind powers the CCU equipment, air pollution increases because the wind electricity is not displacing polluting coal. Only when wind displaces coal does air pollution decrease.

The cost of new coal and wind electricity in the U.S. are a mean of \$102/MWh and \$42.5/MWh, respectively (Table 7.9). The capital cost of carbon capture equipment, \$4,200/kW (Scottmadden, 2017), is about 74 percent the mean capital cost of a new coal plant (\$5,700/kW) (Table 7.9), suggesting that new coal plus CCU is $1.74 \times \$102/\text{MWh} / \$42.5/\text{MWh} = 4.2$ times the cost of new wind. Since carbon capture equipment reduces only 10.8 percent of coal CO₂e over 20 years and 20 percent over 100 years, coal-CCU then costs 39 and 21 times wind per mass-CO₂ removed over 20 and 100 years, respectively. When the health costs of coal are added (\$80/MWh, Table 3.6, Footnote 14), and the fact that the use of gas to run the CCU equipment increases these costs by ~25 percent (Table 3.6, Row p), **coal-CCU costs 65 and 35 times wind per unit mass of CO₂ removed over 20 and 100 years, respectively.**

Finally, Table 3.6 shows that the social cost of coal with CCU powered by gas is 24 percent higher over 20 years and 19 percent higher over 100 years than coal without CCU. Thus, no net social benefit exists of using CCU equipment. When wind powers CCU, the social costs are 40 percent and 37 percent higher, respectively, than no CCU, because using wind for the CCU equipment prevents the wind from replacing dirty coal. When wind replaces coal, and no CCU is used, the social cost drops 43 percent. This is the best scenario.

Table 3.6. Comparison of relative CO₂e emissions, energy use, energy private costs, and energy social costs among three scenarios related to the Petra Nova coal-CCU facility, each over a 20-y and 100-y time frame. The first scenario is using natural gas to power the CCU equipment. Those numbers are derived from data between January and July 2016 and 2017 from the Petra Nova facility (EIA, 2017). The second scenario is obtaining the same amount of energy for the CCU equipment from onshore wind instead of natural gas. The third scenario is using the same quantity of wind electricity required to run the CCU equipment to replace coal electricity from the coal plant. In all cases, the additional energy required to run the CCU equipment is equivalent to 49.7 percent of the energy output of the coal plant (Footnote 8). The coal plant has a nameplate capacity of 654 MW, but only 240 MW (36.7 percent) is subject to CCU. The numbers in the table are all based on the portion subject to CCU. All emission units (including of natural gas emissions) are g-CO₂e/kWh-coal-electricity-generation. From Jacobson (2019).

	Coal with gas-powered CCU 20 y	Coal with gas-powered CCU 100 y	Coal with wind-powered CCU 20 y	Coal with wind-powered CCU 100 y	Wind used for CCU replacing coal + remaining coal 20 y	Wind used for CCU replacing coal + remaining coal 100 y
a) Upstream CO ₂ from coal ¹	97.2	97.2	97.2	97.2	48.9	48.9
b) Upstream CO ₂ e of leaked CH ₄ from coal ²	353	140	353	140	177.6	70.4
c) Coal stack CO ₂ before capture ³	930.6	930.6	930.6	930.6	468.1	468.1
d) Total coal CO ₂ e before capture (a+b+c)	1,381	1,168	1,381	1,168	695	587
e) Remaining stack CO ₂ after capture ⁴	414.6	414.6	414.6	414.6	N/A	N/A
f) CO ₂ captured from stack (c-e)	516.0	516	516	516	N/A	N/A
g) Percent stack CO ₂ captured (f/c)	55.4%	55.4%	55.4%	55.4%	N/A	N/A
h) CO ₂ emissions gas combustion ⁵	200.9	200.9	0	0	0	0
i) Upstream CO ₂ e of CH ₄ from gas leaks ⁶	139.2	55.03	0	0	0	0
j) Upstream CO ₂ from gas mining, transport ⁷	26.85	26.85	0	0	0	0
k) Coal emissions wind would have replaced ⁸	0	0	686.4	580.5	0	0
l) Total CO ₂ e emissions (a+b+e+h+i+j+k)	1,232	934.5	1,551	1,232	695	587
m) Percent of coal CO ₂ e re-emitted (l/d) ⁹	89.2%	80.0%	112%	106%	50.3%	50.3%
n) Percent of coal CO ₂ e captured (100-m)	10.8%	20%	-12%	-6%	49.7%	49.7%
o) Relative CO ₂ e to original ¹⁰	0.892	0.80	1.12	1.06	0.503	0.503
p) Relative air pollution to original ¹¹	1.25	1.25	1.503	1.503	0.503	0.503
q) Energy required relative to original ¹²	1.497	1.497	1.497	1.497	1	1
r) Private cost/kWh relative to original ¹³	1.74	1.74	1.74	1.74	0.71	0.71
s) Social cost before changes (\$/MWh) ¹⁴	334	334	334	334	334	334
t) Social cost after changes (\$/MWh) ¹⁵	413	399	468	459	189	189
u) Social cost ratio (t/s)	1.24	1.19	1.40	1.37	0.57	0.57

¹Coal upstream emissions are estimated as 27 g-CO₂/MJ = 97.2 g-CO₂/kWh (Howarth, 2014). Upstream emissions include emissions from fuel extraction, fuel processing, and fuel transport. Upstream CO₂ emissions (from the portion of the coal plant not replaced) for the wind-replacing some coal cases (last two columns) are the same as in the other cases, but multiplied by 0.503, which equals 1 minus the fraction of coal electricity used to run the carbon capture equipment, which is derived in Footnote 8. Since the electricity used to run the CCU equipment is used to replace coal in this case, upstream coal emissions are reduced accordingly.

²For coal, the 100-year CO₂e from CH₄ leaks is estimated from (Skone, 2015, Slide 17). The emission factor is derived from that number and the 100-year GWP of CH₄, 34 from Myhre et al. (2013). The 20-year CO₂e is then derived from the resulting emission factor (4.1 g-CH₄/kWh) and the 20-year GWP of CH₄, 86. Emissions in the wind cases are reduced as described under Footnote 1.

³The average coal stack emission rate for the Petra Nova facility in 2016, prior to the addition of CCU equipment, is derived from EIA (2017) (see Jacobson, 2019). In the wind-replacing-coal cases (last two columns), the emission rate is reduced as described under Footnote 1.

⁴The coal-stack CO₂ remaining after capture is derived from EIA (2017) (see Jacobson, 2019).

⁵The natural gas combustion emissions resulting from powering the CCU equipment is derived from EIA (2017) (see Jacobson, 2019).

⁶Natural gas upstream leaks are obtained by dividing the raw emission rate of CO₂ from natural gas for each month January through June 2017 (derived from EIA, 2017, in Jacobson, 2019) (in kg-CO₂/MWh-coal-electricity) by the molecular weight of CO₂ (44.0098 g-CO₂/mol) to give the moles of natural gas burned per MWh-coal-electricity. Multiplying the moles burned per MWh by the fractional number of moles burned that are methane (0.939) (Union Gas, 2018) and the molecular weight of methane (16.04276 g-CH₄/mol) gives the mass intensity of methane in the natural gas burned each month (kg-CH₄-burned/MWh-coal-electricity). The upstream leakage rate of methane is then the kg-CH₄-burned/MWh-coal-electricity multiplied by L/(1-L), where L=0.023 is the fraction of methane consumed that leaks (Alvarez et al., 2018), giving the methane leakage rate in kg-CH₄/MWh-coal-electricity. Multiplying the result by the 20- and 100-year GWPs of CH₄ (86 and 34, respectively) (Myhre et al., 2013) gives the CO₂e emission rate of methane leaks each month. The monthly values are linearly averaged over January through June 2017.

⁷The non-CH₄ upstream CO₂e emissions rate is estimated as 15 g-CO₂/MJ-gas-electricity = 54 g-CO₂/kWh-gas-electricity (Howarth, 2014). Multiplying that by 0.497 MWh-electricity from natural gas per MWh-coal-electricity produced (Footnote 8) gives 26.8 kg-CH₄/MWh-coal-electricity.

⁸The coal emissions that wind can replace are estimated as 49.7 percent of the Petra Nova coal plant emissions. The CCU equipment at Petra Nova require 0.497 MWh-electricity from natural gas per MWh-coal-electricity produced. This is calculated by dividing the average gas combustion emission from Petra Nova (200.9 g-CO₂/kWh-coal from the present table) by the combustion emissions from a combined cycle gas plant (404 g-CO₂/kWh-natural-gas).

⁹The percent CO₂ reemitted for the wind cases (last two columns) equals Row l for the wind cases divided by Row d for the non-wind cases.

¹⁰CO₂e emissions relative to coal with no CCU equipment.

¹¹Air pollution emissions relative to coal with no CCU equipment. In the natural gas cases, all air pollution from coal emissions are retained. Although gas is required to produce 0.497 MWh of electricity for the CCU equipment per MWh of coal electricity, gas is assumed to be 50 percent cleaner than coal, so the overall air pollution in this case increases only 25 percent relative to the no CCU case. In the wind-CCU cases, all the emissions from coal are retained. In addition, 49.7 percent more emissions occur since the wind is used to run CCU equipment (which does not reduce air pollution) rather than replace coal use itself, which would reduce air pollution. In the wind-replacing-coal cases, wind reduces coal use 49.7 percent.

¹²The electricity required (either for end-use consumption or to run the CCU equipment) in all cases is 49.7 percent higher than with no CCU, except in the wind-replacing coal case, where no electricity is needed to run the CCU equipment, but electricity is still needed for end use.

¹³The private energy cost in all CCU cases is assumed to be 74 percent higher than coal with no CCU because the CCU equipment (including the gas plant) cost \$4,200/kW, which represents about 74 percent of the mean capital cost of a new coal plant (\$5,700/kW) from Lazard (2018). For simplicity, it was assumed that the cost of a wind turbine running the CCU equipment was the same as of a gas turbine running the equipment. In the wind-replacing-coal cases, the cost of coal was assumed to be a mean of $c = \$102/\text{MWh}$ and of wind, $w = \$42.5/\text{MWh}$ (Lazard, 2018). The ratio was calculated as $(0.503c + 0.497w)/c$.

¹⁴The social cost before changes is the private energy cost of coal without CCU [$\$102/\text{MWh}$ from Lazard, 2018] plus air pollution mortality, morbidity, and non-health environmental costs of air pollution in the U.S. [$\$80/\text{MWh}$ from Jacobson et al., 2019] plus the global climate costs of U.S. emissions ($\$152/\text{MWh}$) (Jacobson et al., 2017).

¹⁵The social cost after changes is the sum of the private energy cost multiplied by Row r, the air pollution health cost multiplied by Row p, and the climate cost multiplied by Row o.

Example 3.9 shows, in more detail, how some of the calculations in Table 3.6 are performed using one out of the six month of data from EIA (2017).

Example 3.9. Calculating emission reduction due to coal with carbon capture.

According to EIA (2017), emissions of CO₂ during January 2016 from the Texas Parish coal power plant, before carbon capture, were 934.4 kg-CO₂/MWh. Emissions during January 2017, from the portion of the coal emissions subject to carbon capture, were 242.2 kg-CO₂/MWh, for a reduction of 692.2 kg-CO₂/MWh. However, the natural gas plant needed to run the carbon capture equipment itself emitted 271.9 kg-CO₂/MWh-coal-electricity. In addition, coal upstream emissions were 97.2, 353, and 140 kg-CO₂e/MWh-coal-electricity for CO₂ from coal mining, CH₄ leaks from coal mining over 20 years, and CH₄ leaks from coal mining over 100 years, respectively. The non-CH₄ upstream emissions from natural gas required for the capture equipment were 36.3 kg-CO₂/MWh-coal-electricity.

First, estimate the upstream CO₂e emissions from CH₄ leaks associated with mining, transporting, and processing the natural gas used to run the gas turbine. Then, calculate the overall 20-year and 100-year CO₂e of the upstream plus stack emissions from the facility after carbon capture. Finally, what percent of the CO₂e upstream plus stack emissions from the facility continue to be emitted over a 20 year and a 100 year time horizon after carbon capture?

Assume natural gas contains a 93.9 percent mole fraction of methane, and the upstream leakage rate of natural gas is 2.3 percent (Alvarez et al., 2018).

Solution:

Dividing the combustion emission rate of CO₂ from natural gas, 271.9 kg-CO₂/MWh-coal-electricity, by the molecular weight of CO₂ (44.0098 g-CO₂/mol) gives the moles of natural gas burned. Multiplying the moles burned by the fractional number of moles burned that are methane (0.939) and the molecular weight of methane (16.04276 g-CH₄/mol) gives the mass intensity of methane in the natural gas burned, 93.1 kg-CH₄-burned/MWh-coal-electricity.

The upstream leakage rate of methane is then $93.1 * 0.023 / (1 - 0.023) = 2.19$ kg-CH₄/MWh-coal-electricity. Multiplying by the 20- and 100-year GWPs of CH₄ (86 and 34, respectively) from Table 1.2 gives CO₂e emissions of the methane leaks as 188.4 and 74.5 kg-CO₂e/MWh-coal-electricity, respectively. Adding the upstream CO₂+CH₄

emissions to the natural gas stack emissions gives 20- and 100-year CO₂e emissions from the gas turbine as 497 and 382 kg-CO₂e/MWh-coal-electricity, respectively.

Adding these emissions to the coal upstream emissions and uncaptured coal emissions gives the 20- and 100-year CO₂e emissions from the gas turbine plus coal plant after capture as 1,189 and 862 kg-CO₂e/MWh-coal-electricity, respectively. The coal stack plus upstream emissions before capture were 1,385 and 1,172 kg-CO₂e/MWh-coal-electricity, respectively.

As such, averaged over 20 years, $1,189 / 1,385 = 85.8$ percent of the original CO₂e from the coal plant and its upstream emissions remain in the air; Over 100 years, 73.6 percent remain in the air. These re-emissions are on top of downstream leaks that may occur with the captured CO₂.

Example 3.10 illustrates that, because coal with CCS/U is (a) expensive, (b) results in more air pollution emissions than coal without CCS/U, and (c) only modestly decreases CO₂ emissions, its social cost is more than 12 times that of wind energy providing the same energy. In addition, the energy cost is 4.2 times that of a wind turbine to produce the same energy.

Example 3.10. Calculating the cost to society of using coal with CCS instead of wind.

Estimate the energy plus health plus climate change cost of a new coal plant with CCS versus that of wind energy under the following assumptions. The cost of wind energy is 4.25 ¢/kWh (Table 7.9), the cost of a new coal plant is 10.2 ¢/kWh (Table 7.9), the cost of CCS equipment is 7.5 ¢/kWh, the average global health cost of coal pollution is 18 ¢/kWh (Table 7.11), and the average global climate cost of coal pollution is 16 ¢/kWh (Table 7.11). Also assume that the CCS equipment requires 25 percent more energy thus increases all emissions by 25 percent. Finally, assume that the CCS equipment reduces the overall CO₂ emission by 15 percent compared with before CCS equipment is added.

Solution:

The social cost of the coal plant is the energy plus health plus climate cost of the plant. In this case, the energy cost of the plant plus equipment is $10.2 + 7.5 = 17.7$ ¢/kWh. The health cost is 1.25×18 ¢/kWh = 22.5 ¢/kWh. The climate cost is 0.85×16 ¢/kWh = 13.6 ¢/kWh. Adding these three together gives 53.8 ¢/kWh. Dividing this by the cost of wind, 4.25 ¢/kWh, gives 12.7 ¢/kWh. Thus, the social cost of coal-CCS in this case is 12.7 times that of wind. The private energy cost of coal-CCS is 4.2 times that of wind.

Tables 3.6 suggests virtually no carbon benefit of and greater air pollution damage from CCS/U before considering the disposition of the captured CO₂. Three reasons for this, aside from the additional combustion emissions of the natural gas turbine, are the upstream coal and gas emissions, the air pollution resulting from the additional gas mining and use, and (when renewable electricity is used to power the capture equipment) the higher fossil emissions due to not using the renewable electricity to displace fossil electricity.

The results here are independent of the fate of the CO₂ after it leaves the CC equipment, thus apply to CCS/U with bioenergy (e.g., BECCS/U) or cement manufacturing. The CCS/U equipment always requires energy. If the energy comes from a fossil fuel, mining and combustion emissions from the fuel cancel most CO₂ captured. If it comes from a renewable, the renewable will not be able to displace fossil emissions, increasing those emissions. In all cases, air pollution increases.

When the fate of captured CO₂ is considered, the problem may deepen. If CO₂ is sealed underground without leaks, little added emissions occur. If the captured CO₂ is used to enhance oil recovery, its current major application, more oil is extracted and burned, increasing combustion CO₂, some leaked CO₂, and air pollution. If the captured CO₂ is used to create carbon-based fuels to replace gasoline and diesel, energy is still required to produce the fuel, the fuel is still burned in vehicles (creating pollution), and little is captured CO₂ to produce the fuel with. A third proposal is to use the CO₂ to produce carbonated drinks. However, along with the issues previously listed, most CO₂ in carbonated drinks is released to the air during consumption.

In sum, CCS/U is not close to a zero-carbon technology. For the same energy cost, wind turbines and solar panels reduce much more CO₂ while also eliminating fossil air pollution and mining, which CCS/U increases. Renewables further reduce pipelines, refineries, gas stations, tanker trucks, oil tankers, and coal trains, oil spills, oil fires, gas leaks, gas explosions, and international conflicts over energy. CCS/U increases these by increasing energy use.

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

Chemical	<i>E</i> -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 ₂ O	121 years	268	298
^c CFCl ₃ (CFC-11)	45 years	7,020	5,350
^d CF ₂ Cl ₂ (CFC-12)	100 years	10,200	10,800
^c CF ₄ (PFC-14)	50,000 years	4,950	7,350
^d C ₂ F 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.

^aLow-lifetime of CO₂ is the data-constrained lifetime upon increasing CO₂ emissions from Jacobson (2012a, Figure 3.12); high-lifetime of CO₂ calculated from Figure 1 of Jacobson (2017), which shows CO₂ decreasing by 65 ppmv (from 400 to 335 ppmv) over 65 years upon elimination of anthropogenic CO₂ emissions. Since the natural CO₂ is 275 ppmv, the anthropogenic CO₂ = 400-275=125 ppmv, and the lifetime of anthropogenic CO₂ ~ 65 y / -ln((125-65) ppmv/125 ppmv) = ~90 years. The GWP of CO₂=1 by definition.

^bPOC 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.

^cFrom Myhre et al. (2013) Table 8.7. Results from Etminan et al. (2016) suggest that the 20-y GWP of CH₄ may be up to 98.

^dFrom Myhre et al. (2013) Table 8.A.1.

^eFrom Myhre et al. (2013), Section 8.2.3.1. Tropospheric ozone is not emitted so does not have a GWP.

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

^gFrom Streets et al. (2001) and Jacobson (2002), including aerosol direct and indirect effects. Values are on a per kg sulfur basis.

References

ABB, HVDC-an ABB specialty, 2004, <https://library.e.abb.com/public/d4863a9b0f77b74ec1257b0c00552758/HVDC%20Cable%20Transmission.pdf> (accessed December 31, 2018).

- ABB, HVDC technology for energy efficiency and grid reliability, 2005, [https://www02.abb.com/global/abbzh/abbzh250.nsf/0/27c2fdbd96a879a4c12575ee00487a77/\\$file/HVD C+-+efficiency+and+reliability.pdf](https://www02.abb.com/global/abbzh/abbzh250.nsf/0/27c2fdbd96a879a4c12575ee00487a77/$file/HVD C+-+efficiency+and+reliability.pdf) (accessed December 31, 2018).
- ABC (American Bird Conservancy, American Bird Conservancy, <https://abcbirds.org> 2019 (accessed January 4, 2019).
- AFDC, P., Public retail gas stations by year, 2014, <https://afdc.energy.gov/data/10333>, (accessed December 3, 2018).
- Aghahosseini A, D. Bogdanov, and C. Breyer, A techno-economic study of an entirely renewable energy-based powers supply for North America for 2030 conditions, *Energies*, 10, 1171, doi:10.3390/en10081171, 2016.
- Aghahosseini A., D. Bogdanov, L.S.N.S. Barbosa, and C. Breyer, Analyzing the feasibility of powering the Americas with renewable energy and inter-regional grid interconnections by 2030, *Renewable and Sustainable Energy Reviews*, 105, 187-205, 2019.
- Allain, R., How much energy can you store in a stack of cement blocks, *Wired*, 2018, <https://www.wired.com/story/battery-built-from-concrete/> (accessed April 10, 2019).
- Allanore, A., L. Yin, and D. Sadoway, A new anode material for oxygen evolution in molten oxide electrolysis, *Nature*, 497, 353-356, 2013.
- Allred, B.W., W.K. Smith, D. Twidwell, J.H. Haggerty, S.W. Running, D.E. Naugle, and S.D. Fuhlendorf, Ecosystem services lost to oil and gas in North America, *Science*, 348, 401-402, 2015.
- Alcade, J., S. Flude, M. Wilkinson, G. Johnson, K. Edlmann, C.E. Bond, V. Scott, S.M.V. Gilfillan, X. Ogaya, and R.S. Haszeldine, Estimating geological CO₂ storage security to deliver on climate mitigation, *Nature Communications*, 9, 2201, 2018.
- Allen, M. R. *et al.*, Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* 458, 1163–1166, 2009.
- Alvarez, R.A., D. Zavalao-Araiza, D.R. Lyon *et al.*, Assessment of methane emissions from the U.S. oil and gas supply chain, *Science*, 361, 186-188, 2018.
- Alvarez R.A., S.W. Pacala, J.J. Winebrake, W.L. Chameides, and S.P. Hamburg, Greater focus needed on methane leakage from natural gas infrastructure. *Proc. Nat. Acad. Sci.* doi: 10.1073/pnas.1202407109, 2012.
- Archer, C.L., and M. Z. Jacobson, Spatial and temporal distributions of U.S. winds and wind power at 80 m derived from measurements, *J. Geophys. Res.*, 108 (D9) 4289, 2003.
- Archer, C.L. and M.Z. Jacobson, Evaluation of global wind power, *J. Geophys. Res.*, 110, D12110, doi:10.1029/2004JD005462, 2005.
- Archer, C.L., and M.Z. Jacobson, Supplying baseload power and reducing transmission requirements by interconnecting wind farms, *J. Applied Meteorol. and Climatology*, 46, 1701-1717, doi:10.1175/2007JAMC1538.1, 2007.
- Arcon/Sunmark, Large-scale showcase projects, 2017, http://arcon-sunmark.com/uploads/ARCON_References.pdf (accessed November 25, 2018).
- Barber, H., Chapter 7, Electric heating fundamentals, In *The Efficient use of Energy*, 2nd edition, pp. 94-114, I.G.C. Dryden, ed., Butterworth-Heinemann, doi:10.1016/B978-0-408-01250-8.50016-7, 1982.
- Barasa, M., D. Bogdanov, A.S. Oyewo, and C. Breyer, A cost optimal resolution for sub-Saharan Africa powered by 100% renewables in 2030, *Renewable and Sustainable Energy Reviews*, 92, 440-457, 2018.
- Barbosa, L.S.N.S., D. Bogdanov, P. Vainikka, and C. Breyer, Hydro, wind, and solar power as a base for a 100% renewable energy supply for South and Central America, *PloS One*, doi:10.1371/journal.pone.0173820, 2017.
- BBC News, Japan confirms first Fukushima worker death from radiation (2018) <https://www.bbc.com/news/world-asia-45423575> (accessed June 9, 2019).
- Becker, S., B.A. Frew, G.B. Andresen, T. Zeyer, S. Schramm, M. Greiner, and M.Z. Jacobson, Features of a fully renewable U.S. electricity-system: Optimized mixes of wind and solar PV and transmission grid extensions, *Energy*, 72, 443-458, 2014.
- Becker, S., B.A. Frew, G.B. Andresen, M.Z. Jacobson, S. Schramm, and M. Greiner, Renewable build-up pathways for the U.S.: Generation costs are not system costs, *Energy*, 81, 437-445, 2015.

- Bellevrat, E., and K. West, Clean and efficient heat for industry, 2018, <https://www.iea.org/newsroom/news/2018/january/commentary-clean-and-efficient-heat-for-industry.html> (accessed November 17, 2018).
- Berthelemy, M., and L.E. Rengel, Nuclear reactors' construction costs: The role of lead-time, standardization, and technological progress, *Energy Policy*, 82, 118-130, 2015.
- Bistak, S., and S.Y. Kim, AC induction motors vs. permanent magnet synchronous motors, 2017, <http://empoweringpumps.com/ac-induction-motors-versus-permanent-magnet-synchronous-motors-fuji/> (accessed January 5, 2018).
- Bizee, Custom degree day data, 2019, <http://www.degreedays.net>, (accessed January 21, 2019).
- Blakers, A., B. Lu, and M. Socks, 100% renewable electricity in Australia, *Energy*, 133, 471-482, 2017.
- Blakers, A., B. Lu, M. Stocks, K. Anderson, and A. Nadolny, Pumped hydro storage to support 100% renewable power, *Energy News*, 36, 11-14, 2018.
- Blakers, A., M. Stocks, B. Lu, C. Cheng, and A. Nadolny, Global pumped hydro atlas, 2019, <http://re100.eng.anu.edu.au/global/> (accessed March 31, 2019).
- Bloomberg NEF, A behind-the-scenes take on lithium-ion battery prices, 2019 <https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/> (accessed June 28, 2019).
- Boden, T., B. Andres, and G. Marland, Global CO₂ emissions from fossil-fuel burning, cement manufacture, and gas flaring: 1751-2011, 2011, http://cdiac.ornl.gov/ftp/ndp030/global.1751_2011.ems (accessed January 24, 2019).
- Boeing, 747-8 Airplane characteristics for airport planning, 2012, http://www.boeing.com/assets/pdf/commercial/airports/acaps/747_8.pdf (accessed March 27, 2019).
- Bogdanov, D., and C. Breyer, North-east Asian super grid for 100% renewable energy supply: Optimal mix of energy technologies for electricity, gas, and heat supply options, *Energy Conversion and Management*, 112, 176-190, 2016.
- Bogdanov, D., J. Farfan, K. Sadovskaia, A. Aghahosseini, M. Child, A. Gulagi, A.S. Oyewo, L.S.N.S. Barbosa, and C. Breyer, Radical transformation pathway towards sustainable electricity via evolutionary steps, *Nature Communications*, 10, 1077, doi: 10.1038/s41467-019-08855-1, 2019.
- Boiocchi, R., K.V. Gemaey, and G. Sin, Control of wastewater N₂O emission by balancing the microbial communities using a fuzzy-logic approach, *IFAC-PapersOnLine*, 49, 1157-1162, 206.
- Bond, T.C., D.G. Streets, K.F. Yarber, S.M. Nelson, J.-H. Woo, and Z. Klimont, A technology-based global emission inventory of black and organic carbon emissions from combustion, *J. Geophys. Res.*, 109, D14203, doi:10.1029/2003JD003697, 2004.
- Bond, T.C., and Bond, T.C., S.J. Doherty, D.W. Fahey, P.M. Forster, T. Berntsen, O. Boucher, B.J. DeAngelo, M.G. Flanner, S. Ghan, B. Karcher, D. Koch, S. Kinne, Y. Kondo, P.K. Quinn, M.C. Sarofim, M.G. Schultz, M. Schulz, C. Venkataraman, H. Zhang, S. Zhang, N. Bellouin, S.K. Guttikunda, P.K. Hopke, M.Z. Jacobson, J.W. Kaiser, Z. Klimont, U. Lohmann, J.P. Schwarz, D. Shindell, T. Storelvmo, S.G. Warren and C.S. Zender, Bounding the role of black carbon in the climate system: A scientific assessment, *J. Geophys. Res.*, 118, 5380-5552, doi: 10.1002/jgrd.50171, 2013 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.
- Boukhalf, S., and N. Kaul, 10 disruptive battery technologies trying to compete with lithium-ion, 2019, <https://www.solarpowerworldonline.com/2019/01/10-disruptive-battery-technologies-trying-to-compete-with-lithium-ion/> (accessed February 2, 2019).
- Bremner, S.P., M.Y. Levy, and C.B. Honsberg, Analysis of tandem solar cell efficiencies under {AM1.5G} spectrum using a rapid flux calculation method, *Progress in Photovoltaics: Research and Applications*, 16, 225-233, 2008.
- Breyer, C., Economics of hybrid photovoltaic power plants, Pro Business ISBN: 978-3863863906, 2012.
- Breyer, C., D. Bogdanov, A. Gulagi, A. Aghahosseini, L.S.N.S. Barbosa, O. Koskinen, M. Barasa, U. Caldera, S. Afanasyeva, M. Child, J. Farfan and P. Vainikka, On the role of solar photovoltaics in global energy transition scenarios, *Prog. Photovolt. Res. Appl.* 25, 727-745, 2017.
- British Petroleum, BP statistical review of world energy, 2018, <https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2018-co2-emissions.pdf> (accessed December 15, 2018).

- Brown, T.W., T. Bischof-Niemz, K. Blok, C. Breyer, H. Lund, and B.V. Mathiesen, Response to ‘Burden of proof: A comprehensive review of the feasibility of 100% renewable electricity systems,’ *Renewable and Sustainable Energy Reviews*, 92, 834-847, 2018.
- Bruckner T., I.A. Bashmakov, Y. Mulugetta, H. Chum, A. de la Vega Navarro, J. Edmonds, A. Faaij, B. Functammasan, A. Garg, E. Hertwich, D. Honnery, D. Infield, M. Kainuma, S. Khennas, S. Kim, H.B. Nimir, K. Riahi, N. Strachan, R. Wiser, and X. Zhang, Energy Systems. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014.
- BTS (Bureau of Transportation Statistics), U.S. oil and gas pipeline mileage, 2018, <https://www.bts.gov/content/us-oil-and-gas-pipeline-mileage> (accessed December 3, 2018).
- Budischak, C., D. Sewell, H. Thompson, L. Mach, D.E. Veron, and W. Kempton, Cost-minimized combinations of wind power, solar power, and electrochemical storage, powering the grid up to 99.9% of the time, *J Power Sources*, 225, 60-74, 2013.
- Build Abroad, Ferrock: A stronger, more flexible and greener alternative to concrete, 2016, <https://buil dabroad.org/2016/09/27/ferrock/> (accessed November 20, 2018).
- [Burke, M., S.M. Hsiang, and E. Miguel, Global non-linear effect of temperature on economic production, Nature, 527, 235-239, 2015.](#)
- Burnett, R., Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter, *Proc. Natl. Acad. Sci.*, 115, 9592-9597, 2018.
- Business Dictionary, Installed capacity: definition, 2019 <http://www.businessdictionary.com/definition/installed-capacity.html> (accessed March 15, 2019).
- CARB (California Air Resources Board), Estimate of premature deaths associated with fine particle pollution (PM_{2.5}) in California using a U.S. Environmental Protection Agency Methodology, 2010, https://www.arb.ca.gov/research/health/pm-mort/pm-report_2010.pdf (accessed January 15, 2019).
- Caldera, U., and C. Breyer, Role that battery and water storage play in Saudi Arabia’s transition to an integrated 100% renewable energy power system, *J. Energy Storage*, 17, 299-310, 2018.
- California Senate, SB 100 FAQs, 2018, <https://focus.senate.ca.gov/sb100/faqs> (accessed February 6, 2019).
- Carbon Cure, Carbon Cure, 2018, <https://www.carboncure.com> (accessed November 20, 2018).
- CDC (Center for Disease Control and Prevention), Research on long-term exposure: Uranium miners, 2000, <https://www.cdc.gov/niosh/pgms/worknotify/uranium.html> (accessed December 9, 2018).
- Cebulla, F., and M.Z. Jacobson, Alternative renewable energy scenarios for New York, *Journal of Cleaner Production*, 205, 884-894, 2018.
- Chakratek, Flywheel specifications and comparison, 2019, <https://www.chakratec.com/technology/> (accessed March 18, 2019).
- Chang, T.P., The Sun’s apparent position and the optimal tilt angle of a solar collector in the northern hemisphere, *Solar Energy* 83, 1274-1284, 2009.
- Child, M., and C. Breyer, Vision and initial feasibility analysis of a decarbonized Finnish energy system for 2050. *Renewable and Sustainable Energy Reviews*, 66, 517-536, 2016.
- Child, M., A. Nordling, and C. Breyer, The impacts of high V2G participation in a 100% renewable Aland energy system, *Energies*, 11, 2206, <https://doi.org/10.3390/en11092206>, 2018.
- CEC (California Energy Commission), A review of transmission losses in planning studies, 2011, <https://www.energy.ca.gov/2011publications/CEC-200-2011-009/CEC-200-2011-009.pdf> (accessed December 31, 2018).
- Clinton, H., Hillary is ready for 100, October 16, 2015, <http://www.c-span.org/video/?c4557641/hillary-readyfor100> (Accessed February 7, 2019).
- Colella, W.G., M.Z. Jacobson, and D.M. Golden, Switching to a U.S. hydrogen fuel cell vehicle fleet: The resultant change in emissions, energy use, and global warming gases, *J. Power Sources*, 150, 150-181, 2005.
- Connolly, D., H. Lund, B.V. Mathiesen, and M. Leahy, The first step to a 100% renewable energy-system for Ireland, *Applied Energy*, 88, 502-507, 2011.

- Connolly, D., and B.V. Mathiesen, Technical and economic analysis of one potential pathway to a 100% renewable energy system, *Intl. J. Sustainable Energy Planning & Management*, 1, 7-28, 2014.
- Connolly, D., H. Lund, and B.V. Mathiesen, Smart energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union, *Renewable and Sustainable Energy Reviews*, 60, 1634-1653, 2016.
- Consumer Reports, Electric lawn mowers that rival gas models, 2017, <https://www.consumerreports.org/push-mowers/electric-lawn-mowers-that-rival-gas-models/> (accessed November 21, 2018).
- Corcoran, B.A., N. Jenkins, and M.Z. Jacobson, Effects of aggregating electric load in the United States. *Energy Policy*, 46, 399-416, 2012.
- Cornell University, How lake source cooling works, 2019, <https://energyandsustainability.fs.cornell.edu/util/cooling/production/lsc/works.cfm> (accessed May 1, 2019).
- Crossley, I, Simplifying and lightening offshore turbines with compressed air energy storage, Wind Power, 2018, <https://www.windpoweroffshore.com/article/1463030/simplifying-lightening-offshore-turbines-compressed-air-energy-storage> (accessed March 18, 2019).
- Czisch, G., PhD Dissertation, University of Kassel, 2005, <https://kobra.uni-kassel.de/handle/123456789/200604119596> (accessed February 24, 2019).
- Czisch, G., and G. Giebel, Realisable scenarios for a future electricity supplies based 100% on renewable energies, Riso-R-1608 (EN), 2007.
- Damkjaer, L., Gram Fjernvarme 2016, 2016, <https://www.youtube.com/watch?v=PdF8e1t7St8> (accessed November 25, 2018).
- Dandelion, Geothermal heating and air conditioning is so efficient, it pays for itself, <https://dandelionenergy.com>, 2018 (accessed November 17, 2018).
- De Coninck, H., A. Revi, M. Babiker, P. Bertoldi, M. Buckeridge, A. Cartwright, W. Dong, J. Ford, S. Fuss, J.-C. Hourcade, D. Ley, R. Mechler, P. Newman, A. Revokatova, S. Schultz, L. Steg, and T. Sugiyama, Chapter 4: Strengthening and implementing the global response, in Intergovernmental Panel on Climate Change, Global Warming of 1.5 °C report, 2018.
- De Gouw, J.A., D.D. Parrish, G.J. Frost, and M. Trainer, Reduced emissions of CO₂, NO_x, and SO₂ from U.S. power plants owing to switch from coal to natural gas with combined cycle technology, *Earth's Future*, 2, 75-82, 2014.
- De Gracia, A., and L.F. Cabeza, Phase change materials and thermal energy storage for buildings, *Energy and Buildings*, 103, 414-419, 2015.
- Delucchi, M, A conceptual framework for estimating the climate impacts of land-use change due to energy crop programs, *Biomass and Bioenergy*, 35, 2337-2360, 2011.
- Delucchi, M.Z., and M.Z. Jacobson, Providing all global energy with wind, water, and solar power, Part II: Reliability, System and Transmission Costs, and Policies, *Energy Policy*, 39, 1170-1190, doi:10.1016/j.enpol.2010.11.045, 2011.
- Denholm, P., Y.-H. Wan, M. Hummon, and M. Mehos, The value of CSP with thermal energy storage in the western United States, *Energy Procedia*, 49, 1622-1631, 2014.
- Denyer, S., Eight years after Fukushima's meltdown, the land is recovering, but public trust is not, Washington Post, 2019, https://www.washingtonpost.com/world/asia_pacific/eight-years-after-fukushimas-meltdown-the-land-is-recovering-but-public-trust-has-not/2019/02/19/0bb29756-255d-11e9-b5b4-1d18dfb7b084_story.html?utm_term=.8344c816d5bb (accessed December 21, 2019).
- De Stercke, S., Dynamics of Energy Systems: a Useful Perspective. IIASA Interim Report No. IR-14-013, International Institute for Applied Systems Analysis, IIASA, Laxenburg, Austria, 2014.
- Diesendorf, M., and B. Elliston, The feasibility of 100% renewable electricity systems: A response to critics, *Renewable and Sustainable Energy Reviews*, 93, 318-330, 2018.
- DOE (U.S. Department of Energy), 2014: The year of concentrating solar power, 2014, https://www.energy.gov/sites/prod/files/2014/05/f15/2014_csp_report.pdf (accessed March 30, 2019).
- DOE (U.S. Department of Energy), Fuel Cells, 2015, https://www.energy.gov/sites/prod/files/2015/11/f27/fcto_fuel_cells_fact_sheet.pdf (accessed January 11, 2019).

- DOE (U.S. Department of Energy), Quadrennial Technology Review, Chapter 6: Innovative clean energy technologies in advanced manufacturing: Technology assessment, 2015, <https://www.energy.gov/sites/prod/files/2016/06/f32/QTR2015-6I-Process-Heating.pdf> (accessed Nov. 17, 2018).
- DOE (U.S. Department of Energy), How do wind turbines work? 2019, <https://www.energy.gov/eere/wind/wind-energy-technologies-office> (accessed March 27, 2019).
- DPC (U.S. Democratic Platform Committee), 2016 Democratic Party Platform, July 9, 2016, https://democrats.org/wp-content/uploads/2018/10/2016_DNC_Platform.pdf (Accessed February 7, 2019)
- Douglas, C.A., G.P. Harrison, and J.P. Chick, Life cycle assessment of the Seagen marine current turbine, *Proc. Inst. Mech. Eng. Part M: J of Engineering for the Maritime Environment*, 222, 1-12, 2008.
- Drake Landing, Drake Landing Solar Community, 2016, <https://www.dlsc.ca/how.htm> (accessed March 26, 2019).
- Drupp, M., Freeman, M., Groom, B., and Nesje, F., *Discounting disentangled: an expert survey on the determinants of the long-term social discount rate* The Centre for Climate Change Economics and Policy Working Paper No. 195 and Grantham Research Institute on Climate Change and the Environment Working Paper No. 172 (CCCEP and Grantham Research Institute), 2015.
- Duan, Y., and D.C. Sorescu, CO₂ capture properties of alkaline earth metal oxides and hydroxides: A combined density functional theory and lattice phonon dynamics study, *J. Chem. Phys.*, 133, 074508, 2010.
- Dvorak, M., C.L. Archer, and M.Z. Jacobson, California offshore wind energy potential, *Renewable Energy*, 35, 1244-1254, doi:10.1016/j.renene.2009.11.022, 2010.
- Dvorak, M.J., E.D. Stoutenburg, C.L. Archer, W. Kempton, and M.Z. Jacobson, Where is the ideal location for a U.S. East Coast offshore grid, *Geophys. Res. Lett.*, 39, L06804, doi:10.1029/2011GL050659, 2012.
- Dvorak, M.J., B.A. Corcoran, J.E. Ten Hoeve, N.G. McIntyre, and M.Z. Jacobson, U.S. East Coast offshore wind energy resources and their relationship to peak-time electricity demand, *Wind Energy*, 16, 977-997, doi:10.1002/we.1524, 2013.
- Earthworks, Responsible minerals sourcing for renewable energy, 2019, <https://earthworks.org/publications/responsible-minerals-sourcing-for-renewable-energy/> (accessed May 1, 2019).
- Eddington S.A., On the radiative equilibrium of the stars, *Mon. Not. Roy. Astronom. Soc.*, 77, 16-35, 1916.
- EIA (Energy Information Administration, U.S.) (2016). *International Energy Outlook 2016* DOE/EIA-0484, 2016, [http://www.eia.gov/forecasts/ieo/pdf/0484\(2016\).pdf](http://www.eia.gov/forecasts/ieo/pdf/0484(2016).pdf), <https://www.eia.gov/forecasts/ieo/>, http://www.eia.gov/forecasts/ieo/ieo_tables.cfm (accessed January 10, 2019).
- EIA (U.S. Energy Information Administration), Hydraulically fractured wells provide two-thirds of U.S. natural gas production, 2016, <https://www.eia.gov/todayinenergy/detail.php?id=26112> (accessed December 2, 2018).
- EIA (U.S. Energy Information Administration), Today in energy, 2017, <https://www.eia.gov/todayinenergy/detail.php?id=33552> (accessed December 4, 2018).
- EIA (U.S. Energy Information Administration), Table 1. Coal production and number of mines by state and mine type, 2017 and 2016, 2018a, <https://www.eia.gov/coal/annual/pdf/table1.pdf> (accessed December 3, 2018).
- EIA (U.S. Energy Information Administration), Frequently asked questions, 2018b, <https://www.eia.gov/tools/faqs/faq.php?id=29&t=6> (accessed December 3, 2018).
- EIA (U.S. Energy Information Administration), Table 4.1. Count of electric power industry power plants by sector, by predominant energy sources within plant, 2007 through 2017, 2018c, https://www.eia.gov/electricity/annual/html/epa_04_01.html (accessed December 3, 2018).
- EIA (U.S. Energy Information Administration), Table 1.1. Total electric power industry summary statistics, 2017 and 2016, 2018d, https://www.eia.gov/electricity/annual/html/epa_01_01.html (accessed December 5, 2018).
- EIA (Energy Information Administration), How much electricity is lost in transmission and distribution in the United States, 2018e, <https://www.eia.gov/tools/faqs/faq.php?id=105&t=3> (accessed December 31, 2018).

- Electrical Systems, Principle of electricity generation, 2019, <http://www.skm-eksys.com/2010/02/practical-power-system.html> (accessed April 5, 2019).
- Electronics Hub, Characteristics and working of P-N junction diode, 2015, <https://www.electronicshub.org/characteristics-and-working-of-p-n-junction-diode/> (accessed March 31, 2019).
- Electronics Tutorials, Capacitor tutorial summary, 2019a, https://www.electronics-tutorials.ws/capacitor/cap_9.html (accessed April 3, 2019).
- Electronics Tutorials, Reactive power, 2019b, <https://www.electronics-tutorials.ws/accircuits/reactive-power.html> (accessed April 3, 2019).
- ELI (Environmental Law Institute), Estimating U.S. government subsidies to energy sources: 2002-2008, 2009, <https://www.eli.org/research-report/estimating-us-government-subsidies-energy-sources-2002-2008> (accessed January 25, 2019).
- Elliston, B., M. Diesendorf, and I. MacGill, Simulations of scenarios with 100% renewable electricity in the Australian National Electricity Market, *Energy Policy*, 45, 606-613, 2012.
- Elliston, B., I. MacGill, and M. Diesendorf, Least cost 100% renewable electricity scenarios in the Australian National Electricity Market, *Energy Policy*, 59, 270-282, 2013.
- Elliston, B., I. MacGill, and M. Diesendorf, Comparing least cost scenarios for 100% renewable electricity with low emission fossil fuel scenarios in the Australian National Electricity Market, *Renew Energy*, 66, 196-204, 2014.
- Enevoldsen, P., and M.Z. Jacobson, Data investigation of installed and output power densities of onshore and offshore wind turbines worldwide, manuscript in review, 2019.
- ENTSO-E (European Network of Transmission System Operators for Electricity), European load data, 2016, <https://www.entsoe.eu/db-query/country-packages/production-consumption-exchange-package-2016> (accessed January 29, 2019).
- Erlich, I., and M. Wilch, Frequency control by wind turbines, IEEE PES General Meeting, July 25-29, 2010, doi: 10.1109/PES.2010.5589911, <https://ieeexplore.ieee.org/document/5589911> (accessed March 2, 2019).
- Esteban, M., J. Portugal-Pereira, B.C. Mclellan, J. Bricker, H. Farzaneh, N. Djalikova, K.N. Ishihara, H. Takagi, and V. Roeber, 100% renewable energy system in Japan: Smoothing and ancillary services, *Applied Energy*, 224, 698-707, 2018.
- Etmnan, M., G. Myhre, E.J. Highwood, and K.P. Shine, Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing, *Geophys. Res. Lett.*, 43, 12614-12623, 2016.
- European Commission, EDGAR: Emissions database for global atmospheric research, 2019, <https://edgar.jrc.ec.europa.eu/background.php> (accessed May 26, 2019).
- EVWind, Current status of concentrated solar power globally, 2018, <https://www.evwind.es/2018/07/25/current-status-of-concentrated-solar-power-csp-globally/64041> (accessed January 9, 2019).
- Faulstich, S., B. Hahn, and P.J. Tavner, Wind turbine downtime and its importance for offshore deployment, *Wind Energy*, 14, 327-337, 2011.
- Feng, Z., Stationary high-pressure hydrogen storage, 2018, https://www.energy.gov/sites/prod/files/2014/03/f10/csd_workshop_7_feng.pdf (accessed November 28, 2018).
- FERC (Federal Energy Regulatory Commission), Current state of and issues concerning underground natural gas storage, 2004, <https://www.ferc.gov/EventCalendar/Files/20041020081349-final-gs-report.pdf> (accessed December 3, 2018).
- Fetter, S., How long will the world's uranium supplies last, *Scientific American*, 9 (2009).
- Fischer, D., and H. Madani, On heat pumps in smart grids: A review. *Renewable and Sustainable Energy Reviews*, 70, 342-357, 2017.
- Flury, K., and R. Frischknecht, Lifecycle inventories of hydroelectric power generation, 2012, ESU Services, <http://esu-services.ch/fileadmin/download/publicLCI/flury-2012-hydroelectric-power-generation.pdf> (accessed December 8, 2018).

- Free Dictionary, Installed capacity: definition, 2019
<https://encyclopedia2.thefreedictionary.com/Installed+Capacity> (accessed March 15, 2019).
- Frew, B.A., S. Becker, M.J. Dvorak, G.B. Andresen, and M.Z. Jacobson, Flexibility mechanisms and pathways to a highly renewable U.S. electricity future, *Energy*, 101, 65-78, 2016.
- Frew, B.A., and M.Z. Jacobson, Temporal and spatial tradeoffs in power system modeling with assumptions about storage: An application of the POWER model, *Energy*, 117, 198-213, 2016.
- Friedlingstein P., R.M. Andrew, J. Rogelj, G.P. Peters, J.G. Canadell, R. Knutti, G.L. Luderer, M.R. Raupach, M. Schaeffer, D.P. van Vuuren, and C. Le Quere, Persistent growth of CO₂ emissions and implications for reaching climate targets. *Nature Geoscience* 7: 709–715, 2014.
- Fthenakis, V., and M. Raugei, Environmental life-cycle assessment of photovoltaic systems, in *The Performance of Photovoltaic (PV) Systems: Modelling, Measurement, and Assessment*, N. Pearsall, Ed., pp. 209-232, 2017.
- Gain K, and A. Duffy, A life cycle cost analysis of large-scale thermal energy storage for buildings using combined heat and power, *Zero Emission Buildings Conference Proceedings*, eds Haase M, Andresen I, Hestnes A (Trondheim, Norway), 7-8 June 2010.
- Garthwaite, J., What should we do with nuclear waste, Stanford Earth, 2018,
<https://earth.stanford.edu/news/qa-what-should-we-do-nuclear-waste#gs.lsfX0x> (accessed March 20, 2019).
- GBD (Global Burden of Disease 2013 Risk Factors Collaborators), Global, regional, and national comparative risk assessment of 79 behavioral, environmental and occupational, and metabolic risks or clusters of risks in 188 countries, 1990-2013: a systematic analysis for the Global Burden of Disease Study 2013, *Lancet*, 386, 2287-2323, 2015.
- GE (General Electric), Haliade-X offshore wind turbine platform,
<https://www.ge.com/renewableenergy/wind-energy/turbines/haliade-x-offshore-turbine>, 2018
 (accessed November 16, 2018).
- Gerber H., Y. Takano, T.J. Garrett, and P.V. Hobbs, Nephelometer measurements of the asymmetry parameter, volume extinction coefficient, and backscatter ratio in Arctic clouds, *J. Atmos. Sci.*, 57, 3021-3033, 2000.
- Geuss, M., Florida utility to close natural gas plants, build massive solar-powered battery, *Ars Technica*, 2019,
<https://arstechnica.com/information-technology/2019/03/florida-utility-to-close-natural-gas-plants-build-massive-solar-powered-battery/> (accessed April 1, 2019).
- GHD, Cassada wind farm decommissioning cost estimate, 2017,
<http://www.charlotteny.org/pdfs/2018/wind/11110309-RPT1%20FINAL%20%207-11-2017.pdf>
 (accessed January 16, 2019).
- Ginnebaugh, D.L., J. Liang, and M.Z. Jacobson, Examining the temperature dependence of ethanol (E85) versus gasoline emissions on air pollution with a largely-explicit chemical mechanism, *Atmos. Environ.*, 44, 1192-1199, doi:10.1016/j.atmosenv.2009.12.024, 2010.
- Ginnebaugh, D.L., and M.Z. Jacobson, Examining the impacts of ethanol (E85) versus gasoline photochemical production of smog in a fog using near-explicit gas- and aqueous-chemistry mechanisms, *Environmental Research Letters*, 7, 045901, doi:10.1088/1748-9326/7/4/045901, 2012.
- Gulagi, A., D. Bogdanov, and C. Breyer, A cost optimized fully sustainable power system for Southeast Asia and the Pacific Rim, *Energies*, 10, 583, doi:10.3390/en10050583, 2017a.
- Gulagi, A. P. Choudhary, D. Bogdanov, and C. Breyer, Electricity system based on 100% renewable for India and SAARC, *PLoS ONE*, doi:10.1371/journal.pone.0180611, 2017b.
- Hampson, S. E., J. A. Andres, M. E. Lee, L. S. Foster, R. E. Glasgow, and E. Lichtenstein, Lay understanding of synergistic risk: the case of radon and cigarette smoking, *Risk Analysis*, 18, 343-350, 1998.
- Hanley, S., Energy Vault proposes and energy storage system using concrete blocks, *Cleantechnica*, 2018,
<https://cleantechnica.com/2018/08/21/energy-vault-proposes-an-energy-storage-system-using-concrete-blocks/> (accessed April 10, 2019).
- Hansen, K., B. Mathiessen, and I.R. Skov, Full energy system transition towards 100% renewable energy in Germany in 2050, *Renewable and Sustainable Energy Reviews*, 102, 1-13, 2019a.
- Hansen, K., C. Breyer, and H. Lund, Status and perspectives on 100% renewable energy systems, *Energy*, 175, 471-480, 2019.

- Hart, E.K., and M.Z. Jacobson, A Monte Carlo approach to generator portfolio planning and carbon emissions assessments of systems with large penetrations of variable renewables, *Renewable Energy*, 36, 2278-2286, doi:10.1016/j.renene.2011.01.015, 2011.
- Hart, E.K., E.D. Stoutenburg, and M.Z. Jacobson, The potential of intermittent renewables to meet electric power demand: A review of current analytical techniques, *Proceedings of the IEEE*, 100, 322-334, doi:10.1109/JPROC.2011.2144951, 2012.
- Hart, E.K., and M.Z. Jacobson, The carbon abatement potential of high penetration intermittent renewables, *Energy and Environmental Science*, 5, 6592-6601, doi:10.1039/C2EE03490E, 2012.
- Harvey, L.D.D., Resource implications of alternative strategies for achieving zero greenhouse gas emissions from light-duty vehicles by 2060, *Applied Energy*, 212, 663-679.
- Hasager, C.B., L. Rasmussen, A. Pena, L.E. Jensen, and P.-E. Rethore, Wind farm wake: the Horns Rev photo case, *Energies*, 6, 696-716, 2013.
- Henshaw, D. L., J. P. Eatough, and R. B. Richardson, Radon as a causative factor in induction of myeloid leukaemia and other cancers, *Lancet*, 335, 1008-1012, 1990.
- Hoste, G.R.G., M.J. Dvorak, and M.Z. Jacobson, Matching hourly and peak demand by combining different renewable energy sources, Stanford University Technical Report, 2009, <https://web.stanford.edu/group/efmh/jacobson/Articles/I/CombiningRenew/HosteFinalDraft> (accessed January 27, 2019).
- Hou, P., P. Enevoldsen, J. Eichman, W. Hu, M.Z. Jacobson, and Z. Chen, Optimizing investments in coupled offshore wind-electrolytic hydrogen storage systems in Denmark, *J. Power Sources*, 359, 186-197, doi:10.1016/j.jpowsour.2017.05.048, 2017.
- Houghton, R.A., Annual net flux of carbon to the atmosphere from land-use change: 1850-2005, 2015, <http://cdiac.ornl.gov/trends/landuse/houghton/1850-2005.txt> (accessed January 24, 2019).
- House (U.S. House of Representatives), H.Res.540, 2015, <https://www.congress.gov/bill/114th-congress/house-resolution/540/text> (accessed February 7, 2019).
- House (U.S. House of Representatives), H.R.3314 – 100 by '50 Act, 2017a, <https://www.congress.gov/bill/115th-congress/house-bill/3314> (accessed February 7, 2019).
- House (U.S. House of Representatives), H.R.3671 – Off Fossil Fuels For A Better Future Act, 2017b, <https://www.congress.gov/bill/115th-congress/house-bill/3671/text> (accessed February 7, 2019).
- House (U.S. House of Representatives), H.R. 330 – Climate Solutions Act of 2019, 2019a, <https://www.congress.gov/bill/116th-congress/house-bill/330/text> (accessed February 7, 2019).
- House (U.S. House of Representatives), Resolution recognizing the duty of the federal government to create a green new deal, 2019b, <https://www.congress.gov/bill/116th-congress/house-resolution/109> <https://apps.npr.org/documents/document.html?id=5729035-Green-New-Deal-FAQ> (accessed February 10, 2019).
- Howarth, R.W., A bridge to nowhere: methane emissions and the greenhouse gas footprint of natural gas, *Energy Science & Engineering*, 2, 47-60, 2014.
- Howarth, R.W., Is shale gas a major driver of recent increase in global atmospheric methane, *Biogeosciences* 16, 3033-3046, 2019.
- Howarth, R.W., R. Santoro, and A. Ingraffea, Methane and the greenhouse gas footprint of natural gas from shale formations, *Climatic Change*, 106, 679-690, 2011.
- Howarth, R.W., R. Santoro, and A. Ingraffea, Venting and leaking of methane from shale gas development: response to Cathles et al., *Climatic Change*, 2012.
- Hu, S-y, and J-h Cheng, Performance evaluation of pairing between sites and wind turbines, *Renewable Energy*, 32, 1934-1947. 2007.
- Hulls, P.J., Development of the industrial use of dielectric heating in the United Kingdom, *J. Microwave Power*, 17, 28-38, 2016.
- ICF Consulting, Life cycle greenhouse gas emissions of natural gas, 2012, <https://www.capp.ca/-/media/capp/customer-portal/documents/215278.pdf> (accessed January 22, 2019).
- IEA (International Energy Agency), Integrated cost-effective large-scale thermal energy storage for smart district heating and cooling, 2018a, https://www.iea-dhc.org/fileadmin/documents/Annex_XII/IEA_DHC_AXII_Design_Aspects_for_Large_Scale_ATES_PTES_draft.pdf (accessed November 25, 2018).

- IEA (International Energy Agency), Wind energy, 2018b <https://www.iea.org/topics/renewables/wind/> (accessed January 9, 2019).
- IEA (International Energy Agency), Geothermal energy, 2018c <https://www.iea.org/topics/renewables/geothermal/> (accessed January 9, 2019).
- IEA (International Energy Agency), Solar PV, 2018d <https://www.iea.org/tcep/power/renewables/solar/> (accessed January 9, 2019).
- IEA (International Energy Agency), *Statistics*, 2019, <https://www.iea.org/statistics/> (accessed January 5, 2019).
- IEC (International Electrotechnical Commission), Efficient electrical energy transmission and distribution, 2007, <https://basecamp.iec.ch/download/efficient-electrical-energy-transmission-and-distribution/> (accessed December 31, 2018).
- IGU (International Gas Union), Natural gas conversion guide, 2018, http://agnatural.pt/documentos/ver/natural-gas-conversion-guide_cb4f0cccd80ccaf88ca5ec336a38600867db5aaf1.pdf (accessed December 2, 2018).
- IHA (International Hydropower Association), 2018 hydropower status report, 2018, <https://www.hydropower.org/publications/2018-hydropower-status-report> (accessed January 9, 2019).
- IPCC (Intergovernmental Panel on Climate Change), *Special Report on Emission Scenarios (SRES) final data*, 2000, http://sres.ciesin.org/final_data.html (accessed January 23, 2019).
- IPCC (Intergovernmental Panel on Climate Change), *IPCC special report on carbon dioxide capture and storage*. Prepared by working group III, Metz. B., O. Davidson, H. C. de Coninck, M. Loos, and L.A. Meyer (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp. <http://arch.rivm.nl/env/int/ipcc/>, 2005 (accessed June 26, 2019).
- IPCC (Intergovernmental Panel on Climate Change), *Special report: Global warming of 1.5°*, 2018, <https://www.ipcc.ch/sr15/> (accessed June 26, 2019).
- IranWatch, Iran's nuclear potential before the implementation of the nuclear agreement, 2015, <https://www.iranwatch.org/our-publications/articles-reports/irans-nuclear-timetable> (accessed December 9, 2018).
- IRENA (International Renewable Energy Agency), Thermal energy storage. IEA-ETSAP and IRENA Technology Brief E17, IRENA, Abu Dhabi, 2013.
- Jacobson M. Z., *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, 1994.
- 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.
- Jacobson, M. Z., Development and application of a new air pollution modeling system. Part III: Aerosol-phase simulations, *Atmos. Environ.*, 31A, 587–608, 1997.
- 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.
- 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.
- 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.
- Jacobson, M. Z., Strong radiative heating due to the mixing state of black carbon in atmospheric aerosols, *Nature*, 409, 695–697, 2001a.
- 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, 5385–5401, 2001b.
- Jacobson, M. Z., and G. M. Masters, Exploiting wind versus coal, *Science*, 293, 1438–1438, 2001.
- 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.
- Jacobson, M. Z., The short-term cooling but long-term global warming due to biomass burning, *J. Clim.*, 17 (15), 2909–2926, 2004.
- Jacobson, M.Z., The health and climate impacts of carbon capture and direct air capture, in review, 2019.

- 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.
- 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, 2005a.
- Jacobson, M.Z., *Fundamentals of Atmospheric Modeling, Second Edition*, Cambridge University Press, New York, 813 pp., 2005b.
- 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.
- Jacobson, M.Z., Effects of ethanol (E85) versus gasoline vehicles on cancer and mortality in the United States, *Environ. Sci. Technol.*, 41 (11), 4150-4157, doi:10.1021/es062085v, 2007.
- 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
- Jacobson, M.Z., On the causal link between carbon dioxide and air pollution mortality, *Geophysical Research Letters*, 35, L03809, doi:10.1029/2007GL031101, 2008a.
- 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, 2008b.
- Jacobson, M.Z., Review of solutions to global warming, air pollution, and energy security, *Energy & Environmental Science*, 2, 148-173, doi:10.1039/b809990c, 2009.
- Jacobson, M.Z., and M.A. Delucchi, A path to sustainable energy by 2030, *Scientific American*, November 2009.
- Jacobson, M.Z., Short-term effects of controlling fossil-fuel soot, biofuel soot and gases, and methane on climate, Arctic ice, and air pollution health, *J. Geophys. Res.*, 115, D14209, doi:10.1029/2009JD013795, 2010a.
- Jacobson, M.Z., The enhancement of local air pollution by urban CO₂ domes, *Environ. Sci. Technol.*, 44, 2497-2502, doi:10.1021/es903018m, 2010b.
- Jacobson, M.Z., and M.A. Delucchi, Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials, *Energy Policy*, 39, 1154-1169, doi:10.1016/j.enpol.2010.11.040, 2011.
- Jacobson, M. Z., *Air Pollution and Global Warming: History, Science, and Solutions*, Second Edition, Cambridge University Press, Cambridge, 375 pp., 2012a.
- Jacobson, M.Z., Investigating cloud absorption effects: Global absorption properties of black carbon, tar balls, and soil dust in clouds and aerosols, *J. Geophys. Res.*, 117, D06205, doi:10.1029/2011JD017218, 2012b.
- Jacobson, M.Z., and C.L. Archer, Saturation wind power potential and its implications for wind energy, *Proc. Nat. Acad. Sci.*, 109, 15,679-15,684, doi:10.1073/pnas.1208993109, 2012.
- Jacobson, M.Z., and J.E. Ten Hoeve, Effects of urban surfaces and white roofs on global and regional climate, *J. Climate*, 25, 1028-1044, doi:10.1175/JCLI-D-11-00032.1, 2012.
- Jacobson, M.Z., R.W. Howarth, M.A. Delucchi, S.R. Scobies, J.M. Barth, M.J. Dvorak, M. Klevze, H. Katkhuda, B. Miranda, N.A. Chowdhury, R. Jones, L. Plano, and A.R. Ingraffea, Examining the feasibility of converting New York State's all-purpose energy infrastructure to one using wind, water, and sunlight, *Energy Policy*, 57, 585-601, 2013.
- Jacobson, M.Z., Effects of biomass burning on climate, accounting for heat and moisture fluxes, black and brown carbon, and cloud absorption effects, *J. Geophys. Res.*, 119, 8980-9002, doi:10.1002/2014JD021861, 2014.
- Jacobson, M.Z., C.L. Archer, and W. Kempton, Taming hurricanes with arrays of offshore wind turbines, *Nature Climate Change*, 4, 195-200, doi: 10.1038/NCLIMATE2120, 2014.
- Jacobson, M.Z., M.A. Delucchi, A.R. Ingraffea, R.W. Howarth, G. Bazouin, B. Bridgeland, K. Burkhart, M. Chang, N. Chowdhury, R. Cook, G. Escher, M. Galka, L. Han, C. Heavey, A. Hernandez, D.F. Jacobson, D.S. Jacobson, B. Miranda, G. Novotny, M. Pellat, P. Quach, A. Romano, D. Stewart, L. Vogel, S. Wang, H. Wang, L. Willman, T. Yeskoo, A roadmap for repowering California for all

- purposes with wind, water, and sunlight, *Energy*, 73, 875-889, doi:10.1016/j.energy.2014.06.099, 2014.
- Jacobson, M.Z., 100% WWS plans for countries and states, United Nations Foundation Earth to Paris Social Good Event, UNFCC, Petit Palais, Paris, France, December 7, 2015, <http://livestream.com/unfoundation/earthtoparisENG/videos/106549410> (accessed February 6, 2019).
- Jacobson, M.Z., M.A. Delucchi, G. Bazouin, Z.A.F. Bauer, C.C. Heavey, E. Fisher, S. B. Morris, D.J.Y. Piekutowski, T.A. Vencill, T.W. Yeskoo, 100 percent clean and renewable wind, water, sunlight (WWS) all-sector energy roadmaps for the 50 United States, *Energy and Environmental Sciences*, 8, 2093-2117, doi:10.1039/C5EE01283J, 2015a.
- Jacobson, M.Z., M.A. Delucchi, M.A. Cameron, and B.A. Frew, A low-cost solution to the grid reliability problem with 100 percent penetration of intermittent wind, water, and solar for all purposes, *Proc. Nat. Acad. Sci.*, 112 (49), 15,060-15,065 doi: 10.1073/pnas.1510028112, 2015b.
- Jacobson, M.Z., M.A. Delucchi, G. Bazouin, M.J. Dvorak, R. Arghandeh, Z. A.F. Bauer, A. Cotte, G.M.T.H. de Moor, E.G. Goldner, C. Heier, R.T. Holmes, S.A. Hughes, L. Jin, M. Kapadia, C. Menon, S.A. Mullendore, E.M. Paris, G.A. Provost, A.R. Romano, C. Srivastava, T.A. Vencill, N.S. Whitney, and T.W. Yeskoo, A 100 percent wind, water, sunlight (WWS) all-sector energy plan for Washington State, *Renewable Energy*, 86, 75-88 2016.
- Jacobson, M.Z., CO₂ from Siple ice core (1750-1953) / Mauna Loa (1959-2014) vs. CO₂ from GATOR-GCMOM model (1750-2100), including WWS and IPCC scenarios after 2014, 2017, <http://web.stanford.edu/group/efmh/jacobson/Articles/I/CountryGraphs/CO2ChangesWithWWS.pdf> (accessed November 29, 2018).
- Jacobson, M.Z., M.A. Delucchi, Z.A.F. Bauer, S.C. Goodman, W.E. Chapman, M.A. Cameron, Alphabetical: C. Bozonnat, L. Chobadi, H.A. Clonts, P. Enevoldsen, J.R. Erwin, S.N. Fobi, O.K. Goldstrom, E.M. Hennessy, J. Liu, J. Lo, C.B. Meyer, S.B. Morris, K.R. Moy, P.L. O'Neill, I. Petkov, S. Redfern, R. Schucker, M.A. Sontag, J. Wang, E. Weiner, A.S. Yachanin, 100 percent clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for 139 countries of the world, *Joule*, 1, 108-121, doi:10.1016/j.joule.2017.07.005, 2017.
- Jacobson, M.Z., M.A. Delucchi, M.A. Cameron, and B.V. Mathiesen, Matching demand with supply at low cost among 139 countries within 20 world regions with 100 percent intermittent wind, water, and sunlight (WWS) for all purposes, *Renewable Energy*, 123, 236-248, 2018a.
- Jacobson, M.Z., M.A. Cameron, E.M. Hennessy, I. Petkov, C.B. Meyer, T.K. Gambhir, A.T. Maki, K. Pflieger, H. Clonts, A.L. McEvoy, M.L. Miccioli, A.-K. von Krauland, R.W. Fang, and M.A. Delucchi, 100 percent clean, and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for 53 towns and cities in North America, *Sustainable Cities and Society*, 42, 22-37, doi:10.1016/j.scs.2018.06.031, 2018b.
- Jacobson, M.Z., V. Jadhav, World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels, *Solar Energy*, 169, 55-66, 2018.
- Jacobson, M.Z., M.A. Delucchi, M.A. Cameron, S.J. Coughlin, C. Hay, I.P. Manogaran, Y. Shu, and A.-K. von Krauland, Impacts of Green-New-Deal energy plans on grid stability, costs, jobs, health, and climate in 143 countries, *Joule*, 2019.
- Jacobson, M.Z., The health and climate impacts of carbon capture and direct air capture, paper in review, 2019.
- Jepsen, K., Ramboll Oil and Gas Operations Team (personal communications), 2018.
- Johnson, G., When radiation isn't the real risk, 2015, <https://www.nytimes.com/2015/09/22/science/when-radiation-isnt-the-real-risk.html> (accessed December 8, 2018).
- Jiang, Q., J.D. Doyle, T. Haack, M.J. Dvorak, C.L. Archer, and M.Z. Jacobson, Exploring wind energy potential off the California coast, *Geophys. Res. Lett.*, 35, L20819, doi:10.1029/2008GL034674, 2008.
- Kadiyala, A., R. Kommalapati, and Z. Huque, Evaluation of the lifecycle greenhouse gas emissions from different biomass feedstock electricity generation systems, *Sustainability*, 8, 1181-1192, 2016.
- Kaldelis, J.K., and D. Apostolou, Life cycle energy and carbon footprint of offshore wind energy. Comparison with onshore counterpart, *Renewable Energy*, 108, 72-84, 2017.
- Kahn, E., The reliability of distributed wind generators, *Electric Power Systems*, 2, 1-14, 1979.

- Kane, M., CATL breaks into 300+ Wh/kg energy density on battery cell level, 2019, <https://insideevs.com/news/343690/catl-breaks-into-300-wh-kg-energy-density-on-battery-cell-level/> (accessed July 17, 2019).
- Karam, P.A., How do fast breeder reactors differ from regular nuclear power plants, *Scientific American*, October 2006.
- Katalenich, S.M., and M.Z. Jacobson, Assessing battery-electric and hydrogen fuel cell land, air, and sea military vehicle potential, in review, 2019.
- Kempton, W., and J. Tomic, Vehicle-to-Grid Power Fundamentals: Calculating Capacity and Net Revenue, *J. Power Sources*, 144, 268-279, 2005a.
- Kempton, W., and J. Tomic, Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy, *J. Power Sources*, 144, 280-294, 2005b.
- Kempton, W., C.L. Archer, A. Dhanju, R.W. Garvine, and M.Z. Jacobson, Large CO₂ reductions via offshore wind power matched to inherent storage in energy end-uses, *Geophys. Res. Lett.*, 34, L02817, doi:10.1029/2006GL028016, 2007.
- Keith, D.W., G. Holmes, D. St. Angelo, and K. Heidel, A process for capturing CO₂ from the atmosphere, *Joule*, 2, 1573-1594, 2018.
- Kirby, B.J., Frequency regulation basics and trends, ORNL/TM-2004/291, 2004, http://www.consultkirby.com/files/TM2004-291_Frequency_Regulation_Basics_and_Trends.pdf (accessed January 28, 2019).
- Ko, N., M. Lorenz, R. Horn, H. Krieg, and M. Baumann, Sustainability assessment of concentrated solar power (CSP) tower plants – Integrating LCA, LCC, and LCWE in one framework, *Procedia CIRP* 69, 395-400, 2018.
- Koomey, J., and N. E. Hultman, A reactor-level analysis of busbar costs for U.S. nuclear plants, 1970-2005, *Energy Policy* 35, 5630-5642, 2007.
- Kougias, I., K. Bodis, A. Jager-Waldau, M. Moner-Girona, F. Monforti-Ferrario, H. Ossenbrink, and S. Szabo, The potential of water infrastructure to accommodate solar PV systems in Mediterranean islands, *Solar Energy*, 136, 174-182, doi:10.1016/j.solener.2016.07.003, 2016.
- Krewski, D., M. Jerrett, R.T. Burnett, R. Ma, E. Hughes, Y. Shi, M.C. Turner, C. Arden Pope III, G. Thurston, E.E. Calle, and M.J. Thun, Extended follow-up and spatial analysis of the American Cancer Society study linking particulate air pollution and mortality, Health Effects Institute, Report No. 140, 2009.
- Kuphaldt, T., What is alternating current (AC), 2019, <https://www.allaboutcircuits.com/textbook/alternating-current/chpt-1/what-is-alternating-current-ac/> (accessed March 31, 2019)
- Lackner, K.S., H.-J. Ziock, and P. Grimes, Carbon dioxide extraction from air: Is it an option? Report LA-UR-99-583, Los Alamos National Laboratory, 1999.
- Lagarde, F., G. Pershagen, G. Akerblom, O. Axelson, U. Baverstam, L. Damber, A. Enflo, M. Svartengren, and G. A. Swedjemark, Residential radon and lung cancer in Sweden: risk analysis accounting for random error in the exposure assessment, *Health Physics*, 72, 269-276, 1997.
- Lazard, Lazard's levelized cost of energy analysis – version 12.0, 2018, <https://www.lazard.com/media/450784/lazards-levelized-cost-of-energy-version-120-vfinal.pdf> (accessed January 16, 2019).
- Lenzen, M., Life cycle energy and greenhouse gas emissions of nuclear energy: A review, *Energy Conversion & Management*, 49, 2178-2199, 2008.
- Le Quere, C. et al., Global carbon budget 2014, *Earth Syst. Sci. Data*, 7, 47-85, 2015.
- Lee, K.K., M.R. Miller, and A.S.V. Shah, Air pollution and stroke, *J. Stroke*, 20, 2-11, 2018.
- Letterman, D., The Late Show With David Letterman, New York City, October 9, 2013, <https://www.youtube.com/watch?v=AqIu2J3vRJc> (accessed February 6, 2019).
- Li, X., K.J. Chalvatzis, and D. Pappas, China's electricity emission intensity in 2020-an analysis at provincial level, *Energy Procedia*, 142, 2779-2785, 2017.
- Liou, K.N., *An Introduction to Atmospheric Radiation*, Academic Press, Amsterdam, 2002.
- Liu, H., G.B. Andresen, and M. Greiner, Cost-optimal design of a simplified highly renewable Chinese network, *Energy*, 147, 534-546, 2018.

- Lu, B., A. Blakers, and M. Stocks, 90-100% renewable electricity for the South West Interconnected System of Western Australia, *Energy*, 122, 663-674, 2017.
- Lund, H., Large-scale integration of optimal combinations of PV, wind, and wave power into the electricity supply, *Renewable Energy*, 31, 503-515, 2006.
- Lund, H., and B.V. Mathiesen, Energy system analysis of 100% renewable energy systems – The case of Denmark in years 2030 and 2050, *Energy*, 34, 524-531, 2009.
- Lund, H., and B.V. Mathiesen, The role of carbon capture and storage in a future sustainable energy system, *Energy* 44, 469-476, 2012.
- Macdonald-Smith, A., South Australia's big battery slashes \$40m from grid control costs in first year, 2018, <https://www.afr.com/business/energy/solar-energy/south-australias-big-battery-slashes-40m-from-grid-control-costs-in-first-year-20181205-h18q11> (accessed January 25, 2019).
- Manwell, J.F., J.G. McGowan, and A.L. Rogers, Wind energy explained – Theory, design, and application, John Wiley & Sons Ltd, p. 98, 2002.
- Marine Energy, Global installed ocean energy power doubles in 2017, 2018 <https://marineenergy.biz/2018/03/12/global-installed-ocean-energy-power-doubles-in-2017/> (accessed January 9, 2019).
- Mason, I.G., S.C. Page, A.G. Williamson, A 100% renewable energy generation system for New Zealand utilizing hydro, wind, geothermal, and biomass resources, *Energy Policy* 38, 3973-3984, 2010.
- Masters, G., *Renewable and Efficient Electric Power Systems*, 2nd Edition, Wiley, Hoboken, New Jersey, 712 pp., 2013.
- Mathiesen, B.V., H. Lund, and K. Karlsson, 100% renewable energy systems, climate mitigation, and economic growth, *Applied Energy*, 88, 488-501, 2011.
- Mathiesen, B.V., H. Lund, D. Connolly, H. Wenzel, P.Z. Ostergaard, B. Moller, S. Nielsen, I. Ridjan, P. Karnoe, K. Sperling, F.K. Hvelplund, Smart energy systems for coherent 100% renewable energy and transport solutions, *Applied Energy*, 145, 139-154, 2015.
- Matthews, H.D., N.P. Gillett, P.A. Stott, and K. Zickfeld, The proportionality of global warming to cumulative carbon emissions, *Nature*, 459, 829-832, 2009.
- Matthews, H.D., *Montreal's emissions targets for 1.5 °C and 2 °C global warming*, 2016, http://ocpm.qc.ca/sites/ocpm.qc.ca/files/pdf/P80/7.2.19_damon_matthews.pdf (accessed January 13, 2018).
- McFadyen, S., Three phase power simplified, 2012, <https://myelectrical.com/notes/entryid/172/three-phase-power-simplified> (accessed April 3, 2019).
- Meador W. E. and W.R. Weaver, Two-stream approximations to radiative transfer in planetary atmospheres: A unified description of existing methods and a new improvement, *J. Atmos. Sci.* 37, 630-43, 1980.
- Meinshausen, M. *et al.* Greenhouse-gas emission targets for limiting global warming to 2°C, *Nature* 458, 1158–1162, 2009.
- Miceli, F., Offshore wind turbines foundation types, 2012, <http://www.windfarmbop.com/offshore-wind-turbines-foundation-types/> (accessed April 4, 2019).
- MIT (Massachusetts Institute of Technology), *The Future of Natural Gas*, 287 pp., 2011, <https://energy.mit.edu/wp-content/uploads/2011/06/MITEI-The-Future-of-Natural-Gas.pdf> (accessed December 2, 2018).
- Monitoring Analytics, Quarterly state of the market report for PJM: January through June, 2015, http://www.monitoringanalytics.com/reports/PJM_State_of_the_Market/2015/2015q2-som-pjm-sec5.pdf (accessed January 19, 2019).
- Moore, M.A., A.E. Boardman, A.R. Vining, D.L. Weimer, and D.H. Greenberg, Just give me a number! Practical values for the social discount rate, *J. Policy Anal. Management*, 23, 789-812, 2004.
- Moore, F.C. D.B. Diaz, Temperature impacts on economic growth warrant stringent mitigation policy, *Nature Climate Change*, 5, 127-131, 2015.
- Morris, C., French nuclear power history – the unknown story, 2015, <https://energytransition.org/2015/03/french-nuclear-power-history/> (accessed June 16, 2019).
- Myhre, G., D. Shindell, F.-M. Breon, W. Collins, J. Fuglestedt, J. Huang, D. Koch, J.F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and H. Zhang, *Anthropogenic and Natural Radiative Forcing*. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

- Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, Ny, USA, 2013.
- NACAG (Nitric Acid Climate Action Group), Nitrous oxide emissions from nitric acid production, 2014, <http://www.nitricacidaction.org/about/nitrous-oxide-emissions-from-nitric-acid-production/> (accessed December 1, 2018).
- Nautical Almanac Office (NAO) and Her Majesty's Nautical Almanac Office, *Astronomical Almanac*. U. S. Government Printing Office, Washington, DC, 1993.
- NASA (National Aeronautics and Space Administration), GISS surface temperature analysis (GISTEMP), 2018 <https://data.giss.nasa.gov/gistemp/maps/> (accessed November 30, 2018).
- NCEE (National Center for Environmental Economics), *Guidelines for Preparing Economic Analyses* (U.S. Environmental Protection Agency), 2014.
- Neftel, A., H. Friedli, E. Moor, H. Lötscher, H. Oeschger, U. Siegenthaler, and B. Stauffer, Historical CO₂ record from the Siple Station ice core. In *Trends: A Compendium of Data on Global Change*, 1994. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.
- Neocarbon Energy, Future energy system, <http://neocarbonenergy.fi/internetofenergy/>, 2016 (accessed December 6, 2016).
- New York Times, Text of President Bush's remarks on global climate, 2001, <https://www.nytimes.com/2001/06/11/world/text-of-president-bushs-remarks-on-global-climate.html> (accessed February 2, 2019).
- Ni, J., Carbon storage in grasslands of China, *J. Arid Environments*, 50, 205-218, 2002.
- Nithyanandam K, and R. Pitchumani, Cost and performance analysis of concentrating solar power systems with integrated latent thermal energy storage, *Energy* 64: 793-810, 2014.
- Nonbol, E., Load-following capabilities of nuclear power plants, Technical University of Denmark, 2013, http://orbit.dtu.dk/files/64426246/Load_following_capabilities.pdf (accessed November 22, 2018).
- NRC (U.S. National Research Council), Real prospects for energy efficiency in the United States, National Academies Press, p. 251, <https://www.nap.edu/read/12621/chapter/6#251>, 2010 (accessed February 2, 2019).
- NREL (National Renewable Energy Laboratory), *Jobs and Economic Development Impact Models (JEDI)*, 2017, <https://www.nrel.gov/analysis/jedi> (accessed January 17, 2019).
- NREL (National Renewable Energy Laboratory), PV Watts Calculator, 2018, <http://pvwatts.nrel.gov> (accessed December 25, 2018).
- NWCC (National Wind Coordinating Collaborative), Wind turbine interactions with birds, bats, and their habitats, 2010, https://www1.eere.energy.gov/wind/pdfs/birds_and_bats_fact_sheet.pdf (accessed January 4, 2018).
- Oil and gas, Threat map, 2018, <https://oilandgasthreatmap.com/threat-map/> (accessed December 3, 2018).
- O'Malley, M., A jobs agenda for our renewable energy future, 2015, <http://www.p2016.org/omalley/omalley070215climate.html> (accessed February 7, 2019).
- OMB (U.S. Office of Management and Budget), Circular A-4, Regulatory Analysis, the White House, Washington, D. C., September 17, 2003, <https://www.whitehouse.gov/sites/whitehouse.gov/files/omb/circulars/A4/a-4.pdf> (accessed January 16, 2019).
- Orsted, New survey shows strong global support for green energy, November 13, 2017, <https://orsted.com/en/Barometer> (accessed February 7, 2019).
- Ostro, B.D., H. Tran, and J.I. Levy, The health benefits of reduced tropospheric ozone in California, *J. Air & Waste Manage. Assoc.*, 56, 1007-1021, 2006.
- Pavel, C.C., R. Lacal-Arantequi, A. Marmier, D. Schuler, E. Tzimas, M. Buchert, W. Jenseit, and D. Blagoeva, Substitution strategies for reducing the use of rare earths in wind turbines, *Resources Policy*, 52, 349-357, 2017.
- Pires, O., X. Munduate, O. Ceyhan, M Jacobs, and H. Snel, Analysis of high Reynolds numbers effects on a wind turbine airfoil using 2D wind tunnel test data, *J. Physics: Conference Series* 753, 022047, 2016.
- Polpong, P. and S. Bovornkitti, Indoor radon, *Journal of the Medical Association of Thailand*, 81, 47-57, 1998.

- Pope, C.A. III, R.T. Burnett, M.J. Thun, E.E. Calle, D. Krewski, K. Ito, and G.D. Thurston, Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution, *JAMA*, 287, 1132-1141, 2002.
- Puiu, T., Solar and wind supply more than 10% of electricity in 18 U.S. states, ZME Science, 2018, <https://www.zmescience.com/science/news-science/solar-wind-electricity-us-stated-04232/> (accessed March 25, 2019).
- Rahi, O.P., A. Kumar, Economic analysis for refurbishment and uprating of hydropower plants, *Renewable Energy*, 86, 1197-1204, 2016.
- Rahman, D., A.J. Morgan, Y. Xu, R. Gao, W. Yu, D.C. Hopkins, and I. Husain, Design methodology for a planarized high power density EV/HEV traction drive using SiC power modules, 2016 IEEE Energy Conversion Congress and Exhibition, Sept. 18-22, 2016, doi: 10.1109/ECCE.2016.7855018, <https://ieeexplore.ieee.org/document/7855018/authors#authors> (accessed March 2, 2019).
- Ramaiah, R., and K.S.S. Shekar, Solar thermal energy utilization for medium temperature industrial process heat applications, *IOP Conf. Ser.: Mater. Sci. Eng.*, 376, 010235, 2018.
- Ramana, M.V., "Nuclear power: Economic, safety, health, and environmental issues of near-term technologies," *Annu. Rev. Environ. Resour.*, 34, 127-152, 2009.
- Ramboll, World's largest thermal heat storage pit in Vojens, 2016, <https://stateofgreen.com/en/partners/ramboll/solutions/world-largest-thermal-pit-storage-in-vojen/> <https://ramboll.com/projects/re/south-jutland-stores-the-suns-heat-in-the-worlds-largest-pit-heat-storage> (accessed November 25, 2018).
- Rasmussen, M.G., G.B. Andresen, and M. Greiner, Storage and balancing synergies in a fully or highly renewable pan-European power system, *Energy Policy*, 51, 642-651, 2012.
- RE100, The world's most influential companies committed to 100% renewable power, 2019, <http://there100.org> (accessed January 26, 2019).
- Rehau, Underground thermal energy storage, 2011 http://www.igshpa.okstate.edu/membership/members_only/proceedings/2011/100611-1030-B-Christopher_percent20Fox_percent20-percent20Rehau_percent20-percent20Underground_percent20Thermal_percent20Energy_percent20Storage.pdf (accessed November 21, 2018).
- REN21 (Renewable Energy Policy Network for the 21st Century), Renewables 2018 global status report, http://www.ren21.net/wp-content/uploads/2018/06/17-8652_GSR2018_FullReport_web_final_.pdf (accessed February 7, 2019).
- Roberts, D., The train goes up, the train goes down: a simple way to store energy, Vox, 2016, <https://www.vox.com/2016/4/28/11524958/energy-storage-rail> (accessed April 10, 2019)
- Roselund, C., Inertia, frequency regulation and the grid, PV Magazine, 2019, <https://pv-magazine-usa.com/2019/03/01/inertia-frequency-regulation-and-the-grid/> (accessed March 2, 2019).
- Ruffalo, M.A., M. Krapels, and M.Z. Jacobson A plan to power the world with wind, water, and sunlight, Talks at Google, Google, Inc., Mountain View, California, June 20, 2012a, http://www.youtube.com/watch?v=N_sLt5gNAQs (accessed February 5, 2019).
- Ruffalo, M.Z., M.Z. Jacobson, M. Krapels, and video from J. Fox, Powering the world, U.S., and New York with wind, water, and sunlight, The Nantucket Project, Nantucket, Massachusetts, October 6, 2012b, <http://vimeo.com/52038463> (accessed February 5, 2019).
- Russell, L.M., C.D. Cappa, M.J. Kleeman, and M.Z. Jacobson, Characterizing the climate impacts of brown carbon, Final report to the California Air Resources Board Research Division, Project 13-330, November 30, 2018.
- Sadiqa, A., A. Gulagi, and C. Breyer, Energy transition roadmap towards 100% renewable energy and role of storage technologies for Pakistan by 2050, *Energy*, 147, 518-533, 2018.
- Sadovskaia, K., D. Bogdanov, S. Honkapuro, and C. Breyer, Power transmission and distribution losses – a model based on available empirical data and future trends for all countries globally, *Electrical Power and Energy Systems*, 107, 98-109, 2019.
- Sanders, B., Combatting climate change to save the planet, 2016, <https://berniesanders.com/people-before-polluters/> (Accessed February 7, 2019).
- Sanders, B., and M. Jacobson, he American people, not big oil, must decide our climate future, The Guardian, April 29, 2017, <https://www.theguardian.com/commentisfree/2017/apr/29/bernie-sanders-climate-change-big-oil> (Accessed February 7, 2019).

- Santin, I., M. Barbu, C. Pedret, and R. Vilanova, Control strategies for nitrous oxide emissions reduction on wastewater treatment plants operation, *Water Research*, 125, 466-477, 2017.
- Sanz-Perez, E.S., C.R. Murdock, S.A. Didas, and C.W. Jones, Direct capture of CO₂ from ambient air, *Chemical Reviews*, 116, 11,840-11,876, 2016.
- Schubel, P.J., and R.J. Crossley, Wind turbine blade design, *Energies*, 5, 3425-3449, 2012.
- Scottmadden, Billion dollar Petra Nova coal carbon capture project a financial success but unclear if it can be replicated, 2017, <https://www.scottmadden.com/insight/billion-dollar-petra-nova-coal-carbon-capture-project-financial-success-unclear-can-replicated/> (accessed December 3, 2018).
- Searchinger, T., R. Heimlich, R.A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes, and T.-H. Yu, Use of U.S. cropland for biofuels increases greenhouse gases through emissions from land-use change, *Science*, 319, 1238-1240, 2008.
- Senate (U.S. Senate), S.Res.632, 2016, <https://www.congress.gov/bill/114th-congress/senate-resolution/632> (accessed February 7, 2019).
- Senate (U.S. Senate), S.987 – 100 by '50 Act, 2017," <https://www.congress.gov/bill/115th-congress/senate-bill/987/text?r=1> (accessed February 7, 2019).
- Senate (U.S. Senate), S.Res.59 – A resolution recognizing the duty of the Federal Government to create a Green New Deal, 2019," <https://www.congress.gov/bill/116th-congress/senate-resolution/59?q=%7B%22search%22%3A%5B%22green+new+deal%22%5D%7D&s=1&r=2> (accessed March 26, 2019).
- Sibbitt B, D. McClenahan, R. Djebbar, J. Thornton, B. Wong, J. Carriere, and J. Kokko, The performance of a high solar fraction seasonal storage district heating system – five years of operation, *Energy Procedia*, 30, 856-865, 2012.
- Sierra Club, 100% commitments in cities, counties, and states, 2019, <https://www.sierraclub.org/ready-for-100/commitments> (accessed January 26, 2019).
- Simivas, S., W. Musial, B. Bailey, and M. Filippelli, Assessment of offshore wind system design, safety, and operation standards, NREL/TP-5000-60573, 2014.
- Skone, T.J., Lifecycle greenhouse gas emissions: Natural gas and power production, 2015 EIA Energy Conference, Washington DC, June 15, 2015, <https://www.eia.gov/conference/2015/pdf/presentations/skone.pdf> (accessed December 2, 2018).
- Smallwood, K.S., Comparing bird and bat fatality rate estimates among North American wind energy projects, *Wildlife Society Bulletin*, 37, 19-33, 2013.
- Socaciu, L., Seasonal sensible thermal energy storage solutions, *Leonardo Electronic Journal of Practices and Technologies*, 10, 49-68, 2011.
- Solutions Project, Our 100% Clean Energy Vision, 2019 <http://www.thesolutionsproject.org/why-clean-energy/> (accessed February 5, 2019).
- Sorensen, B., A plan is outlined to which solar and wind energy would supply Denmark's needs by the year 2050, *Science*, 189, 255-260, 1975.
- Sorensen, P.,A., and T. Schmidt, Design and construction of large scale heat storages for district heating in Denmark, 14th Int. Conf. on Energy Storage, April 25-28, Adana, Turkey, 2018, http://planenergi.dk/wp-content/uploads/2018/05/Soerensen-and-Schmidt_Design-and-Construction-of-Large-Scale-Heat-Storages-12.03.2018-004.pdf (accessed November 25, 2018).
- Sourcewatch, The footprint of coal, 2011, https://www.sourcewatch.org/index.php/The_footprint_of_coal (accessed December 3, 2018).
- Sovacool, B.K., Valuing the greenhouse gas emissions from nuclear power: A critical survey, *Energy Policy*, 36, 2940-2953, 2008.
- Sovacool, B.K., Contextualizing avian mortality: A preliminary appraisal of bird and bat fatalities from wind, fossil-fuel, and nuclear electricity, *Energy Policy*, 37, 2241-2248, 2009.
- Spakovsky, Z.S., Trends in thermal and propulsive efficiency, 2008, <http://web.mit.edu/16.unified/www/FALL/thermodynamics/notes/node84.html> (accessed March 27, 2019).
- Spath, P.L., and M.K. Mann, Life cycle assessment of a natural gas combined-cycle power generation system, National Renewable Energy Lab, NREL/TP-570-27715, 2000, <http://www.nrel.gov/docs/fy00osti/27715.pdf>, Accessed April 24, 2011.

- Stagner, J., Stanford University's "fourth-generation" district energy system, District Energy, Fourth Quarter, 2016, https://sustainable.stanford.edu/sites/default/files/IDEA_Stagner_Stanford_fourth_Gen_DistrictEnergy.pdf (accessed November 27, 2018).
- Stagner, J., Stanford Energy System Innovations, Efficiency and environmental comparisons. 2017, <https://sustainable.stanford.edu/sites/default/files/documents/SESI-CHP-vs-SHP-percent26-CHC.pdf>, (accessed November 24, 2018).
- Statista, Number of retail fuel stations in California from 2009 to 2016, by type, 2017, <https://www.statista.com/statistics/818462/california-fueling-stations-by-type/> (accessed December 3, 2018).
- Steinke, F., P. Wolfrum, and C. Hoffmann, Grid vs. storage in a 100% renewable Europe, *Renewable Energy*, 50, 826-832, 2013.
- Stevens, F., and L. DiCaprio, Interviews at Stanford University for *Before the Flood*, 2014, <https://cee.stanford.edu/programs/atmosphere-energy-program> (accessed February 7, 2019).
- Stone, D., Ferrock basics, 2017, <http://ironkast.com/wp-content/uploads/2017/11/Ferrock-basics.pdf> (accessed November 20, 2018).
- Stoutenburg, E.D., N. Jenkins, and M.Z. Jacobson, Power output variations of co-located offshore wind turbines and wave energy converters in California, *Renewable Energy*, 35, 2781-2791, doi:10.1016/j.renene.2010.04.033, 2010.
- Stoutenburg, E.K., and M.Z. Jacobson, Reducing offshore transmission requirements by combining offshore wind and wave farms, *IEEE Journal of Oceanic Engineering*, 36, 552-561, doi:10.1109/JOE.2011.2167198, 2011.
- Stoutenburg, E.D., N. Jenkins, and M.Z. Jacobson, Variability and uncertainty of wind power in the California electric power system, *Wind Energy*, 17, 1411-1424, doi:10.1002/we.1640, 2014.
- Strata, The footprint of energy: Land use of U.S. electricity production, 2017, <https://www.strata.org/pdf/2017/footprints-full.pdf> (accessed December 3, 2018).
- Streets, D. G., K. Jiang, X. Hu, J. E. Sinton, X.-Q. Zhang, D. Xu, M. Z. Jacobson, and J. E. Hansen, Recent reductions in China's greenhouse gas emissions, *Science*, 294, 1835-1836, 2001.
- Talebizadeh, P., M.A. Mehrabian, and M. Abdolzadeh, Determination of optimum slope angles of solar collectors based on new correlations, *Energy Sources Part A.*, 33, 1567-1580, 2011.
- Tans, P., and R.F. Keeling (2015) Trends in atmospheric carbon dioxide, http://www.esrl.noaa.gov/gmd/ccgg/trends/#mlo_full (accessed January 24, 2019).
- Ten Hoeve, J.E., and M.Z. Jacobson, Worldwide health effects of the Fukushima Daiichi nuclear accident, *Energy and Environmental Sciences*, 5, 8743-8757, 2012.
- Teske, S., D. Giurco, T. Morris, K. Nagrath, F. Mey, C. Briggs, E. Dominish, N. Florin, T. Watari, B. McLellan, T. Pregger, T. Naegler, S. Simon, J. Pagenkopf, B. van den Adel, O. Deniz, S. Schmidt, M. Meinhausen, K. Dooley, and ed. J. Miller, Achieving the Paris Climate Agreement, 2019, <https://oneearth.app.box.com/s/hctp4qlk34ygd0mw3yjdctctsymsdtaqs> (accessed February 25, 2019).
- Tomasini-Montenegro, C., E. Santoyo-Castelazo, H. Gujba, R.J. Romero, and E. Santoyo, Life cycle assessment of geothermal power generation technologies: An updated review, *Applied Thermal Engineering*, 114, 1119-1136, 2017.
- Toon, O.B. and T.P. Ackerman, Algorithms for the calculation of scattering by stratified spheres, *Appl. Opt.*, 20, 3657-60, 1981.
- Toon O.B., C.P. McKay, and T.P. Ackerman, Rapid calculation of radiative heating rates and photodissociation rates in inhomogeneous multiple scattering atmospheres, *J. Geophys. Res.*, 94, 16,287-301, 1989.
- Union Gas, Chemical composition of natural gas, 2018, <https://www.uniongas.com/about-us/about-natural-gas/chemical-composition-of-natural-gas> (accessed December 5, 2018).
- U.S. DOI (U.S. Department of the Interior), Reclamation: Managing water in the west; Hydroelectric power, 2005, <https://www.usbr.gov/power/edu/pamphlet.pdf> (accessed November 22, 2018).
- U.S. EPA (U.S. Environmental Protection Agency), 2008 U.S. National Emissions Inventory (NEI), 2011, <https://www.epa.gov/air-emissions-inventories/2008-national-emissions-inventory-nei-data> (accessed December 2, 2018).
- U.S. EPA, Revision under consideration for the 2018 GHGI: Abandoned wells, 2017, <https://www.epa.gov/sites/production/files/2017->

- [06/documents/6.22.17_ghgi_stakeholder_workshop_2018_ghgi_revision_-_abandoned_wells.pdf](#) (accessed December 3, 2018).
- USGS (U.S. Geological Survey), *Mineral Commodities Summaries 2011*, U.S. Government Printing Office, Washington, D. C., 2018, <https://minerals.usgs.gov/minerals/pubs/mcs/2018/mcs2018.pdf> (accessed January 18, 2019).
- USGS (United States Geological Survey), Lithium Statistics and Information, 2018, <https://minerals.usgs.gov/minerals/pubs/commodity/lithium/mcs-2018-lithi.pdf> (accessed November 23, 2018).
- Ussiri, D., and R. Lal, Global sources of nitrous oxide, In *Soil emission of nitrous oxide and its mitigation*, Springer, pp. 131-175, 2012.
- Van den Bergh, J.C.J.M., and W.J.W. Botzen, A lower bound the social cost of carbon emissions, *Nature Climate Change*, 4, 253-258, 2014.
- Van den Bergh, J.C.J.M., and W.J.W. Botzen, Monetary valuation of the social cost of CO2 emissions: A critical survey, *Ecological Economics*, 114, 33-468, 2015.
- Vavrin, J. Power and energy considerations at forward operating bases (FOBs). United States Army Corps of Engineers, Engineer Research and Development Center, Construction Engineering Research Laboratory, 2010 <http://www.dtic.mil/dtic/tr/fulltext/u2/a566876.pdf> (accessed February 13, 2019).
- Viking Heat Engines, Heat Booster, 2019, <http://www.vikingheatengines.com/news/vikings-industrial-high-temperature-heat-pump-is-available-to-order> (accessed January 13, 2019).
- Vogl, V., M. Ahman, and L.J. Nilsson, Assessment of hydrogen direct reduction for fossil-free steelmaking, *J. Cleaner Production*, 203, 736-745, 2018.
- WEC (World Energy Council), World energy resources: Marine Energy, 2016, https://www.worldenergy.org/wp-content/uploads/2017/03/WEResources_Marine_2016.pdf (accessed January 9, 2019).
- Wieneke, J., H. Lavelaine, P.-J. Panteix, C. Petijean, and C. Rapin, Electrolysis of iron in a molten oxide electrolyte, *J. Applied Electrochemistry*, 48, 115-126, 2018.
- Wigley, T.M.L., Coal to gas: the influence of methane leakage, *Climatic Change*, 108, 601-608, 2011.
- Winther, M., D. Balslev-Harder, S. Christensen, A. Prieme, B. Elberling, E. Crosson, and T. Blunier, Continuous measurements of nitrous oxide isotopomers during incubation experiments, *Biogeosciences*, 15, 767-780, 2018.
- WHO (World Health Organization), 7 million premature deaths annually linked to air pollution, 2014, <http://www.who.int/mediacentre/news/releases/2014/air-pollution/en/> (accessed November 29, 2018).
- WHO (World Health Organization) Health statistics and information systems, 2017a, https://www.who.int/healthinfo/global_burden_disease/estimates/en/ (accessed January 14, 2019).
- WHO (World Health Organization), Global health observatory data, 2017b, https://www.who.int/gho/phe/outdoor_air_pollution/en/ (accessed January 14, 2019).
- Wilkerson, J.T., M.Z. Jacobson, A. Malwitz, S. Balasubramanian, R. Wayson, G. Fleming, A.D. Naiman, and S.K. Lele, Analysis of emission data from global commercial aviation: 2004 and 2006, *Atmos. Chem. Phys.*, 10, 6391-6408, 2010.
- Winnefeld, C., T. Kadyk, B. Bensmann, U. Krewer, and R. Hanke-Rauschenback, Modelling and designing cryogenic hydrogen tanks for future aircraft applications, *Energies*, 11, 105, doi:10.3390/en11010105, 2018.
- Woodford, C., Lithium ion batteries, 2018, <https://www.explainthatstuff.com/how-lithium-ion-batteries-work.html> (accessed March 26, 2019).
- World Bank, Electric power transmission and distribution losses (% of output), 2018, <https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS?end=2014&start=2009> (accessed January 1, 2019).
- World Nuclear Association, World uranium mining production, 2019, <http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/world-uranium-mining-production.aspx> (accessed March 30, 2019).
- World Nuclear News, Green light for next Darlington refurbishment, 2018, <http://world-nuclear-news.org/Articles/Green-light-for-next-Darlington-refurbishment> (accessed December 7, 2018).

- Worldwatch Institute, Energy poverty remains a global challenge for the future, 2019, <http://www.worldwatch.org/energy-poverty-remains-global-challenge-future> (accessed February 13, 2019).
- Zapata, S., M. Casteneda, M. Jiminez, A.J. Aristizabel, C.J. Franco, and I. Dyer, Long-term effects of 100% renewable generation on the Colombian power market, *Sustainable Energy Technologies and Assessments*, 30, 183-191, 2018.
- Zhang, J., S. Chowdhury, and J. Zhang, Optimal preventative maintenance time windows for offshore wind farms subject to wake losses, *AIAA* 2012-5435, 2012.
- Zhou, L., Y. Tian, S.B. Roy, C. Thorncroft, L.F. Bosart, and Y. Hu, Impacts of wind farms on land surface temperature, *Nature Climate Change* 2, 539-543, 2012.