

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

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## 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 (CO<sub>2</sub>e) 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 CO<sub>2</sub> 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 CO<sub>2</sub> 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 CO<sub>2</sub>.
- Spending on carbon capture rather than wind replacing either fossil fuels or bioenergy always increases total social cost substantially. No improvement in capture equipment can change this conclusion, since carbon capture always incurs an equipment cost never incurred by wind, and carbon capture never reduces, instead mostly increases, air pollution and mining.
- New natural gas with CCS/U produces 27-100 times the 100-year CO<sub>2</sub>e as new onshore wind.
- New coal with CCS/U produces 33-211 times the 100-year CO<sub>2</sub>e 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 SO<sub>2</sub> and NO<sub>x</sub> and lower CH<sub>4</sub> emissions from coal. The higher SO<sub>2</sub>, NO<sub>x</sub>, 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  $-162^{\circ}\text{C}$ , 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 CO<sub>2</sub> 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 (CO<sub>2</sub>e – 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 CO<sub>2</sub>e) 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, CO<sub>2</sub>e 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 CO<sub>2</sub>e 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 CO<sub>2</sub>e from a natural gas OCGT is only **8 percent less** than that of coal, and the CO<sub>2</sub>e 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 CO<sub>2</sub>e 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 CO<sub>2</sub> per kilowatt-hour (kWh) of coal combustion, natural gas leaks during the mining and transport of natural gas emit similar or more CH<sub>4</sub> than do CH<sub>4</sub> leaks during coal mining. This is an issue, because CH<sub>4</sub> has a high, positive 20- and 100-year GWP (Table 1.2). As such, the leaked CH<sub>4</sub> from natural gas mining and transport contributes substantially to the CO<sub>2</sub>e of natural gas.

Second, and more important, coal combustion emits more NO<sub>x</sub> and SO<sub>2</sub> per kWh than does natural gas combustion (Table 3.1), and NO<sub>x</sub> and SO<sub>2</sub> 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<sub>x</sub> and SO<sub>2</sub>, 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 CO<sub>2e</sub> emissions of natural gas versus coal on a 20- versus 100-year lifetime. Wigley (2011), for one, estimated the cooling impact of SO<sub>2</sub>, but not NO<sub>x</sub>, when comparing CO<sub>2e</sub> from coal versus natural gas power plants.

**Table 3.1.** Comparison of 20- and 100-year lifecycle global CO<sub>2</sub> equivalent (CO<sub>2e</sub>) 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)			Coal			Natural Gas Open Cycle Gas Turbine			Natural Gas Combined Cycle Gas Turbine		
	20-y GWP	100-y GWP	Emis. factor (g-X/ kWh)	20-y CO <sub>2e</sub> (g-CO <sub>2e</sub> /kWh)	100-y CO <sub>2e</sub> (g-CO <sub>2e</sub> /kWh)	Emis. factor (g-X/ kWh)	20-y CO <sub>2e</sub> (g-CO <sub>2e</sub> /kWh)	100-y CO <sub>2e</sub> (g-CO <sub>2e</sub> /kWh)	Emis. factor (g-X/ kWh)	20-y CO <sub>2e</sub> (g-CO <sub>2e</sub> /kWh)	100-y CO <sub>2e</sub> (g-CO <sub>2e</sub> /kWh)
<sup>a</sup> CO <sub>2</sub> -upstream				97.2	97.2		54	54		54	54
<sup>b</sup> CH <sub>4</sub> -leak	86	34	4.1	353	140	4.35	374	148	3.26	280	111
<sup>c</sup> CO <sub>2</sub> -plant	1	1	905	905	905	540	540	540	404	404	404
<sup>d</sup> BC+OM-plant	3,100	1,550	0.045	141	70	0.0003	0.93	0.47	0.0003	0.93	0.47
<sup>e</sup> NO <sub>x</sub> -N-plant	-560	-159	0.23	-129	-37	0.15	-84	-24	0.015	-8.4	-2.4
<sup>e</sup> SO <sub>2</sub> -S-plant	-1,400	-394	0.75	-1,050	-393	0.005	-7	-2	0.0015	-2.1	-2
<b>Total</b>				<b>317</b>	<b>782</b>		<b>878</b>	<b>716</b>		<b>728</b>	<b>565</b>

All 20- and 100-year GWPs are from Table 1.2. Each CO<sub>2e</sub>, except for upstream values, is the product of an emission factor and a GWP.

<sup>a</sup>Upstream CO<sub>2</sub> emissions from coal mining, processing, and transport are 27 g-CO<sub>2</sub>/MJ, or 97.2 g-CO<sub>2</sub>/kWh and from natural gas are 15 g-CO<sub>2</sub>/MJ = 54 g-CO<sub>2</sub>/kWh (Howarth, 2014).

<sup>b</sup>For coal, the 100-year CO<sub>2e</sub> from CH<sub>4</sub> 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 CH<sub>4</sub> in the present table. The 20-year CO<sub>2e</sub> is then calculated from the emission factor and the 20-year GWP. For natural gas, the CH<sub>4</sub>-leak emission factors in the present table are obtained by multiplying the mass of CH<sub>4</sub> 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 CH<sub>4</sub> required per kWh for a natural gas turbine is the CO<sub>2</sub> combustion emissions from the turbine (present table) multiplied by the ratio of the molecular weights of CH<sub>4</sub>:CO<sub>2</sub> (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-CH<sub>4</sub>/kWh-electricity for open cycle and 138.3 g-CH<sub>4</sub>/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.

<sup>c</sup>Emission factors from Figure 4 of de Gouw et al. (2014) for 2012 U.S. plants; For NO<sub>x</sub>-N, emission factors for NO<sub>x</sub>-NO<sub>2</sub> were multiplied by the ratio of the molecular weight of N to that of NO<sub>2</sub>. For SO<sub>2</sub>-S, emission factors for SO<sub>2</sub> were multiplied by the ratio of the molecular weight of S to that of SO<sub>2</sub>.

<sup>d</sup>The 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 CO<sub>2e</sub> for electricity generation (565 to 716 g-CO<sub>2e</sub>/kWh) (Table 3.1) is on the order of 56 to 72 times that of wind (~10 g-CO<sub>2e</sub>/kWh) (Table 3.5), and the 100-year coal CO<sub>2e</sub> (~780 g-CO<sub>2e</sub>/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 CO<sub>2e</sub> 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<sub>2e</sub> as WWS sources.

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

Whereas natural gas causes more CO<sub>2e</sub> 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<sub>2e</sub> 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), CH<sub>4</sub>, and ammonia (NH<sub>3</sub>) than coal production and use, whereas coal emitted more NO<sub>x</sub>, SO<sub>2</sub>, and particulate matter smaller than 2.5- and 10-μm in diameter (PM<sub>2.5</sub>, PM<sub>10</sub>). Thus, both fuels resulted in significant air pollution, although the higher SO<sub>2</sub>, NO<sub>x</sub>, 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	<b>900</b>
VOC	40	<b>1,130</b>
CH <sub>4</sub>	5	<b>310</b>
NH <sub>3</sub>	11	<b>54</b>
NO <sub>x</sub>	<b>2,800</b>	1,540
SO <sub>2</sub>	<b>7,600</b>	123
PM <sub>2.5</sub>	<b>290</b>	61
PM <sub>10</sub>	<b>420</b>	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 SO<sub>2</sub> and NO<sub>x</sub> emissions evolve to sulfate and nitrate aerosol particles, respectively. Natural gas also emits NO<sub>x</sub>, but less so than does coal (Tables 2.6 and 2.7). Natural gas, on the other hand, emits much less SO<sub>2</sub> 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<sub>2e</sub> 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 km<sup>2</sup> 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
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	Area per installation (km <sup>2</sup> )	Number	Area (km <sup>2</sup> )	Number	Area (km <sup>2</sup> )
<sup>a</sup> Active oil and gas wells	0.05	105,000	3,327	1.3 million	65,000
<sup>b</sup> Abandoned oil wells	0.00005	225,000	6.6	2.6 million	128.5
<sup>b</sup> Abandoned gas wells	0.000025	48,000	0.7	550,000	13.8
<sup>c</sup> Coal mines	50	0	0	680	34,000
<sup>d</sup> Oil refineries	7.28	17	124	135	983
<sup>e</sup> Kilometers of oil pipeline	0.006	4,800	29	258,000	1,550
<sup>e</sup> Kilometers of gas pipeline	0.006	180,000	1,080	2.62 million	15,700
<sup>f</sup> Coal power plants	1.74	1	1.74	359	626
<sup>f</sup> Gas power plants	0.12	37	4.5	1,820	221
<sup>f</sup> Petroleum power plants	0.93	0	0	1,080	1,007
<sup>f</sup> Nuclear power plants	14.9	1	14.9	61	911
<sup>f</sup> Other power plants	0.93	0	0	41	41
<sup>g</sup> Fueling stations	0.0018	10,200	18	156,000	275
<sup>h</sup> Gas storage facilities	12.95	10	130	394	5,102
<b>Total</b>			<b>4,736</b>		<b>126,000</b>
<b>Percent of CA or U.S.</b>			<b>1.2</b>		<b>1.3</b>

<sup>a</sup>Number 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).

<sup>b</sup>The 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 m<sup>2</sup>, and of each gas well, 25 m<sup>2</sup> from Jepsen (2018).

<sup>c</sup>The 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.

<sup>d</sup>The number of oil refineries is from EIA (2018b). The area of each refinery is based on the area of the Richmond, California refinery.

<sup>e</sup>Kilometers 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.

<sup>f</sup>The 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.

<sup>g</sup>The 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.

<sup>h</sup>The 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 CO<sub>2</sub> emitted from a coal or natural gas power plant before the CO<sub>2</sub> 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 CO<sub>2</sub> compared with no CCS, it only marginally reduces CO<sub>2</sub>, 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 CO<sub>2</sub> from other exhaust gases after fossil fuel or biofuel combustion, followed by the transfer of the CO<sub>2</sub> 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-CO<sub>2</sub>, which compares with a fossil fuel emission rate in 2017 of about 37 Gt-CO<sub>2</sub>/y.

Another proposed CCS method is to inject the CO<sub>2</sub> into the deep ocean. The addition of CO<sub>2</sub> to the ocean, however, results in ocean acidification. Dissolved CO<sub>2</sub> in the deep ocean eventually equilibrates with CO<sub>2</sub> in the surface ocean, reducing ocean pH and simultaneously supersaturating the surface ocean with CO<sub>2</sub>, forcing some of it back into the air.

A third type of sequestration method is to mix captured CO<sub>2</sub> with concrete material, trapping the CO<sub>2</sub> inside the concrete (Section 2.4.8.2).

**Carbon capture and use (CCU)** is the same as CCS, except that the isolated CO<sub>2</sub> 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, CO<sub>2</sub> 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 CO<sub>2</sub> is separated from it and sent back into the reservoir. About two additional barrels of oil can be extracted for every ton of CO<sub>2</sub> 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 CO<sub>2</sub>e Decreases due to Carbon Capture

Whereas carbon capture equipment is nominally expected to capture 85 to 90 percent of the CO<sub>2</sub> from a fossil fuel exhaust stream, several factors cause the overall CO<sub>2</sub> and CO<sub>2</sub>e 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 CO<sub>2</sub>e 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 CO<sub>2</sub> 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-CO<sub>2</sub> air pollutants from the fossil fuel exhaust. Such pollutants include CO, NO<sub>x</sub>, SO<sub>2</sub>, 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 CO<sub>2</sub> 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 (CO<sub>2</sub>e) 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 CO<sub>2</sub>e is calculated as the lifecycle emission of CO<sub>2</sub> 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 CO<sub>2</sub>e 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 CO<sub>2</sub>e over 20 years and 28.7 percent over 100 years compared with no carbon capture. A natural gas CCGT emits 34 percent of its CO<sub>2</sub>e 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 CO<sub>2</sub>e 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 CO<sub>2</sub> 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 CO<sub>2</sub>e than indicated in the Table 3.4.

**Table 3.4.** Theoretical lifecycle 20-year and 100-year CO<sub>2</sub>e 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 <sub>2</sub> e Remaining	No Carbon Capture	With Carbon Capture	Percent CO <sub>2</sub> e Remaining	No Carbon Capture	With Carbon Capture	Percent CO <sub>2</sub> e Remaining
20-y CO <sub>2</sub> e/kWh	1,316	664	50.4	1,188	599	50.4	896	305	34.0
100-y CO <sub>2</sub> 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<sub>2e</sub> 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<sub>2e</sub> emissions from coal or gas power plants. Data from real world projects (Section 3.2.3) indicate even less reduction in CO<sub>2e</sub> emissions due to carbon capture than Table 3.4 suggests. Further, the lifecycle CO<sub>2e</sub> 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<sub>2e</sub> Emissions of Energy Technologies

Lifecycle emissions are one component of total carbon equivalent (CO<sub>2e</sub>) 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 CO<sub>2</sub> 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<sub>2e</sub>/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<sub>2e</sub>/kWh for analyses of the climate impacts and g-pollutant/kWh for analyses of health-affecting air pollutants),  $T_{PO}$  is the time lag (in years)

between planning and operation of the technology,  $T_R$  is the times (years) to refurbish the technology, and  $L$  is the operating life (years) of the technology before it needs to be refurbished.

**Example 3.1. Opportunity cost emissions.**

What are the opportunity cost emissions (g-CO<sub>2</sub>e/kWh) over 100 years resulting from Plant B if its planning-to-operation time is 15 years, its lifetime is 40 years, and its refurbishing time is 3 years, whereas these values for Plant A are 3 years, 30 years, and 1 year, respectively? Assume both plants produce the same number of kWh/y once operating, and the background grid emits 550 g-CO<sub>2</sub>e/kWh.

Solution:

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

The background emissions from Plant B are calculated from Equation 3.2 with  $E_G=550$  g-CO<sub>2</sub>e/kWh,  $Y=100$  y,  $T_{PO}=15$  y,  $L=40$  y, and  $T_R=3$  y as  $E_{BR,H}=550$  g-CO<sub>2</sub>e/kWh  $\times [15$  y +  $(100$  y –  $15$  y)  $\times 3$  y /  $43$  y] /  $100$  y =  $115$  g-CO<sub>2</sub>e/kWh.

Similarly, the background emissions from Plant A averaged over 100 years are  $E_{BR,L}=550$  g-CO<sub>2</sub>e/kWh  $\times [3$  y +  $(100$  y –  $3$  y)  $\times 1$  y /  $31$  y] /  $100$  y =  $33.7$  g-CO<sub>2</sub>e/kWh. The difference between the two from Equation 3.1,  $E_{OC}=E_{BR,H}-E_{BR,L}=81.3$  g-CO<sub>2</sub>e/kWh, is the opportunity cost emissions of Plant B over 100 years.

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

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

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

For comparison, the planning-to-operation time of a utility-scale wind or solar farm is generally 3 to 5 years, with a development period of 1 to 3 years and a construction period of 1 to 2 years (Jacobson, 2009). This time applies to both onshore and offshore wind. For example, the 407 MW (49 turbine) Horns Rev 3 offshore wind farm, located in the North Sea off of the west coast of Denmark, required 1 year and 10 months to build (Frangoul, 2019). Wind turbines often last 30 years before refurbishing, and the refurbishing time is 0.25 to 1 year.

Table 3.5 provides the estimate opportunity cost emissions of coal and natural gas with carbon capture due to the time lag between planning and operation of those plants relative to wind or solar farms. The table indicates an investment in fossil fuels with carbon capture instead of wind and solar result in an additional 46 to 62 g-CO<sub>2</sub>e/kWh in opportunity cost emissions from the background grid.

**Table 3.5.** Total 100-year CO<sub>2</sub>e emissions from several different energy technologies. The total includes lifecycle emissions, opportunity cost emissions, anthropogenic heat and water vapor emissions, weapons and leakage risk emissions, and emissions from loss of carbon storage in land and vegetation. All units are g-CO<sub>2</sub>e/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	<sup>a</sup> Lifecycle emissions	<sup>b</sup> Opportunity cost emissions due to delays	<sup>c</sup> Anthropogenic heat emissions	<sup>d</sup> Anthropogenic water vapor emissions	<sup>e</sup> Nuclear Weapons risk or 100-Year CCS/U leakage risk	<sup>f</sup> Loss of CO <sub>2</sub> due to covering Land or clearing vegetation	<sup>g</sup> Total 100-year CO <sub>2</sub> e	<sup>h</sup> Ratio of 100-year CO <sub>2</sub> e to that of wind-onshore
Solar PV-rooftop	15-34	-12 to -16	-2.2	0	0	0	<b>0.8-15.8</b>	<b>0.1-3.3</b>
Solar PV-utility	10-29	0	-2.2	0	0	0.054-0.11	<b>7.85-26.9</b>	<b>0.91-5.6</b>
CSP	8.5-24.3	0	-2.2	0 to 2.8	0	0.13-0.34	<b>6.43-25.2</b>	<b>0.75-5.3</b>
Wind-onshore	7.0-10.8	0	-1.7 to -0.7	-0.5 to -1.5	0	0.0002-0.0004	<b>4.8-8.6</b>	<b>1</b>
Wind-offshore	9-17	0	-1.7 to -0.7	-0.5 to -1.5	0	0	<b>6.8-14.8</b>	<b>0.79-3.1</b>
Geothermal	15.1-55	14-21	0	0 to 2.8	0	0.088-0.093	<b>29-79</b>	<b>3.4-16</b>
Hydroelectric	17-22	41-61	0	2.7 to 26	0	0	<b>61-109</b>	<b>7.1-22.7</b>
Wave	21.7	4-16	0	0	0	0	<b>26-38</b>	<b>3.0-7.9</b>
Tidal	10-20	4-16	0	0	0	0	<b>14-36</b>	<b>1.6-7.5</b>
Nuclear	9-70	64-102	1.6	2.8	0-1.4	0.17-0.28	<b>78-178</b>	<b>9.0-37</b>
Biomass	43-1,730	36-51	3.4	3.2	0	0.09-0.5	<b>86-1,788</b>	<b>10-373</b>
Natural gas-CCS/U	179-405	46-62	0.61	3.7	0.36-8.6	0.41-0.69	<b>230-481</b>	<b>27-100</b>
Coal-CCS/U	230-935	46-62	1.5	3.6	0.36-8.6	0.41-0.69	<b>282-1,011</b>	<b>33-211</b>

<sup>a</sup>Lifecycle emissions are 100-year carbon equivalent (CO<sub>2</sub>e) emissions that result from the construction, operation, and decommissioning of a plant. They are determined as follows:

Solar PV-rooftop: The range is assumed to be the same as the solar PV-utility range, but with 5 g-CO<sub>2</sub>/kWh added to both the low and high ends to account for the use of fixed tilt for all rooftop PV versus the use of some tracking for utility PV.

Solar PV-utility: The range is derived from Fthenakis and Raugei (2017). It is inclusive of the 17 g-CO<sub>2</sub>/kWh mean for CdTe panels at 11 percent efficiency, the 27 g-CO<sub>2</sub>e/kWh mean for multi-crystalline silicon panels at 13.2 percent efficiency, and the 29 gCO<sub>2</sub>e/kWh mean for mono-crystalline silicon panels at 14 percent efficiency. The upper limit of the range is held at the mean for multi-crystalline silicon since panel efficiencies are now much higher than 13.2 percent. The lower limit is calculated by scaling the CdTe mean to 18.5 percent efficiency, its maximum in 2018.

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

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

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

Hydroelectric and wave: From Jacobson (2009).

Tidal: From Douglass et al. (2008).

Nuclear: The range of 9-70 g-CO<sub>2</sub>e/kWh is from Jacobson (2009), which is within the Intergovernmental Panel on Climate Change (IPCC)'s range of 4-110 g-CO<sub>2</sub>e/kWh (Bruckner et al., 2014), and conservative relative to the 68 (10-130) g-CO<sub>2</sub>e/kWh from the review of Lenzen (2008) and the 66 (1.4-288) g-CO<sub>2</sub>e/kWh from the review of Sovacool (2008).

Biomass: The range provided is for biomass electricity generated by forestry residues (43 gCO<sub>2</sub>e/kWh), industry residues (46), energy crops (208), agriculture residues (291), and municipal solid waste (1730) (Kadiyala et al., 2016).

Natural gas-CCS/U: The lower bound is for the CCGT with carbon capture plant from Skone (2015), also provided in Table 3.4. The upper bound is CCGT value without carbon capture, 506 g-CO<sub>2</sub>e/kWh from Table 3.4, multiplied by 80 percent, which is the percent of CO<sub>2</sub>e emissions expected to be captured from the Petra Nova facility that will remain in the air over 100 years (Table 3.6).

Coal-CCS/U: The lower bound is for IGCC with carbon capture from Skone (2015). The upper bound is the coal value without carbon capture, 1,168 g-CO<sub>2</sub>e/kWh from Table 3.6, multiplied by 80 percent, which is the percent of coal lifecycle CO<sub>2</sub>e emissions from the Petra Nova facility that will remain in the air over 100 years (Table 3.6).

<sup>b</sup>Opportunity cost emissions are emissions per kWh over 100 years from the background electric power grid, calculated from Equations 3.1 and 3.2 due to (a) the longer time lag between planning and operation of one energy technology relative to another and (b) additional downtime to refurbish a technology at the end of its useful life compared with the other technology. The planning-to-operation times of the technologies in this table are 0.5-2 years for solar PV-rooftop; 2-5 years for solar PV-utility, CSP, wind-onshore, wind-offshore, tidal, and wave; 3-6 years for geothermal; 8-16 years for hydroelectric; 10-19 years for nuclear; 4-9 years for biomass (without CCS/U), and 6-11 years for natural gas-CCS/U and coal-CCS/U (Jacobson, 2009, except rooftop PV and natural gas-CCS/U values are added and solar PV-rooftop is updated here). The refurbishment times are 0.05-1 year for solar PV-rooftop; 0.25-1 year for solar-PV-utility, CSP, wind-onshore, wind-offshore, wave, and tidal; 1-2 years for geothermal and hydroelectric; 2-4 years for nuclear, and 2-3 years for biomass, coal-CCS/U, and natural gas-CCS/U. The lifetimes before refurbishment are 15 years for tidal and wave; 30 years for solar PV-rooftop, solar PV-utility, CSP, wind-onshore, wind-offshore; 30-35 years for biomass, coal-CCS/U, and natural gas-CCS/U; 30-40 years for geothermal; 40 years for nuclear; and 80 years for hydroelectric (Jacobson, 2009). The opportunity cost emissions are calculated here relative to the utility-scale technologies with the shortest time between planning and operation (solar-PV-utility, CSP, wind-onshore, and wind-offshore). The opportunity cost emissions of the latter technologies are, by definition, zero. The opportunity cost emissions of all other technologies are calculated like in Example 3.1 while assuming a background U.S. grid emission intensity equal to 557.3 g-CO<sub>2</sub>e/kWh in 2017. This is derived from an electricity mix from EIA (2018d) and emissions, weighted by their 100-year GWPs, of CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O 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.

<sup>c</sup>Anthropogenic heat emissions here include the heat released to the air from combustion (for coal or natural gas) or nuclear reaction, converted to CO<sub>2</sub>e (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.

<sup>d</sup>Anthropogenic water vapor emissions here include the water vapor released to the air from combustion (for coal and natural gas) or from evaporation (water-cooled CSP, water-cooled geothermal, hydroelectric, nuclear natural gas, and coal), converted to CO<sub>2</sub>e (see Section 3.2.2.3). Air-cooled CSP and geothermal plants have zero water vapor flux, representing the low end of these technologies. The high end is assumed to be the same as for nuclear, which also uses water for cooling. The low end for hydroelectric power assumes 1.75 kg-H<sub>2</sub>O/kWh evaporated from reservoirs at mid to high latitudes (Flury and Frischknecht, 2012). The upper end is 17.0 kg-H<sub>2</sub>O/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).

<sup>e</sup>Nuclear weapons risk is the risk of emissions due to nuclear weapons use resulting from weapons proliferation caused by the spread of nuclear energy. The risk ranges from zero (no use of weapons over 100 years) to 1.4 g-CO<sub>2</sub>e/kWh (one nuclear exchange in 100 years) (Section 3.3.2.1). The 100-year CCS/U leakage risk is the estimated rate, averaged over 100 years, that CO<sub>2</sub> 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.

<sup>f</sup>Loss of carbon, averaged over 100 years, due to covering land or clearing vegetation is the loss of carbon sequestered in soil or in vegetation due to the covering or clearing 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.  
<sup>§</sup>The total column is the sum of the previous six columns.

### 3.2.2.2. Anthropogenic Heat Emissions

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

Table 3.5 includes the g-CO<sub>2e</sub>/kWh emissions from heat of combustion (for biomass, natural gas, and coal) and from nuclear reaction. However, because the dissipation of the resulting electricity back to heat is due to the consumption rather than production of electricity, that heat release term is not included in the table. In any case, the heat released per unit electricity produced is the same for all technologies.

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

The CO<sub>2e</sub> emissions (g-CO<sub>2e</sub>/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 CO<sub>2</sub> (g-CO<sub>2</sub>/y) that gives a specified anthropogenic mixing ratio of CO<sub>2</sub> in the atmosphere,  $F_{CO_2}$  is the direct radiative forcing (W/m<sup>2</sup>) of CO<sub>2</sub> at the specified mixing ratio,  $A_h$  is the anthropogenic heat flux (W/m<sup>2</sup>) due to a specific electric power producing technology, and  $G_{elec}$  is the annual global energy output of the technology (kWh/y).

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

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

where  $\chi_{CO_2}$  (ppmv) is the specified anthropogenic mixing ratio that gives the current CO<sub>2</sub> radiative forcing,  $C$  is a conversion factor ( $8.0055 \times 10^{15}$  g-CO<sub>2</sub>/ppmv-CO<sub>2</sub>), and  $\tau_{CO_2}$  is the data-constrained  $e$ -folding lifetime of CO<sub>2</sub> against loss by all processes. As of 2019,  $\tau_{CO_2}$  is ~50 years but increasing over time (e.g., Jacobson, 2012a).

Equation 3.4 is derived by noting that the time rate of change of the atmospheric mixing ratio of a well-mixed gas, such as CO<sub>2</sub> is simply,  $d\chi/dt = E - \chi C/\tau$ . In steady state, this simplifies to  $E = \chi C/\tau$ . Scaling the ratio of this equilibrium CO<sub>2</sub> emission rate to the radiative forcing of CO<sub>2</sub> by the ratio of the anthropogenic heat flux to the electricity generation per year producing that heat flux, gives Equation 3.3, the CO<sub>2e</sub> emission rate of the heat flux.

Thus, Equation 3.3 accounts for the emission rate of CO<sub>2</sub> needed to maintain a mixing ratio of CO<sub>2</sub> in the air that gives a specific radiative forcing. It does not use the present day emission rate because that results in a much higher CO<sub>2</sub> mixing ratio than is currently in the atmosphere because CO<sub>2</sub> emissions are not in equilibrium with the CO<sub>2</sub> atmospheric mixing ratio. Equation 3.3 requires a constant emission rate that



gives the observed mixing ratio of CO<sub>2</sub> for which the current direct radiative forcing applies. Similarly, the energy production rate in Equation 3.3 gives a consistent anthropogenic heat flux.

Finally, whereas radiative forcing is a top-of-the-atmosphere value (and represents changes in heat integrated over the whole atmosphere) and heat flux is added to the bottom of the atmosphere, they both represent the same amount of heat added to the atmosphere. In fact, because the anthropogenic heat flux adds heat to near-surface air, it has a slightly greater impact on surface air temperature per unit radiative forcing than does CO<sub>2</sub>. For example, the globally averaged temperature change per unit direct radiative forcing for CO<sub>2</sub> 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<sub>2e</sub> 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<sub>2e</sub> 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 CO<sub>2</sub> direct radiative forcing of  $F_{\text{CO}_2} = 1.82 \text{ W}/\text{m}^2$ , which corresponds to an anthropogenic mixing ratio of CO<sub>2</sub> of  $\chi_{\text{CO}_2} = 113 \text{ ppmv}$  (Myhre et al., 2013). Also assume a CO<sub>2</sub> e-folding lifetime of  $\tau_{\text{CO}_2} = 50 \text{ years}$ .

Solution:

From Equation 3.4, the equilibrium emission rate of CO<sub>2</sub> 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 ( $\text{W}/\text{m}^2$ ) per kWh/y of electricity generated by a solar panel and what is the corresponding CO<sub>2e</sub> 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  $E_{\text{CO}_2}$  and  $F_{\text{CO}_2}$  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 CO<sub>2</sub>e emissions per unit energy (M, g-CO<sub>2</sub>e/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<sub>m</sub>, W/m<sup>2</sup>) 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-H<sub>2</sub>O/kWh) by

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

where L<sub>e</sub>=2.465×10<sup>6</sup> J/kg-H<sub>2</sub>O is the latent heat of evaporation, S=3.1536×10<sup>7</sup> seconds per year, and A<sub>e</sub>=5.092×10<sup>14</sup> m<sup>2</sup> is the surface area of the Earth. For water evaporating from a hydropower reservoir, V = 1.75 to 17 kg-H<sub>2</sub>O/kWh (Table 3.5, footnote c).

Combining Equations 3.5 and 3.6 gives the globally averaged CO<sub>2</sub>e 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<sub>elec</sub>). 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<sub>m</sub>=0.00268 W/m<sup>2</sup> and from nuclear power plants was A<sub>m</sub>=0.000746 W/m<sup>2</sup> (Jacobson, 2014). The total energy generation from natural gas use was G<sub>elec</sub>=7.208×10<sup>12</sup> kWh/y and from nuclear was 2.64×10<sup>12</sup> kWh/y. Calculate the CO<sub>2</sub>e emissions associated with these fluxes.

#### Solution:

Substituting E<sub>CO<sub>2</sub></sub> and F<sub>CO<sub>2</sub></sub> from Example 3.2 and A<sub>m</sub> and G<sub>elec</sub> provided in the problem into Equation 3.5 gives M=3.69 g-CO<sub>2</sub>e/kWh for natural gas and 2.81 g-CO<sub>2</sub>e/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  $V=1.75 \text{ kg-H}_2\text{O/kWh}$  (Flury and Frischknecht, 2012), determine the  $\text{CO}_2\text{e}$  emissions of water vapor from the reservoir.

Solution:

Substituting  $V$  into Equation 3.7 with  $E_{\text{CO}_2}$  and  $F_{\text{CO}_2}$  from Example 3.2 gives the carbon equivalent emissions due to hydropower reservoir evaporation as  $M=2.66 \text{ g-CO}_2\text{e/kWh}$ .

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  $\text{CO}_2\text{e}$  emissions or savings, the conversion of electricity back to heat is not assigned to any particular electric power generator in Table 3.5. However, the addition or extraction of heat and water vapor by the energy technology is.

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

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

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

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

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

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

However, because water vapor is a greenhouse gas, less of it in the air means that more heat radiation from the Earth's surface escapes to space, cooling the ground, reducing internal energy. Since water vapor stays

in the air for days to weeks, its absence due to a wind turbine reduces heat to the surface over that time more than the one-time dissipation of electricity, created by the wind turbine, increases heat.

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

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

The energy taken out of the atmosphere temporarily (because it is returned later as heat from dissipation of electricity) by wind turbines is 1 kWh per 1 kWh of electricity production. The maximum reduction in water vapor, based on global computer model calculations (Chapter 7), due to wind turbines ranges from -0.3 to -1 kg-H<sub>2</sub>O/kWh, where the variation depends on the number and location of wind turbines. Example 3.6 provides an estimate of the CO<sub>2</sub>e savings due to wind turbines from these two factors.

**Example 3.6.** Estimate the globally averaged CO<sub>2</sub>e water vapor and heat emission reductions due to wind turbines. Assuming that wind turbines extract 1 kWh of the wind's kinetic energy for each 1 kWh of electricity produced, estimate the CO<sub>2</sub>e savings per unit energy from reduced heat and water vapor fluxes due to wind turbines considering that, when the turbine is not operating, every 1 kWh of kinetic energy in the wind evaporates 0.3 to 1 kg-H<sub>2</sub>O/kWh and the rest of the energy remains in the atmosphere. Assume the equilibrium emission rate and resulting radiative forcing of CO<sub>2</sub> from Example 3.2.

Solution:

Multiplying the latent heat of evaporation ( $L_e=2.465 \times 10^6$  J/kg) and 1 kWh/ $3.6 \times 10^6$  J by -0.3 to -1 kg-H<sub>2</sub>O/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,  $5.092 \times 10^{14}$  m<sup>2</sup>, gives  $A_m/G_{elec} = -4.6 \times 10^{-17}$  to  $-1.53 \times 10^{-16}$  (W/m<sup>2</sup>)/(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-CO<sub>2</sub>e/kWh.

The heat flux is the difference between -1 kWh/kWh-electricity and -0.21 to -0.69 kWh/kWh-electricity, which is -0.79 to -0.31 kWh/kWh-electricity. Performing the same calculation as above gives the anthropogenic heat flux from wind turbines as -1.77 to -0.70 g-CO<sub>2</sub>e/kWh. The total heat plus water vapor energy flux savings due to wind turbines is thus -2.23 g-CO<sub>2</sub>e/kWh, the same as for solar panels (Example 3.3).

#### 3.2.2.4. Leaks of CO<sub>2</sub> Sequestered Underground

The sequestration of carbon underground due to CCS or CCU (e.g., from injecting CO<sub>2</sub> during enhanced oil recovery) runs the risk of CO<sub>2</sub> leaking back to the atmosphere through existing fractured rock or overly porous soil or through new fractures in rock or soil resulting from an earthquake. Here, a range in the potential emission rate due to CO<sub>2</sub> leakage from the ground is estimated.

The ability of a geological formation to sequester CO<sub>2</sub> for decades to centuries varies with location and tectonic activity. IPCC (2005, p. 216) references CO<sub>2</sub> leakage rates for an enhanced oil recovery operation of 0.00076 percent per year, or 1 percent over 1,000 years, and CH<sub>4</sub> leakage from historical natural gas storage systems of 0.1 to 10 percent per 1,000 years. Thus, while some well-selected sites could theoretically sequester 99 percent of CO<sub>2</sub> for 1,000 years, there is no certainty of this since tectonic activity or natural leakage over 1,000 years is not possible to predict. Because liquefied CO<sub>2</sub> 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 CO<sub>2</sub> 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 CO<sub>2</sub> from a reservoir can be calculated by first estimating how the stored mass of CO<sub>2</sub> changes over time. The stored mass ( $S$ ) of CO<sub>2</sub> 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 CO<sub>2</sub> 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 CO<sub>2</sub> emission rate before carbon capture and storage ranging from 790 to 1,017 g-CO<sub>2</sub>/kWh. Assume also that carbon capture equipment added to the plant captures 90 and 80 percent, respectively, of the CO<sub>2</sub> (giving a low and high, respectively, emission rate of remaining CO<sub>2</sub> to the air). If the captured CO<sub>2</sub> is injected underground into a geological formation that has no initial CO<sub>2</sub> in it, calculate a low and high CO<sub>2</sub> emission rate from leakage averaged over 100 years, 500 years, and 1,000 years. Assume a low and high  $e$ -folding lifetime against leakage of 5,000 years and 100,000 years, respectively. The low value corresponds to 18 percent leakage over 1,000 years, close to that of some observed methane leakage rates. The high value corresponds to a 1 percent loss of CO<sub>2</sub> over 1,000 years (e.g., IPCC, 2005).

Solution:

The low and high injection rates are  $790 \times 0.9 = 711$  g-CO<sub>2</sub>/kWh and  $1,017 \times 0.85 = 864.5$  g-CO<sub>2</sub>/kWh, respectively. Substituting these injection rates into Equation 3.8 (using the high lifetime with the low injection rate and the low lifetime with the high injection rate) and the result into Equation 3.9 gives a leakage rate range of 0.36 to 8.6 g-CO<sub>2</sub>/kWh over 100 years; 1.8 to 42 g-CO<sub>2</sub>/kWh over 500 years, and 3.5 to 81 g-CO<sub>2</sub>/kWh over 1,000 years.

Thus, the longer the averaging period, the greater the average emission rate over the period due to CO<sub>2</sub> 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 CO<sub>2</sub> 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/m<sup>2</sup> and 13.2 kg-C/m<sup>2</sup>, 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 of carbon is then converted to a loss of carbon per unit electricity produced by the energy facility over a specified period of time. For purposes of Table 3.5, this period is 100 years. Example 3.8 provides an example calculation of CO<sub>2</sub>e emissions from the covering land with an energy facility.

**Example 3.8.** Estimating the loss of carbon stored in vegetation and soil due to an energy facility.

Assume a 425 MW coal facility has a 65 percent capacity factor and has a footprint of 5.2 km<sup>2</sup>, including the land for the coal facility, mining, railway transport, and waste disposal. Calculate the emission rate of CO<sub>2</sub> 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  $1.15 \text{ kg-C/m}^2$ , for a total of  $5.64 \text{ kg-C/m}^2$ . Multiplying by 1,000 g/kg and the molecular weight of CO<sub>2</sub> (44.0095 g-CO<sub>2</sub>/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 CO<sub>2</sub>e 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 CO<sub>2</sub>e emissions as onshore wind per unit electricity generated. Natural gas-CCS/U results in 27 to 100 times the emissions as onshore wind.

The reasons for the high CO<sub>2</sub>e emissions of coal and natural gas with carbon capture, are (1) coal and gas plants need 25 to 50 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 50 percent (Example 3.9), (2) the capture equipment allows 10 to 30 percent of the CO<sub>2</sub> in the power plant exhaust to escape (Example 3.9), (3) CO<sub>2</sub>e 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 CO<sub>2</sub> occurs once CO<sub>2</sub> 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 50 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, CO<sub>2</sub> has been captured and separated primarily from mined natural gas or, in one case, from gasified coal. In all such cases, the CO<sub>2</sub> 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 CO<sub>2</sub> was used for enhanced oil recovery, and the CCU equipment was installed at high cost. One project experienced equipment problems, resulting in much more CO<sub>2</sub> 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 CO<sub>2</sub> 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 CO<sub>2</sub> 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 7). 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 CO<sub>2</sub> is compressed and piped to an oil field, where it is used to enhance oil recovery. CO<sub>2</sub> from the gas turbine is not captured. Natural gas production also has upstream CO<sub>2</sub>e emissions, including CH<sub>4</sub> leaks, which are not captured. Upstream CO<sub>2</sub> and CH<sub>4</sub> 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 CO<sub>2</sub> and only 33.9 percent of coal plus gas combustion CO<sub>2</sub>. 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 CO<sub>2</sub> 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 CC equipment, CO<sub>2</sub>e decreases by 37.4 percent over 20 years and 44.2 percent over 100 years compared with no CC (Table 3.6, Figure 1). The CO<sub>2</sub>e decrease exceeds that in the CCU-gas case because wind powering CC equipment case does not result in any combustion or upstream emissions from wind, as seen in Figure 3.1.

However, using the wind electricity that powers the CC equipment instead to replace coal electricity directly at the same plant reduces CO<sub>2</sub>e by 49.7 percent compared with no CC (Table 3.6, Figure 3.1). It is not 100 percent because only the wind used to run the capture equipment replaces coal. More wind would be needed to replace the whole coal plant. This third strategy is the best for reducing CO<sub>2</sub>e among the three cases. Using solar PV to replace coal directly results in a similar benefit as using wind.

But, CO<sub>2</sub>e is only part of the story. Because CCU equipment does not capture health-affecting air pollutants, air pollution emissions continue from coal and rise by about 25 percent compared with no capture from the use of natural gas to run the Petra Nova equipment (Table 3.6). Even when wind powers the CC equipment, air pollution from the coal plant continues as before (but not from using the new wind turbine). Only when wind partially replaces the use of coal itself does air pollution decrease by ~50 percent (Table 3.6).

**Table 3.6.** Comparison of relative CO<sub>2</sub>e emissions, electricity use, and electricity total social costs among three scenarios related to the Petra Nova coal-CCU facility, each over a 20-yr and 100-yr time frame. The first scenario is using natural gas to power the carbon capture (CC) equipment. This is based on data from the Petra Nova facility (EIA, 2017). The second scenario is running the CC equipment with onshore wind instead of natural gas. The third is using the same quantity of wind electricity required to run the CC equipment to instead replace coal electricity from the coal plant. In all cases, the additional energy required to run the CC equipment is equivalent to 49.7 percent of the energy output of the coal plant (Footnote 7). The coal plant has a nameplate capacity of 654 MW, but only 240 MW (36.7 percent) is subject to CC. The numbers in the table are all based on the portion subject to CC. All emission units (including of natural gas emissions) are g-CO<sub>2</sub>e/kWh-coal-electricity-generation. From Jacobson (2019).



	Coal with gas-powered CC 20 yr	Coal with gas-powered CC 100 yr	Coal with wind-powered CC 20 yr	Coal with wind-powered CC 100 yr	Wind used for CC replacing coal + remaining coal 20 yr	Wind used for CC replacing coal + remaining coal 100 yr
a) Upstream CO <sub>2</sub> from coal <sup>1</sup>	97.2	97.2	97.2	97.2	48.9	48.9
b) Upstream CO <sub>2</sub> e of leaked CH <sub>4</sub> from coal <sup>2</sup>	353	140	353	140	177.6	70.4
c) Coal stack CO <sub>2</sub> before capture <sup>3</sup>	930.6	930.6	930.6	930.6	468.1	468.1
d) Total coal CO <sub>2</sub> e before capture (a+b+c)	1,381	1,168	1,381	1,168	695	587
e) Remaining stack CO <sub>2</sub> after capture <sup>4</sup>	414.6	414.6	414.6	414.6	--	--
f) CO <sub>2</sub> captured from stack (c-e)	516.0	516	516	516	--	--
g) Percent stack CO <sub>2</sub> captured (f/c)	55.4%	55.4%	55.4%	55.4%	--	--
h) CO <sub>2</sub> emissions gas combustion <sup>5</sup>	200.9	200.9	0	0	0	0
i) Upstream CO <sub>2</sub> e of CH <sub>4</sub> from gas leaks <sup>6</sup>	139.2	55.03	0	0	0	0
j) Upstream CO <sub>2</sub> from gas mining, transport <sup>7</sup>	26.85	26.85	0	0	0	0
k) Total CO <sub>2</sub> e emissions (a+b+e+h+i+j)	1,232	934.5	865	652	695	587
l) Percent of coal CO <sub>2</sub> e re-emitted (k/d) <sup>8</sup>	<b>89.2%</b>	<b>80.0%</b>	<b>62.6%</b>	<b>55.8%</b>	<b>50.3%</b>	<b>50.3%</b>
m) Percent of coal CO <sub>2</sub> e captured (100-l)	<b>10.8%</b>	<b>20%</b>	<b>37.4%</b>	<b>44.2%</b>	<b>49.7%</b>	<b>49.7%</b>
n) Relative CO <sub>2</sub> e to original (l/100) <sup>9</sup>	0.892	0.80	0.626	0.558	0.503	0.503
o) Relative air pollution to original <sup>10</sup>	1.25	1.25	1.0	1.0	0.503	0.503
p) Energy required relative to original <sup>11</sup>	1.497	1.497	1.497	1.497	1	1
q) Private energy cost/kWh relative to original <sup>12</sup>	1.74	1.74	1.74	1.74	0.71	0.71
r) Social cost before changes (\$/MWh) <sup>13</sup>	334	334	334	334	334	334
s) Social cost after changes (\$/MWh) <sup>14</sup>	413	399	353	342	189	189
t) Social cost ratio (s/r)	1.24	1.19	1.06	1.02	0.57	0.57

<sup>1</sup>Coal upstream emissions are estimated as 27 g-CO<sub>2</sub>/MJ = 97.2 g-CO<sub>2</sub>/kWh (Howarth, 2014). Upstream emissions include emissions from fuel extraction, fuel processing, and fuel transport. Upstream CO<sub>2</sub> 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 7. Since the electricity used to run the CC equipment is used to replace coal in this case, upstream coal emissions are reduced accordingly.

<sup>2</sup>For coal, the 100-year CO<sub>2</sub>e from CH<sub>4</sub> leaks is estimated from (Skone, 2015, Slide 17). The emission factor is derived from that number and the 100-year GWP of CH<sub>4</sub>, 34 from Myhre et al. (2013). The 20-year CO<sub>2</sub>e is then derived from the resulting emission factor (4.1 g-CH<sub>4</sub>/kWh) and the 20-year GWP of CH<sub>4</sub>, 86. Emissions in the wind cases are reduced as described under Footnote 1.

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

<sup>4</sup>The coal-stack CO<sub>2</sub> remaining after capture is from EIA (2017).

<sup>5</sup>The natural gas combustion emissions resulting from powering the CC equipment is from EIA (2017).

<sup>6</sup>Natural gas upstream leaks are obtained by dividing the raw emission rate of CO<sub>2</sub> from natural gas for each month January through June 2017 from EIA (2017) (in kg-CO<sub>2</sub>/MWh-coal-electricity) by the molecular weight of CO<sub>2</sub> (44.0098 g-CO<sub>2</sub>/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-CH<sub>4</sub>/mol) gives the mass intensity of methane in the natural gas burned each month (kg-CH<sub>4</sub>-burned/MWh-coal-electricity). The upstream leakage rate of methane is then the kg-CH<sub>4</sub>-burned/MWh-coal-electricity multiplied by L/(1-L), where L=0.023 is the fraction of all methane produced (from conventional and shale rock sources) that leaks (Alvarez et al., 2018), giving the methane leakage rate in kg-CH<sub>4</sub>/MWh-coal-electricity. This leakage rate is conservative based on a more recent full-lifecycle leakage rate estimate of methane from shale rock alone of L=0.035 (Howarth, 2019). Using the latter estimate would result in CCS/U with natural gas re-emitting even more CO<sub>2</sub>e than calculated here. Multiplying the kg-CH<sub>4</sub>/MWh-coal-electricity by the 20- and 100-year GWPs of CH<sub>4</sub> (86 and 34, respectively) (Myhre et al., 2013) gives the CO<sub>2</sub>e emission rate of methane leaks each month. The monthly values are linearly averaged over January through June 2017.

<sup>7</sup>The non-CH<sub>4</sub> upstream CO<sub>2</sub>e emissions rate is estimated as 15 g-CO<sub>2</sub>/MJ-gas-electricity = 54 g-CO<sub>2</sub>/kWh-gas-electricity (Howarth, 2014). Multiplying that by 0.497 MWh-electricity from natural gas per MWh-coal-electricity produced gives 26.8 kg-CH<sub>4</sub>/MWh-coal-electricity. 0.497 MWh-electricity from natural gas per MWh-coal-electricity produced, or 49.7 percent, is calculated by dividing the average gas combustion emission from Petra Nova (200.9 g-CO<sub>2</sub>/kWh-coal from the present table) by the combustion emissions per unit electricity from a combined cycle gas plant (404 g-CO<sub>2</sub>/kWh-natural-gas).

<sup>8</sup>The percent CO<sub>2</sub> reemitted for the wind cases (last two columns) equals Row k for the wind cases divided by Row d for either of the non-wind cases.

<sup>9</sup>CO<sub>2</sub>e emissions relative to coal with no CC equipment.

<sup>10</sup>Air pollution emissions relative to coal with no CC equipment. In the natural gas cases, all air pollution from coal emissions still occurs. Although gas is required to produce 0.497 MWh of electricity for the CC 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 CC case. In the wind-CC cases, all upstream and combustion emissions from coal still occur.

<sup>11</sup>The electricity required (for end-use consumption plus to run the CC equipment) in all CC cases is 49.7 percent higher than with no CC. In the wind-replacing coal case, no electricity is needed to run the CC equipment, but electricity is still needed for end use.

<sup>12</sup>The private energy cost in all CC cases is assumed to be 74 percent higher than coal with no CC because the CC equipment (including the gas plant) costs \$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 CC 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 final ratio was calculated as  $(0.503c + 0.497w)/c$ .

<sup>13</sup>The 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 coal power plant emissions in the U.S. plus the global climate costs of U.S. emissions ( $\$152/\text{MWh}$ ) (Jacobson et al., 2017). U.S. coal power plant emissions health costs are estimated as  $\$80/\text{MWh}$ , which is twice the background grid health cost of  $\$40/\text{MWh}$  (Jacobson et al., 2019). In the worldwide average, from the same source, the health cost of background grid emissions is estimated as  $\$169/\text{MWh}$ , so use of the U.S. number here is likely to underestimate the health costs of using carbon capture outside the U.S.

<sup>14</sup>The social cost after changes is the sum of the private energy cost multiplied by Row q, the air pollution health cost multiplied by Row o, and the climate cost multiplied by Row n.

The equipment cost of new coal and wind electricity in the U.S. are a mean of  $\$102/\text{MWh}$  and  $\$42.5/\text{MWh}$ , respectively (Lazard, 2018). The capital cost of CC equipment,  $\$4,200/\text{kW}$  (Scottmadden, 2017), is about 74 percent the capital cost of a new coal plant ( $\$5,700/\text{kW}$ ) (Lazard, 2018), suggesting that new coal plus CCU is  $1.74 \times \$102/\text{MWh} / \$42.5/\text{MWh} = 4.2$  times the equipment cost of new wind. Since CC equipment reduces only 10.8% of coal CO<sub>2</sub>e over 20 yr and 20 percent over 100 yr, the equipment for coal-CCU powered by natural gas alone costs 39 and 21 times that of wind-replacing coal per mass-CO<sub>2</sub> removed over 20 and 100 years, respectively.

Major additional social costs associated with coal electricity generation are air pollution and climate costs. The health cost of coal emissions in the U.S. is calculated as a mean of  $\$80/\text{MWh}$ , which is much lower than the world average ( $\$169/\text{MWh}$ , Table 3.6, Footnote 13). Since the use of CC equipment requires 50 percent more electricity than the coal plant produces but the health cost of natural gas emissions are about half those of coal, the use of gas to run the CC equipment increases health costs by about 25 percent compared with no capture (Table 3.6, Row o). Mean climate costs of U.S. emissions are estimated as  $\$152/\text{MWh}$ , close to the world mean of  $\$160/\text{MWh}$  (Table 3.6, Footnote 13). CC equipment with natural gas is estimated to reduce this cost by only 10.8 and 20 percent over 20 and 100 years, respectively (Table 3.6, Row n).

In sum, the total social cost (equipment plus health plus climate cost) of coal-CCU powered by natural gas is over twice that of wind replacing coal directly (Table 3.6, Figure 3.1). Moreover, the social cost of coal with CC powered by natural gas is 24 percent higher over 20 years and 19 percent higher over 100 years

than coal without CC. Thus, no net social benefit exists of using CC equipment. In other words, from a social cost perspective, using CC equipment powered by natural gas causes more damage than does doing nothing at all.

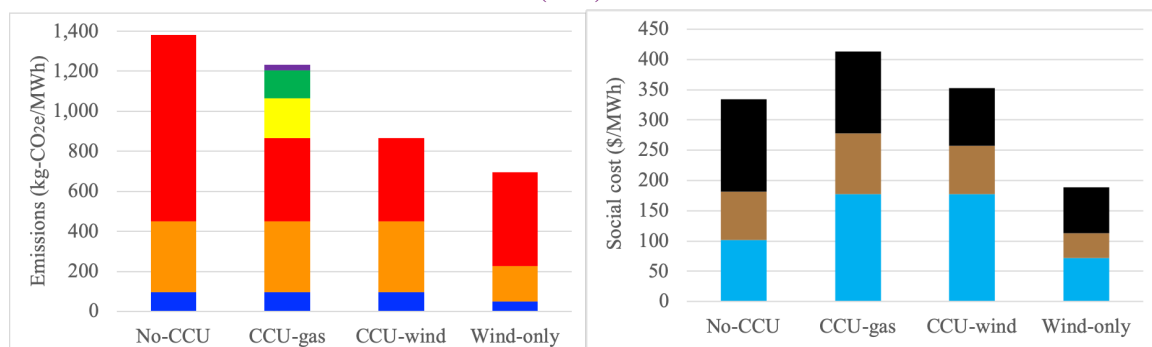
In fact, in order for the social cost of using the CC equipment powered by natural gas to be less than that of doing nothing, the CO<sub>2e</sub> reemitted by the Petra Nova plant would need to be 37% or less instead of 89.8% over 20 years. However, this is all but impossible, because 59.2% of the re-emissions is due to upstream coal and gas emissions and natural gas combustion emissions, so little to do with how effective the CC equipment is at capturing carbon. In other words, even if the CC equipment captured 100% of the stack CO<sub>2</sub>, which no-one is proposing is feasible, the reemissions would still be 59.2%. As such, the data indicate that **no technological improvement will result in the social cost of using CC equipment powered by natural gas being less than that of not using the equipment.**

When wind powers CC equipment, the social costs are still 6 and 2 percent higher over 20 and 100 years, respectively, than not using CC (Table 3.6, Figure 3.1). Although wind-powering-CC decreases CO<sub>2e</sub>, thus climate cost, compared with coal without CC, wind-CC allows the same air pollution emissions from coal as no CC, and the cost of the wind plus CC equipment outweighs the CO<sub>2e</sub> cost reduction (Figure 3.1).

Only when wind replaces coal electricity production directly does the total social cost drop 43 percent compared with no CC (Table 3.6). This is the best scenario. A similar benefit occurs if wind replaces natural gas and no CC is used.

When CC is powered by wind, it is theoretically possible, albeit challenging, to reduce the total social cost below that of no CC. However, **it is impossible to reduce the total social cost below that of wind replacing coal electricity directly** because wind-powering-CC also incurs a CC equipment cost and never reduces air pollution or mining from coal, whereas wind replacing coal incurs no CC equipment cost and eliminates coal air pollution and mining (Jacobson, 2019).

**Figure 3.1.** Left: CO<sub>2e</sub> emissions, averaged over 20 years, from the Petra-Nova coal plant before (No-CCU) and after (CCU-gas) the addition of CCU equipment powered by natural gas. Also shown are emissions when the CCU equipment is powered by wind energy (CCU-wind) and when the portion of wind energy used to power the CCU equipment is instead used only to replace a portion of the coal power (thus some power is generated by coal and some by wind). Blue is upstream CO<sub>2e</sub> from coal mining and transport aside from CH<sub>4</sub> leaks; orange is upstream CO<sub>2e</sub> from coal mining CH<sub>4</sub> leaks; red is coal combustion CO<sub>2</sub>; yellow is natural gas combustion CO<sub>2</sub>; green is CO<sub>2e</sub> from natural gas mining and transport CH<sub>4</sub> leaks; and purple is natural gas mining and transport CO<sub>2e</sub> aside from CH<sub>4</sub> leaks. Right: Mean estimate of social costs per unit electricity over 20 years generated by the coal plant (in the first three cases) or the residual coal plant plus replacement wind plant (fourth case) for each of the four cases shown on the left. Light blue is the cost of electricity generation plus CCU equipment; brown is air pollution health cost; and black is 20-year climate cost. All data are from Table 3.6 and Jacobson (2019).



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 CO<sub>2</sub> during January 2016 from the Texas Parish coal power plant, before carbon capture, were 934.4 kg-CO<sub>2</sub>/MWh. Emissions during January 2017, from the portion of the coal emissions subject to carbon capture, were 242.2 kg-CO<sub>2</sub>/MWh, for a reduction of 692.2 kg-CO<sub>2</sub>/MWh. However, the natural gas plant needed to run the carbon capture equipment itself emitted 271.9 kg-CO<sub>2</sub>/MWh-coal-electricity. In addition, coal upstream emissions were 97.2, 353, and 140 kg-CO<sub>2</sub>e/MWh-coal-electricity for CO<sub>2</sub> from coal mining, CH<sub>4</sub> leaks from coal mining over 20 years, and CH<sub>4</sub> leaks from coal mining over 100 years, respectively. The non-CH<sub>4</sub> upstream emissions from natural gas required for the capture equipment were 36.3 kg-CO<sub>2</sub>/MWh-coal-electricity.

First, estimate the upstream CO<sub>2</sub>e emissions from CH<sub>4</sub> 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 CO<sub>2</sub>e of the upstream plus stack emissions from the facility after carbon capture. Finally, what percent of the CO<sub>2</sub>e 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 CO<sub>2</sub> from natural gas, 271.9 kg-CO<sub>2</sub>/MWh-coal-electricity, by the molecular weight of CO<sub>2</sub> (44.0098 g-CO<sub>2</sub>/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-CH<sub>4</sub>/mol) gives the mass intensity of methane in the natural gas burned, 93.1 kg-CH<sub>4</sub>-burned/MWh-coal-electricity.

The upstream leakage rate of methane is then  $93.1 * 0.023 / (1-0.023) = 2.19$  kg-CH<sub>4</sub>/MWh-coal-electricity. Multiplying by the 20- and 100-year GWPs of CH<sub>4</sub> (86 and 34, respectively) from Table 1.2 gives CO<sub>2</sub>e emissions of the methane leaks as 188.4 and 74.5 kg-CO<sub>2</sub>e/MWh-coal-electricity, respectively. Adding the upstream CO<sub>2</sub>+CH<sub>4</sub> emissions to the natural gas stack emissions gives 20- and 100-year CO<sub>2</sub>e emissions from the gas turbine as 497 and 382 kg-CO<sub>2</sub>e/MWh-coal-electricity, respectively.

Adding these emissions to the coal upstream emissions and uncaptured coal emissions gives the 20- and 100-year CO<sub>2</sub>e emissions from the gas turbine plus coal plant after capture as 1,189 and 862 kg-CO<sub>2</sub>e/MWh-coal-electricity, respectively. The coal stack plus upstream emissions before capture were 1,385 and 1,172 kg-CO<sub>2</sub>e/MWh-coal-electricity, respectively.

As such, averaged over 20 years,  $1,189 / 1,385 = 85.8$  percent of the original CO<sub>2</sub>e 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 CO<sub>2</sub>.

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 CO<sub>2</sub> 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 16.9 ¢/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 CO<sub>2</sub> 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  $1.25 \times 16.9$  ¢/kWh = 21.1 ¢/kWh. The climate cost is  $0.85 \times 16$  ¢/kWh = 13.6 ¢/kWh. Adding these three together gives 52.4 ¢/kWh. Dividing this by the cost of wind, 4.25 ¢/kWh, gives 12.3. Thus, the social cost of coal-CCS in this case is 12.3 times that of wind. The private energy cost of coal-CCS is 4.2 times that of wind.

Tables 3.6 suggests little carbon benefit of and greater air pollution damage from CCS/U powered by natural gas before considering the disposition of the captured CO<sub>2</sub>. Two reasons for this, aside from the additional combustion emissions of the natural gas turbine, are the upstream coal and gas emissions and the air pollution resulting from the additional gas mining and use.

The results here are independent of the fate of the CO<sub>2</sub> 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 CO<sub>2</sub> 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 CO<sub>2</sub> is considered, the problem may deepen. If CO<sub>2</sub> is sealed underground without leaks, little added emissions occur. If the captured CO<sub>2</sub> is used to enhance oil recovery, its current major application, more oil is extracted and burned, increasing combustion CO<sub>2</sub>, some leaked CO<sub>2</sub>, and air pollution. If the captured CO<sub>2</sub> 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 CO<sub>2</sub> to produce the fuel with. A third proposal is to use the CO<sub>2</sub> to produce carbonated drinks. However, along with the issues previously listed, most CO<sub>2</sub> 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 CO<sub>2</sub> 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. In fact, CCS/U powered by either fossils or renewables always increases total social costs relative to using renewables to eliminate fossil fuel and bioenergy power generation directly.

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

Chemical	E-folding lifetime	20-Year GWP	100-Year GWP
<sup>a</sup> CO <sub>2</sub>	50-90 years	1	1
<sup>b</sup> BC+POC in fossil fuel soot	3-7 days	2,400-3,800	1,200-1,900
<sup>b</sup> BC+POC in biofuel soot	3-7 days	2,100-4,000	1,060-2,020
<sup>c</sup> CH <sub>4</sub>	12.4 years	86	34
<sup>c</sup> N <sub>2</sub> O	121 years	268	298
<sup>c</sup> CFCl <sub>3</sub> (CFC-11)	45 years	7,020	5,350
<sup>d</sup> CF <sub>2</sub> Cl <sub>2</sub> (CFC-12)	100 years	10,200	10,800
<sup>c</sup> CF <sub>4</sub> (PFC-14)	50,000 years	4,950	7,350
<sup>d</sup> C <sub>2</sub> F <sub>6</sub> (PFC-116)	10,000 years	8,210	11,100

<sup>e</sup> Tropospheric O <sub>3</sub>	23 days	--	--
<sup>f</sup> NO <sub>x</sub> -N	< 2 weeks	-560	-159
<sup>g</sup> SO <sub>x</sub> -S	< 2 weeks	-1,400	-394

GWP=Global Warming Potential.

<sup>a</sup>Low-lifetime of CO<sub>2</sub> is the data-constrained lifetime upon increasing CO<sub>2</sub> emissions from Jacobson (2012a); high-lifetime of CO<sub>2</sub> calculated from Figure 1 of Jacobson (2017), which shows CO<sub>2</sub> decreasing by 65 ppmv (from 400 to 335 ppmv) over 65 years upon elimination of anthropogenic CO<sub>2</sub> emissions. Since the natural CO<sub>2</sub> is 275 ppmv, the anthropogenic CO<sub>2</sub> = 400-275=125 ppmv, and the lifetime of anthropogenic CO<sub>2</sub>  $\sim 65 \text{ y} / -\ln((125-65) \text{ ppmv}/125 \text{ ppmv}) = \sim 90$  years. The GWP of CO<sub>2</sub>=1 by definition.

<sup>b</sup>POC is primary organic carbon co-emitted with black carbon from combustion sources. In the case of diesel exhaust, it is mostly lubricating oil and unburned fuel oil. In all cases, POC includes both absorbing organic (brown) carbon (BrC) and less absorbing organic carbon. Soot particles contain both BC and POC. The lifetime is from Jacobson (2012b) and the GWP is from Jacobson (2010a, Table 4), which accounts for direct effects, optical focusing effects, semi-direct effects, indirect effects, cloud absorption effects, and snow-albedo effects. The GWPs here are the surface temperature response after 20 or 100 years per unit continuous mass emissions (STRE) of BC+POC relative to the same for CO<sub>2</sub>. STREs are analogous to GWPs (Jacobson, 2010a, Table 4 footnote).

<sup>c</sup>From Myhre et al. (2013) Table 8.7. Results from Etminan et al. (2016) suggest that the 20-y GWP of CH<sub>4</sub> may be up to 98.

<sup>d</sup>From Myhre et al. (2013) Table 8.A.1.

<sup>e</sup>From Myhre et al. (2013), Section 8.2.3.1. Tropospheric ozone is not emitted so does not have a GWP.

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

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

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