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

In

100% Clean, Renewable Energy and Storage for Everything

Textbook in Preparation

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

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April 18, 2019

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Summary

Coal and natural gas with carbon capture have been advertised as zero-carbon sources of electric power that should be implemented as solu tions to global warming, air pollution, and energy security. Natural gas has also been proposed as a bridge fuel between coal and renewables. The purpose of this section is to evaluate these claims.

The main result is that neither coal nor natural gas with carbon capture is remotely close to a zero-carbon technology. At best they reduce ~22 percent carbon equivalent emissions (CO_2e) over a 20 year time frame and ~34 percent over a 100-year time frame. However, at the same time, they increase air pollution and land degradation compared with no carbon capture by ~25 percent. In addition, the current use of the captured CO_2 for enhancing oil recovery causes even greater damage to climate and human health. Finally, the cost of installing carbon capture equipment is still enormous.

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 22 percent (rather than 90%) of the intended CO_2 emissions are reduced over a 20-year time frame and only 34 percent are reduced over a 100-year time frame.
- Even these emission savings may be offset fully by emissions from the oil recovered with the CO_2.
- New natural gas plants with carbon capture produce 27-86 times the 100-year CO_2e emissions as new onshore wind.
- New coal plants with carbon capture produce 33-183 times the 100-year CO_2e emissions as new onshore wind.
- Without carbon capture, open cycle natural gas turbines and combined cycle natural gas turbines cause 2.5 and 2 times, respectively, the global warming per unit energy over a 20 year time frame as a coal plant and only 8-29 percent less warming over 100 years than a coal plant.
- The reason is the higher SO_2 and NO_x and lower CH_4 emissions from coal. The higher SO_2, NO_x, and particulate emissions from coal result in coal causing about five times the premature mortality as gas.
- As such, natural gas is not a bridge fuel.
- Instead, coal and gas are both horrendous for climate, health, and land although coal causes greater health problems.
- In comparison, wind, water, and solar power substantially address nearly all climate, health, and energy security problems.

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

Natural gas is a colorless, flammable gas containing a mass (mole) fraction of about 88.5 (93.9) percent methane plus smaller amounts of ethane, propane, butane, pentane, hexane, nitrogen, carbon dioxide, and oxygen (Union Gas, 2018). It is often found near petroleum deposits. Worldwide, 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^{o}C, the temperature at which it condenses to a liquid at ambient pressure. LNG has a volume that is 1/600th 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 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_2 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_2e – Section 1.2.1.5) 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 either incorrect or 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

First, as shown in Table 3.1, when used in an electric power plant, natural gas substantially increases, rather than decreases, global warming (CO_2e) compared with coal over a 20-year time frame, and the difference over 100 years, while more favorable to gas, is relatively small. Regardless, CO_2e emissions from both gas and coal are much larger than 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_2e from using natural gas with a CCGT or an OCGT is 2 and 2.5 times, respectively, that using coal (Table 3.1). Over a 100-year time frame, the CO_2e from a natural gas OCGT is only 8 percent less than that of coal; the CO_2e from a natural gas CCGT is only 29 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 significant 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_2e 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_2 per kilowatt-hour (kWh) of coal combustion, natural gas leaks during its mining and transport emit similar or more CH_4 than do CH_4 leaks during coal mining. CH_4 has a high, positive 20- and 100-year GWP (Table 1.2). As such, the leaked CH_4 from natural gas mining and transport contributes almost as much CO_2e as do the direct CO_2 emissions from natural gas combustion.

Second, and more important, coal combustion emits much more NO_x and SO_2 per kWh than does natural gas combustion (Table 3.1), and NO_x and SO_2 both produce cooling aerosol particles, which offset or mask much of global warming (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 and the resulting sunlight reflection by the clouds back to space. As such, NO_x and SO_2, 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_2e emissions of natural gas versus coal on a 20- versus 100-year lifetime. Wigley

(2011), for one, estimated the cooling impact of SO_2, but not NO_x, when comparing CO_2e from coal versus natural gas power plants.

Table 3.1. Comparison of 20- and 100-year lifecycle global CO_2 equivalent (CO_2e) 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.

			Coal			Natural Gas Open Cycle Gas Turbine			Natural Gas Combined Cycle Gas Turbin		
Chemical (X)	20-y GWP	100-y GWP	Emis. factor (g-X/kWh)	20-y CO_2e (g-CO_2e/kWh)	100-y CO_2e (g-CO_2e/kWh)	Emis. factor (g-X/kWh)	20-y CO_2e (g-CO_2e/kWh)	100-y CO_2e (g-CO_2e/kWh)	Emis. factor (g-X/kWh)	20-y CO_2e (g-CO_2e/kWh)	100- CO_2 (g-CC /kWl
[a]CO_2e-upstream				160	160		100	100		100	100
[b]CH_4-leak	86	34	4.1	353	140	4.84	400	162	3.1	255	103
[c]CO_2-plant	1	1	905	905	905	540	540	540	404	404	404
[d]BC+OM-plant	3,100	1,550	0.045	141	70	0.0003	0.93	0.47	0.0003	0.93	0.47
[c]NO_x-N-plant	-560	-159	0.23	-129	-37	0.15	-84	-24	0.015	-8.4	-2.4
[c]SO_2-S-plant	-1,400	-394	0.75	-1,050	-393	0.005	-7	-2	0.0015	-2.1	-2
Total				**380**	**845**		**950**	**776**		**749**	**603**

All 20- and 100-year GWPs are from Table 1.2. Each CO_2e is the product of the emission factor and a GWP, except for upstream totals, which are estimated from Skone (2015), slide 15, removing methane leaks since these are calculated here separately. Upstream emissions include emissions from fuel extraction, fuel processing, and fuel transport.

[b]CH_4-leak emission factors for natural gas are obtained by multiplying the CH_4 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 CH_4 required per kWh for a combustion turbine is estimated from the volume of gas per unit electricity in an open cycle plant (0.270 m^3-gas/kWh-electricity) and a combined cycle plant (0.172 m^3-gas/kWh-electricity) (IGU, 2018), the natural gas mass density, 0.845 kg/m^3, 0.2778 kWh/MJ, and the mass fraction of methane in natural gas, 0.885 (Union Gas, 2018). The results are 202 g-CH_4/kWh-electricity for open cycle and 129 g-CH_4/kWh-electricity for combined cycle. The overall U.S. methane leakage rate from natural gas, which includes leaks from drilling and from pipe transmission and distribution to electric power plants, industrial facilities, and buildings is ~3.7 percent for conventionally drilled natural gas and ~4.6 percent for shale gas (Howarth, 2019; Howarth et al., 2011, 2012). With shale gas at 2/3 of the U.S. natural gas production in 2015 (EIA, 2016), that gives a mean overall leakage rate of ~4.3 percent. However, the leakage rate 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. For coal, the 100-year CO_2e from CH_4 leaks is estimated from Skone (2015), Slide 17. The emission factor is derived from this number and the 100-year GWP from the present table, and the 20-year CO_2e is derived from the emission factor and the 20-year GWP.

[c]Emission factors from Figure 4 of de Gouw et al. (2014) for 2012 U.S. plants; For NO_x-N, emission factors for NO_x-NO_2 were multiplied by the ratio of the molecular weight of N to that of NO_2. For SO_2-S, emission factors for SO_2 were multiplied by the ratio of the molecular weight of S to that of SO_2.

[d]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_2e for electricity generation (600 to 800 g-CO_2e/kWh) (Table 3.1) is on the order of 60 to 80 times that of wind (~10 g-CO_2e/kWh) (Table 3.5) and the 100-year coal CO_2e (~850 g-CO_2e/kWh) is ~85 times that of wind. Similarly, both coal and gas produce much more air pollution than do WWS sources (Section 3.1.2).

The CO_2e 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 causes greater long-term global warming than do 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 is worse than other fossil fuels over 20 years and similar (for electricity) or worse (for heating and transportation) over 100 years. All fossil fuels emit 1.5 to 2 orders of magnitude the CO_2e as WWS sources.

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

Whereas, natural gas causes more CO_2e emissions over 20 years and a similar level over 100 years, coal emits more health-affecting air pollutants than does natural gas, which is the main reason it has a lower CO_2e over 20 years than does natural gas. Nevertheless, both natural gas and coal are much worse for human health than are WWS technologies, which emit no air pollutants during their operation, only during their manufacture and decommissioning. Such WWS emissions will disappear to zero as all energy transitions to WWS since even manufacturing will be powered by WWS at that point.

Table 3.2 provides U.S. emissions from all natural gas and coal uses in the United States in 2008. The table indicates that natural gas production and use in the U.S. emitted more CO, volatile organic carbon (VOC), CH_4, and ammonia (NH_3) than coal production and use, whereas coal emitted more NO_x, SO_2, and particulate matter smaller than 2.5- and 10-μm in diameter ($PM_{2.5}$, PM_{10}). Thus, both fuels resulted in significant air pollution, although the higher SO_2, NO_x, and particulate matter emissions from coal resulted in overall greater air pollution health problems from coal than natural gas.

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

	Coal All Uses	NG All Uses
CO	680	**900**
VOC	40	**1,130**
CH_4	5	**310**
NH_3	11	**54**
NO_x	**2,800**	1,540
SO_2	**7,600**	123
$PM_{2.5}$	**290**	61
PM_{10}	**420**	71

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

Most SO_2 and NO_x emissions evolve to sulfate and nitrate aerosol particles, respectively. Natural gas also emits NO_x, but less so than does coal (Tables 2.6 and 2.7). Natural gas, on the other hand, emits much less SO_2 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 cause about 5,000 out of the 60,000 to 65,000 premature mortalities each year in the U.S. from air pollution (Jacobson et al., 2015a). Coal-related emissions are estimated to cause 20,000 to 30,000 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.

As such coal causes more mortalities than does natural gas, but both cause far more mortalities than do WWS technologies. The combination of the much higher CO_2e emissions and premature mortality 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.

However, whereas, natural gas plants can help with peaking and load following, they are not needed. 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 (Jacobson et al., 2017). 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 drilled and pipes laid every year to supply a world thirsty for gas. When gas wells become depleted, new wells much 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^2 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 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. Land areas required for the fossil fuel and nuclear infrastructure in California and the United States.

		California		United States	
	Area per installation (km^2)	Number	Area (km^2)	Number	Area (km^2)
[a]Active oil and gas wells	0.05	105,000	3,327	1.3 million	65,000
[b]Abandoned oil wells	0.00005	225,000	6.6	2.6 million	128.5

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

[a]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).

[b]Number of abandoned U.S. oil and gas wells 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^2, and of each gas well, 25 m^2 from Jepsen (2018).

[c]Number of coal mines 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.

[d]Number of oil refineries from EIA (2018b). The area of each refinery is based on the area of the Richmond, California refinery.

[e]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.

[f]Number of coal, gas, petroleum, nuclear and other power plants is 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.

[g]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.

[f]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 need and energy required to continuously mine, transport, and process fossil fuels and uranium. This activity consumes 12.6 percent of all energy worldwide (Jacobson et al., 2017). 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 12.6 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_2 emitted from a coal or natural gas power plant before the CO_2 is released from the stack. This would be done with carbon capture and sequestration (CCS) technology 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_2 compared with no CCS, it only marginally reduces CO_2, 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_2 from other exhaust gases after fossil fuel or biofuel combustion, followed by the transfer of the CO_2 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_2, which compares with a fossil fuel emission rate in 2017 of about 37 Gt-CO_2/y.

Another proposed CCS method is to inject the CO_2 into the deep ocean. The addition of CO_2 to the ocean, however, results in ocean acidification. Dissolved CO_2 in the deep ocean eventually equilibrates with CO_2 in the surface ocean, reducing ocean pH and simultaneously supersaturating the surface ocean with CO_2, forcing some of it back into the air.

A third type of sequestration method is to mix captured CO_2 with concrete material, trapping the CO_2 inside the concrete (Section 2.4.8.2).

Carbon capture and use (**CCU**) is the same as CCS, except that the isolated CO_2 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_2 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_2 is separated from it and sent back into the reservoir. About two additional barrels of oil can be extracted for every ton of CO_2 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_2e Decreases Due to Carbon Capture

Whereas carbon capture equipment is expected to capture 85 to 90 percent of the CO_2 from a fossil fuel exhaust stream, several factors cause the overall CO_2 and CO_2e 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 percent more energy, thus requires 25 percent more fuel, to run the carbon capture equipment than does a plant without the equipment (IPCC, 2005).
2) Carbon capture equipment does not capture the upsteam CO_2e emissions resulting from mining, transporting, or processing the fossil fuel used in the plant. Instead, such emissions increase 25 percent because 25 percent more fuel is needed. This offsets a portion of the captured CO_2 from the plant exhaust and increases the air pollution emissions associated with the mining, transporting, and processing of the fuel.
3) The carbon capture equipment does not capture any of the non-CO_2 air pollutants from the fossil fuel exhaust. Such pollutants include CO, NO_x, SO_2, organic gases, mercury, toxins, BC, BrC, fly ash, and other aerosol components, all of which affect health. Instead, those pollutants increase 25 percent because 25 percent more fossil fuel from the plant is needed to run the CCS equipment.
4) The chance that CO_2 sequestered underground leaks increases over time and varies with geological formation.

One way to estimate the climate impact of carbon capture equipment when it is 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_2e) emissions of a technology per unit electric power generation (kWh), 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_2e is calculated as the lifecycle emission of CO_2 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 estimated 20- and 100-year lifecycle CO_2e 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_2e 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_2e 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_2e 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_2 emitted by the stack escape.

Table 3.4. Lifecycle 20-year and 100-year CO_2e 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.

	Average U.S. Coal Plant			Coal SCPC Plant			Natural Gas CCGT Plant		
	No Carbon Capture	With Carbon Capture	Percent CO_2e Remaining	No Carbon Capture	With Carbon Capture	Percent CO_2e Remaining	No Carbon Capture	With Carbon Capture	Percent CO_2e Remaining
20-y CO_2e/kWh	1,316	664	50.4	1,188	599	50.4	896	305	34.0
100-y CO_2e/kWh	1,205	346	28.7	965	277	28.7	506	179	35.4

All values are from Skone (2015), except the percent remaining for average U.S. coal was assumed the same as from Coal SCPC, and the CO_2e values with carbon capture for average U.S. coal were calculated from the percent remaining and the no carbon capture values.

The results in Table 3.4 suggest that carbon capture does not come close to eliminating CO_2e emissions from coal or gas power plants. Data from real world projects (Section 3.2.3) indicate even less reduction in CO_2e emissions due to carbon capture than Table 3.4 suggests. Further, the lifecycle CO_2e emissions from a natural gas or coal plant with carbon capture are not the only emissions associated with the plant. Lifecycle emissions can be placed in context only when all relevant emissions associated with a plant are accounted for and compared with emissions from other energy technologies, as discussed next.

3.2.2. Total CO_2e Emissions Of Energy Technologies

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

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 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.

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

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

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

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 (g-CO_2e/kWh) of the background grid, T_{PO} is the time lag (in years) between planning and operation of the technology, T_R is the times (years) to refurbish the technology, and L is the operating life (years) of the technology before it needs to be refurbished.

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

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

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

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

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

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

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

For comparison, the planning-to-operation time of a utility-scale wind or solar farm is generally 3 to 5 years, with a development period of 1 to 3 years and a construction period of 1 to 2 years (Jacobson, 2009). Wind turbines often last 30 years before refurbishing, and the refurbishing time is 0.25 to 1 year.

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

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

Technology	[a]Lifecycle	[b]Opportuni	[c]Anthro-	[d]Anthro-	[e]Nuclear	[f]Loss of CO_2	[g]**Total**	**Ratio of**

	emissions	ty cost emissions due to delays	pogenic heat emissions	pogenic water vapor emissions	Weapons risk or 100-Year CCS/U leakage risk	due to covering Land or clearing vegetation	**100-year CO_2e**	**100-year CO_2e to that of wind-onshore**
Solar PV-rooftop	15-34	-12 to -16	-2.2	0	0	0	**0.8-15.8**	**0.1-3.3**
Solar PV-utility	10-29	0	-2.2	0	0	0.054-0.11	**7.85-26.9**	**0.91-5.6**
CSP	8.5-24.3	0	-2.2	0 to 2.8	0	0.13-0.34	**6.43-25.2**	**0.75-5.3**
Wind-onshore	7.0-10.8	0	-1.7 to -0.7	-0.5 to -1.5	0	0.0002-0.0004	**4.8-8.6**	**1**
Wind-offshore	9-17	0	-1.7 to -0.7	-0.5 to -1.5	0	0	**6.8-14.8**	**0.79-3.1**
Geothermal	15.1-55	14-21	0	0 to 2.8	0	0.088-0.093	**29-79**	**3.4-16**
Hydroelectric	17-22	41-61	0	2.7 to 26	0	0	**61-109**	**7.1-22.7**
Wave	21.7	4-16	0	0	0	0	**26-38**	**3.0-7.9**
Tidal	10-20	4-16	0	0	0	0	**14-36**	**1.6-7.5**
Nuclear	9-70	64-102	1.6	2.8	0-1.4	0.17-0.28	**78-178**	**9.0-37**
Biomass	43-1,730	36-51	3.4	3.2	0	0.09-0.5	**86-1,788**	**10-373**
Natural gas-CCS/U	179-336	46-62	0.61	3.7	0.36-8.6	0.41-0.69	**230-412**	**27-86**
Coal-CCS/U	230-800	46-62	1.5	3.6	0.36-8.6	0.41-0.69	**282-876**	**33-183**

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

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

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

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

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

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

Hydroelectric and wave: From Jacobson (2009).

Tidal: From Douglass et al. (2008).

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

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

Natural gas-CCS/U: The lower bound is for the CCGT with carbon capture plant from Skone (2015), also provided in Table 3.4. The upper bound is CCGT value without carbon capture, 506 g-CO_2e/kWh from Table 3.4, multiplied by 66.4 percent, which is the percent of CO_2e emissions expected to be captured from the Petra Nova facility that will remain in the air over 100 years (Example 3.9).

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, 1,205 g-CO_2e/kWh from Table 3.4, multiplied by 66.4 percent, which is the percent of CO_2e emissions expected to be captured from the Petra Nova facility that will remain in the air over 100 years (Example 3.9).

[b]Opportunity cost emissions are emissions per kWh over 100 years from the background electric power grid, calculated from Equations 3.1 and 3.2 due to (a) the longer time lag between planning and operation of one energy technology relative to another and (b) additional downtime to refurbish a technology at the end of its useful life compared with the other technology. The planning-to-operation times of the technologies in this table are 0.5-2 years for solar PV-rooftop; 2-5 years for solar PV-utility, CSP, wind-onshore, wind-offshore, tidal, and wave; 3-6 years for geothermal; 8-16 years for hydroelectric; 10-19 years for nuclear; 4-9 years for biomass (without CCS/U), and 6-11 years for natural gas-CCS/U and coal-CCS/U (Jacobson, 2009, except rooftop PV and natural gas-CCS/U values are added

and solar PV-rooftop is updated here). The refurbishment times are 0.05-1 year for solar PV-rooftop; 0.25-1 year for solar-PV-utility, CSP, wind-onshore, wind-offshore, wave, and tidal; 1-2 years for geothermal and hydroelectric; 2-4 years for nuclear, and 2-3 years for biomass, coal-CCS/U, and natural gas-CCS/U. The lifetimes before refurbishment are 15 years for tidal and wave; 30 years for solar PV-rooftop, solar PV-utility, CSP, wind-onshore, wind-offshore; 30-35 years for biomass, coal-CCS/U, and natural gas-CCS/U; 30-40 years for geothermal; 40 years for nuclear; and 80 years for hydroelectric (Jacobson, 2009). The opportunity cost emissions are calculated here relative to the utility-scale technologies with the shortest time between planning and operation (solar-PV-utility, CSP, wind-onshore, and wind-offshore). The opportunity cost emissions of the latter technologies are, by definition, zero. The opportunity cost emissions of all other technologies are calculated as in Example 3.1 assuming a background U.S. grid emission intensity equal to 557.3 g-CO_2e/kWh in 2017. This is derived from an electricity mix from EIA (2018d) and emissions, weighted by their 100-year GWPs, of CO_2, CH_4, and N_2O from mining, transporting, processing and using fossil fuels, biomass, or uranium. The reason tidal power has opportunity cost emissions although its planning-to-operation time is the same as onshore wind is due to tidal's shorter lifetime. Thus, it has more down time over 100 years than do other technologies. See Section 3.2.2.1. The opportunity cost emissions of offshore and onshore wind are assumed to be the same because new projects suggest offshore wind, particularly with faster assembly techniques and with floating turbines, are easier to permit and install now than a decade ago. Although natural gas plants don't take so long as coal plants between planning and operation, natural gas combined with CCS/U is assumed to take the same time as coal with CCS/U.

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

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

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

[f]Loss of carbon, averaged over 100 years, due to covering land or clearing vegetation is the loss of carbon sequestered in soil or in vegetation due to the covering or clearing 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.

[g]The total column is the sum of the previous four 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; the dissipation of motive energy by friction; the combustion of fossil fuels,

biofuels and biomass for energy; nuclear reaction; and the heat from anthropogenic biomass burning. The relative worldwide contributions to each category of heat by each energy generating technology are provided in Jacobson (2014).

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

Solar PV and CSP convert solar radiation to electricity, thereby reducing the flux of heat to the ground or rooftop below PV panels. This is reflected in Table 3.5 as a negative heat flux.

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

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

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

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

$$E_{CO2} = \chi_{CO2} C/\tau_{CO2} \tag{3.4}$$

where χ_{CO2} (ppmv) is the specified anthropogenic mixing ratio that gives the current CO_2 radiative forcing, C is a conversion factor (8.0055×10^{15} g-CO_2/ppmv-CO_2), and τ_{CO2} is the data-constrained *e*-folding lifetime of CO_2 against loss by all processes. As of 2019, τ_{CO2} is ~50 years but increasing over time (e.g., Jacobson, 2012a, Figure 3.12).

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

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

Finally, whereas radiative forcing is a top-of-the-atmosphere value (and represents changes in heat integrated over the whole atmosphere) and heat flux is added to the bottom of the atmosphere, they both represent the same amount of heat added to the atmosphere. In fact, because the anthropogenic heat flux adds heat to near-surface air, it has a slightly greater impact on surface air temperature per unit radiative

forcing than does CO_2. For example, the globally averaged temperature change per unit direct radiative forcing for CO_2 is ~0.6 K/(W/m^2) (Jacobson, 2002), whereas the temperature change per unit anthropogenic heat plus water vapor flux is ~0.83 K/(W/m^2) (Jacobson, 2014). As such, the estimated CO_2e values for heat fluxes in particular in Table 3.5 may be slightly underestimated.

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

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

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

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

E_{CO2}=1.809×10^{16} g-CO_2/y.

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

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

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

Multiplying the avoided heat (-1 kWh/y) by 1000 W/kW and dividing by 8760 h/y and by the area of the Earth gives A_h=-2.24×10^{-16} W/m^2. Substituting this, G_{elec}=1 kWh/y, and E_{CO2} and F_{CO2} from Example 3.2 into Equation 3.3 gives H=-2.23 g-CO_2e/kWh.

Finally, for hydropower, evaporation of water vapor at the surface of a reservoir by the sun increases anthropogenic water vapor emissions (Section 3.2.2.3). Because evaporation requires energy, it cools the surface of the reservoir. The energy used to evaporate the water becomes embodied in latent heat carried by the water vapor. However, the water vapor eventually condenses in the air (forming clouds), releasing the heat back to the air. As a result, 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 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. Finally, 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, as discussed in Chapter 7, wind turbines reduce water vapor, a greenhouse gas, by reducing wind speeds, and water evaporation is a function of wind speed (and temperature) (Jacobson and Archer, 2012; Jacobson et al., 2018a).

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

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

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

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

where L_e=2.465×10^6 J/kg-H_2O is the latent heat of evaporation, S=3.1536×10^7 seconds per year, and A_e=5.092×10^{14} m^2 is the surface area of the Earth. For water evaporating from a hydropower reservoir, V = 1.75 to 17 kg-H_2O/kWh (Table 3.5, footnote c).

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

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

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

Example 3.4. Calculate the carbon-equivalent anthropogenic water vapor emissions from natural gas and nuclear plants.
The global anthropogenic water vapor flux from natural gas power plants in 2005 was A_m=0.00268 W/m^2 and from nuclear power plants was A_m=0.000746 W/m^2 (Jacobson, 2014). The total energy generation from natural gas use was G_{elec}=7.208×10^{12} kWh/y and from nuclear was 2.64×10^{12} kWh/y. Calculate the CO_2e emissions associated with these fluxes.

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

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

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

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

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

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

However, **wind turbines have an additional effect, which is to reduce water vapor, a greenhouse gas**. When wind from dry land blows over a lake, for example, the dry wind sweeps water vapor molecules away from the surface of the lake. More water vapor molecules must then evaporate from the lake to maintain saturation of water over the lake. 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. Thus, the ground warming is cancelled by the air-cooling due to wind turbines reducing evaporation. However, because water vapor is a greenhouse gas, less of it in the air means that more heat radiation from the Earth's surface escapes to space, cooling the ground, reducing internal energy. Since water vapor stays in the air for days to weeks, its absence due to a wind turbine reduces heat to the surface over that time more than the one-time dissipation of electricity, created by the wind turbine, increases heat.

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

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

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

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

Solution:
Multiplying the latent heat of evaporation (L_e=2.465×10^6 J/kg) and 1 kWh/3.6×10^6 J by -0.3 to -1 kg-H_2O/kWh gives the reduction in energy available to evaporate water as -0.21 to -0.69 kWh per kWh of electricity-produced. Multiplying 1000 W/kW and dividing by 8760 h/y and by the area of the Earth, 5.092×10^{14} m^2, gives A_m/G_{elec} = -4.6×10^{-17} to -1.53×10^{-16} (W/m^2)/(kWh/y). Substituting this and E_{CO2} and F_{CO2} from Example 3.2 into Equation 3.5 gives the anthropogenic water vapor energy flux from wind turbines as -0.46 to -1.53 g-CO_2e/kWh.

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

3.2.2.4. Leaks of CO_2 Sequestered Underground

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

The ability of a geological formation to sequester CO_2 for decades to centuries varies with location and tectonic activity. IPCC (2005, p. 216) references CO_2 leakage rates for an enhanced oil recovery operation of 0.00076 percent per year, or 1 percent over 1000 years, and CH_4 leakage from historical natural gas storage systems of 0.1 to 10 percent per 1000 years. Thus, while some well-selected sites could theoretically sequester 99 percent of CO_2 for 1000 years, there is no certainty of this since tectonic activity or natural leakage over 1000 years is not possible to predict. Because liquefied CO_2 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_2 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_2 from a reservoir can be calculated by first estimating how the stored mass of CO_2 changes over time. The stored mass (S) of CO_2 at any 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_2 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_2 emission rate before carbon capture and storage ranging from 790 to 1,017 g-CO_2/kWh. Assume also that carbon capture equipment added to the plant captures 90 and 80 percent, respectively, of the CO_2 (giving a low and high, respectively, emission rate of remaining CO_2 to the air). If the captured CO_2 is injected underground into a geological formation that has no initial CO_2 in it, calculate a low and high CO_2 emission rate from leakage averaged over 100 years, 500 years, and 1000 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 1000 years, close to that of some observed methane leakage rates. The high value corresponds to a 1 percent loss of CO_2 over 1000 years (e.g., IPCC, 2005).

Solution:
The low and high injection rates are 790 × 0.9 = 711 g-CO_2/kWh and 1,017 × 0.85 = 864.5 g-CO_2/kWh, respectively. Substituting these injection rates into Equation 3.8 (using the high lifetime with the low injection rate and the low lifetime with the high injection rate) and the result into Equation 3.9 gives a leakage rate range of 0.36 to 8.6 g-CO_2/kWh over 100 years; 1.8 to 42 g-CO_2/kWh over 500 years, and 3.5 to 81 g-CO_2/kWh over 1000 years.

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

3.2.2.5. Emissions From Covering of Land or Clearing of Vegetation

Emissions from the **covering of land or clearing of vegetation** are emissions of CO_2 itself due to (a) reducing the carbon stored in soil and in the vegetation above the soil by covering 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 both cover land and reduce vegetation.

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

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

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

Solution:
The energy generated over one year from this plant is 425 MW × 8760 h/y × 0.65 × 1000 kW/MW = 2.42×10^9 kWh/y. Over 100 years, the energy produced is 2.42×10^{11} kWh.

The carbon lost in soil is 0.34 × 13.2 kg-C/m^2 = 4.5 kg-C/m^2 and that lost from vegetation is 1.15 kg-C/m^2, for a total of 5.64 kg-C/m^2. Multiplying by 1000 g/kg and the molecular weight of CO_2 (44.0095 g-CO_2/mol), then dividing by the molecular weight of carbon (12.0107 g-C/mol) give 20,700 g-CO_2/m^2. Multiplying this by the land area covered by the facility and dividing by the 100-year energy use gives an emission rate from lost soil and vegetation carbon as 0.44g-CO_2/kWh, averaged over 100 years.

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

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_2 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 183 times the CO_2e emissions as onshore wind. Natural gas-CCS/U results in 27 to 86 times the emissions as onshore wind.

The reasons for the high CO_2e emissions of coal and natural gas with carbon capture, are (1) coal and gas plants need 25 to 55 percent more energy to run the carbon capture equipment, and this increases the upstream emissions (fuel mining, transport, and processing) of coal and gas by 25 to 55 percent (Example 3.9), (2) the capture equipment allows 10 to 30 percent of the CO_2 in the power plant exhaust to escape (Example 3.9), (3) CO_2e 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) some leaks of CO_2 occurs once CO_2 is sequestered, and (5) 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 gas without carbon capture are 100 to 200 times those of onshore wind per unit energy. Adding carbon capture to a coal or gas plant increases air pollution emissions another 25 to 55 percent.

The high air pollution and climate-relevant emission rates of coal and natural gas with carbon capture suggest that spending money on them represents an opportunity cost relative to spending money on lower-emitting technologies.

3.2.3. Carbon Capture Projects

To date, CO_2 has been captured and separated primarily from mined natural gas or, in one case, from gasified coal. In all such cases, the CO_2 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_2 was used for enhanced oil recovery, and the CCU equipment was installed at high cost. One project experienced problems with the equipment, resulting in much more CO_2 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_2 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 second plant with CCU equipment was the **Texas Parish power plant** in Thompsons, Texas. The plant was retrofitted with CCU equipment as part of the **Petra Nova** project and began operating with the equipment during January 2017. The CCU equipment (240 MW) is connected to and receives 37 percent of the emissions from a 654 MW pulverized coal boiler that produces steam for a steam turbine that generates electricity. The retrofit project cost $1 billion ($4,200/MW), including a $190 million grant from the U.S. government, on top of the cost of the coal plant itself.

The captured CO_2 is compressed and piped to an oil field, where it is used to enhance oil recovery. However, a separate gas turbine was built just to provide electricity and steam for the carbon capture equipment, and the CO_2 emissions from that turbine are not captured. In addition, the natural gas for the steam turbine has upstream CO_2e emissions, including CH_4 leaks, which are not captured. Those CO_2e emissions, combined with the emissions of the additional oil produced by the captured CO_2, result in the CCU equipment possibly increasing the overall CO_2e from the plant by an estimated 2 percent (Scottmadden, 2017).

Calculations in Example 3.9 using data from EIA (2017) suggest that, of the CO_2 reductions that were supposed to occur with the Petra Nova carbon capture equipment, only 21.6 percent are estimated to occur over a 20-year time horizon and 33.6 percent, over a 100-year time horizon. The reason is that CO_2e emissions from the gas turbine needed to power the CCS equipment, from the upstream mining, transporting, and processing of the natural gas for the turbine, and from upstream methane leaks offset most of the benefits of the capture equipment.

Example 3.9. Calculating emission reduction due to coal with carbon capture.
According to EIA (2017), emissions of CO_2 during January 2016 from the Texas Parish coal power plant, before carbon capture was implemented, were 934.4 kg-CO_2/MWh. Emissions during January 2017, after carbon capture was implemented, were 680.4 kg-CO_2/MWh, for a reduction of 254 kg-CO_2/MWh. However, the natural gas plant needed to run the carbon capture equipment itself emitted 99.8 kg-CO_2/MWh-coal-electricity.

First, estimate the upstream methane emissions from leaks associated with mining, transporting, and processing the natural gas used to run the gas plant. Also estimate the upstream fossil fuel combustion emissions of CO_2 assuming such emissions are 10 percent of the combustion emissions from the natural gas turbine (ICF Consulting, 2012). Next, calculate the overall 20-year and 100-year CO_2e of the upstream plus stack CH_4 and CO_2 emissions from the natural gas facility.

What percent of the CO_2 captured was effectively reemitted due to the CO_2e of $CH_4 + CO_2$ from natural gas, assuming a 20 year and a 100 year time horizon? What percent of the theoretical maximum emission reductions were actually obtained by the carbon capture equipment? 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 emission rate of CO_2 from natural gas, 99.8 kg-CO_2/MWh, by the molecular weight of CO_2 (44.0098 g-CO_2/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_4/mol) gives the mass intensity of methane in the natural gas burned, 34.2 kg-CH_4-burned/MWh.

The upstream leakage rate of methane is then 34.2 * 0.023 / (1-0.023) = 0.804 kg-CH_4/MWh. Multiplying by the 20- and 100-year GWPs of CH_4 (86 and 34, respectively) from Table 1.2 gives CO_2e emissions of the methane leaks as 69.2 and 27.3 kg-CO_2e/MWh, respectively. The upstream CO_2 combustion emissions rate is 10 percent of 99.8 kg-CO_2/MWh, or 9.98 kg-CO_2/MWh. Adding the upstream CO_2+CH_4 emissions to the gas turbine stack emissions gives 20- and 100-year CO_2e emissions from the gas turbine as 179 and 137 kg-CO_2e/MWh, respectively.

As such, averaged over 20 years, 179 / 254 = 70.4 percent of the CO_2 captured by the capture equipment is effectively re-emitted (offset) by the gas plant. Averaged over 100 years, 137 / 254 = 54 percent is re-emitted. These re-emissions are on top of downstream leaks that may occur with the captured CO_2.

The theoretical maximum reduction in emissions during January 2107 was 37 percent of the total coal plant emissions, 934.4 kg-CO_2e/MWh = 347.7 kg-CO_2e/MWh. The actual emission reduction from the coal stack was 254 kg-CO_2e/MWh, so the carbon capture equipment itself reduced only 73 percent (254 / 347.7) of emissions. Conversely, the equipment allowed 27 percent of emissions to escape.

Further, of that 254 kg-CO_2e/MWh, 179 kg-CO_2e/MWh will be returned to the air over a 20-year time frame due to the gas plant, indicating that only a net of 75 kg-CO_2e/MWh will be removed. Thus, only 75 / 347.7 = 21.6 percent of the maximum possible coal plant emission reduction will be realized over 20 years.

Over a 100-year time frame, 137 kg-CO_2e/MWh will be returned to the air, thus 254 – 137 = 117 kg-CO_2e/MWh will be removed. Thus, only 117 / 347.7 = 33.6 percent of the maximum possible coal plant emission reduction will be realized over 100 years. As such, 66.4 percent of CO_2e from the plant will remain in the air after carbon capture.

In sum, this carbon capture project does not come close to achieving zero emissions or significant emissions reductions, even before accounting for additional emissions it causes from downstream underground leaks of sequestered CO_2.

Example 3.10 illustrates that, because coal with CCS is (a) expensive, (b) results in more air pollution emissions than coal without CCS, and (c) only modestly decreases CO_2 emissions, its cost to society is more than 10 times that of wind energy providing the same energy. As such, it is not a cost effective method of addressing climate change, and it worsens air pollution.

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 health cost of coal pollution is 12.7 ¢/kWh (Table 7.11), and the climate cost of coal pollution is 15.8 ¢/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_2 emission by 22 percent before CCS equipment was 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 × 12.7 ¢/kWh = 15.9 ¢/kWh. The climate cost is 0.78 × 15.8 ¢/kWh = 12.3 ¢/kWh. Adding these three together gives 45.9 ¢/kWh. Dividing this by the cost of wind, 4.25 ¢/kWh, gives 10.8. Thus, the social cost of coal-CCS is 10.8 times that of wind. The direct energy cost of coal-CCS is 3.9 times that of wind.

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

Chemical	*E*-folding lifetime	20-Year GWP	100-Year GWP
[a]CO_2	50-90 years	1	1
[b]BC+POC in fossil fuel soot	3-7 days	2,400-3,800	1,200-1,900
[b]BC+POC in biofuel soot	3-7 days	2,100-4,000	1,060-2,020
[c]CH_4	12.4 years	86	34
[c]N_2O	121 years	268	298

[c]$CFCl_3$ (CFC-11)	45 years	7,020	5,350
[d]CF_2Cl_2 (CFC-12)	100 years	10,200	10,800
[c]CF_4 (PFC-14)	50,000 years	4,950	7,350
[d]C_2F_6 (PFC-116)	10,000 years	8,210	11,100
[e]Tropospheric O_3	23 days	--	--
[f]NO_x-N	< 2 weeks	-560	-159
[g]SO_x-S	< 2 weeks	-1,400	-394

GWP=Global Warming Potential.

[a]Low-lifetime of CO_2 is the data-constrained lifetime upon increasing CO_2 emissions from Jacobson (2012a, Figure 3.12); high-lifetime of CO_2 calculated from Figure 1 of Jacobson (2017), which shows CO_2 decreasing by 65 ppmv (from 400 to 335 ppmv) over 65 years upon elimination of anthropogenic CO_2 emissions. Since the natural CO_2 is 275 ppmv, the anthropogenic CO_2 = 400-275=125 ppmv, and the lifetime of anthropogenic CO_2 ~ 65 y / -ln((125-65) ppmv/125 ppmv) = ~90 years. The GWP of CO_2=1 by definition.

[b]POC is primary organic carbon co-emitted with black carbon from combustion sources. In the case of diesel exhaust, it is mostly lubricating oil and unburned fuel oil. In all cases, POC includes both absorbing organic (brown) carbon (BrC) and less absorbing organic carbon. Soot particles contain both BC and POC. The lifetime is from Jacobson (2012b) and the GWP is from Jacobson (2010a, Table 4), which accounts for direct effects, optical focusing effects, semi-direct effects, indirect effects, cloud absorption effects, and snow-albedo effects.

[c]From Myhre et al. (2013) Table 8.7.

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

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

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

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

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