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## RESEARCH ARTICLE

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## Committed Emissions of the U.S. Power Sector, 2000–2018

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### Key Points:

- While CO<sub>2</sub> emissions in the U.S. power sector fell 24% from 2000 to 2018, total committed emissions decreased by only 12%
- Coal plants from 2000 to 2018 retired at a capacity-weighted average of 50 years, limiting reductions in committed emissions from early closure
- Committed emissions from coal and gas plants are incompatible with U.S. climate goals barring a significant reduction in historic usage

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**Abstract** Annual carbon dioxide (CO<sub>2</sub>) emissions from the U.S. power sector decreased 24% from 2000 to 2018, while carbon intensity (CO<sub>2</sub> per unit of electricity generated) declined by 34%. These reductions have been attributed in part to a shift from coal to natural gas, as gas-fired plants emit roughly half the CO<sub>2</sub> emissions as coal plants. To date, no analysis has looked at the coal-to-gas shift from the perspective of commitment accounting—the cumulative future CO<sub>2</sub> emissions expected from power infrastructure. We estimate that between 2000 and 2018, committed emissions in the U.S. power sector decreased 12% (six GtCO<sub>2</sub>), from 49 to 43 GtCO<sub>2</sub>, assuming average generator lifetimes and capacity factors. Taking into consideration methane leakage during the life cycle of coal and gas plants, this decrease in committed emissions is further offset (e.g., assuming a 3% leakage rate, there is effectively no reduction at all). Thus, although annual emissions have fallen, cumulative future emissions will not be substantially lower unless existing coal and gas plants operate at significantly lower rates than they have historically. Moreover, our estimates of committed emissions for U.S. coal and gas plants finds steep reductions in plant use and/or early retirements are already needed for the country to meet its targets under the Paris climate agreement—even if no new fossil capacity is added.

**Plain Language Summary** The substitution of natural gas for coal plants has been promoted as a way to lower greenhouse gas emissions, because CO<sub>2</sub> emissions per unit electricity generated from gas are roughly half that of coal. The potential for such coal-to-gas reductions is demonstrated by the U.S. power sector, where increased use of natural gas for electricity generation has occurred alongside substantial reductions in annual CO<sub>2</sub> emissions. However, changes in annual emissions are only part of the story; such reductions have been accompanied by large changes in the age and composition of the U.S. generating fleet. These infrastructure changes are reflected in an accounting of “committed” emissions or the emissions that are expected to occur over the entire operating life of power plants. We find that although annual emissions from power plants decreased by 24% between 2000 and 2018, committed emissions decreased by only 12%, as coal plants at the end of their operating lifetime were replaced by new gas plants with potentially long operating lifetimes. We find that very large reductions in the use of U.S. coal and gas plants are already needed for the country to meet its targets under the Paris climate agreement—even if no new coal or gas plants are built.

## 1. Introduction

The U.S. power sector has gone through large changes in the past two decades, including the growth of natural gas. Low natural gas prices, capital costs, and build times of combined cycle gas-fired power plants in the 1990s led to a large expansion in U.S. gas-fired capacity in the beginning of this century (CERA, I, 2008; Colpier & Cornland, 2002). From 2000 to 2005, over 156 GW of combined cycle gas capacity was commissioned, followed by an additional 99 GW from 2006 to 2018 (Energy Information Administration [EIA], 2019b). At the same time, innovations in hydraulic fracturing technology dramatically increased domestic gas supplies and further decreased prices (EIA, 2019b) and use of natural gas by the power sector surged.

In addition to gas power, solar and wind power capacity has also increased. From 2000 to 2018, the U.S. commissioned 93 GW of wind power and 63 GW of solar power (thermal and photovoltaic; EIA, 2019a; SEIA, 2019). Nearly half of the wind and solar additions (74 GW, or 47%) have been added since 2015. As a result of the increased capacity, solar and wind power has grown from providing less than 1% of power generation in 2000 to nearly 9% in 2018 (EIA, 2012, 2019b).

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Concomitant with the growth in gas and renewable use was a decline in coal use. Between 2000 (EIA, 2012) and 2018, the share of U.S. electricity from coal fell by nearly half, from 52 to 27% (EIA, 2019b). As the use of coal decreased, so did CO<sub>2</sub> emissions from the power sector: between 2000 and 2018, emissions from the U.S. power sector decreased 24%, from 2.31 to 1.76 Gt (EIA, 2012, 2019b). The average CO<sub>2</sub> emissions intensity of U.S. electricity production from 2000 to 2018 decreased 34%, from 646 to 426 kg CO<sub>2</sub>/MWh (Schivley et al., 2018, 2019).

Various studies have credited part or even most of the decline in annual U.S. CO<sub>2</sub> emissions to increased gas use. From 2000 and 2018, electricity from natural gas more than doubled, growing from 16% of electricity consumed in 2000 to 35% in 2018, passing coal's share in 2015 (EIA, 2019b). On average, gas-fired combined cycle plants emit 50 to 60% less CO<sub>2</sub> per megawatt-hour (MWh) than coal plants (Zoelle et al., 2015). Given its greater usage and lower CO<sub>2</sub> emissions compared to coal, studies have attributed between 15 (Feng et al., 2015, 2016) and 40% (Kotchen & Mansur, 2016; Mohlin et al., 2018) of the ~11% decline (646 Mt) in 2007–2013 U.S. CO<sub>2</sub> emissions to increased natural gas use. A U.S. Energy Department report estimates coal-to-gas switching reduced CO<sub>2</sub> emissions between 2005 and 2014 by 1.2 Gt of CO<sub>2</sub> (Murphy & Cunliff, 2016).

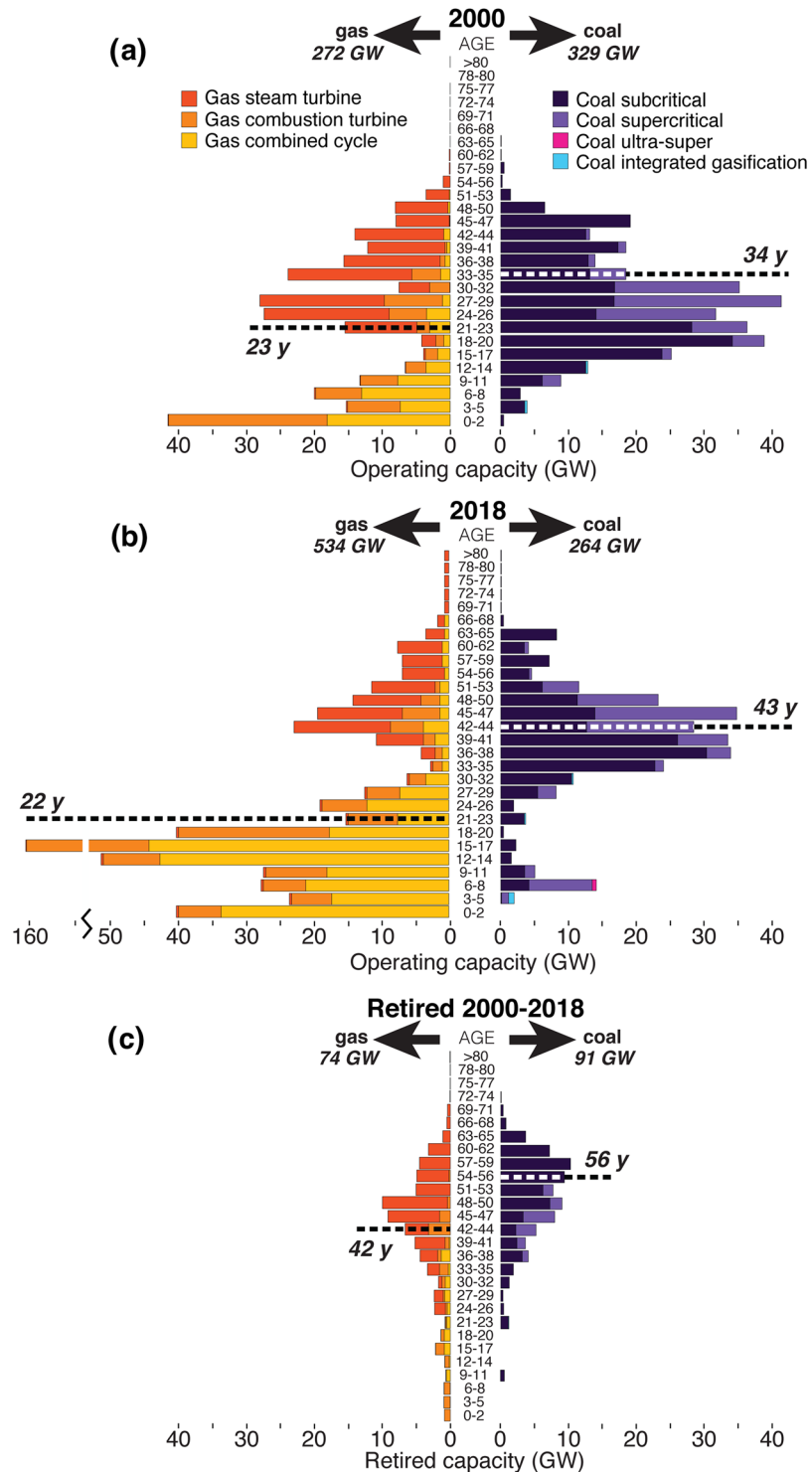
However, increased electricity generation from wind and solar power, as well as decreases in the energy intensity of the U.S. economy and reduced power demand from the 2008 global recession, also helped reduce emissions (Feng et al., 2015; Mohlin et al., 2018; Prasad & Munch, 2012). Some studies have emphasized that these other factors may be more important to long-term decreases in U.S. greenhouse gas emissions. For example, as abundant natural gas displaces coal, it may also delay deployment of lower-carbon sources of electricity such as renewables and nuclear, resulting in little to no net climate benefit over time (Davis & Shearer, 2014; McJeon et al., 2014; Shearer et al., 2014). In addition, the climate benefits of CO<sub>2</sub> emissions avoided by the use of gas may be partially or completely offset by fugitive emissions (i.e., leakage) of the greenhouse gas methane during extraction and transport of the gas (Alvarez et al., 2018; Balcombe et al., 2018; Brandt et al., 2014).

To date, no paper has focused on the decrease in U.S. power sector emissions from the perspective of “committed emissions”—the cumulative future CO<sub>2</sub> emissions from fossil fuel energy infrastructure assuming expected lifetimes and utilization rates (i.e., capacity factor). Because the increase in global mean temperatures and cumulative CO<sub>2</sub> emissions is roughly proportional (Allen et al., 2009; Matthews et al., 2009), committed emissions are a proxy for the aggregate climate impacts of any change in energy infrastructure and/or its operation. Studies have estimated the globally committed CO<sub>2</sub> emissions of all carbon-emitting infrastructure (Davis et al., 2010; Tong et al., 2019) and of operating and proposed fossil power plants (Cui et al., 2019; Davis & Socolow, 2014; Pfeiffer et al., 2016, 2018), as well as power sector commitments in specific countries, including China (Jiang et al., 2017) and India (Shearer et al., 2017).

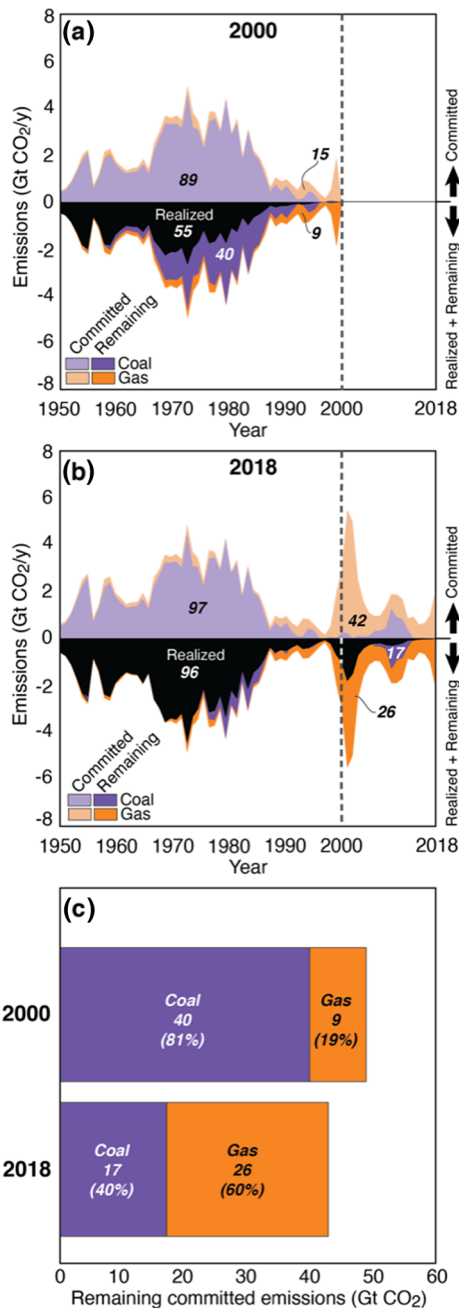
For this analysis, we estimate U.S. committed CO<sub>2</sub> emissions across two different time periods (1950–2000 and 1950–2018) to examine how decreases in annual emissions from 2000 to 2018 compare to changes in emission commitments brought about by shifts in the age and composition of the power fleet. Given the sensitivity of emissions to plant usage, we also estimate committed emissions across a range of lifetimes and utilization rates. We then examine the degree to which committed emissions put the United States at risk of infrastructural inertia impeding the rate and cost-effectiveness of pledged CO<sub>2</sub> emission reductions. While the current administration has moved to withdraw from the Paris climate agreement, an exit is not effective until November 2020 (Tollefson, 2017).

## 2. Materials and Methods

Commitment accounting estimates cumulative emissions from a power plant or CO<sub>2</sub>-emitting asset over its assumed lifetime (Davis & Socolow, 2014). At any point in time, the committed emissions of an operating power plant may be divided according to the fraction of these emissions that have already been “realized” (i.e., emitted) and the fraction “remaining” (i.e., expected in the future). For an electricity generating unit (“generator”), the accounting therefore requires the following information: (1) the year the generator began operating, (2) the year the generator retired (if applicable), (3) emissions per unit of electricity generated, and (4) capacity factor (i.e., the ratio of the plant's actual generation to its maximum potential generation).



**Figure 1.** Age distributions of coal- and gas-fired power plants. Total U.S. coal and gas power capacity by plant age in (a) 2000 and (b) 2018, and (c) retirements by age from 2000 to 2018. The median age for each is represented as dotted lines. From 2001 to 2018, 235 GW of combined cycle gas capacity and 27 GW of gas turbines were added, net of retirements, lowering the median age for gas plants from 23 to 22 years. For coal, 26 GW of power capacity was added and 90 GW was retired from 2001 to 2018, decreasing total U.S. coal power capacity by 64 GW and increasing the median age for coal plants from 34 to 43 years. Nearly 60% of capacity that retired from 2000 to 2018 was 50 years of age or older, with a median of 56 years (c). In all, the power fleet from gas and coal increased by 207 GW from 2000 to 2018.



**Figure 2.** Commitment accounting of coal- and gas-fired generators as of 2000 and 2018. Assuming average capacity factors and lifetimes, committed CO<sub>2</sub> emissions from coal and gas plants (a) 1950 to 2000 and (b) 1950 to 2018 increased 35 Gt, from 104 Gt in 2000 to 139 Gt in 2018. Remaining committed CO<sub>2</sub> emissions from coal (shaded purple) decreased from 40 Gt in 2000 to 17 Gt in 2018, as emissions were realized, while remaining committed emissions for gas increased from 9 Gt in 2000 to 26 in 2018, due to new gas plants. (c) Altogether, remaining emissions decreased 6 Gt from 2000 to 2018, from 49 to 43 Gt, as the realization of emissions from aging and retired coal plants were partially offset by new emission commitments from increased gas capacity. The majority of remaining emissions shifted from coal plants (81% in 2000) to gas plants (60% in 2018). During this time, 41 Gt of committed CO<sub>2</sub> emissions (black) were realized, growing from 55 Gt in 2000 to 96 Gt in 2018.

CO<sub>2</sub> emissions per MWh were calculated using the heat rate (i.e., thermal energy per unit electricity generated) of the plant and the emission factor of the fuel. Heat rate values were derived from the U.S. Energy Information Administration (EIA) for gas combined cycle plants and gas turbines (EIA, 2019b) and the U.S. Environmental Protection Agency for coal plants (Sargent & Lundy, 2009). Emission factor values were derived from the U.S. Department of Energy for coal type (Hong & Slatick, 1994) and the EIA for natural gas (EIA, 2016). Efficiency declines of 25% for coal plants, 20% for combined cycle plants, and 25 to 50% for gas turbines were applied to units 30 years and above, consistent with the average increase in CO<sub>2</sub> emissions per MWh from aging generators (EIA, 2018).

For our reference case, we use average capacity factors of 60% for coal and combined cycle, and 10% for gas turbines, to capture both historic and recent averages (2000–2018 averages are 61% for coal, 46% for combined cycle, and 8% for turbines; by 2018, coal had declined to 54%, while combined cycle and turbines increased to 58 and 12%, respectively [EIA, 2019b]). We use an average lifetime of 50 years for coal-fired plants and gas-fired plants, rounding from their historical capacity-weighted average of 46 years (50 and 42 years, respectively; EIA, 2019a; Monitor, 2019). We also test the sensitivity of committed emissions to lifetimes and capacity factors  $\pm 50\%$  of the reference averages, as upper- and lower-bound scenarios. Operating plants that have already exceeded their assumed lifetime are randomly retired over the next 5 years (Davis & Socolow, 2014).

Life-cycle methane emissions for coal and gas plants were derived from the U.S. Department of Energy's National Energy Technology Laboratory, which estimate 0.5 t CO<sub>2</sub>e/MWh for gas plants for every 1% of leakage, and an average of 0.5 t CO<sub>2</sub>e/MWh for coal plants, at a global warming potential of 34 for methane over 100 years (Schwartz et al., 2014).

### 3. Generator Data

Generator data are from two data sets: the U.S. EIA form 860 M (March 2019) for natural gas plants (EIA, 2019a) and the Global Energy Monitor (GEM) database (January 2019) for coal plants (Monitor, 2019). The U.S. EIA 860 is a publicly available database that includes information on each operating, retired, and planned power generator in the United States. The GEM database is also publicly available and includes each operating, retired, and planned coal generator with a nameplate capacity of 30 MW or more. Additionally, the GEM database includes plant type and coal type per unit, used here to calculate CO<sub>2</sub> emissions.

### 4. Results

From 2000 to 2018, the United States added 229 GW of combined cycle gas-fired capacity and 42 GW of gas turbines (net of 7 and 66 GW of retirements, respectively), while reducing coal-fired capacity by 64 GW (net of 26 GW of new capacity added). Combining coal and gas, total generating capacity increased by 207 GW. Figure 1 shows these capacity changes between 2000 and 2018 along with

**Table 1**  
*Modeled Lifetimes and Capacity Factors*

	Lifetime (years)			Capacity factor		
	Average	50% below	50% above	Average (%)	50% below	50% above
Coal	50	25	75	60	30	90
Gas combined cycle	50	25	75	60	30	90
Gas turbine	50	25	75	10	5	15

Average lifetime and capacity factor used to estimate committed emissions, and the lower bound (50% below) and upper bound (50% above) values.

their effect on the age distribution of U.S. gas- and coal-fired generating capacity. For example, over the 17 years, the median age (dashed lines) of gas-fired capacity decreased by 1 year (from 23 to 22 years), while the median age of coal-fired capacity increased by 9 years (from 34 to 43 years; Figures 1a and 1b). Nearly 60% (53 GW) of the coal-fired capacity retired over this period was 50 years or older, with a median age of 56 years (Figure 1c).

In turn, Figure 2 shows the effects of the capacity changes between 2000 and 2018 on committed CO<sub>2</sub> emissions assuming average lifetimes and capacity factors (see Table 1). Here, 1950 is used as the starting point, as it is the first year of significant coal power capacity additions (over 1.5 GW), and thus the first year of significant committed emissions.

New gas-fired capacity is visible as large additional commitments since 2000, most of which remain to be emitted in the future (yellow and orange areas in Figure 2b that are not visible in Figure 2a). Between 2000 and 2018, remaining committed emissions related to coal-fired capacity (dark purple in the bottom halves of each panel in Figure 2) decreased by 23 GtCO<sub>2</sub> (from 40 to 17 GtCO<sub>2</sub>), as emissions from coal plants were realized. Remaining committed emissions related to gas-fired capacity (dark yellow and orange) increased by 17 GtCO<sub>2</sub> (from 9 to 26 GtCO<sub>2</sub>), as new gas plants were added. Thus, while committed emissions from coal decreased as the plants reached 50+ years and were taken offline, the reduction was partially offset by new emission commitments from increased gas capacity, leading to an overall 6 GtCO<sub>2</sub> reduction in remaining emissions from 2000 and 2018 (from 49 to 43 GtCO<sub>2</sub>). The majority of remaining emissions shifted from coal plants (81% in 2000) to gas plants (60% in 2018; Figure 2c). During this time, 41 Gt of committed emissions (black) were realized, growing from 55 GtCO<sub>2</sub> in 2000 to 96 GtCO<sub>2</sub> in 2018.

Methane also affects emission commitments, as methane leakage into the atmosphere can result in substantial CO<sub>2</sub>-equivalent (CO<sub>2</sub>e) emissions. We therefore consider how life-cycle methane emissions for both coal and gas use affect cumulative CO<sub>2</sub>e commitments from 2000 to 2018. If 1% of natural gas production escapes into the atmosphere unburned, the difference between 2000 and 2018 commitments is reduced from 6 to 5 GtCO<sub>2</sub>e (Table 2). At a 2% leakage rate, the reduction drops to 2 GtCO<sub>2</sub>e and disappears altogether at a 3% leakage rate (0 GtCO<sub>2</sub>e). Currently, the U.S. Environmental Protection Agency estimates methane leakage to be around 1.4%, although other studies suggest that leakage may be underestimated (Alvarez et al., 2018; Balcombe et al., 2018; Brandt et al., 2014).

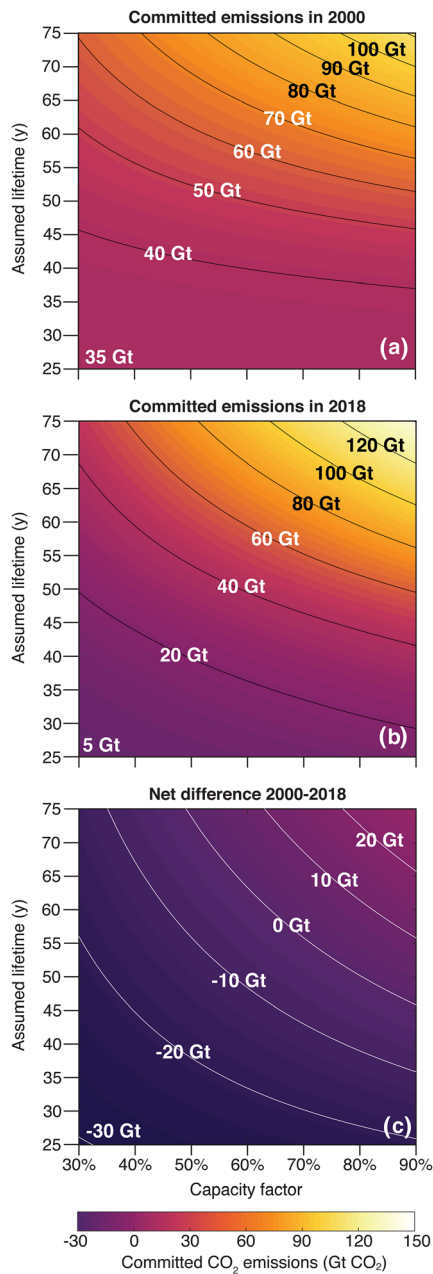
Remaining committed emissions are dependent on how long and often the plants are used. Figure 3 therefore looks at remaining CO<sub>2</sub> commitments for coal and gas plants in 2000 and 2018 at ±50% of the reference averages (Table 1) to model the range in historic usage. Remaining committed emissions for the year 2000 (Figure 3a) range from 35 GtCO<sub>2</sub> (pink) to 111 GtCO<sub>2</sub> (yellow), depending on the capacity factor and lifetime. The range begins at 35 GtCO<sub>2</sub> since 35 of the 49 GtCO<sub>2</sub> of remaining emissions in 2000 have already been realized through 2018. Remaining committed emissions for the year 2018 (Figure 3b) range from 5 GtCO<sub>2</sub> (purple) to 140 GtCO<sub>2</sub> (yellow), showing that future emissions are highly dependent on plant usage. Thus, 2018 commitments can either be up to 30 GtCO<sub>2</sub> lower or 29 GtCO<sub>2</sub> higher than commitments in 2000, depending on if plants are used at low-capacity factors and lifetimes (dark purple) or high-capacity factors over longer lifetimes (light purple), respectively (Figure 3c).

It is important to note the high sensitivity of emissions to plant usage and lifetime, resulting in a wide range of future committed emissions. Reducing the average lifetime of current coal and gas plants from 50 to 40 years would result in 33 GtCO<sub>2</sub> of remaining commitments rather than 43 GtCO<sub>2</sub>; also reducing the average capacity factor from 60 to 50% would lower commitments further to 22 GtCO<sub>2</sub>. Retiring coal and gas plants at 50 years but reducing usage immediately to a 30% capacity factor would lower remaining commitments to 10 GtCO<sub>2</sub> and could back-up the increased deployment of

**Table 2**  
*Difference in 2000 and 2018 Committed Emissions*

	1% leakage	2% leakage	3% leakage
2000	52	53	54
2018	47	51	54
Difference (2018–2000)	–5	–2	0

Committed emissions (GtCO<sub>2</sub>e) in 2000 and 2018 for coal and gas plants at average life-cycle methane emissions for coal and a 1 to 3% methane leakage rate for natural gas.



**Figure 3.** Changes in committed emissions 2000–2018. Remaining committed emissions in (a) 2000 and (b) 2018, and (c) net varied by lifetimes and capacity factors ranging from 50 to  $-50\%$  of reference averages (Table 1). Remaining committed CO<sub>2</sub> emissions for the year 2000 (a) range from 35 Gt (pink, 30% capacity factor and 25-year lifetime) to 111 Gt (90% capacity factor and 75-year lifetime), as 35 Gt of the 49 Gt of remaining emissions in 2000 have already been realized through 2018. Remaining committed CO<sub>2</sub> emissions for the year 2018 (b) range from 5 Gt (purple, 30% capacity factor and 25-year lifetime) to 140 Gt (yellow, 90% capacity factor and 75-year lifetime), showing that future emissions are highly dependent on how often and for how long the plants are used. Combining the two time periods (c), remaining CO<sub>2</sub> commitments in 2018 can be up to 30 Gt lower than they were in 2000, if the plants are used at low-capacity factors and lifetimes (dark purple), or up to 29 Gt higher and if the plants are used at high capacity factors over longer lifetimes (light purple).

intermittent, renewable power capacity. Conversely, an increase in the historic use or lifetime of coal and gas plants will enlarge future commitments, while any coal or gas plants built after 2018 will also increase commitments, unless offset by early retirements or reduced plant usage.

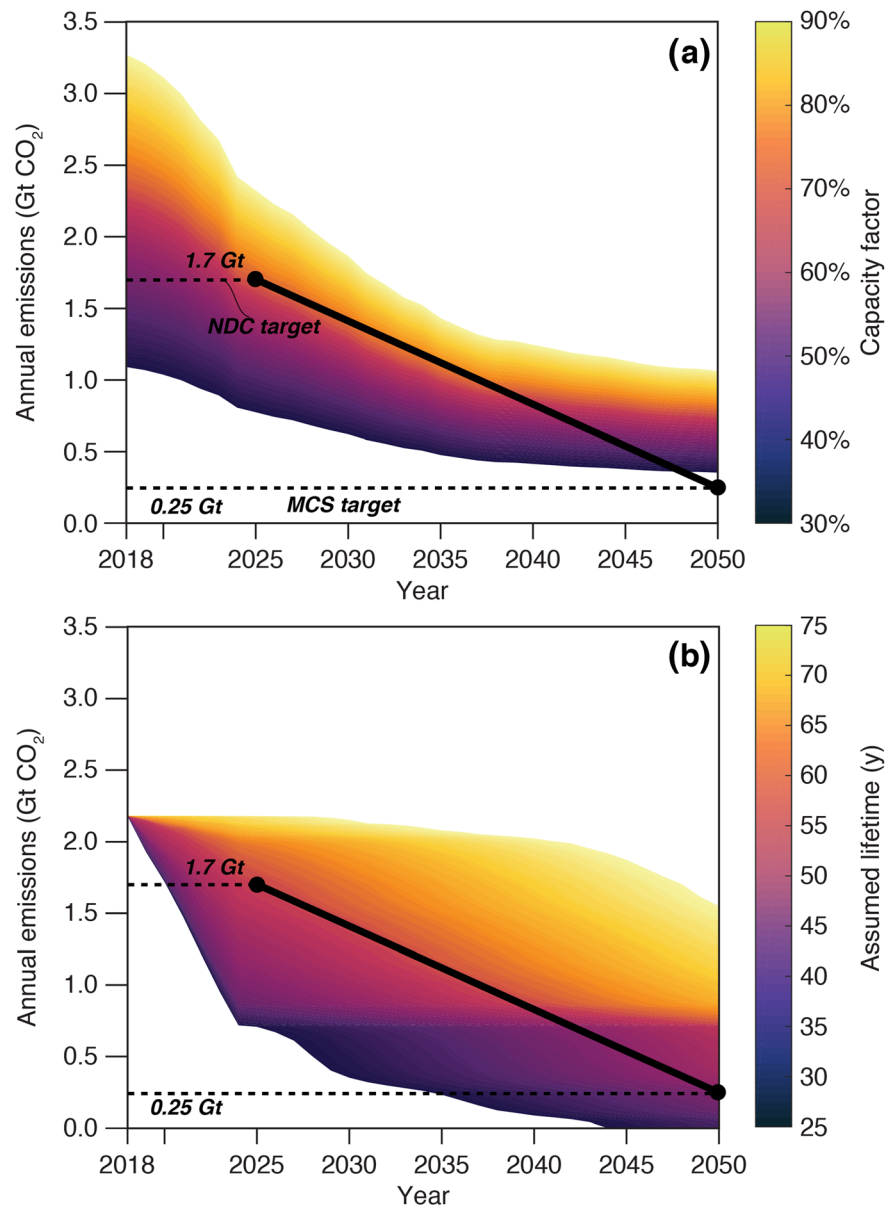
Given the inherent uncertainties in estimating future emissions, Figure 4 looks at a range of future CO<sub>2</sub> emissions from currently operating U.S. coal and gas plants through 2050 at  $\pm 50\%$  of the reference averages (Table 1) and compares the emissions against the country's climate targets, assuming no new coal or gas plants are added. As part of its nationally determined contribution (NDC) for the Paris agreement, the United States pledged a 26 to 28% reduction in its GHG emissions by 2025 (below 2005 levels), with “best efforts” toward the 28% reduction. According to the NDC, the U.S. target is “consistent with a straight line emission reduction pathway from 2020 to deep, economy-wide reductions of 80% or more by 2050” (Government, U. S., 2015).

In 2016, the U.S. government released a mid-century strategy (MCS) for achieving the 80% by 2050 reduction (House, 2016). In all four scenarios modeled, gas plants without carbon capture and storage (CCS) provided at most 2 EJ of power generation by 2050 (there are no coal plants without CCS in any scenario by 2050). At the average heat rate and emission factor for combined cycle gas plants, the 2 EJ of unabated gas power (i.e., without CCS) would emit around 0.25 GtCO<sub>2</sub> in 2050. The steep reductions in emissions for power usage reflects two main factors: (1) cost-competitive alternatives to fossil fuel electricity are increasingly available, unlike other sectors, and (2) industry, transport, and heating will likely require electrification to decrease their share of emissions, putting further weight on the power sector to decarbonize (Davis et al., 2018; House, 2016; Iyer et al., 2017).

The black line in Figure 4 shows a “straight line emission reduction pathway” from 1.7 GtCO<sub>2</sub> in 2025—consistent with the NDC goal of a “best effort” 28% decrease in power sector emissions over 2005—to 0.25 GtCO<sub>2</sub> by 2050, the estimated maximum emissions allotted for unabated gas plants by 2050 in the MCS. Emissions above the line offer a guideline for the reductions in the usage and lifetime of current unabated coal and gas plants needed for the United States to meet its NDC and MCS targets.

Over historically average lifetimes (50 years), current coal and gas plants can continue operating at an average 60% capacity factor through 2025 and still be compatible with the U.S. NDC, as long as no new coal or gas plants are added. However, the average capacity factor needs to fall to 40% by 2045 (purple shading) and 20% by 2050 to meet the U.S. climate target in 2050 (black line; Figure 4a). The 2050 target affects 332 GW of gas plants and 25 GW of coal plants, unless retired early or retrofitted with CCS.

Conversely, if existing generators operate at historically average capacity factors (60% coal and gas plants, 10% turbines), the units must retire or retrofit at 40 years by 2050; the capacity factor is too high for all plants to continue operating as historically through 2050 (Figure 4b). This equates to 34 GW of coal plants and 409 GW of



**Figure 4.** Future CO<sub>2</sub> emissions from currently operating coal- and gas-fired plants. Future emissions from currently operating coal and gas plants will depend upon the average lifetimes and utilization of those plants (Table 1). (a) If existing plants operate over historically average lifetimes, the targeted reductions in U.S. power-related emissions (its NDC and MCS, denoted by the solid black line) can be met at the current average capacity factor (60%) in 2025, but must decrease below 30% to meet the MCS target in 2050. (b) Similarly, if existing plants operate at average capacity factors, plants must retire or retrofit by 40 years or sooner (purple shading) to meet the MCS for 2050. By 2050, the climate target will affect over 300 to 400 GW of currently operating power plants, mainly gas, unless retired early or retrofitted with CCS.

gas plants retiring or retrofitting with CCS by 2050, reflecting the young age of the gas fleet. Thus, lowering plant usage (Figure 4a) can help reduce the large early retirements required in Figure 4b.

In short, even if no new coal or gas plants are added, over 300 to 400 GW of existing coal and gas plants will require large reductions in usage, retrofits with CCS, or early retirement to meet U.S. climate goals. This analysis reflects similar studies finding that existing infrastructure is already incompatible with the Paris climate agreement and that strengthening NDCs can help prevent early retirement of fossil fuel infrastructure (Binsted et al., 2020; Iyer et al., 2015). In addition, issues of fairness and equity arguably require faster,

deeper cuts from historically large emitters like the United States than planned by its Paris pledges (Du Pont et al., 2017; Meinshausen et al., 2015; Peters et al., 2015). Rather than strengthen the NDC, however, the Trump Administration has tried to revoke it and roll back many of the policies the NDC and MCS relied on for emissions reductions. However, the Trump Administration has introduced tax credits for every ton of CO<sub>2</sub> captured with CCS technology, which may help bolster wider adoption; currently, less than 1 GW of all U.S. coal and gas power capacity are equipped with CCS (EIA, 2019a).

## 5. Conclusions

Although annual CO<sub>2</sub> emissions in the power sector decreased by 24% between 2000 and 2018, committed CO<sub>2</sub> emissions decreased by a more modest 12% (6 Gt), assuming average generator lifetimes and utilization rates. This is because the decrease in annual emissions of the U.S. power sector occurred alongside a build-up of 335 GW of new gas capacity, offsetting some of the decreases in committed emissions from 90 GW of retired coal plants. The rise in committed emissions from gas plants was not counteracted by the early closure of coal plants, most of which (60%) retired at 50 years of age or above (Mills et al., 2017). Additionally, methane leakage from natural gas production further reduces the difference in emission commitments from 2000 to 2018 to between 5 and 0 GtCO<sub>2</sub>e at a 1 to 3% leakage rate, respectively.

In 2010, Davis et al. emphasized that the aging U.S. power plant fleet represented a critical opportunity to cost-effectively transition the country's power sector away from fossil fuels. At the time the capacity-weighted mean age of U.S. plants was 32 years—near the historical retirement age of 36 to 39 years (Davis et al., 2010). Here, we show that in the years since, this opportunity has been largely missed: in 2018, the capacity-weighted mean age of fossil fuel-fired plants in the United States has now decreased to 29 years, while the historical retirement age is 46 years. If no new fossil infrastructure had been built after 2000, there would be just 14 GtCO<sub>2</sub> remaining committed today, assuming average rates; instead, commitments have been renewed by natural gas.

However, while the fossil fuel-burning infrastructure underlying current committed emissions exists, its future operation is not certain. Reducing the capacity factors and operating lifetimes of fossil plants, for example, by improving the competitiveness of non-emitting, renewable energy sources, will decrease remaining committed emissions. Phasing out coal power could lower future commitments from 43 GtCO<sub>2</sub> to as low as 26 GtCO<sub>2</sub>. Reducing gas plant usage to an average 50% capacity factor and 40-year lifetime would lower commitments further to 22 GtCO<sub>2</sub>. Future commitments of between 26 and 22 GtCO<sub>2</sub> would result in a 47 to 55% decrease over 2000 commitments (49 GtCO<sub>2</sub>). Conversely, commissioning more unabated gas power capacity could increase future commitments, with 42 GW of gas power currently under development (EIA, 2019a). If these gas plants are built, greater reductions in coal and gas plant usage will be needed to meet climate targets.

This analysis finds that while annual emissions decreased from 2000 to 2018, committed emissions are potentially large due to the build-up of a large, young gas fleet, requiring large reductions in plant usage to meet climate goals. Thus, for decarbonization goals it is critically important to assess not just annual emissions and carbon intensity but also the age and composition of the power fleet. Indeed, our analysis demonstrates a potential shortcoming of relying on annual CO<sub>2</sub> emissions as an indicator of decarbonization efforts: short-term emission reductions may belie longer-term emission commitments. In contrast, remaining committed emissions reflect a longer-term perspective that may be useful in assessing the climate implications of macro-level changes of energy system transitions.

## Conflict of Interests

The authors declare no conflict of interests relevant to this study.

## Data Availability Statement

This study comprises two data sets that are both publicly available: the U.S. Energy Information Administration's 860 Monthly Electric Generator Inventory (March 2019), available at <https://www.eia.gov/electricity/data/eia860m/>, and Global Energy Monitor's Global Coal Plant Tracker (January 2019), available at <https://globalenergymonitor.org/coal/global-coal-plant-tracker/>

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## References

- Allen, M. R., Frame, D. J., Huntingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M., & Meinshausen, N. (2009). Warming caused by cumulative carbon emissions toward the trillionth tonne. *Nature*, *458*(7242), 1163–1166. <https://doi.org/10.1038/nature08019>
- Alvarez, R. A., Zavala-Araiza, D., Lyon, D. R., Allen, D. T., Barkley, Z. R., Brandt, A. R., et al. (2018). Assessment of methane emissions from the US oil and gas supply chain. *Science*, *186*–188, eaar7204. <https://doi.org/10.1126/science.aar7204>
- Balcombe, P., Brandon, N., & Hawkes, A. (2018). Characterising the distribution of methane and carbon dioxide emissions from the natural gas supply chain. *Journal of Cleaner Production*, *172*, 2019–2032.
- Binsted, M., Iyer, G. C., Edmonds, J. J., Vogt-Schilb, A., Arguello, R., Cadena, A., et al. (2020). Stranded asset implications of the Paris Agreement in Latin America and the Caribbean. *Environmental Research Letters*, *15*(4). <https://iopscience.iop.org/article/10.1088/1748-9326/ab506d>
- Brandt, A. R., Heath, G., Kort, E., O'Sullivan, F., Pétron, G., Jordaan, S., et al. (2014). Methane leaks from North American natural gas systems. *Science*, *343*(6172), 733–735.
- CERA, I. (2008). IHS CERA Power Capital Costs Index shows power plant construction costs decreasing slightly, IHS CERA.
- Colpier, U. C., & Cornland, D. (2002). The economics of the combined cycle gas turbine—an experience curve analysis. *Energy Policy*, *30*(4), 309–316.
- Cui, R. Y., Hultman, N., Edwards, M. R., He, L., Sen, A., Surana, K., et al. (2019). Quantifying operational lifetimes for coal power plants under the Paris goals. *Nature Communications*, *10*(1), 1–9.
- Davis, S. J., Caldeira, K., & Matthews, H. D. (2010). Future CO<sub>2</sub> emissions and climate change from existing energy infrastructure. *Science*, *329*(5997), 1330–1333.
- Davis, S. J., Lewis, N. S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I. L., et al. (2018). Net-zero emissions energy systems. *Science*, *360*(6396), eaas9793. <https://doi.org/10.1126/science.aas9793>
- Davis, S. J., & Shearer, C. (2014). A crack in the natural-gas bridge. *Nature*, *514*(7523), 436.
- Davis, S. J., & Socolow, R. H. (2014). Commitment accounting of CO<sub>2</sub> emissions. *Environmental Research Letters*, *9*(8), 084018.
- Du Pont, Y. R., Jeffery, M. L., Gütschow, J., Rogelj, J., Christoff, P., & Meinshausen, M. (2017). Equitable mitigation to achieve the Paris Agreement goals. *Nature Climate Change*, *7*(1), 38.
- EIA (2012). Annual energy review 2011, Energy Information Administration.
- EIA (2016). Carbon dioxide emissions coefficients, Energy Information Administration, February.
- EIA (2018). Emissions by plant and by region 2017, Energy Information Administration, November.
- EIA (2019a). 860 monthly electric generator inventory, Energy Information Administration, March.
- EIA (2019b). Monthly energy review, Energy Information Administration, March.
- Feng, K., Davis, S. J., Sun, L., & Hubacek, K. (2015). Drivers of the US CO<sub>2</sub> emissions 1997–2013. *Nature Communications*, *6*(1), 7714. <https://doi.org/10.1038/ncomms8714>
- Feng, K., Davis, S. J., Sun, L., & Hubacek, K. (2016). Correspondence: Reply to 'Reassessing the contribution of natural gas to US CO<sub>2</sub> emission reductions since 2007'. *Nature Communications*, *7*(1), 10693. <https://doi.org/10.1038/ncomms10693>
- Government, U. S. (2015). United States Nationally Determined Contribution (First Submission), UNFCCC.
- Hong, B., & Slatick, E. (1994). *Carbon dioxide emission factors for coal*, EIA Quarterly Coal Report, DOE/EIA-0121(94/Q1) (pp. 1–8).
- House, W. (2016). *United States mid-century strategy for deep decarbonization*. Paper presented at United Nations Framework Convention on Climate Change, Washington, DC.
- Iyer, G. C., Clarke, L. E., Edmonds, J. A., Kyle, G. P., Ledna, C. M., McJeon, H. C., & Wise, M. (2017). *US electric power sector transitions required to achieve 80% reductions in economy-wide greenhouse gas emissions: Results based on a state-level model of the US energy system*. Richland, WA: Pacific Northwest National Laboratory (PNNL).
- Iyer, G. C., Edmonds, J. A., Fawcett, A. A., Hultman, N. E., Alsalam, J., Asrar, G. R., et al. (2015). The contribution of Paris to limit global warming to 2 C. *Environmental Research Letters*, *10*(12), 125002. <https://doi.org/10.1088/1748-9326/10/12/125002>
- Jiang, S., Chen, Z., Shan, L., Chen, X., & Wang, H. (2017). Committed CO<sub>2</sub> emissions of China's coal-fired power generators from 1993 to 2013. *Energy Policy*, *104*, 295–302.
- Kotchen, M. J., & Mansur, E. T. (2016). Correspondence: Reassessing the contribution of natural gas to US CO<sub>2</sub> emission reductions since 2007. *Nature Communications*, *7*(1), 10648. <https://doi.org/10.1038/ncomms10648>
- Matthews, H. D., Gillett, N. P., Stott, P. A., & Zickfeld, K. (2009). The proportionality of global warming to cumulative carbon emissions. *Nature*, *459*(7248), 829–832. <https://doi.org/10.1038/nature08047>
- McJeon, H., Edmonds, J., Bauer, N., Clarke, L., Fisher, B., Flannery, B. P., et al. (2014). Limited impact on decadal-scale climate change from increased use of natural gas. *Nature*, *514*(7523), 482–485.
- Meinshausen, M., Jeffery, L., Gütschow, J., Du Pont, Y. R., Rogelj, J., Schaeffer, M., et al. (2015). National post-2020 greenhouse gas targets and diversity-aware leadership. *Nature Climate Change*, *5*(12), 1098–1106. <https://doi.org/10.1038/nclimate2826>
- Mills, A. D., Wiser, R. H., & Seel, J. (2017). *Power plant retirements: Trends and possible drivers*. Berkeley, CA: Lawrence Berkeley National Lab (LBNL).
- Mohlin, K., Camuzeaux, J. R., Muller, A., Schneider, M., & Wagner, G. (2018). Factoring in the forgotten role of renewables in CO<sub>2</sub> emission trends using decomposition analysis. *Energy Policy*, *116*, 290–296.
- Monitor, G. E. (2019). *Global coal plant tracker*.
- Murphy, C., & Cunliff, C. (2016). *Environment baseline, volume 1: Greenhouse gas emissions from the U.S. power sector*, U.S. Department of Energy Report. Available at <https://energy.gov/epa/downloads/environment-baseline-vol-1-greenhouse-gas-emissions-us-power-sector>
- Peters, G. P., Andrew, R. M., Solomon, S., & Friedlingstein, P. (2015). Measuring a fair and ambitious climate agreement using cumulative emissions. *Environmental Research Letters*, *10*(10), 105004. <https://doi.org/10.1088/1748-9326/10/10/105004>
- Pfeiffer, A., Hepburn, C., Vogt-Schilb, A., & Caldecott, B. (2018). Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement. *Environmental Research Letters*, *13*(5), 054019.
- Pfeiffer, A., Millar, R., Hepburn, C., & Beinhooker, E. (2016). The '2 C capital stock' for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy. *Applied Energy*, *179*, 1395–1408.
- Prasad, M., & Munch, S. (2012). State-level renewable electricity policies and reductions in carbon emissions. *Energy Policy*, *45*, 237–242.
- Sargent, D., & Lundy, L. (2009). *Coal-fired power plant heat rate reductions*. Chicago, IL.
- Shivley, G., Azevedo, I., & Samaras, C. (2018). Assessing the evolution of power sector carbon intensity in the United States. *Environmental Research Letters*, *13*(6), 064018. <https://doi.org/10.1088/1748-9326/aabe9d>

- Schivley, G., Goldstein, A., Samaras, C., Azevedo, I. L., Zhai, H., & Matthews, H. S. (2019). *Power sector carbon index: Data, sources, and methods*.
- Schwietzke, S., Griffin, W. M., Matthews, H. S., & Bruhwiler, L. M. (2014). Natural gas fugitive emissions rates constrained by global atmospheric methane and ethane. *Environmental Science & Technology*, 48(14), 7714–7722.
- SEIA (2019). 2018 year in review *Rep.*, <https://www.seia.org/research-resources/solar-market-insight-report-2018-year-review>
- Shearer, C., Bistline, J., Inman, M., & Davis, S. J. (2014). The effect of natural gas supply on US renewable energy and CO<sub>2</sub> emissions. *Environmental Research Letters*, 9(9), 094008.
- Shearer, C., Fofrich, R., & Davis, S. J. (2017). Future CO<sub>2</sub> emissions and electricity generation from proposed coal-fired power plants in India. *Earth's Future*, 5(4), 408–416.
- Tollefson, J. (2017). Trump pulls United States out of Paris climate agreement. *Nature*, 546(7657), 198.
- Tong, D., Zhang, Q., Zheng, Y., Caldeira, K., Shearer, C., Hong, C., et al. (2019). Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target. *Nature*, 572(7769), 373–377.
- Zoelle, A., Keairns, D., Pinkerton, L. L., Turner, M. J., Woods, M., Kuehn, N., et al. (2015). *Cost and performance baseline for fossil energy plants, volume 1a: Bituminous coal and natural gas*. NETL.