Climate Impacts of Coal and Natural Gas

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Abstract

Natural gas has large carbon benefits over coal when used for electricity generation, but these benefits can be reduced by emissions of fugitive methane. This paper analyzes the time-evolution of radiative forcing from both natural gas and coal-based electricity generation using simplified pulse response and radiative forcing functions with a range of assumptions for fugitive methane leakage and electricity generation efficiency. We find that it would require leakage rates of between 4.8% and 9.3% to make natural gas result in more average forcing than coal over the next 100 years. Net radiative forcing from both carbon dioxide and methane are similar for coal and natural are over the first decade or so of generation, with increased divergence thereafter driven by the relatively short 8-year atmospheric half-life of the fugitive methane component. Natural gas can serve a viable bridge away from coal-based generation if avoiding longer-term climate impacts is prioritized and fugitive methane emissions are minimized, reducing radiative forcing by up to 56 percent over the next 100 years compared to conventional coal.

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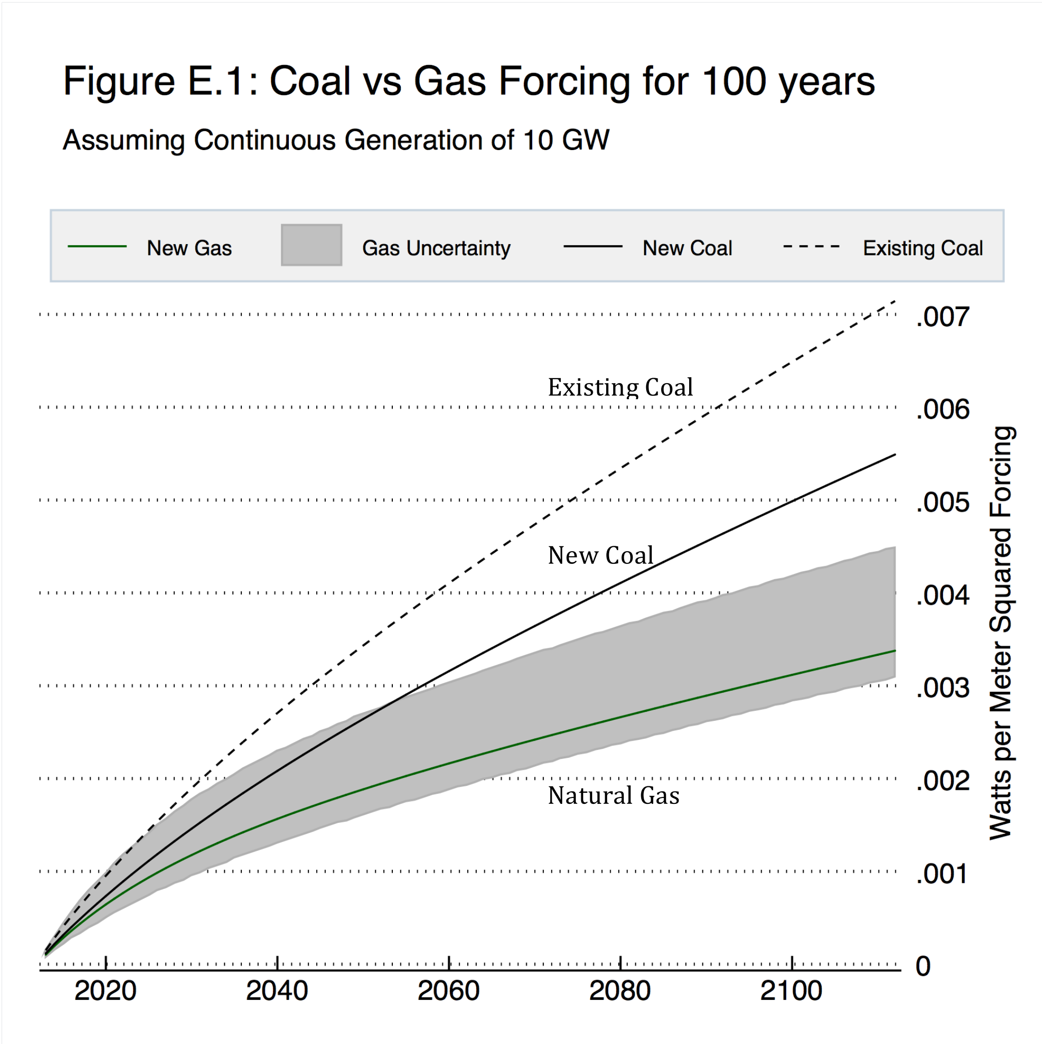
Executive Summary

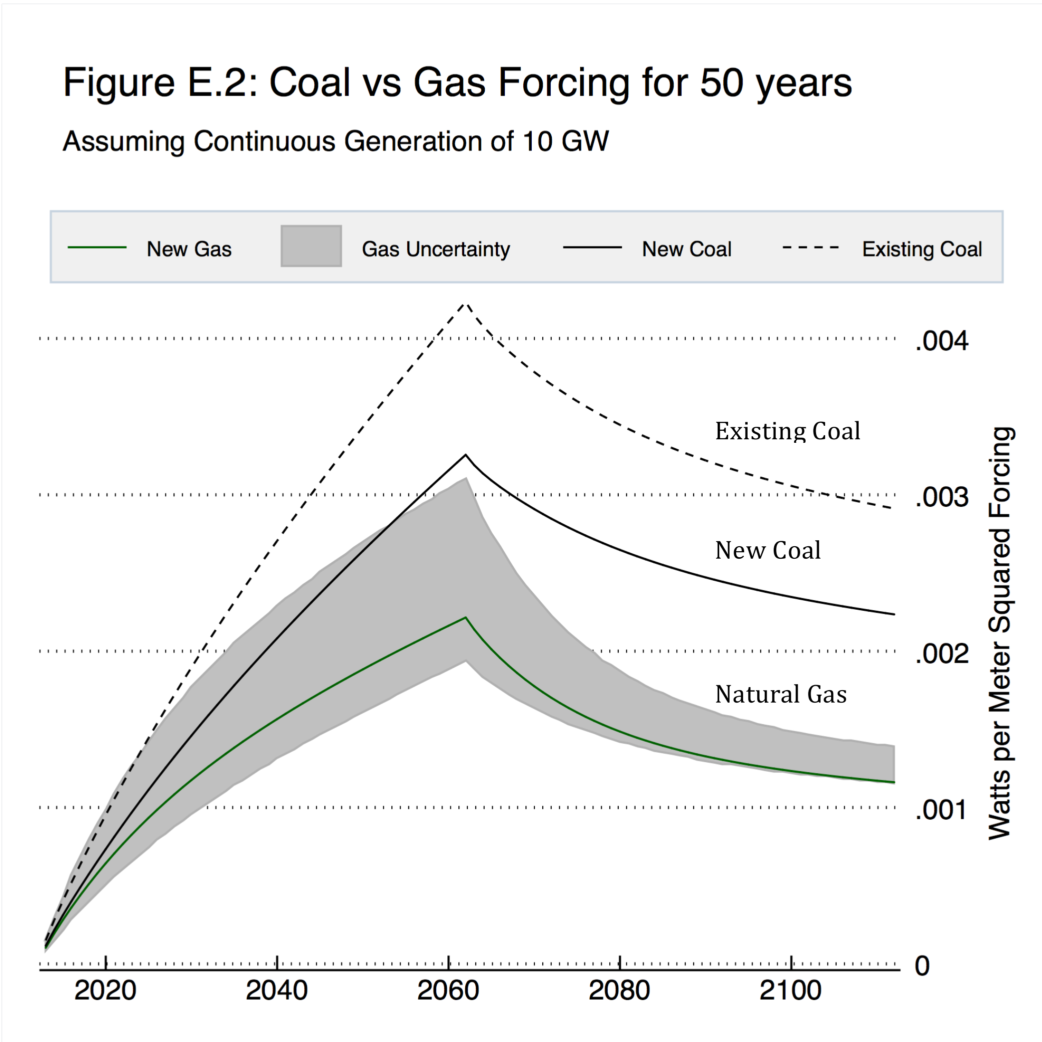
There has been quite a bit of discussion and confusion both in the public debate and the academic literature about the climate impacts of switching from coal to natural gas. Some have argued that increased use of natural gas might produce more global warming than coal because of leakages, since its primary component methane (CH_4) is a particularly potent greenhouse gas [1, 2]; a ton of CH_4 leaked has a global warming impact that is initially 44 times that of a ton of CH_4 burned, although CH_4's short atmospheric half-life of 8 years ameliorates this effect. Others have argued that electricity produced by natural gas results in less than half of the overall longer-term greenhouse gas impacts (combined CO_2 and CH_4) than coal [3, 4], so a switch would reduce warming. The real answer is more nuanced; it depends on the time-frame considered, how long we continue to use gas going forward, and if the sunk costs involved in developing natural gas infrastructure hinder or help the development of future near-zero carbon technologies. Those nuances are the subject of this paper.

By comparing the time-evolution of radiative forcing from both CO_2 and CH_4 emissions associated with coal and natural gas, we will examine the sensitivity of the coal versus gas question to the leakage rate, the years of coal displaced, the generation efficiencies of the plants, and other important factors. In the vast majority of cases, natural gas results in lower emissions than coal over all timeframes considered. We will show that it would take a methane leakage rate of 9.3% to make new natural gas on average worse than existing coal plants for continuous electricity generation over a 100-year timeframe. Over a shorter 20-year timeframe, where many critics of gas tend to focus, it would still take a leakage rate of 4.8% to make new natural gas have a greater warming impact than existing coal. When comparing new natural gas to new, higher-efficient coal generation, we find that it would still require leakage rates of 6.1% over 100 years and 3% over 20 years to make natural gas worse than coal. Results for a range of leakage rates and power plant efficiencies shown in Figure E1.



The "forcing" – that is, the additional warming caused by the injection of greenhouse gases into the atmosphere -- due to assumed continuous operation of 10 gigawatt coal and natural gas power plants over the period of 100 years. The effects include not only the emission of CO_2 from both kinds of plants, but also from the leakage of CH_4 from natural gas plants. The "New Gas" line (in the center of the grey band) assumes 2% leakage and 50% electric generation efficiency. The grey band shows the range that would result from 1% leakage/50% generation efficiency to 4% leakage/42% efficiency. For coal, two lines are plotted; the dashed line represents current average U.S. coal generation efficiency (33%) while the dotted line shows the lower emissions that would result if the coal-to-electricity efficiency were improved to 43%.

The U.S. EPA 2012 estimates of natural gas leakage rates are around 1.5% over the course of production, transmission, storage, and distribution [20]. Other recent studies have posited higher leakage rates than the EPA inventory, implying leakage rates of between 1.8% and 4% [5, 6, 19]. In either case, methane leakage rates are low enough that natural gas is preferable to coal from a climate perspective over longer timeframes even under the highest leakage rate assumptions. Given that many leaks can be cost-effectively remediated [7], and regulation of fugitive (leaked) methane emissions is likely in the future, system-wide leakage rates are likely to decline over the coming years.



Same as previous Figure, but with both gas and coal generation being replaced by a near-zero carbon alternative after 50 years. The grey band narrows beyond 2070 since the leaked methane has a short lifetime in the atmosphere and no longer contributes to greenhouse forcing.

In cases where natural gas is used for 50 years or less as a bridge fuel away from coal, but eventually phased out for near-zero carbon generation sources, natural gas results in less than half the global warming impact of existing coal 100-years out. It would take leakage rates of over 11.5% to make new natural gas produce more average warming than existing coal over the century in this scenario. If we compare new gas to new coal electricity generation, it would take a leakage rate of over 7.4% to result in the same climate forcing over 100 years in this scenario. The 20-year equivalent leakage rates are the same as in the non-bridge-fuel scenario. Figure E2 shows typical results assuming a transition to carbon-free energy after 50 years.

Natural gas is still preferable to coal even if the use of gas as an immediate bridge fuel results in a modest delay in adopting near-zero carbon generation sources down the road, provided that the switch to gas does not delay renewables more than half a year or so for every year of coal it displaces.

Some researchers have suggested that methane is critical to address in the short-term because of the need to reduce climate change impacts over the next 20 years [1]. This conflicts with much of the academic literature on climate change impacts, which suggests that impacts will be much more significant near the end of the century than in the beginning [8]. Spurning the opportunity to shift from coal to natural gas due to concerns about short-term warming may inadvertently commit the world to a longer-term warming future.

Introduction

Natural gas generation capacity has increased dramatically in the United States over the past decade as a result of the falling price of natural gas due to the rapid pace of shale gas development [9]. A significant amount of coal base load generation has been replaced by natural gas, contributing to declining U.S. carbon emissions in recent years [10]. While carbon emissions from natural gas generation are around 60% lower than emissions from coal, natural gas use results in increased methane emissions from leakage during production, transmission, storage, and distribution, offsetting some of the climate benefit.

The potential for natural gas to displace coal and reduce carbon emissions has led to suggestions that natural gas could be used as a "bridging fuel" away from coal until near-zero carbon energy sources are more economically viable at scale for baseload generation [11]. Critics of this idea have suggested that investment in natural gas infrastructure would require sunk capital costs that would potentially delay the date at which near-zero carbon technologies could be adopted compared to a world where a gas was not used as a bridge fuel [12]. Others have suggested that widespread natural gas generation capacity could help support the future adoption of distributed near-zero carbon generation sources, as its fast dispatch potential helps allay grid intermittency issues.

Moving Away from Global Warming Potential Comparisons

Comparing the effects of emitting methane (CH_4) and carbon dioxide (CO_2) is a surprisingly challenging problem. CH_4 is a much more powerful greenhouse gas than CO_2. Even though there is much less of it in the atmosphere (it is generally measured in parts per billion rather than parts per million in the case of CO_2) it is one of the major contributors to greenhouse warming, responsible for approximately half the forcing of CO_2 globally [21]. However, CH_4 only stays in the atmosphere for a short period of time before decomposing and reacting with oxygen to form CO_2 and water vapor [15]. Much of the CO_2, on the other hand, stays in the atmosphere for hundreds if not thousands of years [14]. This means that any comparison requires weighing the short-term impacts of CH_4 against the long-term impacts of CO_2, as well as consideration of the duration of use of natural gas and coal for electricity generation.

Much of the literature on greenhouse-gas lifecycle comparisons between coal and natural gas has focused on simplified Global Warming Potential (GWP) analysis of annual emissions from each fuel [1, 4]. GWP calculates the time-integrated forcing from discrete pulses of different greenhouse gases to allow comparisons over different timeframes, usually 20 and 100 years. It does not allow for easy comparisons of the time-evolution of warming from differing lengths of generation, or precise estimates of warming at particular future periods. Other studies have incorporated more detailed modeling of greenhouse gas radiative forcing and atmospheric lifetimes [2, 3]. Although the use of these simplified 20 and 100 year GWPs allows a simplified discussion, their use can also lend itself to conclusory analysis. For example, opponents of natural gas might choose to emphasize the 20-year effects of fugitive methane since they are large, but supporters might pick the 100 year effects to make them seem small.

To gain deeper understanding, a more appropriate and accurate approach is to use atmospheric gas lifetime and radiative forcing models to determine the actual amount of warming for different future scenarios of energy use. This allows us to estimate how much warmer or cooler the earth would be in any given year for cases where gas or coal are used for different periods of time, and can help better understand the viability of natural gas as a bridging fuel away from coal and toward future near-zero-emission generation sources.

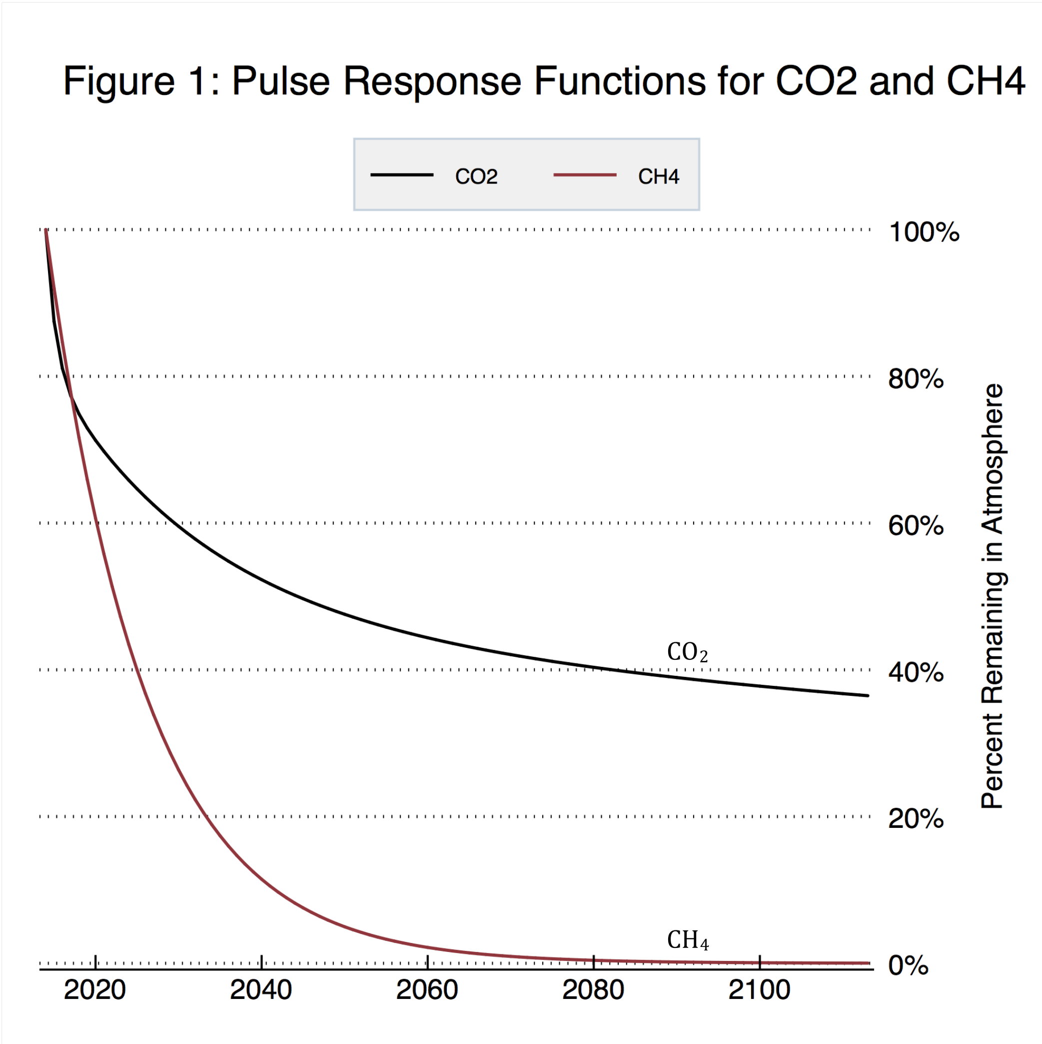
Modeling Atmospheric Residence Times

CO_2 and CH_4 have vastly different atmospheric lifetimes. For this discussion, the atmospheric lifetime functions from the Bern Carbon Cycle Model [14] and Joos and Bruno [15] are used for CO_2 and CH_4, respectively. The results of these models can be fit to a set of mathematical equations, which model the response to a discrete one-time emissions pulse [13]:

$$G_{co_2}(t) = 0.217 + 0.259e^{-t/172.9} + 0.338e^{-t/18.51} + 0.186e^{-t/1.186}$$

$$G_{ch_4}(t) = e^{-t/12}$$

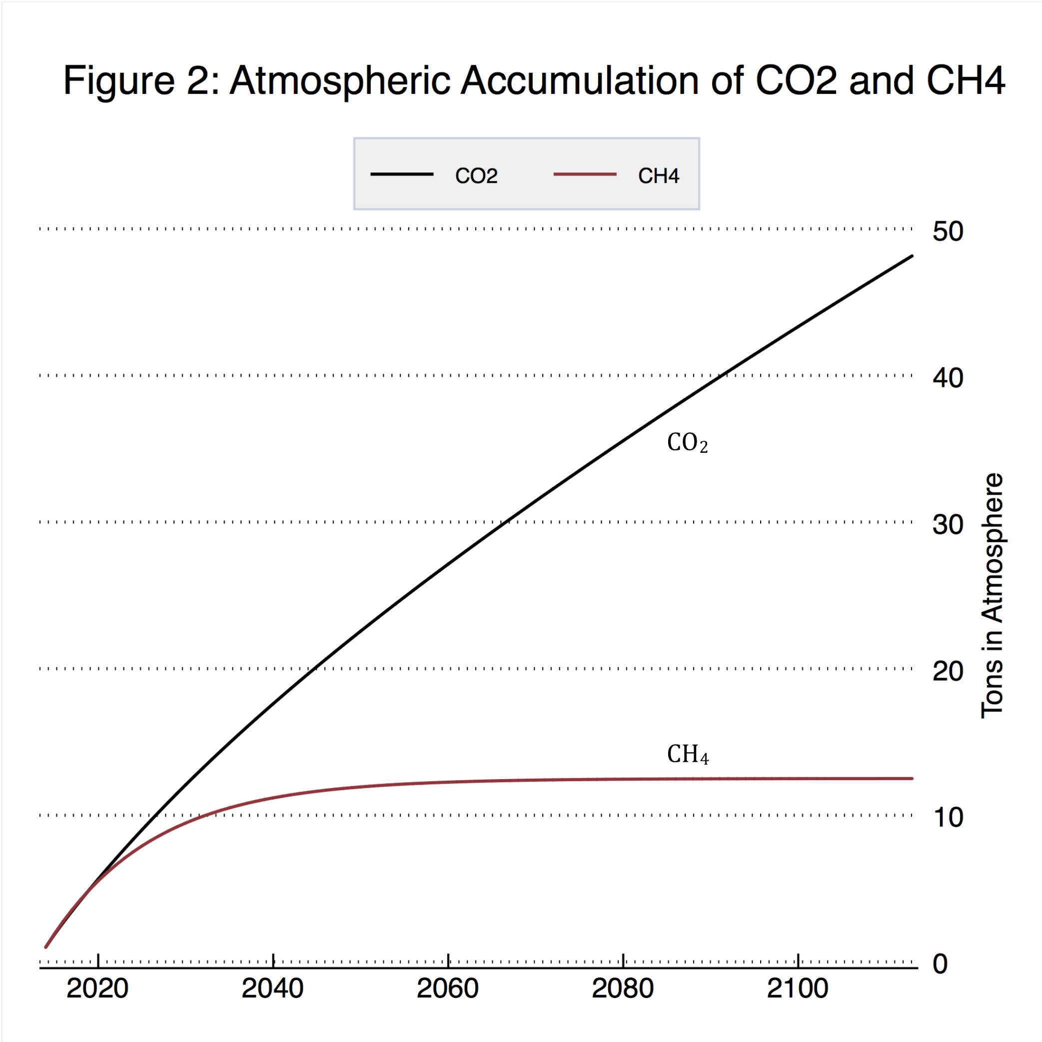
Note that CH_4 decays exponentially, with a mean-life of only 12 years (half-life of 8 yrs), but that CO_2 has a very long tail, represented in the equation by the constant term and by the exponential with the 172.9 year mean life. This long tail is a consequence of the complex carbon chemistry of the ocean [18] discovered by Roger Revelle, i.e. the Revelle effect, and the slow rate of mixing in the ocean.



The time dependence of CO_2 and CH_4 in the atmosphere, assuming a 1-ton pulse injection in 2014. For both CO_2 and CH_4, there is an initial rapid drop. CH_4 continues to fall exponentially, but CO_2 develops a long "tail" and a substantial amount persists for a very long time.

These equations estimate the percent of the initial pulse that remains in the atmosphere after t years, as shown in Figure 1. While about 20% of each gas is removed from the atmosphere during the first 4 to 5 years, the curves diverge sharply after that point. Only 10% of the original CH_4 remains after 30 years, and virtually all of it is gone after 50 years. This short atmospheric residence time is due to CH_4 decomposing and reacting with oxygen to form CO_2 and water vapor. CO_2, on the other hand, remains in the atmosphere until absorbed by the oceans and vegetation. While the upper layer of the ocean absorbs a portion quickly, a sizable portion takes thousands of years to be completely removed [14].

As a result of this behavior, CO_2 tends to accumulate in the atmosphere over time with continued emissions. CH_4, on the other hand, reaches equilibrium after a few decades where the rate of atmospheric decomposition matches the rate of emissions, and will only increase if the rate of emissions increases. This equilibrium is shown by the flattening of the CH_4 curve in Figure 2.



Atmospheric accumulation of CO_2 and CH_4 for nominal emission rates of 1-ton per year. The flattening that takes place for CH_4 is a result of its relatively short lifetime in the atmosphere.

Figure 2 shows the accumulation in the atmosphere of CO_2 and CH_4 if one ton of each is emitted each year over the next 100 years. In this scenario, there are nearly 50 tons of CO_2 remaining in the atmosphere in the year 2113, but only 12.5 tons of CH_4 remaining at the same date. This means that the impact of continued CO_2 emissions will become stronger over time, while the impact of CH_4 will plateau and remain flat. Conversely, ceasing CO_2 emissions will result in a slow reduction in atmospheric concentrations, while CH_4 in the atmosphere will be removed quickly if emissions cease.

The Radiative Forcing of CO_2 and CH_4

CO_2 and CH_4 have very different climate effects, as represented by their respective radiative forcing (in watts per square meter). Atmospheric concentrations of these gases can be used to calculate radiative forcing by using a set of equations derived from radiative transfer models.

For the purposes of this analysis the radiative forcing functions from the latest Intergovernmental Panel on Climate Change (IPCC) report are used. (Our general conclusions, however, do not depend strongly on the nature of the models used.) One simple model of the radiative forcing of an increase of CO_2 in the atmosphere (in parts per million – ppm) is given by [16]:

$$\Delta F_{co_2} = 5.35 \cdot \ln \frac{(P_{co_2} + \alpha_{co_2})}{P_{co_2}}$$

Here P_{co_2} represents the initial concentration of CO_2 in the atmosphere prior to the addition being evaluated, while α_{co_2} repesents the additional CO_2 added for each scenario. For the purposes of this analysis, P_{co_2} is set at 400 parts per million (ppm), the approximate value at the current time.

According to the IPCC, the direct radiative forcing of a given increase of CH_4 in the atmosphere (in parts per billion – ppb) can be approximated by [16]:

$$\Delta F_{ch_4,direct} = 0.036\left(\sqrt{P_{ch_4} + \beta_{ch_4}} - \sqrt{P_{ch_4}}\right) - f\left(P_{ch_4} + \beta_{ch_4},\ P_{n_2o}\right) + f\left(P_{ch_4}, P_{n_2o}\right)$$

where

$$f(M, N) = 0.47\ln(1 + 2.01 \cdot 10^{-5}(MN)^{0.75} + 5.31 \cdot 10^{-15}M(MN)^{1.52})$$

In this equation P_{ch_4} is the initial concentration of atmospheric CH_4, while β_{ch_4} is the addition being evaluated. P_{n_2o} is the initial concentration of nitrous oxide, which is needed as a component of the atmospheric chemistry of CH_4. For this analysis, P_{ch_4} is set to 1800 ppb and P_{n_2o} is set to 320 ppm, reflecting current atmospheric concentrations.

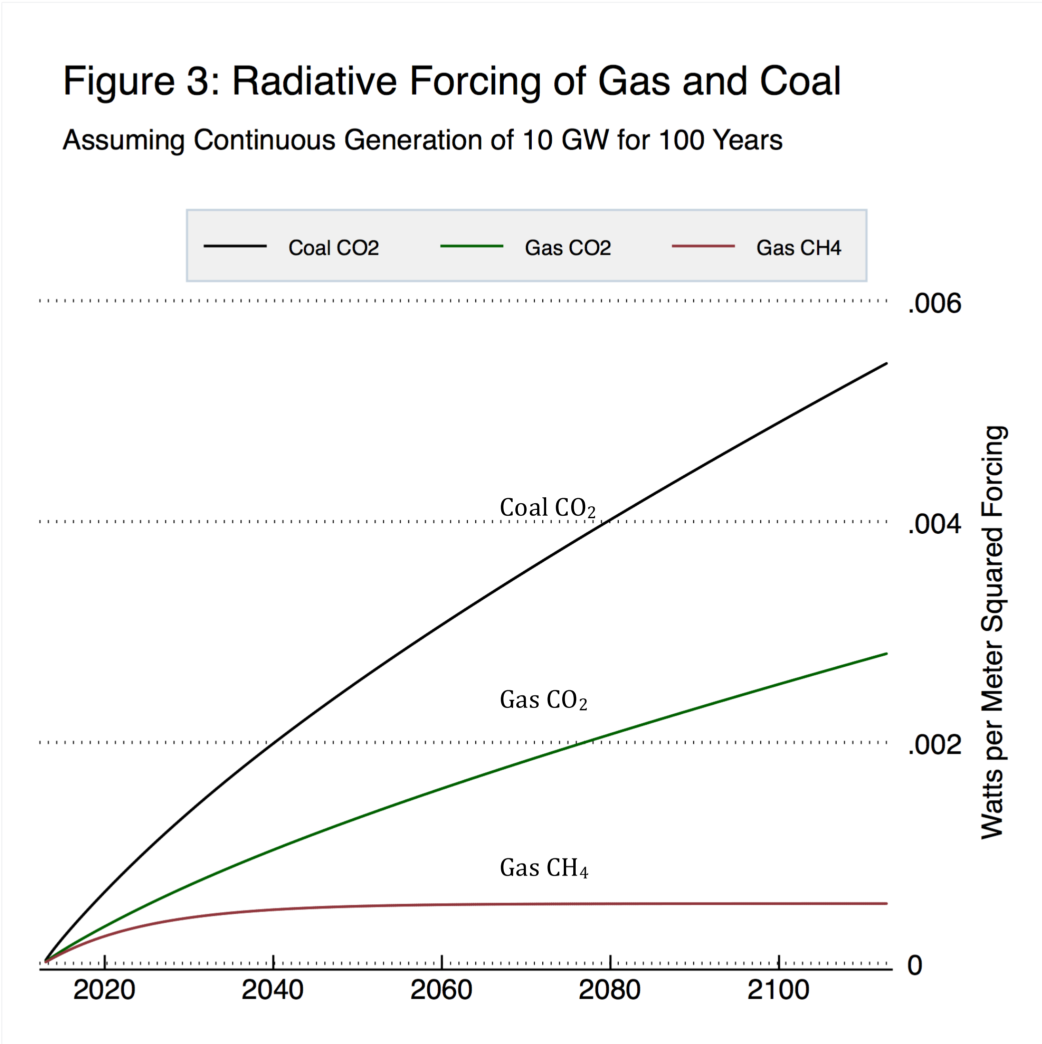
CH_4 emissions are also responsible for indirect radiative forcing due to their secondary effects on tropospheric ozone formation and stratospheric water vapor concentrations [17]. This is a complex process, but based on a recommendation by Drew Shindell (personal communication) we model these secondary effects as multiplying the radiative forcing from CH_4 by roughly 1.5, such that total radiative forcing equals:

$$\Delta F_{ch_4} = 1.5 \cdot \Delta F_{ch_4,direct}$$

Based on these equations, we can calculate that one ton of leaked CH_4 from natural gas operations has roughly 120 times the radiative forcing as a ton of CO_2 in the year that it is leaked. When a ton of CH_4 is burned to generate electricity, it combines with oxygen in the air to produce 2.75 tons of CO_2 (e.g. $CH_4 + 2O_2 = CO_2 + 2H_2O$). This means that a ton of CH_4 leaked has a radiative forcing impact of approximately 44 times that of a ton of CH_4 burned (120/2.75). After 100 years the radiative forcing of that ton of CH_4 is effectively zero, while the ton of CO_2 is still close to 40% of its original radiative forcing.

Comparing Coal and Natural Gas

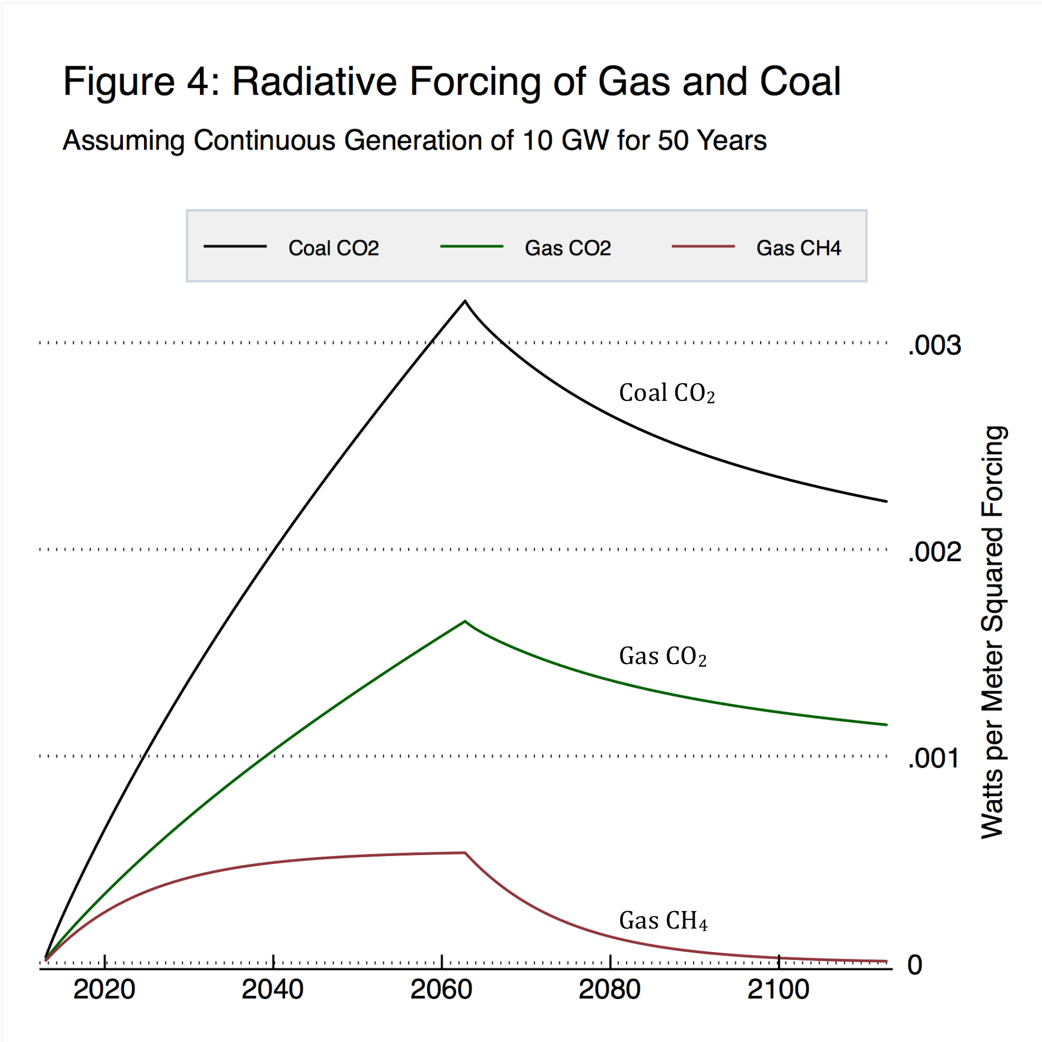
To estimate the relative climate change contribution of coal and natural gas, we examine two different scenarios. Both scenarios compare 10 GW of electric generation using coal to the same generation from natural gas, with an assumed 100% capacity factor. Both scenarios use a coal electric generation efficiency of 43%, a gas generation efficiency of 50%, and a leakage rate of 2% of produced methane. These efficiencies correspond to the average new gas and best available new coal plant entering production today. The carbon content per unit of energy (prior to combustion) is given as 55 grams CO_2 per MJ and 92 grams CO_2 per MJ for coal and gas, respectively [22, 1].



Radiative forcing associated with the production of 10 GW of electric power. Three effects are shown: the upper curves shows the effect of CO_2 from coal plants that have a 43% efficiency; the middle curve shows the CO_2 effect from burning natural gas at 50% efficiency; and the lower curve shows the effect of the fugitive methane, assumed to have a leakage rate of 2%.

In the first scenario, shown in Figure 3, electric generation continues for both fuels for 100 years. In any given year, CO_2 emissions from natural gas are roughly half that of coal due to a combination of lower carbon intensity per energy content and higher electric generation efficiency. CO_2 emissions from natural gas include both direct emissions and indirect emissions due to methane decomposition in the atmosphere.

Forcing due to CH_4 leakage from natural gas is roughly equal to the forcing from gas CO_2 emissions for the first few years, but quickly diverges downwards. After 100 years, the radiative forcing from CH_4 leakage is only 20 percent of the natural gas CO_2 forcing. Overall combined forcings (CO_2 + CH_4) from natural gas are comparable to coal for the first 5 years or so, but about 40% lower than coal after 100 years. For natural gas generation to have the same average radiative forcing as new high-efficient coal generation over the first 20 years would require a leakage rate of over 3%. Over the full century, it would take a leakage rate of 6.1% for natural gas to be worse than new high-efficient coal.

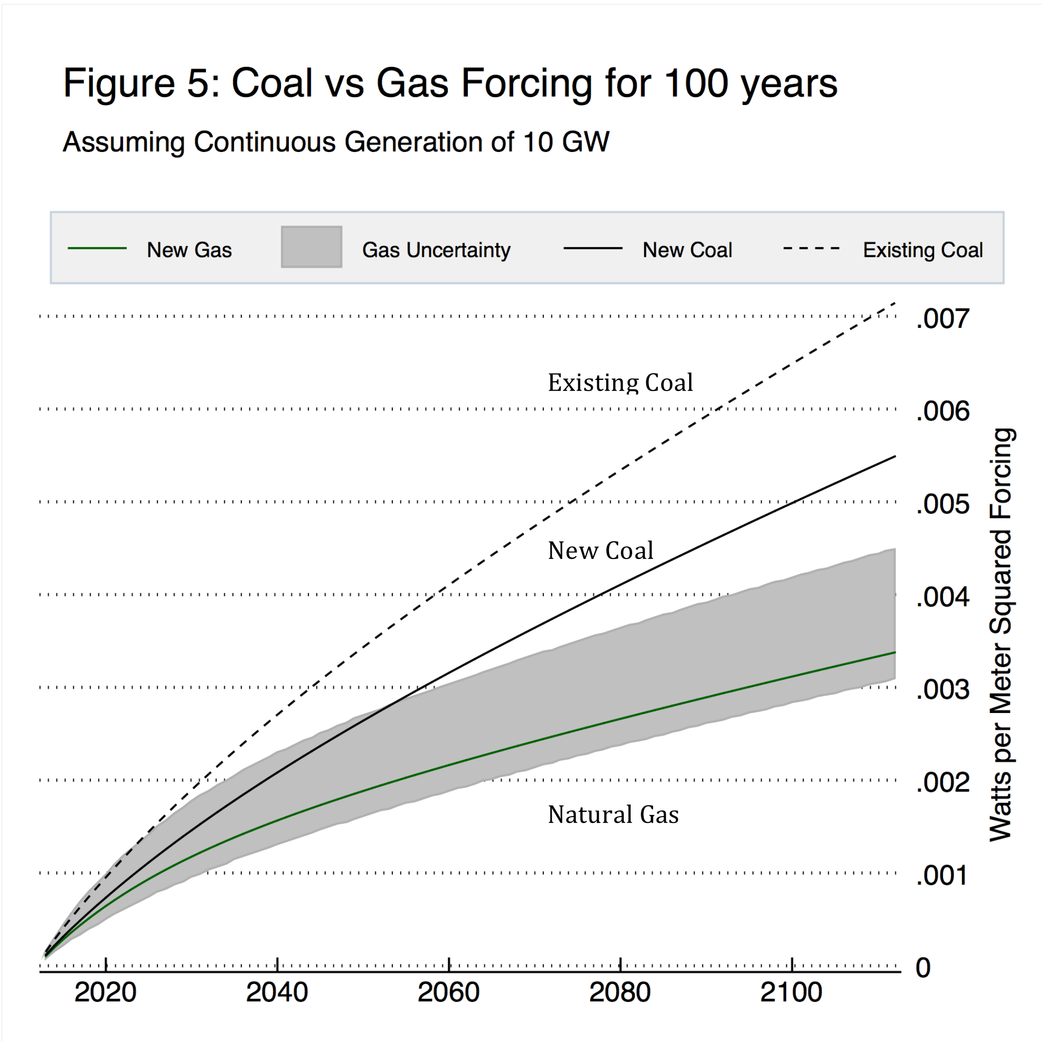


Same as Figure 3, but with a near-zero carbon alternative introduced after 50 years.

In the second scenario, both coal and gas electric generation are discontinued after 50 years and replaced by an assumed near-zero carbon energy source. In this case the atmospheric concentration (and corresponding radiative forcing) of CH_4 declines quickly after natural gas generation stops, while CO_2 slowly declines. By the year 2113 there is almost no forcing remaining from the CH_4 in the atmosphere, and the combined forcing of CH_4 and CO_2 from natural gas is approximately half of the forcing produced from coal.

Accounting for Uncertainties in Leakage and Efficiency

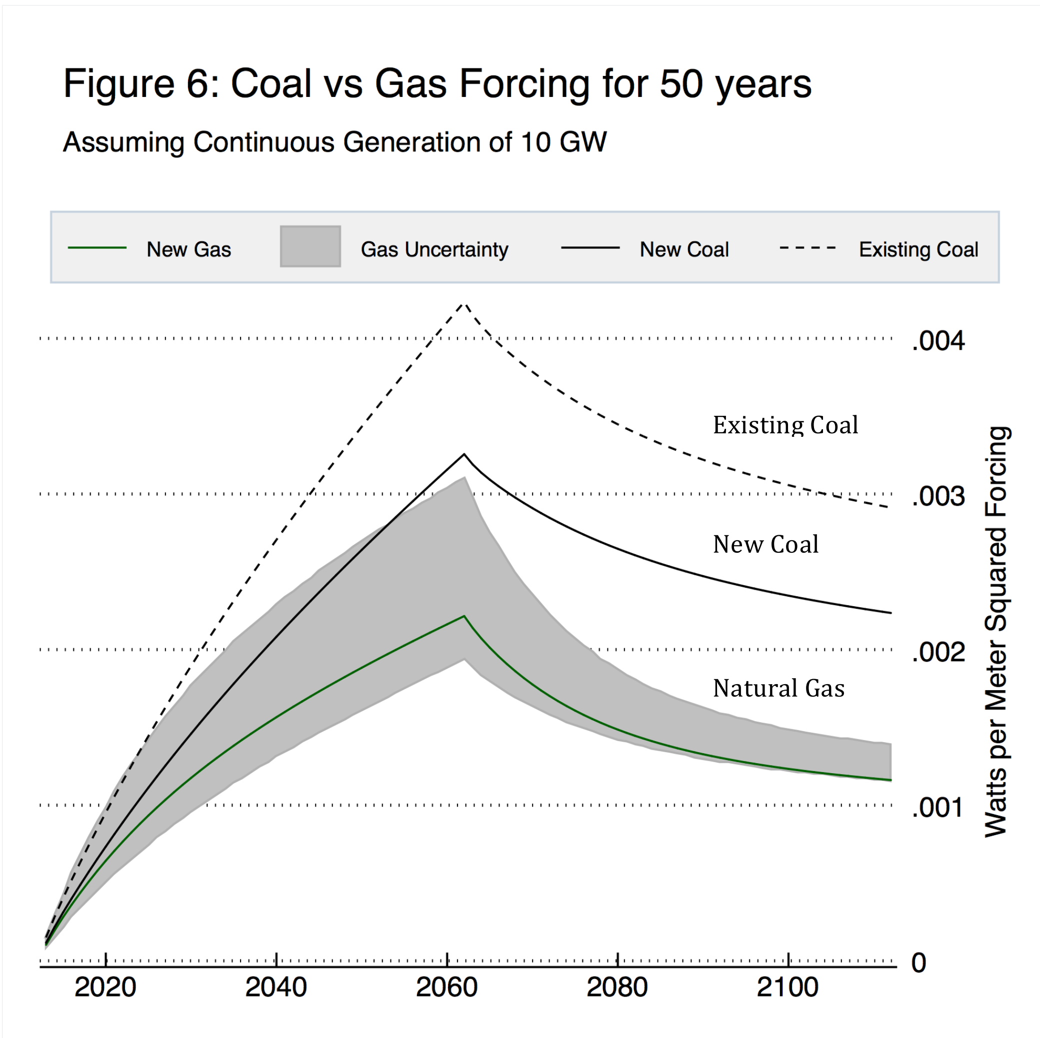
The two scenarios examined previously assumed fixed generation efficiencies and leakage rates for each fuel. In practice, natural gas electric generation efficiencies can range from 42% on the low end to upwards of 50% on the high end. Natural gas leakage is also poorly bounded, with some estimates as low as 1% and others at 4% or more [5]. Coal electric generation efficiency for existing plants is around 33%, but some newer coal plants have achieved efficiencies of up to 43% or more.



Green gas line represents a base case of 2% leakage at 50% electrical generation efficiency. Grey band shows a range from 1% leakage with 50% efficiency to 4% leakage with 42% efficiency. New coal efficiency is assumed to be 43%, while current coal efficiency is 33%.

To account uncertainties in electric generation efficiency and leakage rates, a range of plausable values for both were examined. Figure 5 shows the estimated radiative forcing (in watts per meter squared) for the scenario where both gas and coal electric generation continue for 100 years. The dashed black line represents current coal (at 33% generation efficiency), the solid black line representing the best available new coal (43% generation efficiency), the green line representing the new natural gas base case (50% generation efficiency, 2% leakage), and the gray band showing the range from 42% generation efficiency with 4% leakage at the high end to 50% generation efficiency with 1% leakage at the low end. Figure 5 also includes a small CH_4 forcing from methane released in the course of coal production [13].

In the highest leakage/lowest generation efficiency case, natural gas is still reduces warming at least 20% compared to new coal plants and 38% compared to current coal after 100 years. In the lowest leakage/highest generation efficiency case, natural gas results in 60% less warming than current coal and 50% less warming than new coal after 100 years. It would take a leakage rate of over 4.8% in the worst case (low efficient gas vs. new coal) and over 9.3% in the best case (new gas vs. current coal) for natural gas to have the same average warming as coal over the 100-year period.



Same as Figure 5, but with a near-zero carbon alternative introduced after 50 years.

When gas is used as a bridging fuel away from coal and toward a near-zero-carbon alternative, natural gas use results in even greater reductions in radiative forcing compared to coal. For the best case of 50% efficiency and 1% leakage, new natural gas plants result in a reduction in century-scale average radiative forcing of up to 56 percent compared to current coal , as shown in Figure 6. In this scenario it would take at least 5.9% leakage in the worse case (low-efficiency gas vs. new coal) and 11.5% leakage in the best case (new gas vs. current coal) for natural gas to result in greater average warming than coal over the next 100 years.

The Potential for Natural Gas as a Bridge Fuel

Because CH_4 and CO_2 operate over very different timeframes, the potential benefits of replacing coal with natural gas will depend on the time horizon considered. If we are worried about the effects of climate change more in the near term than in the long term, than the focus would be on reducing CH_4 immediately. However, if we are more concerned about the impacts of climate change 50 to 100 years out, we would emphasize reducing CO_2 emissions and not worry as much about the less persistent CH_4 emissions.

Some economists who study the impacts of climate change on social and natural systems argue that these impacts are highly nonlinear. They suggest that the negative impacts on the world will be relatively modest for less than a degree or two of warming, and that each additional degree of warming would bring significantly more damages [8]. In this case, measures focusing on the longer-term forcing (e.g. post-2050) would be preferred to reducing short-term forcing. If these economists are correct, then likely CH_4 leakage rates should not be as large a concern as CO_2 emissions. The atmospheric concentration of CH_4 can be rapidly reduced simply by reducing CH_4 emissions in the future, while the atmospheric CO_2 we accumulate today will persist for a long time regardless of future emissions [22, 23].

If we focus on the longer-term climate impacts, natural gas has significant potential to serve as a bridge fuel toward a lower carbon future, immediately displacing more carbon-intensive coal-based generation. A rapid transition from coal to natural gas can buy time for the development of near-zero carbon technologies at the scale and cost necessary to meet future energy demands, while reducing century-scale warming by up to 56 percent vis-à-vis coal. Natural gas development in place of coal can also play a significant role in the reduction of air pollution in the developing world, providing an additional incentive to prioritize a rapid transition away from coal [24].

Ultimately natural gas is still a fossil fuel, and its combustion and leakage contribute to global warming. However, even if leakage rates are higher than currently estimated, a rapid transition from coal to natural gas would still result in a significant reduction in warming, especially over longer timeframes. Leakage rates are a problem that can be cost-effectively addressed with technology and better monitoring, while reducing the carbon emissions from coal-fired generation is likely to prove much more difficult and costly. In a world where a cost-competitive near-zero carbon energy source is not readily available, particularly in developing countries, replacing coal electric generation with natural gas could provide an effective strategy to mitigate climate change and reduce harmful air pollution.

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