Climate benefits of natural gas as a bridge fuel and potential delay of near-zero energy systems

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highlights
• Substituting natural gas for coal power plants may confer climate benefits.
• Delays in deploying low-emission power could offset climate benefits of natural gas.
• Natural gas may reduce CO2 emissions, yet result in additional near-term warming.
• Natural gas leakage and plant efficiencies affect relative benefits of gas vs. coal.

ABSTRACT

Natural gas has been suggested as a "bridge fuel" in the transition from coal to a near-zero emission energy system. However, the expansion of natural gas risks a delay in the introduction of near-zero emission energy systems, possibly offsetting the potential climate benefits of a gas-for-coal substitution. We use a schematic climate model to estimate CO2 and CH4 emissions from integrated energy systems and the resulting changes in global warming over various timeframes. Then we evaluate conditions under which delayed deployment of near-zero emission systems would result in loss of all net climate benefit (if any) from using natural gas as a bridge. Considering only physical climate system effects, we find that there is potential for delays in deployment of near-zero-emission technologies to offset all climate benefits from replacing coal energy systems with natural gas energy systems, especially if natural gas leakage is high, the natural gas energy system is inefficient, and the climate change metric emphasizes decadal time scale changes.

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1. Introduction

Substituting new natural gas energy systems for new (or planned) coal energy systems could potentially facilitate near term reduction in greenhouse gas emissions, and act as a bridge to some future near-zero emission energy systems [1–6]. Others have argued that such introduction of natural gas energy system would confer little or no climate advantage [6–11] and could even be counterproductive from a climate perspective [12–15]. Studies considering economic feedbacks have concluded that lower natural gas prices could lead to increased energy consumption and reduced deployment of near-zero emission energy systems [10,20]. Brouwer et al. analyzed operational flexibility and economics of power plants in future low-carbon power systems [21]. Gorbacheva and Sovacool reviewed the risks and rewards of investing in coal-fired electricity [22]. Sanchez and Mays’ study indicated that leakage control is essential for natural gas to deliver a smaller GHG footprint than coal [23]. Qadrdan et al. discussed the impact of transition to a low carbon power system on the gas network [24]. Tokimatsu et al. suggested that zero emissions scenario may be possible in this century [25]. For additional literature reviews, please see S1 of the SOM section.

Concerns have been raised [13,14] that the expansion of a natural gas infrastructure could potentially delay the introduction of near-zero emission energy systems, and that this delay could offset possible advantages that might otherwise accrue from using natural gas as a bridge fuel.

We focus on climate effects of greenhouse gas emissions from coal and natural-gas based electricity production. In this study, we define a breakeven operational period as the time period of

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natural gas usage that results, according to the chosen climate metric, in an equivalent climate effect as the reference coal case. For more details on the breakeven analysis, please see S2 of the SOM section. As a shorthand, we use the word 'better' to refer to deployments that would result in lower values on temperature change, radiative forcing, or cumulative emission metrics; we use 'worse' to refer to deployments that would result in higher values for these metrics. (If a deployment is 'better', we say there is a 'benefit' from that deployment relative to the alternative.) In our scenarios, if the natural gas energy system is operated longer than the breakeven period, then the climate consequences of the operation of the natural gas energy system will be worse than those from the operation of the reference coal energy system for the 40 year period considered here (Fig. 1). The time evolution of global mean temperature change for coal and gas over a 100-year period are shown in Fig. 2. Temperature changes projected for the operation of different coal and natural-gas energy systems, and different upstream natural gas leakage rates, can be found in Figs. 3 and 4, along with an estimate of the breakeven operational period for natural gas energy systems (see Fig. S1 for a version of Fig. 2 with construction/building period greenhouse gas emissions considered).

2. Methods
2.1. Energy system GHG emissions

The energy systems considered in this study are natural gas energy systems, coal energy systems and near-zero emission energy systems with capacity of 1 GW. Most of the life cycle GHG emissions from fossil fuel (coal and natural gas) energy systems occur during the operational period and not the construction period [6,26,27]. Therefore, in the main part of this paper, we consider emissions only during the operational period (the construction phase is presented in Fig. S1). The major emissions from natural gas and coal electricity generation are CO2 and CH4 [11]. SO2 and NOx can be well-controlled during energy system operation [28,29]. The thermal energy released from the combustion of fossil fuels is very smaller than the radiative forcing from CO2 [30]. Our study focuses on greenhouse gas emissions. Life-cycle analysis (LCA) data for all scenarios of natural gas and coal energy systems are provided in Zhang et al. [11]. Annual GHG emissions of fossil fuel energy systems are calculated by energy system GHG emissions models, which is a submodel in the simple energy system and climate model (SEGCM) as described in [11]. This model estimates CO2 and CH4 emissions from natural gas energy systems based on energy system efficiency and natural gas leakage rate.

For natural gas energy systems [11], annual CO2 emissions are represented by

\[
E_{\text{ng CO2}} = \frac{\text{molpc}_c \cdot R_{\text{leak}} \cdot \text{molpc}_t}{1 - R_{\text{leak}}} \cdot \frac{\text{Molmass}_{CO2}}{\text{Molmass}_{ng}} \cdot \frac{\text{Electr}_{ng}}{\text{HV}_{ng} \cdot \eta_{ng}}
\]

and annual CH4 emissions are represented by

\[
E_{\text{ng CH4}} = \frac{R_{\text{leak}} \cdot \text{molpc}_t}{1 - R_{\text{leak}}} \cdot \frac{\text{Molmass}_{CH4}}{\text{Molmass}_{ng}} \cdot \frac{\text{Electr}_{ng}}{\text{HV}_{ng} \cdot \eta_{ng}}
\]
For coal energy systems [11], annual CO2 emissions are represented by

$$E_{\text{coal CO2}} = \text{masspct}_{C_{\text{coal}}} \times \left( \frac{\text{Molmass}_{\text{CO2}}}{\text{Molmass}_{C}} \right) \times \left( \frac{\text{Electr}_{\text{coal}}}{\text{HV}_{\text{coal}} \times \eta_{\text{coal}}} \right), \quad (3)$$

and annual CH4 emissions are represented by

$$E_{\text{coal CH4}} = \text{rate}_{\text{CH4/CO2 coal}} \times E_{\text{coal CO2}}, \quad (4)$$

where molpct$_{C_{\text{ng}}}$ is molar carbon per molar natural gas; masspct$_{C_{\text{coal}}}$ is the mass percent of carbon in coal; $R_{\text{leak}}$ is natural gas leakage rate; rate$_{\text{CH4/CO2 coal}}$ is the ratio of CH4 emissions to CO2 emissions from coal mining; molpct$_{\text{CH4/CO2}}$ is the molar fraction of methane in natural gas; Molmass$_{\text{CO2}}$, Molmass$_{C}$, Molmass$_{\text{CH4}}$, Molmass$_{\text{ng}}$ are molar masses of CO2, CH4, carbon and natural gas; Electr$_{\text{ng}}$ and Electr$_{\text{coal}}$ are 1 GW; HV$_{\text{ng}}$ and HV$_{\text{coal}}$ are heating value of natural gas and coal; $\eta_{\text{ng}}$ and $\eta_{\text{coal}}$ are the efficiencies of natural gas and coal power plants [11]. Thermal efficiency for a typical and the best coal energy system are 34.3% and 51%, and the values for a typical and the best natural gas energy system are 40.3% and 60% [31]. It should be noted that the “best” coal system was a research facility operated for a brief period and was not a commercial deployment [31]. Natural gas leakage rate data were taken from [9,15,27,32–34]. For more details of the model used and definitions of specific terms, see [11].

2.2. Climate model

The climate model used here is described more fully in Zhang et al. [11]. We apply the Joos et al. [35] parameter of the CO2 impulse response function and Prather et al. [36] parameters of the CH4 impulse response function to estimate atmospheric greenhouse gas concentrations. Radiative forcing (RF) is calculated using equations from IPCC Assessment Report [37]. Global mean temperature changes ($\Delta T$) are estimated from the RF by using a simple energy balance model that represents the effective heat capacity.
of the climate system as a simple box-diffusion model, as described in [38].

\[
\frac{\partial T}{\partial t} = k_c \frac{\partial^2 T}{\partial z^2} \tag{5}
\]

\[
\left. \frac{\partial T}{\partial z} \right|_{z=0} = \frac{\lambda \Delta T - RF(t)}{\rho C_v F_p} \tag{6}
\]

\[
\Delta T(t)_{100} = 0 \tag{7}
\]

\[
\left. \frac{\partial T}{\partial z} \right|_{z=z_{\text{net}}} = 0. \tag{8}
\]

Model parameters were chosen to mimic median results from the Climate Model Intercomparison Project phase 5 (CMIP5) [38]. The climate sensitivity parameter (\(\lambda\)) is 1.051. The ratio of adjusted radiative forcing to the classical radiative forcing derived from the IPCC formula is 0.775. The thermal diffusivity (\(k_c\)) is 4.24 \times 10^3 \text{ m}^2/\text{s}.

2.3. Climate change metrics

Equivalent carbon dioxide emissions (CO2eq) are defined using a weighted sum of CO2 (\(E_{\text{CO2}}\)) and CH4 (\(E_{\text{CH4}}\)) emissions:

\[
\text{CO2eq} = E_{\text{CO2}} + \text{GWP} \times E_{\text{CH4}}. \tag{9}
\]

GWP is 100-year global warming potential from IPCC AR5 [39]. For one of our metrics, we use cumulative CO2eq emissions over a 100-year time horizon (CO2eq100).

We also use a time-averaged radiative forcing metric (\(RF\)) which at time \(t\) is

\[
RF(t) = \frac{1}{t} \int_0^t RF(t) dt. \tag{10}
\]

where \(RF\) is the radiative forcing predicted by the SECGM model [11].

Further, we use the time-averaged temperature change metric (\(\Delta T\)), which is the time-average temperature change in time and calculated as

\[
\Delta T(t) = \frac{1}{t} \int_0^t \Delta T(t) dt. \tag{11}
\]

2.4. Scenarios

We evaluate multiple scenarios of natural gas used as a bridge fuel against a reference coal scenario. Our reference coal scenario involves the continued operation of a coal energy system (for \(N\) more years) followed by a transition to a near-zero GHG emission energy system (top bar in Fig. 1). All considerations of “delays” refer to additional years added between this otherwise immediate transition from the coal energy system to the near-zero GHG emission energy system. In the natural gas scenarios used in this study, coal energy systems are immediately replaced by natural gas energy systems but then operated an additional period (of \(D\) years) beyond when the reference coal energy system is retired (for a total natural gas energy system operation period of \(N + D\) years) followed by an immediate transition to near-zero GHG emission energy system (two bottom bars in Fig. 1). We quantitatively compare an \(N\)-year reference coal energy system with an \((N + D)\)-year natural gas energy system by evaluating the breakeven operational period of various natural gas energy systems across several 20-year, 100-year and 500-year time-scale climate metrics (e.g., \(\Delta T_{20}, \Delta T_{100}, \Delta T_{500}, RF_{100}\) and CO2eq100).

We define a breakeven operational period is the operational period of a natural gas energy system that, according to the chosen climate metric, results in an equivalent climate effect as the reference coal case over a 100-year period. We compared several natural gas energy systems, simulating varying natural gas leakage rates and natural gas energy system efficiencies, to our reference coal cases by estimating their effect on global mean temperature. We then evaluate how many years earlier or later natural gas energy system could alter the transition to a near-zero-emission energy system while providing an equivalent climate effect as the reference coal case. We examine how this delay changes with the choice of climate metric and timeframe.

3. Results

3.1. The impact of time horizon

The climate impact of coal vs. natural gas is strongly dependent on the choice of time horizon (20, 100, or 500 years). Because methane (the main component of natural gas), mole for mole, acts as a much stronger greenhouse gas than carbon dioxide but for a much shorter amount of time [40], climate change metrics that emphasize the near term (e.g., 20 years) tend to give greater weight to methane relative to CO2 than do climate change metrics that emphasize the long term (e.g., 500 years). Thus, metrics that emphasize shorter time scales tend to place more emphasis on the importance of achieving low natural gas leakage rates, whereas metrics that emphasize longer time scales tend to place more importance on efficient using of low-carbon-intensity fuels. As shown in Fig. 4, if the primary concern is climate benefit over the first 20 years, then the evaluation of relative merits of natural gas versus coal energy systems depends primarily on the natural gas leakage rate. For the lowest leakage rate case we considered, 0%, the breakeven delay is 60 years or longer (0% is only used for a theoretical analysis and is not intended to represent an achievable leakage rate). Conversely, for the highest leakage rate case we considered, 6%, the breakeven delay is less than –30 years (6% is the mean high-value of recent published data) [8,9,34,41,42], meaning transitional energy systems must be shut down more than 30 years before the comparable coal energy systems. However, if the emphasis is on climate conditions several centuries into the future, then the breakeven delay appears to be relatively insensitive to natural gas leakage rate, giving relatively similar breakeven delays across all leakage rates considered.

3.2. The impacts of climate metrics

For the climate change metrics considered here (global warming potential, GWP; mean radiative forcing; and mean temperature change; Fig. 3), the time period over which metric is assessed is far more important than whether radiative forcing or temperature change is the metric being evaluated (Figs. 3 and 4). This makes sense when viewed in light of previous findings that over half of the equilibrium climate change occurs within the first decade after a change in radiative forcing [38]. This tells us that temperature change closely tracks radiative forcing but with some delay. Thus, results using a temperature metric are similar to the results that would be obtained with a radiative forcing metric evaluated with a time horizon that is approximately one decade longer. Results using an equivalent CO2 metric based on 100-year GWP values (Fig. 3) have a longer effective time horizon. Since the 100-year GWP measure considers radiative forcing up to 100-years after the time of the emission, for an energy system that operates for 40 years radiative forcing effects would be considered out to year 140. In the case with zero natural gas leakage, shorter time
horizons emphasize the operational period of the reference coal energy system, and thus predict longer breakeven delays for the operation of the natural gas energy system. Longer horizons emphasize the time after the breakeven delay, when the warming from the extended operation of natural gas energy system exceeds the warming caused by the 40-year life of the coal energy system (Figs. 2 and 4). Changing from temperature-based, to radiative-forcing-based, to GWP-based metrics (Fig. 3) acts to lengthen the effective time horizon under consideration.

3.3. The impacts of reference scenarios

The generation efficiency of the reference coal energy system impacts the degree to which the introduction of near-zero-emission energy systems could be delayed without losing any net climate benefit from using natural gas as a bridge fuel. Break-even delay occurs earlier with a more efficient reference coal energy system than with a less efficient reference energy system (Figs. 2–4). Some of the apparent disagreement among prior studies was due to the fact that different studies assumed different reference coal energy systems [1,6,12,43,44]. The appropriate reference energy system depends on the particular situation under consideration. If the focus is on replacing an existing coal energy system with a natural gas energy system, then the appropriate efficiency of the coal energy system should be the actual energy system efficiency, which we represent schematically here as the world “typical” coal energy system efficiency of 34.3% [31]. If the natural gas energy system under consideration is a high-efficiency modern natural gas energy system, then the “best” natural gas energy system efficiency of 60% [27] may be an appropriate point of comparison. However, if a new energy system is considered being built today, it could potentially be either a high efficiency natural gas energy system (60%) or a high efficiency coal energy system (51%) [26]. In this case, it could be appropriate to compare the high-efficiency natural gas energy system against a high-efficiency coal energy system. Breakeven delays for these comparisons are shown in Figs. S2 and S3.

4. Discussion and conclusions

Concern has been expressed that the expansion of natural gas infrastructure could delay the introduction of near-zero emission energy systems such as solar, wind, or nuclear power (Figs. 3 and 4). When natural gas leakage rates are high, the natural gas energy system is inefficient, and the coal energy system is efficient, there is no near-term advantage to replacing coal energy systems with natural gas energy systems (Figs. 2 and S1). Using metrics that average temperature or radiative forcing change over a 100-year period starting at the time of energy system operation, we find that when a typical coal energy system that would otherwise be utilized for 40 years is replaced by the highest efficiency natural gas energy system, with a 4% natural gas leakage rate, the introduction of near-zero emission energy systems can be delayed more than 24 additional years without producing additional century-averaged warming; however, in this scenario the natural gas energy system would produce more warming than the coal energy system during its 40 years of operation (Fig. 2). Thus, there are circumstances in which natural gas may be offered as a bridge fuel to produce near-term CO₂ emissions reductions, yet result in additional near-term warming.

It has been suggested that preventing “dangerous anthropogenic interference with the climate system” [45] would require emission reductions of 80% by year 2050. The use of natural gas cannot directly result in emission reductions of this magnitude. While there is some potential to produce modest reductions in the amount of climate change by substituting inefficient coal energy systems with efficient natural gas energy systems, the potential for natural gas to reduce greenhouse gas emissions is limited. Even this limited potential for benefit from expanded natural gas deployment could be eroded if the expanded natural gas deployment delays introduction of near zero emission energy systems.

This study focuses on the climate impacts of bridge fuel on the deployment of near-zero emission energy systems by analyzing the maximum delay (“breakeven delay”) that could occur without losing all climate benefit from using natural gas as a bridge fuel. Our study shows net climate benefit from using natural gas as a bridge fuel can be achieved even with delays in introduction of near-zero emission systems, especially, when the coal energy system is inefficient; the natural gas energy system is efficient; the natural gas leakage rate is low; and the evaluation time horizon is longer. However, transition to natural gas (in the absence of other companion system such as carbon capture and storage) cannot provide the deep reductions in greenhouse gas emissions needed to “stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.” If the introduction of natural gas substantially delays the transition to near-zero emission systems, there is potential that the introduction of natural gas could lead to greater amounts of warming than would have occurred otherwise.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2015.10.016.

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