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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 CO_2 emissions, yet result in additional near-term warming.
- Natural gas leakage and plant efficiencies affect relative benefits of gas vs. coal.

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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 CO_2 and CH_4 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.

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]. The coal-based energy system largely dissipates carbon dioxide and other pollutants [16–19]. 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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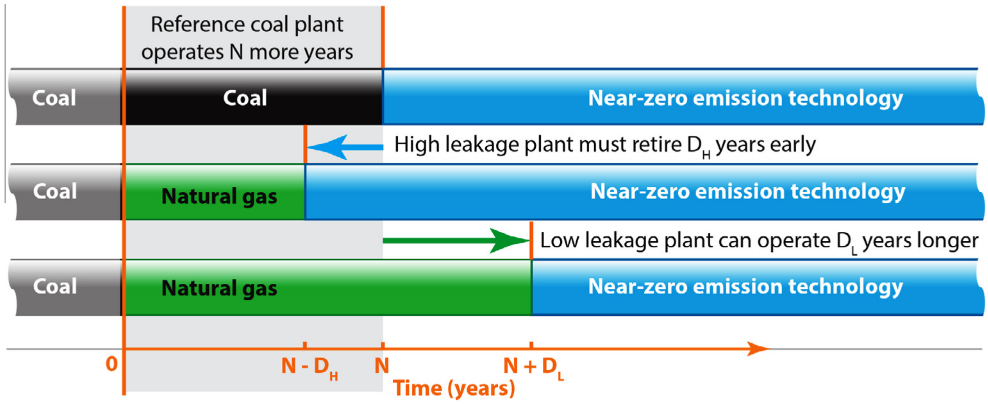

Fig. 1. Concept diagram for transitions from coal energy system to near-zero emission energy systems. For simplicity, we focus on a reference coal energy system with an additional *N*-years of operating life (*N* is 40 in this study), and a natural gas energy system that is either retired D_H years earlier than the reference period, or D_L years later than the reference period. After these operational periods, we assume these energy systems are replaced by an idealized near-zero-emission energy system. In our work, depending on the specific characteristics of the natural gas and coal energy systems, and the climate metric chosen, we find the values for D_H or D_L that would cause the natural gas system to be no better or worse than the coal system (the "breakeven" time). D_L would then represent the maximum delay that could occur in the deployment of near-zero emission technology without losing all benefit from the use of natural gas.

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

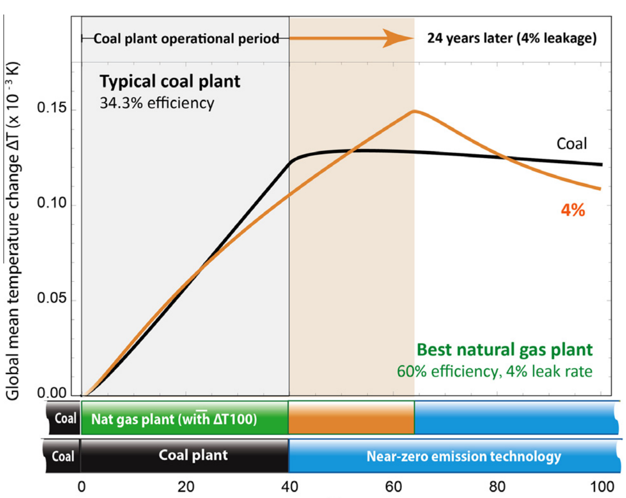

Fig. 2. Global mean warming from the most efficient natural gas and the most efficient and world typical efficiency coal energy systems operating at 1 GWe. We show the breakeven operational period of natural gas energy systems using $\overline{\Delta T}100$, the average temperature change over the 100 year period. The natural gas energy system operating for 64 years, with a 4% natural gas leakage rate (Zhang et al. [11]), produces the same amount of warming averaged over the century as the coal energy system operating for 40 years. This indicates that, using this metric in this example, the transition to natural gas energy system could delay introduction of near-zero emission energy systems by 24 years without losing all of the climate benefits of shifting from coal to natural gas energy system.

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 CO_2 and CH_4 [11]. SO_2 and NO_x 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 CO_2 [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 CO_2 and CH_4 emissions from natural gas energy systems based on energy system efficiency and natural gas leakage rate.

For natural gas energy systems [11], annual CO_2 emissions are represented by

$$E_{ng\cdot CO_2} = \left[\frac{molpct_{C/ng} - R_{leak} * molpct_{CH_4/ng}}{1 - R_{leak}}\right] * \left[\frac{Molmass_{CO_2}}{Molmass_{ng}}\right] * \left[\frac{Electr_{ng}}{HV_{ng} * \eta_{ng}}\right]; \quad (1)$$

and annual CH_4 emissions are represented by

$$E_{ng\cdot CH_4} = \left[\frac{R_{leak} * molpct_{\frac{CH_4}{ng}}}{1 - R_{leak}}\right] * \left[\frac{Molmass_{CH_4}}{Molmass_{ng}}\right] * \left[\frac{Electr_{ng}}{HV_{ng} * \eta_{ng}}\right]. \quad (2)$$