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Letter

Contribution of Regionalized Methane Emissions to Greenhouse Gas Intensity of Natural Gas-Fired Electricity and Carbon Capture in the United States

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ABSTRACT: Natural gas is a fossil fuel primarily comprised of methane, a powerful greenhouse gas. As such, both combustion and direct atmospheric emissions of natural gas contribute to climate change. Natural gas supply chain methane emissions vary substantially based on extraction region and processes, such that natural gas end users experience very different lifecycle greenhouse gas intensities even for similar uses. Methane emissions have relevant implications for decarbonization pathways that use natural gas to generate electricity (with or without carbon capture) or remove carbon dioxide from the atmosphere. This Letter combines state-specific estimates of the methane emissions intensity of natural gas supplies with generator-level modeling to estimate the contribution of methane emissions to the greenhouse gas intensity of natural gas-fired electricity and carbon capture in the United States. For existing electricity generation, state-specific methane emissions factors are matched to individual natural gas-fired generators to estimate the [minimum, maximum] range for the carbon dioxide equivalent contribution of methane (100-year global warming potential = 29.8) relative to direct carbon dioxide emissions by balancing authority ([15%, 48%]), utility ([13%, 48%]), and the North American Electric Reliability Corporation region ([16%, 36%]). Methane emissions constrain the greenhouse gas avoidance or removal potential of natural-gas-fired carbon capture.

■ INTRODUCTION

Decarbonization targets in the United States (U.S.) increasingly include "net zero" language allowing for a combination of positive- and negative-greenhouse gas (GHG) activities that collectively result in zero overall GHG emissions.[1,2] Net zero emissions targets are particularly salient in the context of the ongoing use of fossil fuels, especially natural gas, for limited applications like flexible backup power.[3] Natural gas currently fuels about 40% of U.S. electricity generation,[4] with ongoing construction of new units,[5] and future energy systems could be designed to include natural gas with carbon capture and storage (CCS)[6,7] or natural gas-fired direct air capture (DAC).[8] One major challenge, however, is that natural gas is both a fossil fuel that produces carbon dioxide (CO_2) on combustion and is itself primarily a GHG (methane, CH_4) that contributes to climate change if it enters the atmosphere.[9] Research suggests that CH_4 emissions are underestimated in official records[10−14] and are sufficiently high to make meaningful contributions to the GHG intensity of natural gas use,[10] though allocation remains challenging.[15]

Decarbonization policy focused on combustion emissions[16] misses climate-relevant natural gas supply chain CH_4 emissions. Although CH_4 emissions could theoretically be mitigated[17−19] with rapid climate benefits,[20] understanding CH_4's role in GHG intensity of natural gas-fired activities is decision-relevant when committing to new natural gas facilities that could be stranded by GHG policy[21] without careful attention to emissions. Particularly given regional variability in CH_4 emissions from the natural gas supply,[13,14,22,23] natural gas' role in decarbonization could be highly context dependent. This Letter addresses the research question: what are the implications of CH_4 emissions for the GHG intensity of natural gas-fired electricity, future natural gas with carbon capture, and natural gas-fired DAC in the U.S.?

■ MATERIALS AND METHODS

U.S. methane emissions associated with natural gas-fired power generation (with and without CCS) and DAC are modeled at the unit level, based on basin-level estimates of the CH_4 intensity of natural gas supplies to industrial users, aggregated to the state

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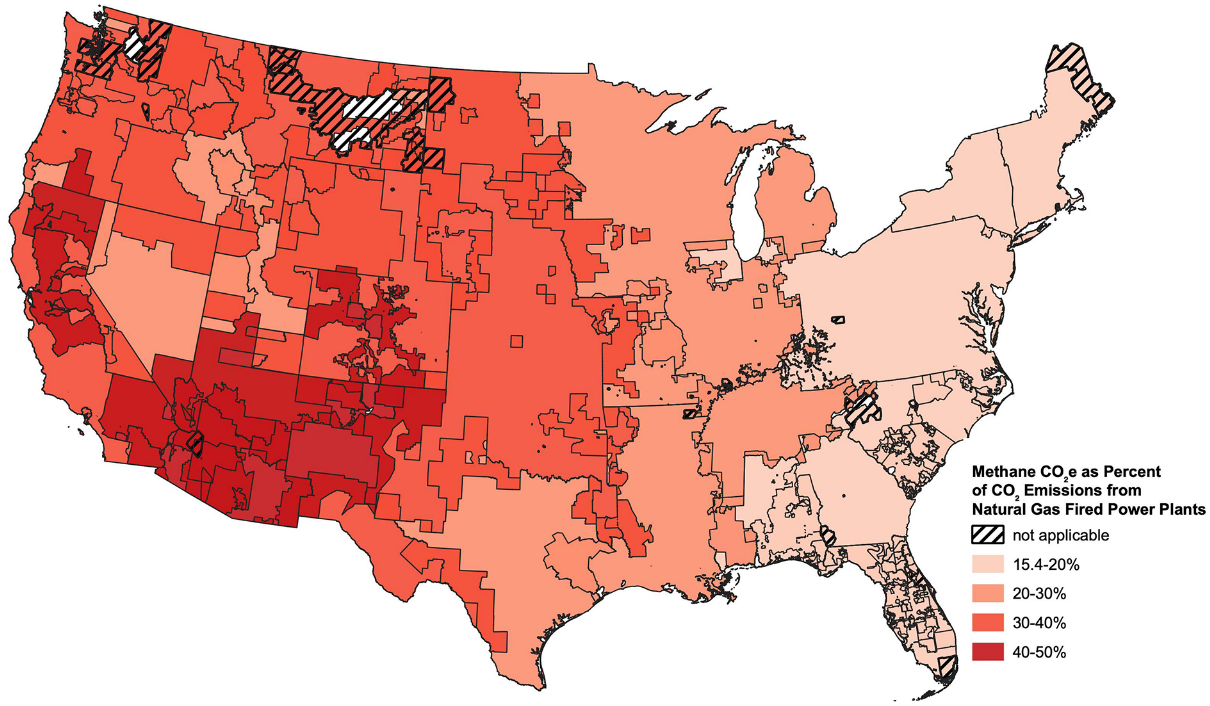

Figure 1. Natural gas supply related CO_2e (GWP-100 = 29.8) emissions from CH_4 as a proportion of direct CO_2 emissions by natural gas fleets by balancing authority (note some balancing authorities overlap in space).

or national level.[10,22,24] Analysis focuses on two main outputs: evaluation of supply chain CH_4 as a proportion of GHG emissions for (1) existing (2019) natural gas-fired electricity and (2) hypothetical future natural gas-fired carbon capture activities (CCS and DAC). This section describes the modeling approach and analytical assumptions (see Supporting Information for the full model).

For existing natural gas-fired electricity, GHG emissions were modeled at the generator level using best-available CO_2 and CH_4 emissions factors. Generator-level combustion CO_2 emissions were taken from the 2019 Federal Emissions & Generation Resource Integrated Database (eGRID)[25] where available (~25% of modeled CO_2 emissions) and estimated as the product of the Energy Information Administration (EIA)'s natural gas emissions factor[26] and estimated generator-level fuel consumption otherwise (~75% of modeled CO_2 emissions). Some records suggest unusual ratios between natural gas consumption and combustion emissions, potentially due to interactions among gross and net generation. This work assumes EIA and eGRID data are correct unless stated otherwise.

Supply chain CH_4 emissions are not available as a federal data product. Thus, as for the majority of the CO_2 emissions estimates, generator-level supply chain CH_4 emissions were estimated as the product of a best-available consumer-level emissions factor and estimated generator-level fuel consumption. Production-stage CH_4 emissions factors were taken from a data set generated using 2018 pipeline flows and trade relationships to derive a basin-level natural gas supply fuel mix for each state.[22] Like electricity consumers (but unlike many coal consumers), natural gas consumers draw from a blended supply rather than one or a few specific production resources. Underlying basin-level emissions intensity[27] has a 2015 base year; the 2.5% of natural gas consumed in the U.S. but produced in Canada is assigned nearest-neighbor emissions intensity from U.S. basins.[22] See Burns and Grubert,[22] especially Figure 3 and the Data File, for details. Processing, transmission, and storage CH_4 emissions were estimated at 0.5% (mass emitted/mass withdrawn).[10,24]

To associate emissions to generators, then to organizing units relevant for grid planning and regulation, data from EIA Forms 860,[28] 861,[29] and 923[30] (2019 base year) were associated with records for natural gas-fired generators operable as of 2019. These data were the natural gas-based heat rate (natural gas electricity fuel per net generation, based on fuel- and prime-mover-level fuel consumption data by plant) and generation (used to infer fuel consumption); ownership (whole and partial); and organizing units [utilities, which sell electricity; North American Electric Reliability Corporation (NERC) regions, which oversee electricity reliability; and balancing authorities, which manage power grid operations].

Given the importance of estimated fuel consumption for assigning GHG emissions, records for which fuel consumption estimates are not robust were removed. All records for natural gas units with a 2019 production of less than 8760 megawatt-hours (MWh)/year [i.e., continuous 1 megawatt (MW) output] were removed (~1500 units), as were records for units without an identifiable heat rate (74 units). Combined cycle units share fuel, so physically impossible heat rates were preserved for the steam component of combined cycle units, but other heat rates below 3412 British thermal units (btu) per kilowatt-hour (kWh), the heat rate implying 100% thermal efficiency, were eliminated (seven units). Other unusually low heat rates (<6,824 btu/kWh, or 50% thermal efficiency) were spot checked (607 units). The vast majority were combined heat and power units not owned by utilities, suggesting that heat not derived from new natural gas fuel inputs might have contributed to generation and thus, under this work's definition of heat rate (natural gas fuel per net generation), such heat rates were plausible. Records for Alaska and Washington, DC (44 units) were removed due to a lack of CH_4 emissions data.

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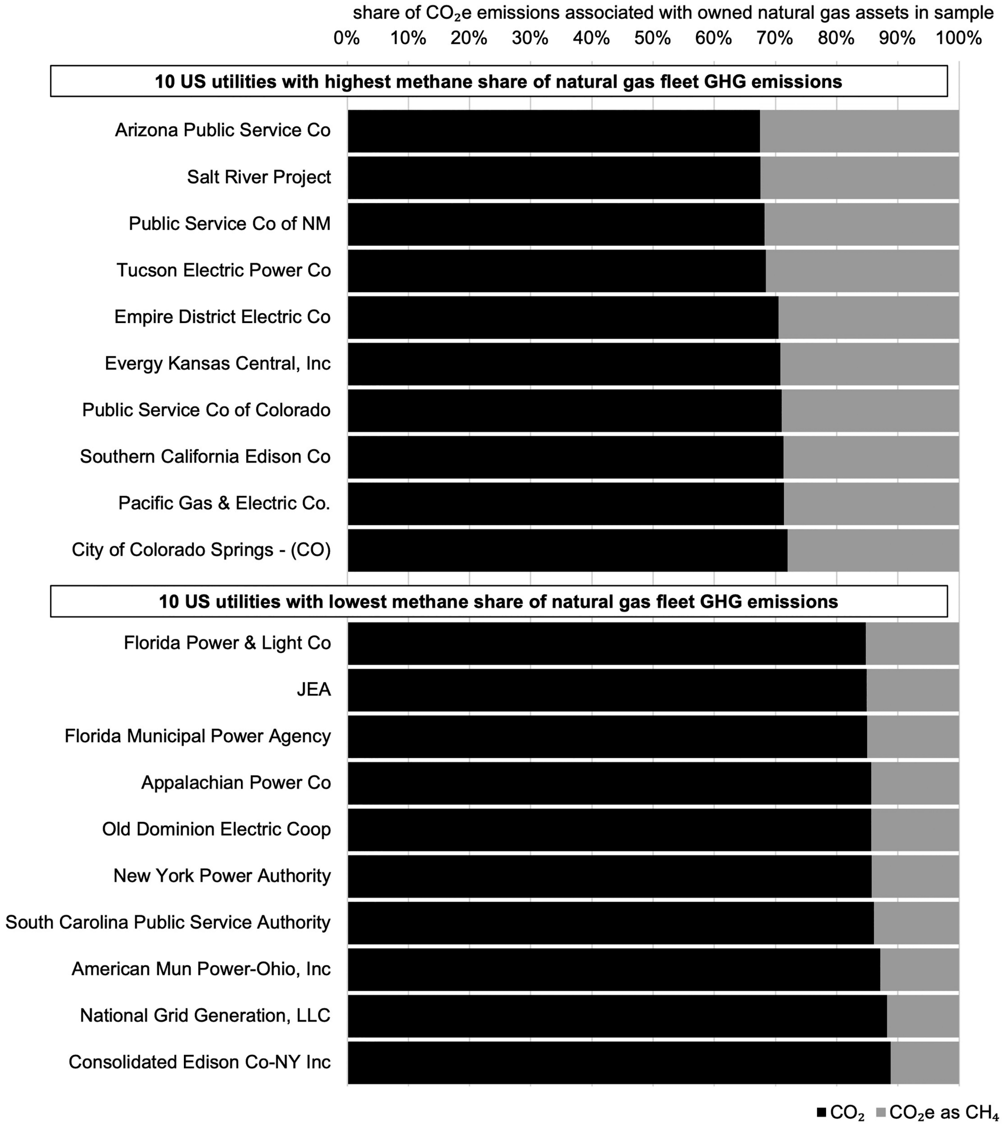

Figure 2. Impact of natural gas supply related methane emissions on specific utility natural gas fleet emissions profiles (highest and lowest 10 U.S. utilities by methane share of natural gas fleet greenhouse gas emissions, natural gas fleets with over 1 million tons CO_2 emissions in 2019).

Although data on generation and emissions were assigned at the generator level where possible, many records needed to be constructed from lower resolution data. For generation, generators were associated with generator-specific EIA 923 data where possible and otherwise assigned a share of reported plant-, fuel-, and prime-mover-specific generation proportional to their capacity share of generators with the same characteristics. For example, two equal-capacity natural gas combustion turbines at the same plant would each be assigned half of the natural gas combustion turbine-fired electricity generated at that plant. Data for generators that produced at least 500,000 MWh in 2019 were manually reviewed for inconsistencies in generator ID between EIA 860 and 923 records (e.g., "1" vs "001"), leading to 16 reconciliations. Total natural gas generation included in this model is 1.56 billion MWh, versus 1.59 billion MWh in EIA 923 records (2019).

Estimates of CO_2 and CH_4 emissions (as CO_2-equivalents, CO_2e) associated with natural gas generators that were operable as of 2019 and not excluded from analysis due to one of the above data cleaning interventions are presented in the Supporting Information by utility ("Results-Utilities"), NERC region ("Results-NERC Regions"), and Balancing Authority ("Results-Balancing Authorities"). Unless stated otherwise, all results presented in this Letter assume a 100-year global warming potential (GWP-100) of 29.8 for fossil CH_4 with climate-carbon feedback;[31] users can change this on the "Assumptions" tab in the Supporting Information. Although GWP is a contested[32−35] and not completely stable[24] metric, it is commonly used in climate policy and thus selected as the most immediately regulatory relevant characterization factor.

Estimated CO_2e intensities of hypothetical CCS units are based on EIA projections of heat rates for new natural gas units with and without CCS.[36] Estimated CO_2e intensities of hypothetical DAC units are based on assumptions in a recent DAC publication focused on natural gas-fired DAC,[37] assuming power generation by a new-build natural gas combined cycle (NGCC) plant with CCS.[36] Where not otherwise stated, this work assumes 90% capture for CCS[36] and 1.9% (mass emitted/mass withdrawn; national average) methane emissions from production through delivery to an industrial consumer.[10,22]

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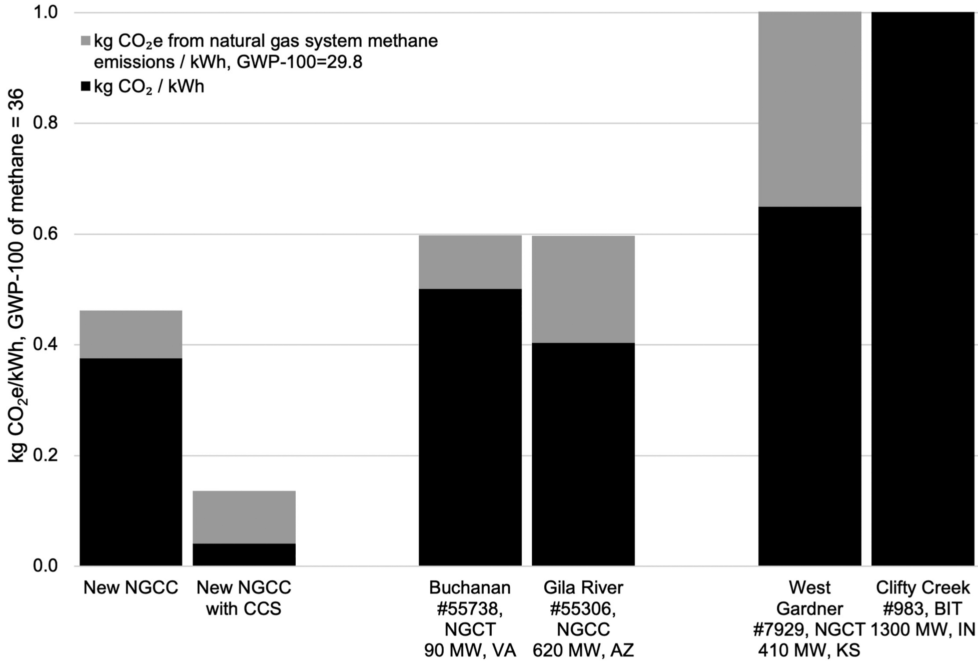

Figure 3. Impact of natural gas supply-related methane emissions on specific plant emissions profiles, comparing CO_2e emissions [kilogram (kg)/kWh; GWP-100 = 29.8] for (1) new-build NGCC units with and without CCS; (2) two existing natural gas-fired power plants with roughly equal CO_2e intensities but different heat rates and CH_4 intensities; and (3) an existing natural gas-fired power plant with CO_2e intensity roughly equal to the CO_2 intensity of the average U.S. bituminous coal-fired power plant, represented by Clifty Creek.

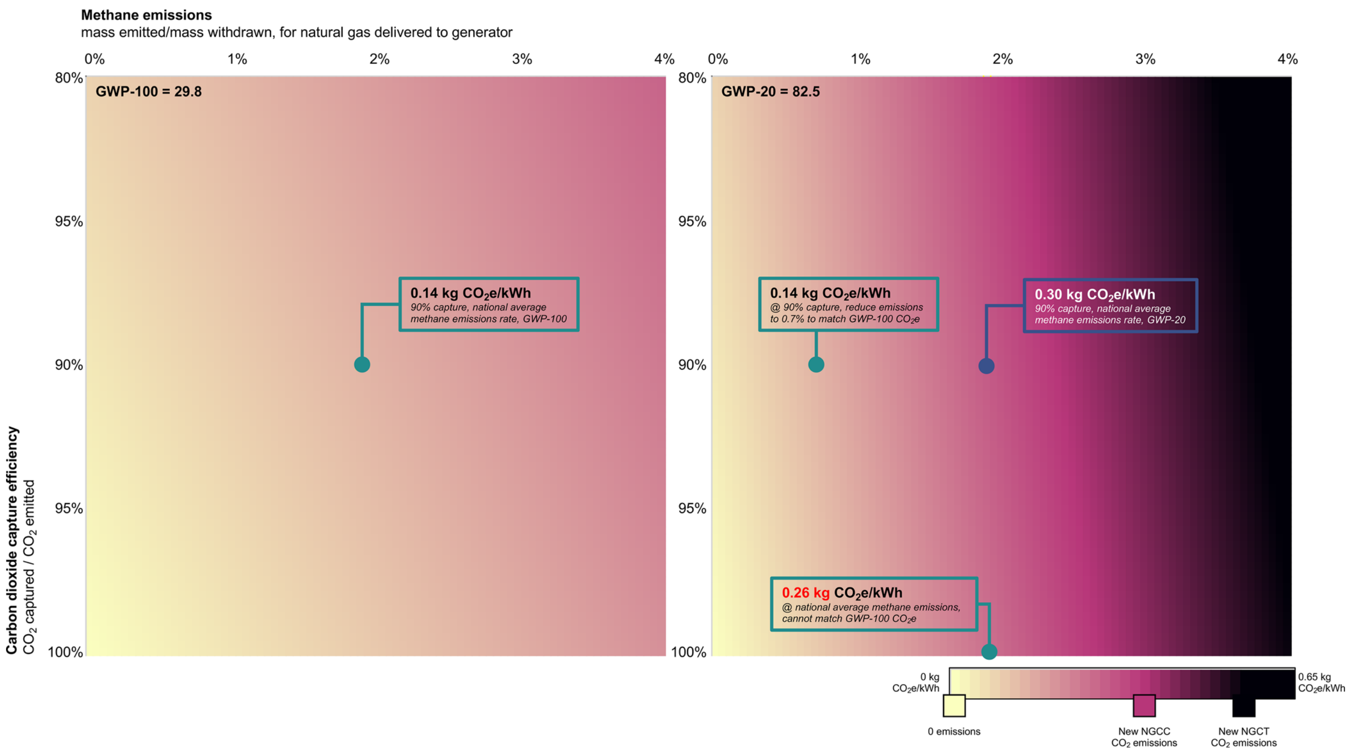

Figure 4. Influence of CCS capture rate and methane emissions on total CO_2e emissions per kWh at an NGCC unit with CCS. Labels show an archetypical unit [90% capture, national average methane emissions; green (GWP-100) and blue (GWP-20)] and, for GWP-20, necessary process improvements required to reach GWP-100 CO_2e emissions as a guide (green), showing that emissions are more sensitive to methane emissions than capture efficiency for expected ranges.

■ RESULTS AND DISCUSSION

Estimated total CH_4 emissions associated with the 2019 U.S. natural gas fleet are about 8% higher using state-specific emissions factors at the generator level than if the national average emissions rate is universally applied,[22] suggesting that, on average, due to their locations, natural gas-fired power plants receive higher-emission fuel than natural gas end users overall. Figure 1 shows the CO_2e contribution from natural gas supply

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CH_4 emissions as a percentage of CO_2 emissions from natural gas-fired generation by balancing authority for the continental U.S., assigned based on natural gas-fired generators participating in that balancing authority as of 2019 (see Supporting Information).

At the balancing authority level, CO_2e from natural gas fleet methane emissions is a maximum of 48% and minimum of 15% of those fleets' combustion CO_2 emissions. For NERC regions, this range (as [minimum, maximum]) is [16%, 36%]; for utilities' owned natural gas fleets, it is [13%, 48%].

Figure 2 shows the same value as presented in Figure 1, but for the 10 utilities with the highest and lowest CH_4 contribution to their natural gas fleets' CO_2e emissions. Notably, many of these utilities operate in states that have enacted or proposed zero-carbon electricity targets, with unclear treatment of CH_4—particularly for CH_4 emissions originating out of state.

Figure 3 demonstrates the impact of CH_4 emissions on specific power plants. As Figure 3 shows, CCS lowers CO_2 emissions but increases CH_4 emissions for new NGCCs, based on EIA heat rate assumptions.[36] High CH_4 emissions for Arizona's (AZ) natural gas supply render CO_2e intensity for an efficient NGCC (heat rate = 7600 btu/kWh) roughly equal to that of a less efficient natural gas combustion turbine (NGCT) (heat rate = 9780 btu/kWh) with a lower-CH_4 natural gas supply in Virginia (VA). A relatively inefficient NGCT (heat rate = 13 100 btu/kWh) with a high-CH_4 natural gas supply in Kansas (KS) has a CO_2e intensity roughly equal to that of the bituminous coal (BIT) fleet, represented here by Clifty Creek, in Indiana (IN).[21] As of 2019, the U.S. generating fleet was 26% NGCC, 13% NGCT, and 8% bituminous coal by nameplate capacity[28] (33%, 3%, and 7% by generation[30]); see the Supporting Information for details on the natural gas fleet, including steam turbines.

Natural gas-fired electricity is not GHG neutral even with CCS (Figure 3), due both to incomplete capture and to CH_4 emissions. Figure 4 shows a two-dimensional gradient of emissions from NGCC with CCS, assuming EIA heat rate,[36] varying CO_2 capture efficiency from 80 to 100% (vertical axis), and methane emissions from 0 to 4% (horizontal axis), assuming GWP-100 = 29.8 (left panel) and GWP-20 = 82.5 (right panel). Note that this analysis does not account for increasing heat rate penalty for high capture rates.[38] Emissions for an archetypical NGCC with CCS (90% capture, national average CH_4 emissions) are highlighted, at 0.14 kg of CO_2e/kWh (GWP-100) and 0.30 kg of CO_2e/kWh (GWP-20).

Natural gas-fired power plants with CCS could have CO_2e emissions rates ranging from 0 to roughly equal to CO_2 emissions rates from a new unabated NGCC (assuming GWP-100 for CH_4) or a new unabated NGCT (assuming GWP-20 for CH_4), though note that such units would also have CH_4 emissions. The impact of CH_4 emissions on total natural gas-related GHG estimates illustrates the importance of creating CH_4-conscious GHG policy. For example, under a policy requiring the use of GWP-20, as in New York State,[39] 90% CO_2 capture and national average emissions suggest a CO_2e footprint for NGCCs with CCS roughly equal to CO_2 emissions from an NGCC without capture, with limited scope to reduce emissions by improving CO_2 capture rate. That is, meaningful emissions reductions essentially require lowering CH_4 emissions, which power plant operators and even states might have limited ability to do, particularly for states that do not have full jurisdiction over their natural gas supply.

Just as CH_4 leakage has implications for the role of natural gas CCS, the influence of CH_4 leakage on the viability of natural gas-fired DAC is substantial. Assuming energy requirements of 366 kWh of natural gas-fired electricity with CCS and 5.25 gigajoules (GJ) of direct natural gas heat[37] per tonne of captured CO_2, net CO_2e emissions removal using natural gas fuel is only about 60% of CO_2 capture, assuming estimated U.S. average CH_4 leakage.[10,22] At this energy intensity and methane emissions level, the 2019 U.S. natural gas supply could theoretically remove about 3 gigatonnes of carbon-dioxide-equivalent ($GtCO_2e$) per year; unrealistically assuming transport and storage requires no additional natural gas energy. For [0%, 4%] methane emissions from the natural gas fuel supply chain, this removal potential is estimated at [3.6 $GtCO_2$e, 2.6 $GtCO_2$e,]. For GWP-100 = 29.8, methane emissions need to be at least 13.2% for CO_2e removal potential to be negative under these energy intensity assumptions, which is much higher than observed basin-level emissions rates in the U.S.[13] For GWP-20 = 82.5, CO_2e removal potential is negative at emissions of 5.2% and above, which are observed for supplies sourced from places like the San Joaquin basin[13] after accounting for midstream emissions.

Methane emissions pose a meaningful challenge for the GHG intensity of natural gas-fired activities, including electricity and potentially carbon removal. Climate policy should recognize that natural gas supplies do not have uniform emissions profiles and that natural gas-fired CO_2 capture is likely to increase CH_4 emissions due to increased fuel requirements.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.1c00531.

> Data, assumptions, analysis, and original-format figures, including state-level methane leakage assumptions; generator-level methane analysis; utility, NERC region, and balancing authority results for natural gas-fired power; and detailed calculations for DAC and CCS analysis (XLSX)

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Notes

The authors declare no competing financial interest.

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