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ORIGINAL RESEARCH

The greenhouse gas effects of increased US oil and gas production

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Abstract

Increased oil and natural gas production in the United States has decreased domestic natural gas prices and global oil prices. The resulting greenhouse gas (GHG) impacts have received substantial attention, with most focus on natural gas and relatively little on oil. In this paper, I provide an estimate of how increased production affects these emissions through changes in the US energy mix, methane emissions, and—crucially—global oil prices. Under a high oil and gas production scenario, US GHG emissions in 2030 are 100–600 million metric tons of carbon dioxide equivalent (2–10%) higher than under a low production scenario. Under the high production scenario, lower global oil prices and increased consumption raise non-US carbon dioxide emissions by 450–900 million metric tons relative to a low production scenario in 2030. These estimates assume that OPEC does not strategically reduce production to offset U.S. gains.

Keywords Shale gas · Tight oil · Hydraulic fracturing · Greenhouse gas · Carbon dioxide · Methane

Introduction

Over roughly the past decade, a suite of technological advances often referred to as the "shale revolution" have dramatically increased oil and natural gas production in the United States. Since 2008, crude oil production increased from 5 million barrels per day (MMB/day) to more than 11 MMB/day in late 2018, and natural gas marketed production grew from 21 trillion cubic feet per year (TCF/year) to 29 TCF/year in 2017 [1, 2].

At the same time, global concerns surrounding climate change have increased. Global average temperatures have risen by roughly 1 °C above preindustrial levels, and limiting warming to 1.5° or 2° by 2100, as agreed by nations in the 2015 Paris Climate Accord, will require unprecedented reductions in carbon dioxide (CO_2) and other greenhouse gas emissions [3].

This paper deploys existing modeling tools and recent evidence on greenhouse gas (GHG) emissions from the oil and gas sector to assess whether continued growth in US oil and natural gas production is likely to increase or decrease domestic and global GHG emissions. It is structured as follows. Section two reviews the "Recent literature". Details on the modeling framework and data sources appear in "Materials and methods" section. "Results" section presents the results, including numerous scenarios and sensitivities, followed by a discussion of the implications of these results in "Discussion" section. "Conclusion" section concludes.

Recent literature

A robust debate has emerged in the public and scientific community regarding the effects of the shale revolution on a variety of environmental and economic issues, including climate change [4]. On one hand, the low-cost supply of natural gas has displaced coal consumption in the US power sector, helping reduce power sector CO_2 emissions to levels not seen since the early 1990s [5].

On the other hand, natural gas competes for investment dollars with zero-carbon electricity sources such as wind and solar power. Low natural gas prices have reduced electricity prices, making it more difficult for nuclear power plants to operate profitably, with substantial potential impacts in the coming decades [6]. Lower energy prices also encourage greater energy consumption, which in turn will tend to increase emissions [7].

Most economic analyses of the climate impacts of the shale revolution have focused exclusively or primarily on natural gas. Brown and Krupnick [8] find that a scenario

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with abundant natural gas would slightly increase CO_2 emissions relative to a scenario with limited resources. They note that with climate policies, abundant natural gas reduces compliance costs for the economy as a whole, though they do not consider the potential impact of methane emissions (discussed in detail below).

Newell and Raimi [9] use the National Energy Modeling System (the same modeling tool employed here) and estimate that GHG emissions under a high oil and gas production scenario could be slightly higher or lower than under a reference case, with impacts ranging from roughly − 0.5 to + 0.3% depending on assumptions about methane emissions and the choice of methane's global warming potential (GWP). Excluding the transport sector, where oil is the leading fuel, emissions decrease by 0.5–1.5% under a high oil and gas scenario relative to a reference scenario, driven by the displacement of coal in the power sector.

Hausman and Kellogg [10] find that increased natural gas production from 2007 to 2013 led to an increase in US GHG emissions as a result of higher energy demand, particularly in the industrial sector. They also calculate welfare changes due to lower natural gas prices and find large gains for most domestic consumers and losses for domestic producers, resulting in net welfare gains of $48 billion annually. However, this figure does not include environmental damages, which could range from $3 billion to $28 billion per year due to uncertainty over methane emissions and changes in coal exports resulting from lower natural gas prices. They also note that continued innovation in the oil and gas sector could disadvantage non-GHG-emitting sources in the medium to long run, a topic examined below.

Gillingham and Huang [11] use a modified version of NEMS (Yale-NEMS) to model a range of scenarios in the US. They find that CO_2 emissions are higher under an abundant gas scenario than a carbon pricing scenario, but that welfare is maximized in a scenario where carbon pricing is paired with abundant gas due to lower emissions of GHGs and other pollutants.

Few et al. [12] apply a global energy system model to examine the effects of high levels of shale gas production on the costs of meeting a climate change target of 2 °C above preindustrial levels by 2100. They find that if globally coordinated action to reduce emissions is taken, abundant shale gas does not substantially reduce the costs of achieving the goal. They also point out that high levels of methane emissions could make reaching these targets more difficult under scenarios with abundant global natural gas consumption.

An earlier effort from multiple teams deploying globally integrated assessment models finds a relatively modest effect on global CO_2 emissions (− 2 to + 11%) and total climate forcing (− 0.3 to + 7%) under a scenario with globally abundant natural gas [13].

Other work has focused on the life cycle footprint of natural gas relative to other fuels such as coal. With one notable exception related to the issue of methane emissions [14], studies consistently find that the life cycle GHG emissions of natural gas are well below those of coal [e.g., 15, 16] at national (US) scales. Studies have also examined the emissions impacts of increased exports of US liquefied natural gas (LNG), finding that the climate impacts of LNG exports to certain regions are ambiguous largely because of uncertainty surrounding the fuels displaced by imported LNG and the rate of methane emissions [17].

The GHG implications of increased US oil production have been examined in less detail. While US natural gas prices are determined primarily by domestic market supply and demand, oil prices are determined by global market forces. As a result, increased US gas production mainly affects domestic natural gas demand, while increased oil production will affect global oil demand. However, the global nature of the oil market also means that increased production in the United States will in part displace other, higher-cost producers, moderating the net effect on global supplies.

In recent years, it has become increasingly clear that the growth in US oil production measurably affected global prices, with Kilian [18] estimating that increased US production reduced global prices by $10/barrel in 2014, though other factors such as slowing demand likely played larger roles in determining prices [19, 20].

Erickson and Lazarus [21] examine the potential emissions effects of reduced production of coal, oil, and natural gas on US federal lands. They do not calculate the price effects of these changes but instead use elasticities of supply drawn from the literature to estimate changes in total market supplies. In the central case, they estimate that each barrel of oil left unproduced in the US would lead to reduced global consumption of 0.61 barrels, though this ranges from 0.08 to 0.7 depending on price and elasticity assumptions.

Somewhat distinct from the economic effects of increased or decreased production is the aforementioned topic of methane emissions. Methane (CH_4) is a short-lived but powerful GHG, and its contribution to the emissions footprint of shale gas has received substantial attention. In its annual "Inventory of U.S. Greenhouse Gas Emissions and Sinks," the US Environmental Protection Agency (EPA) estimates methane emissions from all anthropogenic sources, including oil and gas systems. In its most recent greenhouse gas inventory (GHGI), EPA indicates that methane emissions from oil and natural gas systems increased from 201 million metric tons of carbon dioxide equivalent ($MMTCO_2e$) in 2005 to 204 $MMTCO_2e$ in 2016 [5]. This increase of roughly 1.6% is well below the growth in oil and gas production, which together grew from 32 quadrillion British thermal units (QBtu) in 2005 to 51 QBtu in 2016, an increase of 60% [22].

An influential but widely criticized paper by Howarth et al. [14] asserts that methane emissions from shale gas wells are far higher than those from "conventional" wells. The author's methane emissions estimates, which are not based on original data, are far higher than those from EPA and would mean that the life cycle GHG footprint of shale gas could be greater than that of coal. However, this paper relies on a number of questionable or incorrect assumptions (e.g., assuming that all methane during certain phases of production activities was "vented" as methane rather than "flared" and converted into CO_2, a common industry practice), which biased its results upward [23].

In subsequent years, several dozen studies have gathered data on methane emissions from oil and natural gas systems [e.g., 24–30], greatly improving understanding of the issue. A 2018 meta-analysis [31] incorporates the findings from studies covering nine major oil- and gas-producing regions to estimate nationwide emissions totals, finding that methane emissions from oil and gas systems were roughly 60% higher than EPA estimated but well below what Howarth et al. [14] suggested.

Materials and methods

Estimating US emissions

To estimate future GHG impacts of higher or lower levels of domestic oil and gas production, I turn to the US Energy Information Administration (EIA), which maintains the National Energy Modeling System (NEMS). NEMS is an integrated energy-economy model that uses multiple modules to calculate energy demand, supply, prices, and more.[1]

Each year, EIA uses NEMS to produce its Annual Energy Outlook (AEO), the 2018 version of which projects annual trends in energy consumption, production, prices, and more through the year 2050. This includes CO_2 emissions from each fuel and sector. Methane emissions are not included as part of the NEMS output, requiring the use of additional sources, which I describe later in this section.

Results from the AEO were gathered through EIA's interactive data visualization tool,[2] which allows users to examine multiple scenarios and download data. Here, I analyze five scenarios: (1) a reference case, which assumes that no new policies are implemented and technologies develop along recent trajectories; (2) a high oil and gas resource and technology case (HOG), which assumes that the ultimate recovery from US oil and gas wells is higher than expected under the reference case due to a variety of factors [32]; (3) a low oil and gas resource and technology case (LOG), which assumes lower-than-expected recovery; (4) a HOG case with full implementation of the Clean Power Plan (CPP), which would have required emissions reductions from the power sector of more than 30% below 2005 levels by 2030; and (5) a LOG case with the CPP.

To estimate greenhouse gas emissions associated with these scenarios, I rely on two sources: (1) NEMS's estimate of domestic CO_2 emissions from each fuel and (2) a range of estimates for domestic methane emissions from oil, natural gas, and coal systems based on estimates from EPA.

Annual CO_2 emissions for each fuel, which are subject to relatively little uncertainty, are taken directly from EIA's AEO.

To estimate methane emissions, I take EPA's 2018 GHGI as a starting point. The GHGI indicates 2016 methane emissions from natural gas systems, coal mining, and petroleum systems at 163.5, 53.8, and 38.6 $MMTCO_2e$, respectively. These estimates use a 100-year global warming potential (GWP) of 25, a figure that is well below other estimates, such as the Intergovernmental Panel on Climate Change's 100-year GWP for methane of 34 and its 20-year GWP of 86 [33]. To illustrate the range of potential impacts, I use all three GWPs in the analysis that follows.

Attribution of methane emissions between oil and natural gas systems is complex because most wells produce a combination of dry natural gas (methane), natural gas liquids (ethane, propane, butane, etc.), and crude oil. Much of the associated gas produced from "oil" wells[3] is captured and marketed separately from the oil, raising the question of whether some portion of methane emissions from "oil" wells should be attributed to natural gas systems. Similarly, it may be appropriate to attribute a share of methane emissions from "natural gas" wells to petroleum systems, as many natural gas wells produce substantial volumes of liquid hydrocarbons. For this paper, I attribute all methane released from natural gas and petroleum systems, as defined by the EPA in its GHGI, to "natural gas" and "oil." Future research can improve these estimates by more precisely apportioning methane emissions to these integrated systems.

This approach includes methane emissions for domestically-produced fuels that may be consumed either in the US or abroad. The rationale for attributing domestic methane emissions to the US, even if the energy is consumed elsewhere, is based on standard international emissions accounting protocols [34], along with the notion that domestic public policies and applications of emissions abatement technologies could reduce those emissions.

[1] Detailed documentation is available online at https://www.eia.gov/outlooks/aeo/nems/documentation/.

[2] https://www.eia.gov/outlooks/aeo/data/browser/.

[3] States define wells as an "oil" well or "natural gas" well based on the ratio of liquids to gases they produce.

I do not include methane emissions from abandoned oil and gas wells or abandoned underground coal mines (which EPA estimates emit 7.1 and 6.7 $MMTCO_2e$, respectively), as these sources are not directly affected by changes in the level of oil and gas production or consumption over time.[4]

Because methane emissions occur primarily during the upstream and midstream phases of development, rather than the downstream phase associated with end-use consumption [5, 31], I estimate methane emissions in future years based on annual production (rather than consumption) levels of oil, natural gas, and coal. To make this estimate, I calculate the annual methane emissions from each fuel source per unit of energy produced in 2016. For example, EIA estimates that crude oil production in 2016 was 18.6 QBtu, while EPA estimates that methane emissions from petroleum systems were 38.6 $MMTCO_2e$ (assuming a 100-year GWP of 25) in that year, resulting in 2.1 $MMTCO_2e$ per QBtu of crude oil produced.

It is worth noting that multiple recent studies have estimated methane emissions from downstream sources such as local distribution pipelines [35] and manufacturing facilities [36] to be at least 10 times greater than the estimates I rely on for this analysis. These recent studies suggest that downstream emissions estimates will need to be revised upwards. However, these new data are not sufficient to draw conclusions about nationwide downstream emissions, as work in other regions of the US has found that downstream emissions well below existing estimates [37].

Because of the continued uncertainty over methane emissions from oil and gas systems, I use a range of sensitivities to analyze the potential impacts of methane under different assumptions. These include the different GWPs noted above and three scenarios for emissions rates. Each of these scenarios makes the simplifying assumption that the ratio of methane emissions per unit of energy produced remains constant over time, though in reality, newer sources may be less "leaky" than older infrastructure [e.g., 37, 38]. Changes in technology and policy could alter these trends but are highly uncertain.

I incorporate methane emissions using the following three scenarios: (1) EPA's methane emissions estimates from oil and gas systems are accurate; (2) actual methane emissions are 60% *higher* than EPA's figures, as estimated in Alvarez et al. [31]; and (3) actual methane emissions are 50% *lower* than EPA's estimates. This lower scenario is included because of the emergence of policies to reduce methane emissions in certain producing states [e.g., 39], as well as announcements from major producers committing to reduce methane emissions from their supply chains [e.g., 40]. These developments, should they continue and be implemented effectively, have the potential to substantially reduce methane emissions below current levels.

Table 1 Methane emissions by fuel source under different assumptions

2016 emissions ($MMTCO_2e$)	Oil	Natural gas	Coal
CH_4 (GWP = 25)	38.6	163.5	53.8
CH_4 (GWP = 34)	52.5	222.4	73.2
CH_4 (GWP = 86)	132.8	562.4	185.1
2016 energy production (QBtu)	18.6	32.6	15.3
CH_4 per energy produced assuming EPA GHGI is accurate ($MMTCO_2e$/QBtu)			
CH_4 (GWP = 25)	2.1	5.0	3.5
CH_4 (GWP = 34)	2.8	6.8	4.8
CH_4 (GWP = 86)	7.1	17.3	12.1
CH_4 per energy produced assuming actual emissions are 50% of EPA GHGI ($MMTCO_2e$/QBtu)			
CH_4 (GWP = 25)	1.0	2.5	1.8
CH_4 (GWP = 34)	1.4	3.4	2.4
CH_4 (GWP = 86)	3.6	8.6	6.0
CH_4 per energy produced assuming actual emissions are 160% of EPA GHGI ($MMTCO_2e$/QBtu)			
CH_4 (GWP = 25)	3.3	8.0	5.6
CH_4 (GWP = 34)	4.5	10.9	7.7
CH_4 (GWP = 86)	11.4	27.6	19.4

Table 1 shows EPA's estimates of 2016 CH_4 emissions under different assumptions about GWP and the rate of methane emissions from oil and natural gas systems. It also shows the estimated rates of methane emissions per unit of oil, natural gas, and coal produced under those different assumptions.

To estimate the total domestic GHG impacts of these different scenarios, I examine CO_2 and CH_4 emissions from each fuel source in the year 2030.[5] CO_2 emissions under each scenario (reference, HOG, LOG, HOG with CPP, LOG with CPP) are adjusted to reflect the impact of methane under different assumptions about emissions rates and choice of GWP.

Estimating non-US emissions

As noted above, natural gas prices are determined primarily by domestic supply and demand, while oil prices are set globally. So while changes in natural gas prices enabled

[4] Methane emissions from these sources could, however, be indirectly affected by market changes. For example, higher oil and/or natural gas prices could increase funds available for some states to identify and plug abandoned wells, reducing methane emissions.

[5] Alternative approaches, including examining the year 2050 and summing emissions from 2018 to 2050, produce qualitatively similar results.

by shale development mostly affect US consumers, changes in oil prices resulting from increased US production affect demand globally.[6]

NEMS does not provide global estimates for oil consumption under the scenarios analyzed here, but it *does* estimate global oil price changes resulting from different levels of US supply. While it is not possible to precisely estimate the effects of these price changes on global demand without an integrated global model, demand elasticities drawn from the literature can help provide estimates about what the effects may be.

However, estimates of the global price elasticity of demand for crude oil vary substantially. Two commonly cited figures come from Dahl [41], who estimates long-run price elasticities of oil demand for developing countries of − 0.13 to − 0.26, and Cooper [42], who estimates elasticities for developed countries from − 0.18 to − 0.45. A review of recent studies in Huntington et al. [43] finds that the average demand elasticity across several studies in a variety of nations is − 0.15, with estimates of − 0.25 for the Middle East and − 0.26 for all non-OECD nations. Krupnick et al. [44] estimate a median long-run price elasticity of demand for non-US consumption of − 0.5, with a 5th to 95th percentile range of − 0.42 to − 0.61.

These figures range widely for a variety of reasons. Primarily, it is difficult to anticipate consumer behavior and technology trends over decadal time scales, which is what a long-term elasticity estimate. For example, consumer demand for petroleum products could become more elastic in the years to come if electric vehicles continue to grow more affordable, as drivers could more easily opt for an electric vehicle in a world of higher oil prices.

To estimate the change in non-US CO_2 emissions under the different scenarios, I start with global (Brent) oil prices estimated by NEMS in 2030 under the different scenarios. I then apply a range of estimates of long-term price elasticity of demand for crude oil from the literature to non-US crude oil demand.[7] These long-term price elasticities are, ranging from lowest to highest: − 0.15 [43], − 0.2 [41], − 0.32 [42], and − 0.5 [44]. I also conduct a bounding exercise using the levels of US crude oil exports to check the feasibility of the estimates based on elasticities (details provided in "Results" section).

[6] In recent years, the US has become a large natural gas exporter, and projections show continued growth in exports, which will tend to reduce global LNG prices. However, as noted earlier, the net emissions effects of these increased exports are ambigious depending on a variety of factors, and estimating them is beyond the scope of this analysis.

[7] I exclude the United States in this calculation because NEMS estimates changes in domestic but not global demand in response to global price changes.

Table 2 Change in US energy production, prices, and consumption relative to reference case in 2030

Scenario	GDP (%)	Production			Prices			Consumption				
		Oil (%)	Natural gas (%)	Coal (%)	Oil (%)	Natural gas (%)	Coal (%)	Oil (%)	Natural gas (%)	Coal (%)	Nuclear (%)	Renew-ables (%)
HOG	+0.2	+27	+18	− 18	− 12	− 26	− 0.7	+0.3	+13	− 21	− 15	− 4
LOG	− 0.8	− 24	− 22	+14	+10	+63	+2.5	− 0.1	− 17	+17	+3	+20
HOG w/ CPP	+0.1	+27	+18	− 29	− 12	− 25	− 3.9	+0.1	+14	− 33	− 13	− 5
LOG w/ CPP	− 1.0	− 24	− 18	− 4	+9	+64	+1.3	− 0.5	− 16	+3.6	+3	+29

Results

US energy prices and consumption

As Table 2 shows, the HOG and LOG cases lead to large differences in a certain production, price, and consumption outcomes relative to the reference case. Under the HOG case, increased oil and gas development boosts gross domestic product (GDP) by 0.2%, which will tend to increase emissions, all else equal. Under this scenario, oil production is 27% higher and natural gas production is 18% higher, reducing prices by 12% for oil and 26% for gas relative to the reference case. Oil consumption is only slightly higher under the HOG case, reflecting the relatively inelastic demand for oil in the United States (notably, the projections assume the full implementation of Obama-era Corporate Average Fuel Economy [CAFE] standards), while natural gas consumption is more than 13% higher, as it pushes out competing fuels for electricity generation and in other sectors.

Displaced by natural gas, coal production and consumption decline by 18 and 21%, respectively, reducing CO_2 emissions. (Coal exports are slightly higher under the HOG case, explaining most of the difference between changes in production and consumption.) Nuclear and renewable electricity, which also compete with natural gas in the power sector, are respectively 15 and 4% lower than under the reference case, which will tend to increase CO_2 emissions.

Under the HOG with CPP case, oil and gas production and consumption trends are similar to those under the HOG case without the CPP, but the effects on coal are more substantial. Under the HOG scenario with the CPP, coal production declines by 29% while consumption falls by 33% relative to the reference case. Under the HOG case, the CPP has a relatively modest effect on nuclear and renewables.

Under the LOG case, most of the effects on production, prices, and consumption are the inverse of those seen under the HOG case. Of particular interest is the large change in coal and renewables consumption under the LOG case, with coal demand growing by 17% relative to the reference case and renewables growing by 20%. Adding the CPP to this scenario significantly reduces the demand for coal, with most of the additional electricity generation coming from renewables.

Figure 1 shows trends in energy consumption for these fuels from 2018 to 2030 under each case.

US emissions

Under nearly all scenarios and assumptions, greenhouse gas emissions are highest under the HOG case. Compared with the LOG case, emissions under the HOG case are 2–10% higher in 2030. Compared with the reference case, emissions under the HOG case range from roughly equal to 2% higher.

Under all scenarios other than those assuming that methane emissions are 50% lower than EPA estimates, the HOG with CPP case leads to higher emissions than the LOG (without CPP) case. In other words, low levels of oil and natural gas production do more to reduce emissions than the implementation of the CPP unless methane emissions are reduced substantially. Figure 2 illustrates total GHG emissions in 2030 under different cases and assumptions.

Although this range of scenarios reflects substantial changes in the future energy system, the impact on CO_2 emissions from higher or lower levels of oil and gas production is small. Compared with the LOG case, the HOG case results in CO_2 emissions that are 0.6% higher in 2030.

Instead, the largest driver in terms of GHG impact is methane emissions associated with higher or lower levels of domestic production. With an assumption of low methane emissions (far left of Fig. 2), total GHG emissions under the HOG case are 2% higher than under the LOG case. Assuming the same level of CO_2 but a higher rate of methane emissions and a 20-year GWP of 86 (far right of Fig. 2), the HOG case leads to 10% higher emissions than the LOG case.

Adding the CPP reduces CO_2 emissions by 3% under the HOG case and 5% under the LOG case, suggesting that the CPP would reduce emissions more substantially in a world where natural gas prices are higher, increasing the relative competitiveness of zero-emissions nuclear and renewables.

CO_2 emissions from domestic oil consumption change little under the different scenarios, again reflecting the relatively inelastic estimates for US oil demand, along with the fact that the CPP does not directly regulate the transportation sector, where most oil is consumed. If the CAFE standards developed under the Obama administration (which are assumed to be implemented in this version of NEMS) were substantially weakened, domestic consumption may become more responsive to changes in petroleum product prices, increasing consumption levels and the associated GHG impacts of the HOG case.

Non-US emissions

EIA's 2018 International Energy Outlook projects global oil demand in 2030 of 209.5 QBtu [45]. Under the reference case, US oil demand in 2030 is 35.7 QBtu, leaving non-US oil demand of 173.7 QBtu, equivalent to 89.4 MMB/day [46].

Under the HOG and LOG cases, global (Brent) oil prices in 2030 are respectively 12% lower and 10% higher than under the reference case in 2030 (Table 2). Using the range of elasticities from the literature cited above, these

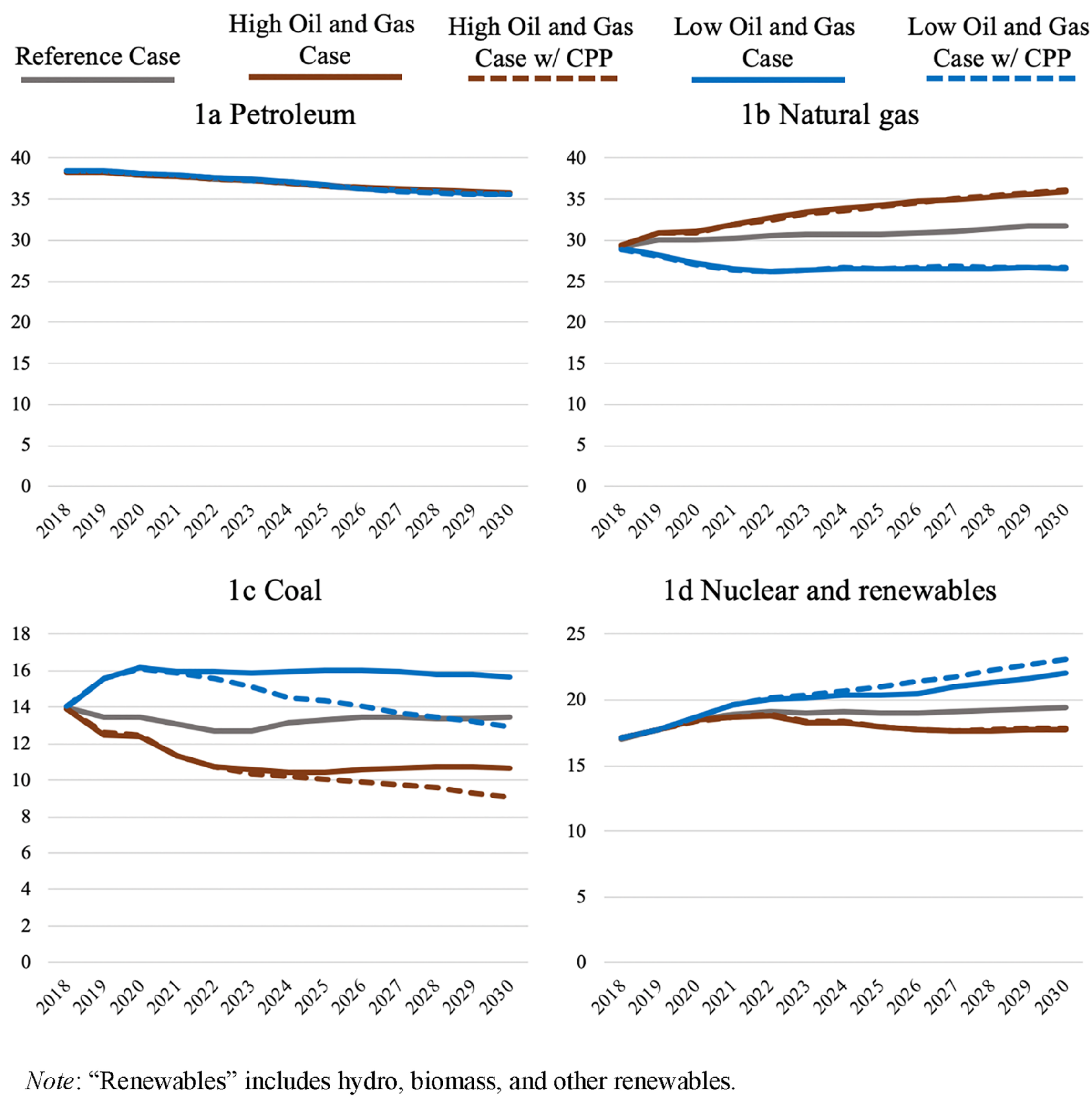

Fig. 1 US energy consumption under five cases (QBtu). Renewables" includes hydro, biomass, and other renewables Source: EIA's AEO 2018.

price differentials suggest non-US oil consumption would be 2–6% (1.6–5.4 MMB/day) higher under the HOG case and 1–5% (1.3–4.3 MMB/day) lower under the LOG case relative to the reference case. Non-US oil demand is 3–11% (2.9–9.7 MMB/day) higher under the HOG case than under the LOG case.

To check the feasibility of these results, I conduct a bounding exercise based on the levels of US oil exports estimated under the different scenarios in NEMS. This exercise is based on the premise that the increase in global oil demand under the various scenarios cannot be greater than the increase in US oil exports under those same scenarios. For example, US oil production in 2030 is roughly 6 MMB/day higher under the HOG case than under the LOG case, while US oil consumption is roughly 0.1 MMB/day higher. This additional supply on the global market lowers prices, which in turn reduces supplies from non-US sources. Therefore, global oil consumption in 2030 cannot be more than 5.9 MMB/day higher under the HOG case relative to the LOG case. This bounding exercise demonstrates that the higher elasticities of − 0.32 and − 0.5 are not appropriate for an analysis examining the year 2030, as they would have estimated a global demand response greater than 5.9 MMB/day.[8]

[8] Extending the analysis to 2050 or beyond would make the higher elasticities relevant. For example, US crude oil production in 2050 is roughly 12 MMB/d higher under the HOG case than under the LOG case, with little change in domestic consumption, suggesting the possibility of a substantially larger impact on global oil consumption.

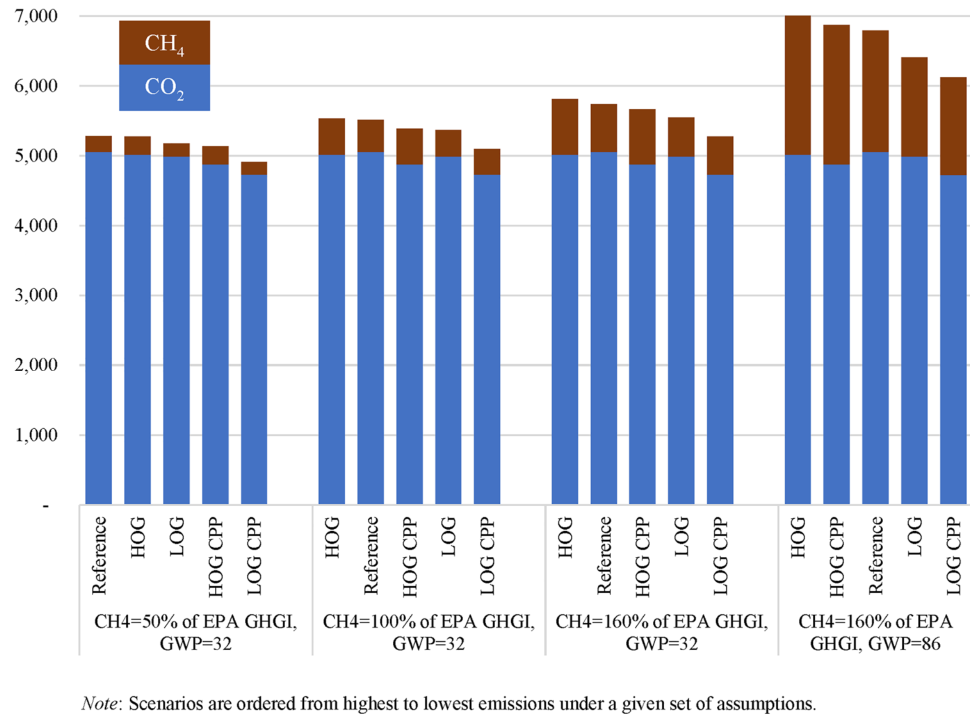

Fig. 2 US GHG emissions, 2030 (MMTCO$_2$e). Scenarios are ordered from highest to lowest emissions under a given set of assumptions

Table 3 Non-US oil consumption and associated emissions, 2030

Elasticity	Reference	HOG	LOG	HOG – Reference	LOG – Reference	HOG – LOG
Oil demand (MMB/d)						
– 0.15	89.4	91.1	88.2	1.6	(1.3)	2.9
– 0.20	89.4	91.6	87.8	2.1	(1.7)	3.8
Upper bound	89.4	92.5	86.7	3.1	(2.8)	5.9
CO_2 emissions (MMT CO_2)						
– 0.15	14,037	14,293	13,837	256	(201)	457
– 0.20	14,037	14,370	13,776	333	(261)	594
Upper bound	14,037	14,524	13,602	487	(435)	923

With a more limited range of elasticities, I can now estimate the non-US GHG emissions impacts of increased US oil production. Using a standard metric of 0.43 metric tonnes of CO_2 per barrel [47], the absolute changes in CO_2 emissions are substantial, as shown in Table 3. Under the HOG case, non-US emissions in 2030 would be roughly 250–500 MMT CO_2 higher than under the reference case and 450–900 higher than under the LOG case. To put these figures in context, 2016 CO_2 emissions from fossil fuel combustion were 417 MMT for Brazil [48].

Discussion

Key findings in context

Since roughly 2010, abundant natural gas resulting from the shale revolution has helped reduce US GHG emissions by displacing coal-fired electricity. However, the above results suggest that high levels of US oil and gas production are likely to result in substantially higher emissions

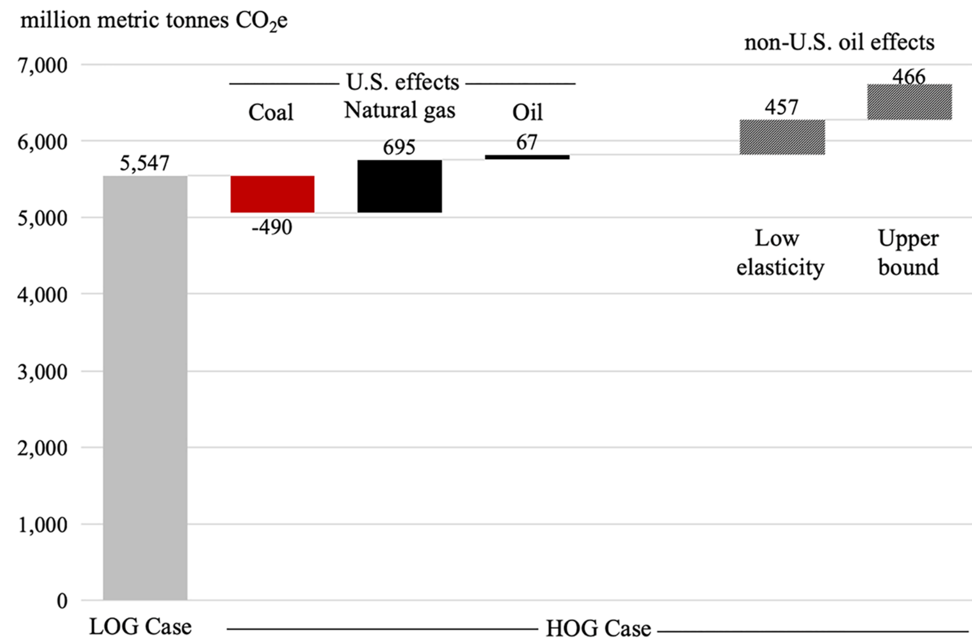

Fig. 3 US and non-US differences in GHG emissions between the LOG and HOG cases

in the decades to come, mostly due to the global effects of lower oil prices.

Focusing first on US effects, the costs of wind and solar electricity generation have fallen dramatically over the past decade [49], changing the relative impacts of inexpensive natural gas in the power sector. While low-cost gas will continue to reduce CO_2 emissions by displacing coal, these reductions are more than offset by numerous factors, including slowed deployment of renewables and earlier retirement of nuclear power plants. Along with these effects in the power sector, low-cost natural gas reduces electricity and other end-use prices below what they otherwise would be, encouraging greater consumption and increasing emissions.

However, methane emissions associated with higher or lower levels of US oil and gas production are likely to have an even larger effect on total GHG emissions. Under a scenario with high levels of oil and natural gas production, increased methane emissions are likely to swamp the GHG effects of policies such as the CPP unless methane emissions are dramatically reduced below current levels.

Internationally, the effect of increased US oil production on global oil consumption and associated emissions appear to be substantial. To be sure, the magnitude is difficult to estimate precisely. The key uncertainty in this analysis is the price elasticity of demand, shaped by factors including the future availability of substitutes for petroleum fuels such as electricity, along with the potential for strategic behavior by non-US oil producers such as OPEC nations. For example, these producers could coordinate production cuts to partially or completely offset US gains, a possibility not accounted for in the EIA's price projections.

To illustrate the potential size of the effects examined in this paper, Fig. 3 shows the differences in 2030 emissions under the LOG and HOG cases. The left side of the figure shows that under the LOG case, US GHG emissions are 5547 MMTCO_2e in 2030, assuming methane emissions are 60% higher than EPA estimates and using a 100-year methane GWP of 32.[9] Under the HOG case, total US CO_2 and CH_4 emissions from coal are 490 MMTCO_2e lower, natural gas emissions are 695 MMT higher, and oil emissions are 67 MMT higher.

The international effects are substantially larger on net. Using the low range of non-US demand elasticity (− 0.15), lower oil prices under the HOG case lead to additional CO_2 emissions of 457 MMT in 2030. Using the upper bound, emissions are 466 MMT higher still. The cumulative impacts are a US increase in CO_2e emissions of 273 MMT and a non-US increase of between 457 and 923 MMTCO_2e, for a total increase of 730–1196 MMTCO_2e. For context, CO_2 emissions from fossil fuel combustion across all of Central and South America were 1,184 MMTCO_2 in 2016 [48]. Including both US and non-US effects, CO_2e emissions are 13–22% higher under the HOG case than under the LOG case.

Given the fact that the United States accounts for roughly 20% of global oil consumption, the increase in US oil-related emissions is small relative to changes in non-US emissions. This is due primarily to the difference between the price elasticity of demand embedded in NEMS and the elasticities

[9] I choose this level of methane emissions based on the most recent available meta-analysis from Alvarez et al. [31].

applied from the literature. As noted above, changes in US oil demand responding to lower or higher prices are muted, particularly on the upside, by the assumptions that Obama-era CAFE standards are implemented through the projection period. The relaxation of this assumption would likely lead to a larger increase in US consumption brought about by increased domestic production and the consequent lower prices. In addition, the United States is projected to account for a smaller proportion of global oil demand in 2030, at roughly 17% under EIA's International Energy Outlook [45].

Study limitations and future research

This study is limited by several factors and raises numerous questions that future research can help answer.

First, I do not estimate the welfare effects from increased US oil and gas production. These effects are shaped by many factors including the economic impacts of lower energy prices, which will tend to enhance welfare in the United States and globally. To estimate the welfare effects of the scenarios described in this paper, a broader modeling exercise would be required that quantifies both the benefits of decreased energy prices and the negative impacts of increased pollution (including GHGs and local pollutants). Such analyses could build on the work of Hausman and Kellogg [10], who estimate national-scale welfare effects, and Bartik et al. [50], who quantify the local welfare effects of shale development.

Second, the application of multiple estimates for price elasticity of demand is not ideal. Because the HOG and LOG cases included in EIA's projections are not fully integrated into a global model, the non-US demand response to lower oil prices must be estimated using a second source, in this case a range of estimates taken from the literature. In addition, the global oil price estimated by NEMS under the different cases already assumes a global demand response to increased US production, which in turn feeds back into the projected levels of oil and gas production in the United States and globally, raising a potential endogeneity issue with applying external global demand elasticities to a NEMS-derived oil price. Moreover, NEMS does not account for decisions taken by major producing nations such as members of OPEC, which could behave strategically to support oil prices in response to increased US production.

Third, the levels of methane or other upstream emissions associated with non-US oil and natural gas production are not included here. If non-US production-related emissions including both CH_4 and CO_2 are higher than US levels, as suggested by some estimates [51, 52], any decrease in non-US production brought about by lower prices under the HOG case could result in a net reduction in GHGs due to the lower methane emissions from US oil compared with non-US oil. Alternatively, if US oil displaced lower-carbon sources, the net effect could be an increase in emissions. These lower carbon sources could potentially include lower emissions fuels such as biofuels or energy carriers such as electricity generated by low-carbon sources.

Fourth, other analyses have suggested that certain parameters embedded in NEMS do not accurately reflect likely real-world developments. Thus the potential exists that NEMS underestimates US demand elasticities for natural gas consumption in the industrial sector [10], which would tend to result in higher emissions under the HOG case, and that NEMS does not effectively project the future costs of wind and solar energy [53], which would have uncertain effects on GHG emissions depending on other assumptions around the price of generating electricity from other sources.

Finally, this analysis does not include the international GHG effects of increased US exports of natural gas and coal under the HOG case. Previous literature has suggested that the global GHG effects of natural gas and coal exports are ambiguous and depend on a number of assumptions, the analysis of which are outside of the scope of this analysis. For exports of natural gas, global emissions could decrease if the primary fuel displaced is coal, while emissions could increase if more renewables or other lower-emissions sources are displaced [17]. For coal exports, important considerations include the elasticity of supply for seaborne coal, along with the thermal efficiency of the combustion units where the coal is ultimately burned [54].

Conclusions

Increased US oil and gas production has had large economic and environmental impacts in the United States and globally. While many authors have examined the impacts of increased natural gas production on greenhouse gas emissions in the United States, little work has been done to estimate the non-US impacts of lower global oil prices resulting from increased US production. This paper estimates both of these effects under high and low US oil and gas production scenarios. The results show that US-only greenhouse gas emissions are likely to 2–10% higher under a high production scenario, under a range of assumptions about methane emissions, and that the non-US effects may be substantially larger. Due primarily to lower oil prices and increased non-US oil consumption, global greenhouse gas emissions under the high production scenario are roughly 700–1200 MMT higher in 2030 than under the low production scenario. For reference, 2016 CO_2 emissions from fossil fuel combustion were 417 MMT for Brazil and 1184 MMT for the entirety of Central and South America.

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Compliance with ethical standards

Conflict of interest The author declares no conflicts of interest.

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