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Greenhouse Gas Emissions from Shale Gas: Is this a “Clean” Fuel?



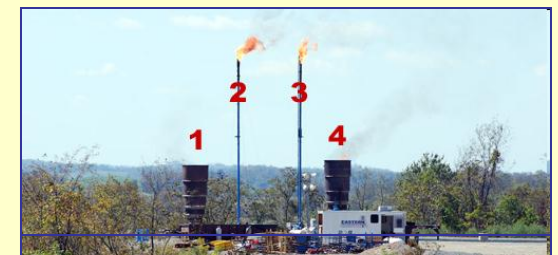
Robert Howarth, Ph.D.

*The David R. Atkinson Professor of Ecology
& Environmental Biology*

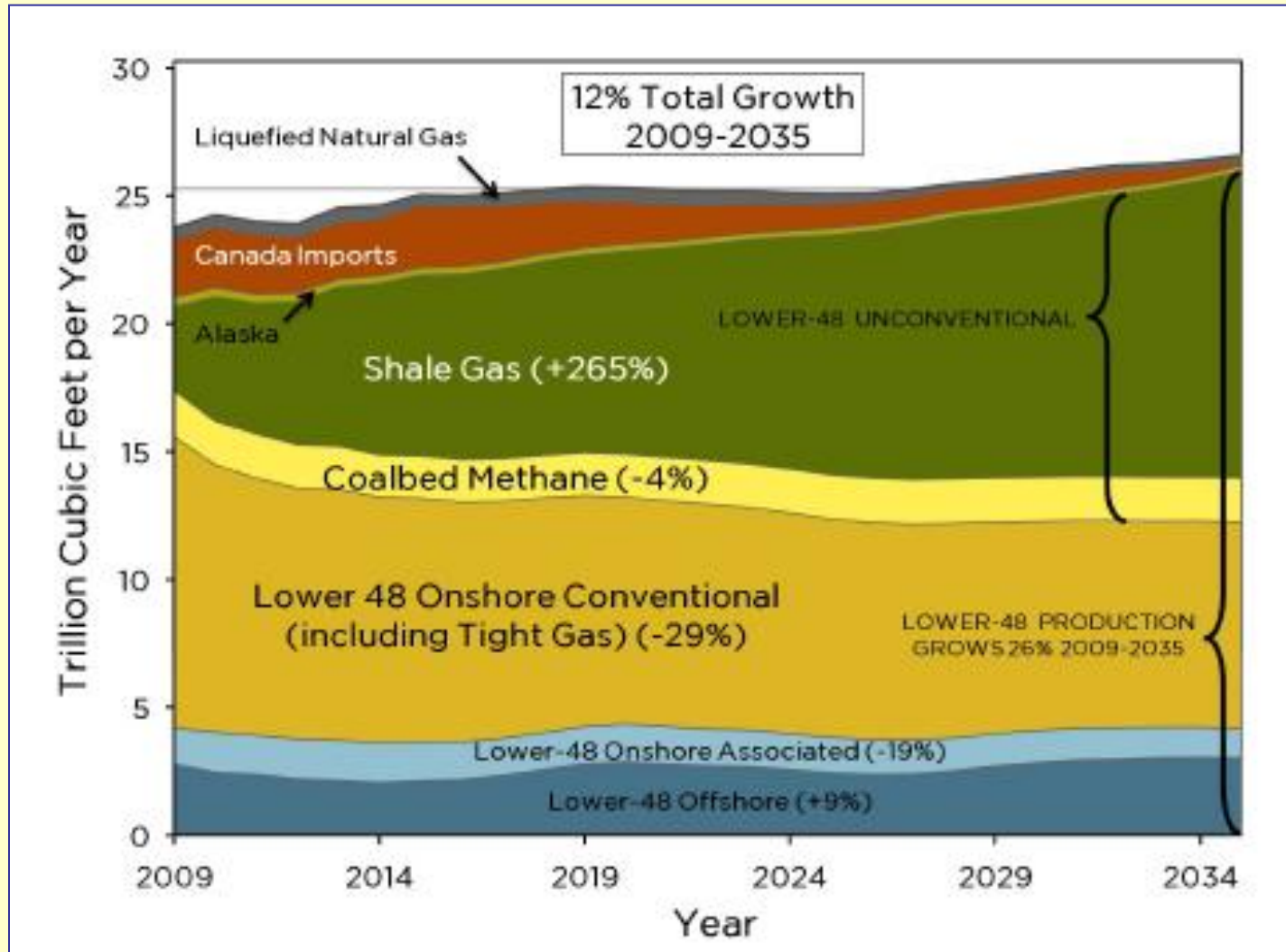
Cornell University

Carnegie Endowment for International Peace

May 19, 2011



Predicted sources of natural gas for the United States



Hughes (2011), based on EIA/DOE annual energy outlook

“From a CO₂ emissions standpoint, [shale gas] is 60 percent cleaner than coal”

“60 Minutes” on CBS Television on November 14, 2010 made essentially same statement

Many others....



Methane and the greenhouse-gas footprint of natural gas from shale formations

A letter

Robert W. Howarth · Renee Santoro ·
Anthony Ingraffea

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Abstract We evaluate the greenhouse gas footprint of natural gas obtained by high-volume hydraulic fracturing from shale formations, focusing on methane emissions. Natural gas is composed largely of methane, and 3.6% to 7.9% of the methane from shale-gas production escapes to the atmosphere in venting and leaks over the lifetime of a well. These methane emissions are at least 30% more than and perhaps more than twice as great as those from conventional gas. The higher emissions from shale gas occur at the time wells are hydraulically fractured—as methane escapes from flow-back return fluids—and during drill out following the fracturing. Methane is a powerful greenhouse gas, with a global warming potential that is far greater than that of carbon dioxide, particularly over the time horizon of the first few decades following emission. Methane contributes substantially to the greenhouse warming it on a 20-year time scale that for conventional gas or oil is so over 20 years. Compared to conventional gas and perhaps more than twice as much when compared over 100 years.

Keywords Natural gas · Shale gas · Life cycle analysis · LCA · Bridge fuel ·

Article
Material, which is available

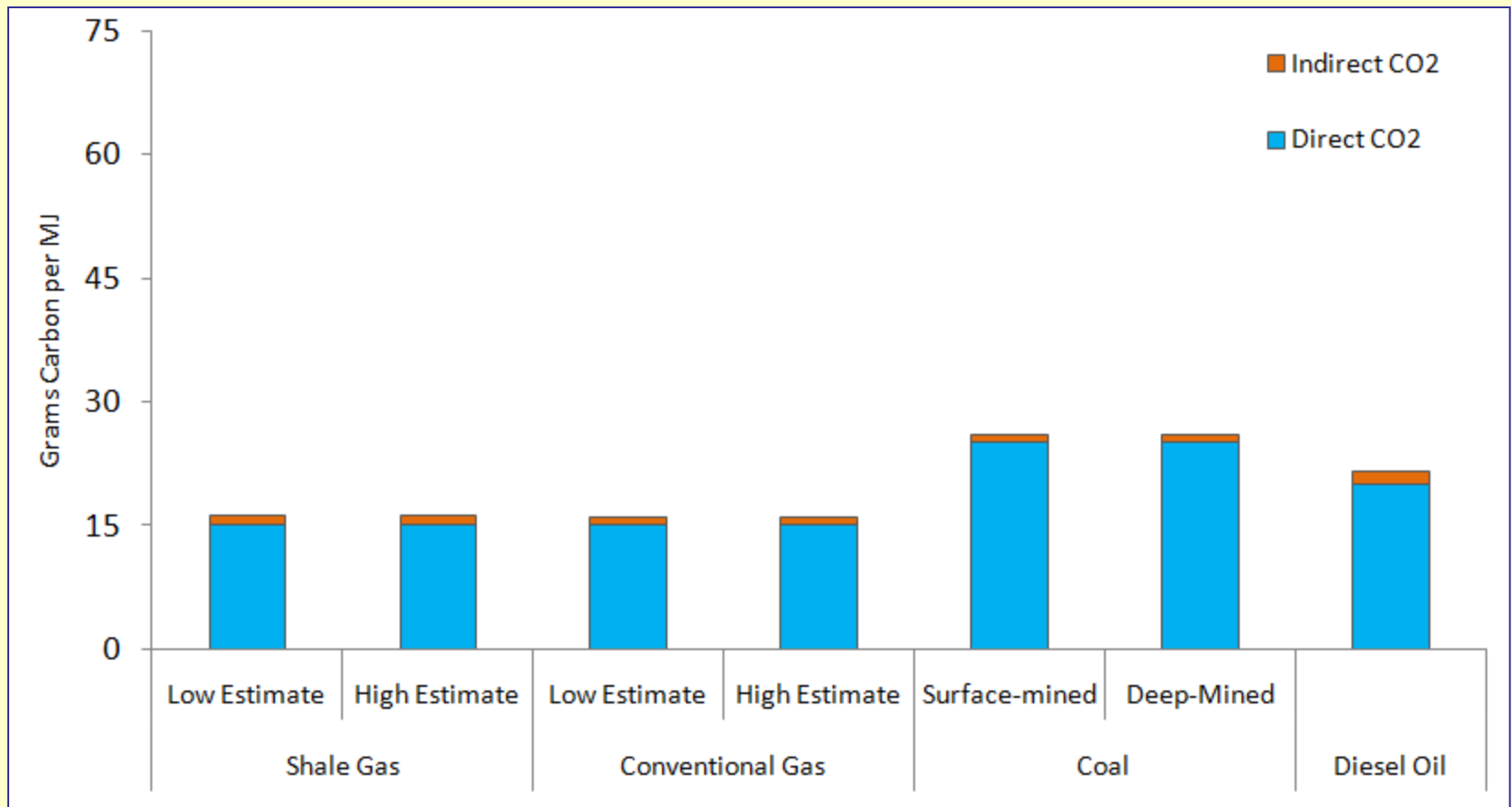
University, Ithaca, NY 14853, USA

First comprehensive analysis of greenhouse gas emissions from shale gas.

Peer-reviewed by highly respected journal.

Published April 12, 2011.

Direct carbon dioxide emissions during combustion of fossil fuels plus indirect carbon dioxide emissions



Methane emissions – the Achilles' heel of shale gas

- **Natural gas is mostly methane.**
- **Methane is 2nd most important gas behind human-increased global warming.**
- **Methane is much more potent greenhouse gas than carbon dioxide, so even small leaks matter.**

Methane is vented and leaked:

- **during initial flow-back period**
- **routinely and continuously at the well site**
- **during liquid unloading**
- **during gas processing**
- **during transmission, storage, and distribution**

We used the best available data to estimate methane venting and leaks:

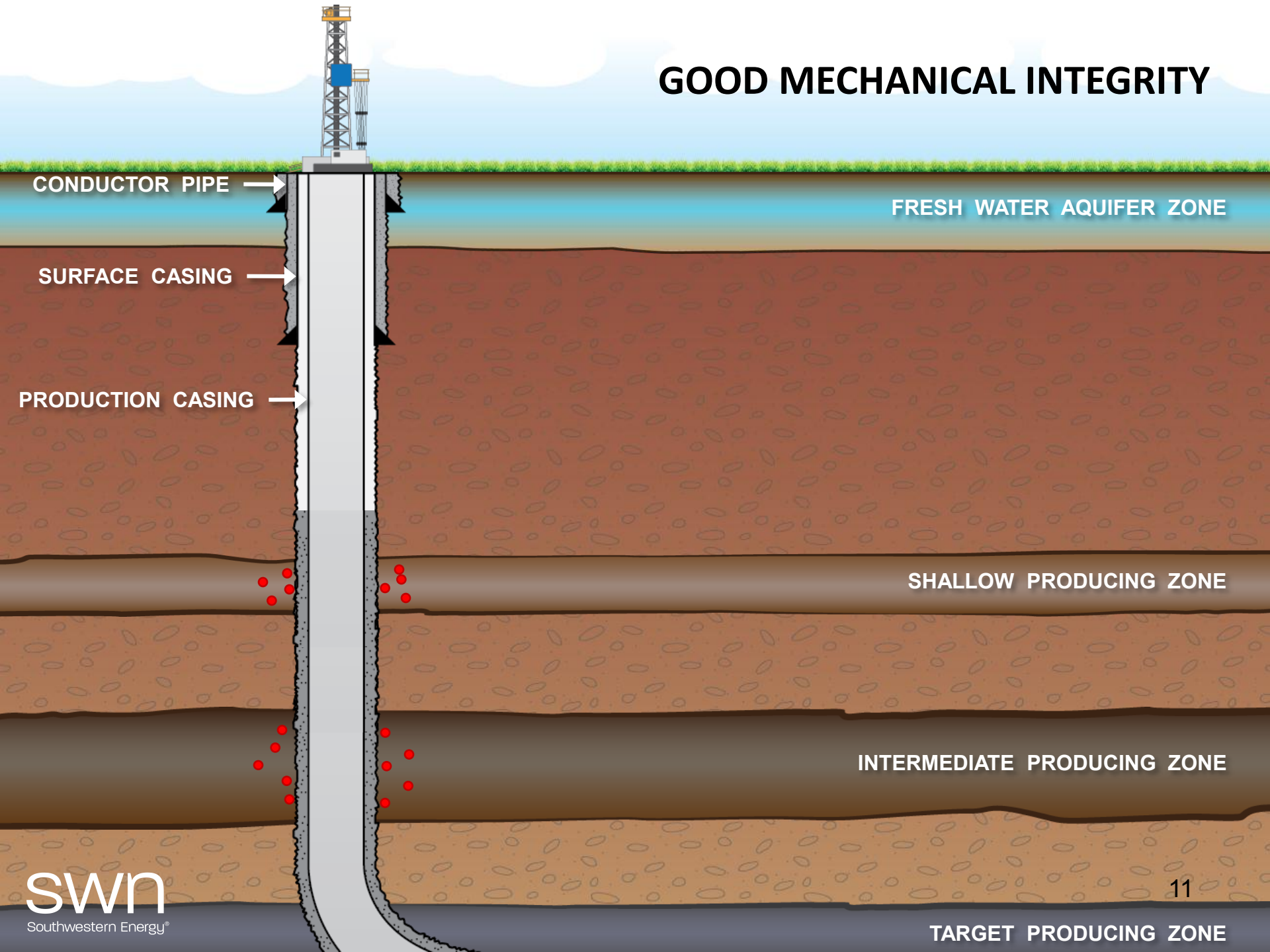
- **Peer-reviewed publications, when available.**
- **EPA report from November 30, 2010.**
- **GAO (2010) report.**
- **American Petroleum Institute (2009) report.**
- **archived PowerPoint presentations from EPA & industry, financial disclosure reports, etc.**

Sources of methane leaks (as percentage of life-time total production):

	<u>Conventional Gas</u>	<u>Shale Gas</u>
Initial drilling & completion	0.01%	1.9%
Routine leaks & emissions at well site	0.3 to 1.9%	0.3 to 1.9%
Venting during liquid unloading	0 to 0.26%	0 to 0.26%
Emissions during gas processing	0 to 0.19%	0 to 0.19%
TOTAL FOR PRODUCTION & PROCESSING	0.31 to 2.4%	2.2 to 4.3%

1.8- to 7-fold more methane leakage from shale gas during development and processing

GOOD MECHANICAL INTEGRITY



CONDUCTOR PIPE

FRESH WATER AQUIFER ZONE

SURFACE CASING

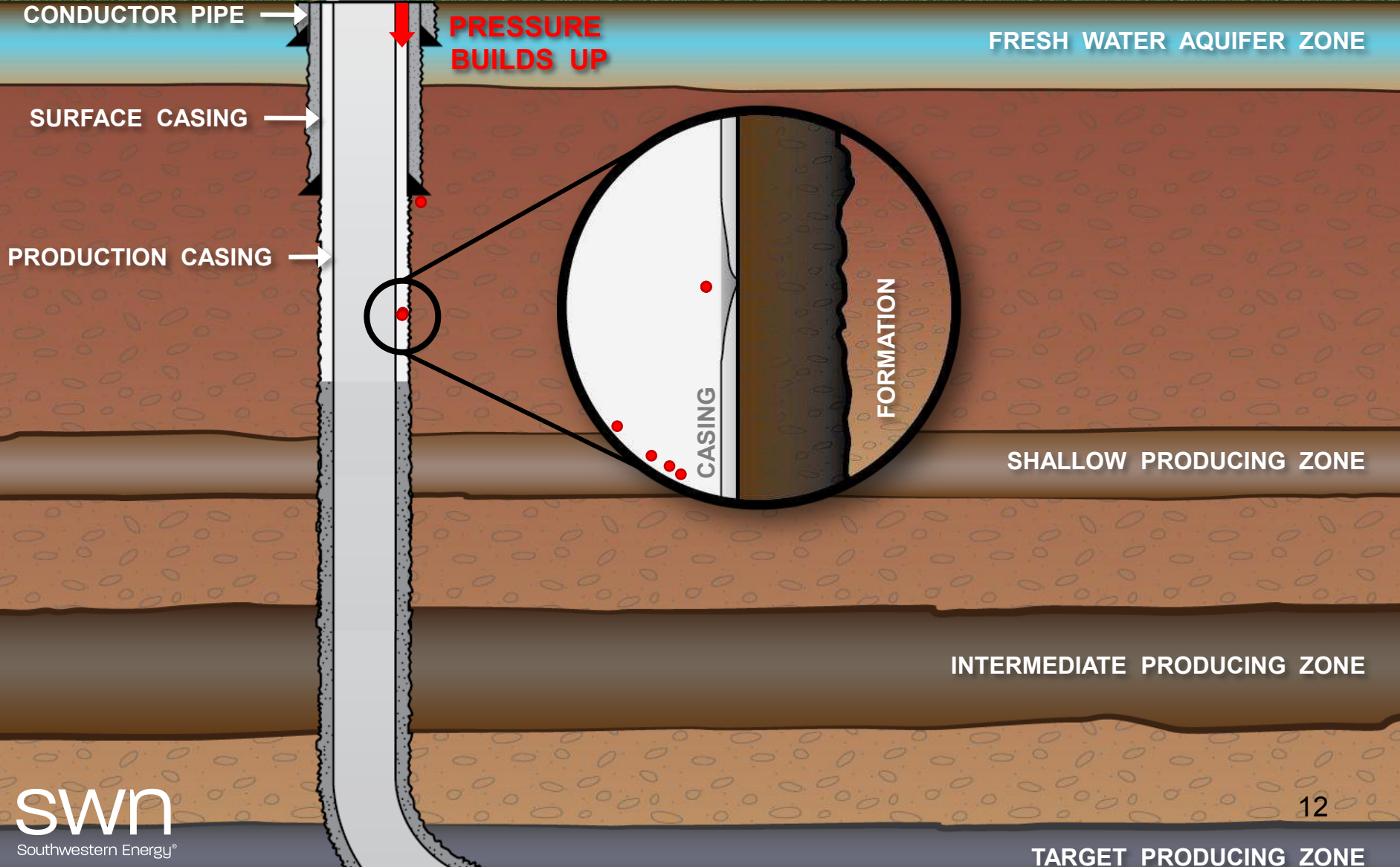
PRODUCTION CASING

SHALLOW PRODUCING ZONE

INTERMEDIATE PRODUCING ZONE

TARGET PRODUCING ZONE

LEAK THROUGH CASING



Sources of methane leaks (as percentage of life-time total production):

	<u>Conventional Gas</u>	<u>Shale Gas</u>
Initial drilling & completion	0.01%	1.9%
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TOTAL FOR PRODUCTION & PROCESSING	0.31 to 2.4%	2.2 to 4.3%

But, this is only part of the story, as the gas has to be delivered stored, transported, and distributed.

Methane (natural gas) leaks from tanks, pipelines, compressors, etc.

Naked eye

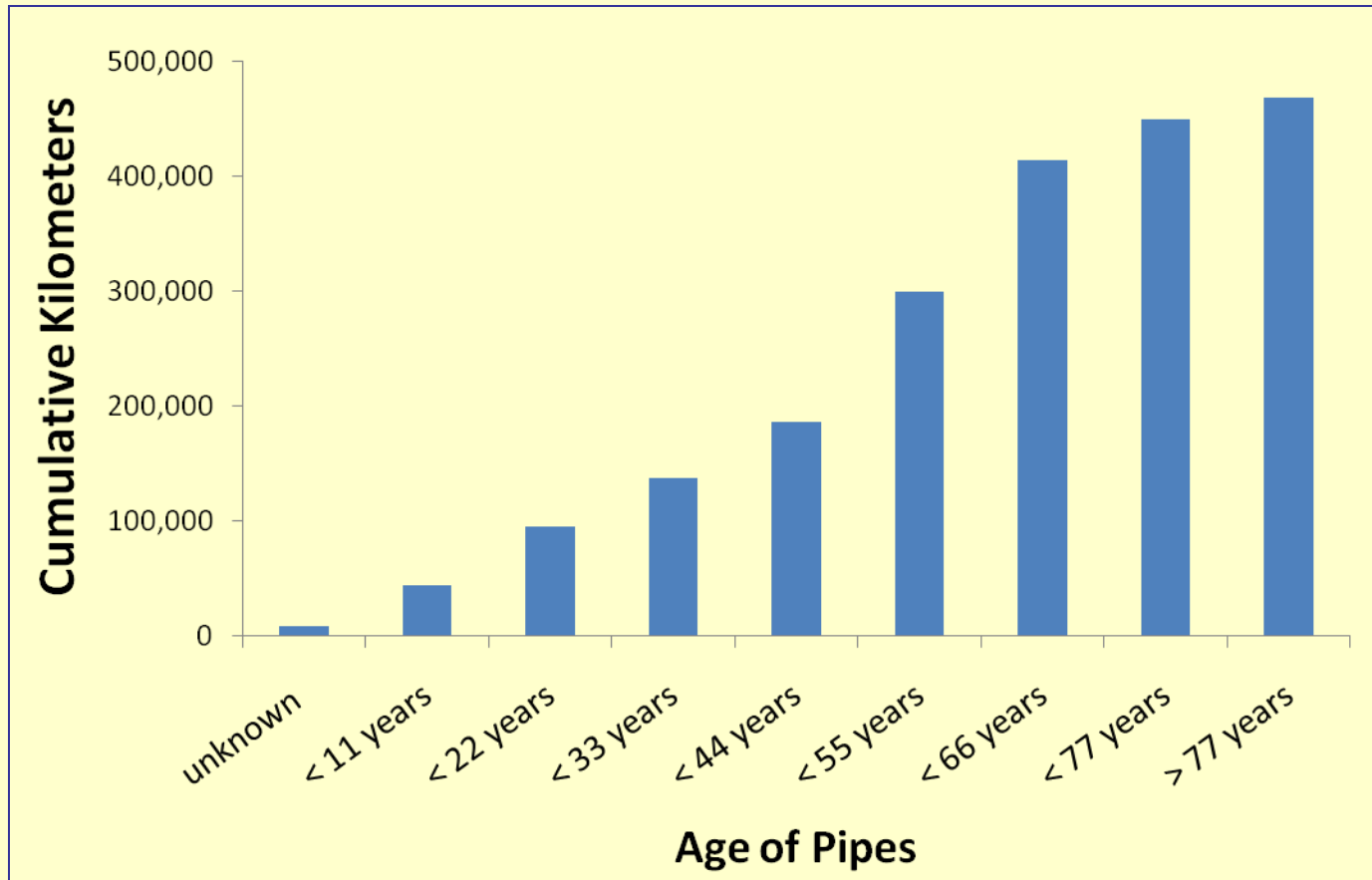


Infra-red (42)



Methane is not visible to naked eye, but can be “seen” with infra-red cameras.

Half of the natural gas transmission pipelines in the US are more than half a century old



Sources: PHMSA 2009 Transmission Annual Data

Two approaches for estimating leakage during transmission, storage, and distribution

1) Direct measurements, based on measurements on Russian pipeline during last 10-15 years (Lelieveld et al. 2005), with extrapolations from EPA (1996) study = 1.4%

Two approaches for estimating leakage during transmission, storage, and distribution

1) Direct measurements, based on measurements on Russian pipeline during last 10-15 years (Lelieveld et al. 2005), with extrapolations from EPA (1996) study = 1.4%

2) “missing and unaccounted for gas,” based on range of values in Texas over past decade (Percival 2010) = mean value of 3.6%

Sources of methane leaks (as percentage of life-time total production):

	<u>Conventional Gas</u>	<u>Shale Gas</u>
Initial drilling & completion	0.01%	1.9%
Routine leaks & emissions at well site	0.3 to 1.9%	0.3 to 1.9%
Venting during liquid unloading	0 to 0.26%	0 to 0.26%
Emissions during gas processing	0 to 0.19%	0 to 0.19%
Transmission, storage, and distribution	1.4 to 3.6%	1.4 to 3.6%
Total	1.7 to 6.0%	3.6 to 7.9%

Urban infrastructure is old.... In Philadelphia, gas distribution pipes are 100 years old, made of un-welded iron pipe.

Gas leakage within the city is ~ 3%.



Chris Kimmerle, Executive Director, Philadelphia Gas Commission, pers. comm, April 19, 2011

How do our methane emission estimates compare with others from the peer-reviewed literature?

How do our methane emission estimates compare with others from the peer-reviewed literature?

- 1) There are no other peer-reviewed papers on methane emissions from shale gas....**

The only current and credible report, from EPA on November 30, 2010, was not peer-reviewed. Our estimates are broadly consistent with this EPA report.

How do our methane emission estimates compare with others from the peer-reviewed literature?

2) We can compare our estimates for conventional gas with 2 other peer-reviewed papers

- Howarth et al. (2011) = 1.7% to 6%
- Hayhoe et al. (2002), “best estimate” = 3%
(range of 0.7% to 10%)
- Jamarillo et al. (2007) = 1.1%
(based entirely on EPA 1996 report; in 2010, EPA greatly increased these estimates)

Methane is far greater in its global warming potential than is carbon dioxide

- 105-fold, compared over 20-year period following emission.
- 33-fold, compared over 100-year period following emission.

Improved Attribution of Climate Forcing to Emissions

Drew T. Shindell,* Greg Faluvegi, Dorothy M. Koch, Gavin A. Schmidt, Nadine Unger, Susanne E. Bauer

Evaluating multicomponent climate change mitigation strategies requires knowledge of the diverse direct and indirect effects of emissions. Methane, ozone, and aerosols are linked through atmospheric chemistry so that emissions of a single pollutant can affect several species. We calculated atmospheric composition changes, historical radiative forcing, and forcing per unit of emission due to aerosol and tropospheric ozone precursor emissions in a coupled composition-climate model. We found that gas-aerosol interactions substantially alter the relative importance of the various emissions. In particular, methane emissions have a larger impact than that used in current carbon-trading schemes or in the Kyoto Protocol. Thus, assessments of multigas mitigation policies, as well as any separate efforts to mitigate warming from short-lived pollutants, should include gas-aerosol interactions.

Multicomponent climate change mitigation strategies are likely to be much more cost effective than carbon dioxide (CO₂)-only strategies (1, 2) but require quantification of the relative impact of different emissions that affect climate. Because globally and annually averaged radiative forcing (RF) is generally a good predictor of global mean surface temperature change, a scale related to RF is a logical choice for comparing emissions. The most widely used, and that adopted in the Kyoto Protocol, is the global warming potential (GWP), defined as the integrated global mean RF out to a chosen time of an emission pulse of

1 kg of a compound relative to that for 1 kg of CO₂. GWPs are thus based on radiative impact and atmospheric residence time and can include both the direct radiative effect of emitted species and radiative effects from indirect chemical responses. Previous studies, including the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), provide estimates of RF and GWPs of short-lived gas emissions (3–5). However, except for the indirect effect of NO_x emissions on nitrate aerosol, gas-aerosol interactions were not included. These interactions occur primarily through ozone precursors altering the availability of oxidants, influencing aerosol formation rates, and through sulfate-nitrate competition for ammonium.

We used the composition-climate model Goddard Institute for Space Studies (GISS) Model for Physical Understanding of Composition-

Climate Interactions and Impacts (G-PUCCINI) (6) to calculate the response to removal of all anthropogenic methane, carbon monoxide (CO) plus volatile organic compounds (VOCs), NO_x, SO₂, and ammonia emissions. This model couples gas-phase, sulfate (7), and nitrate (8) aerosol chemistry within the GISS ModelE general circulation model (GCM). Anthropogenic emissions are from a 2000 inventory (9). We calculated both the “abundance-based” RF owing to the net atmospheric composition response by species when all emissions are changed simultaneously and the “emissions-based” forcing attributable to the responses of all species to emissions of a single pollutant (Fig. 1). The sum of the forcings that take place via response of a particular species in the emissions-based analysis (each represented by a different color in Fig. 1) is approximately equal to the forcing due to that species in the abundance-based analysis. Likewise, the sums of all emissions-based and all abundance-based forcings are similar. Hence, the two viewpoints provide different but compatible pictures of how emissions and composition changes influence RF.

Emissions of NO_x, CO, and methane have substantial impacts on aerosols by altering the abundance of oxidants, especially hydroxyl, which convert SO₂ into sulfate. Global burdens of hydroxyl and sulfate change by 18% and 13% for increased NO_x, by –13% and –9% for CO, and by –26% and –11% for methane (sulfate forcing closely follows the sulfate burden change). Coupling in the other direction is very weak because reactions of gas-phase species upon aerosol surfaces have only a small effect on the global burden of the radiatively active species ozone and methane (e.g., anthropogenic SO₂ emissions enhance the removal of NO_x through reactions on particulate

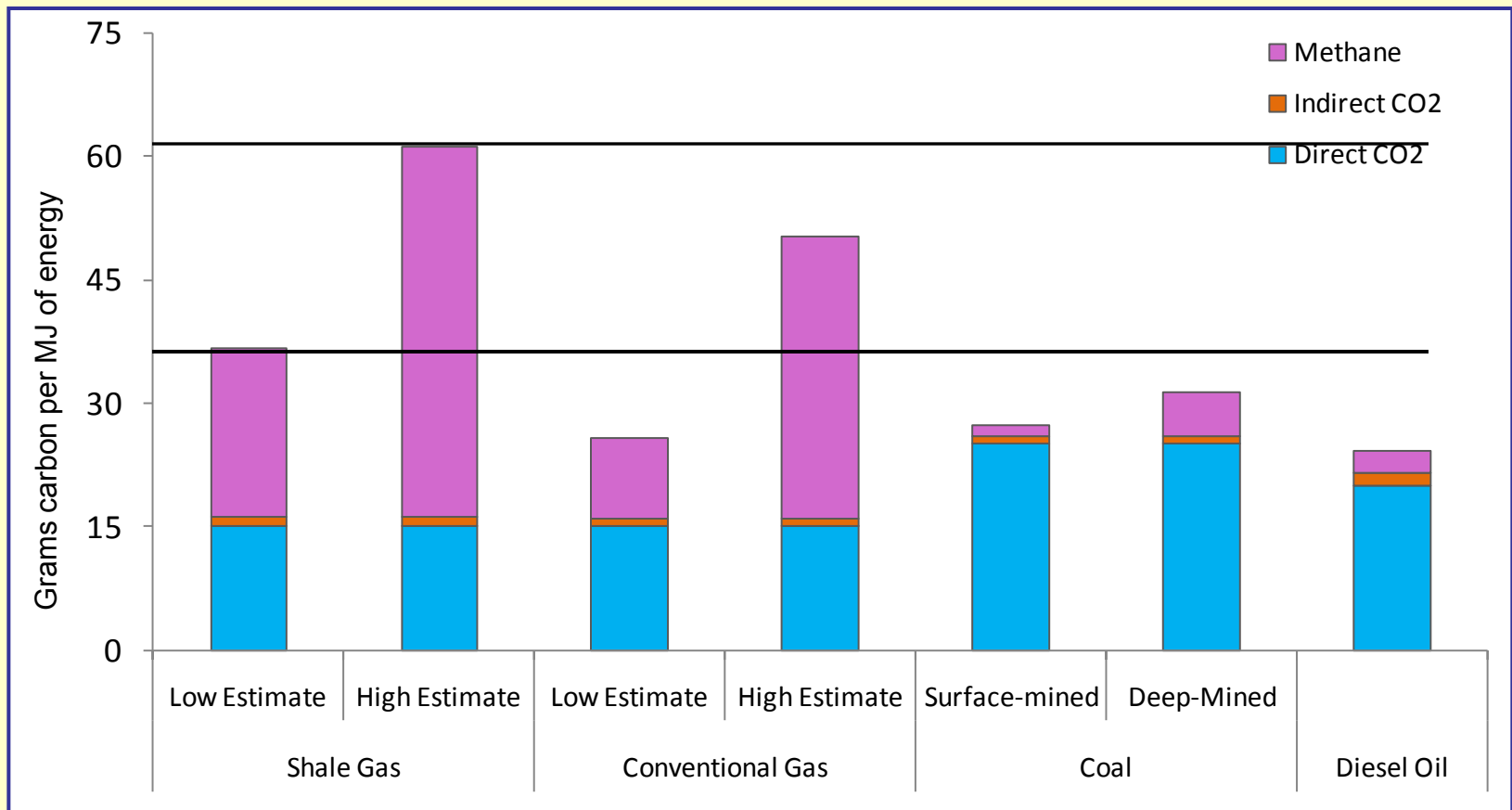
NASA Goddard Institute for Space Studies and Columbia University, New York, NY 10025, USA.

*To whom correspondence should be addressed. E-mail: drew.t.shindell@nasa.gov

Converting methane to global warming potential equivalents, in terms of CO₂

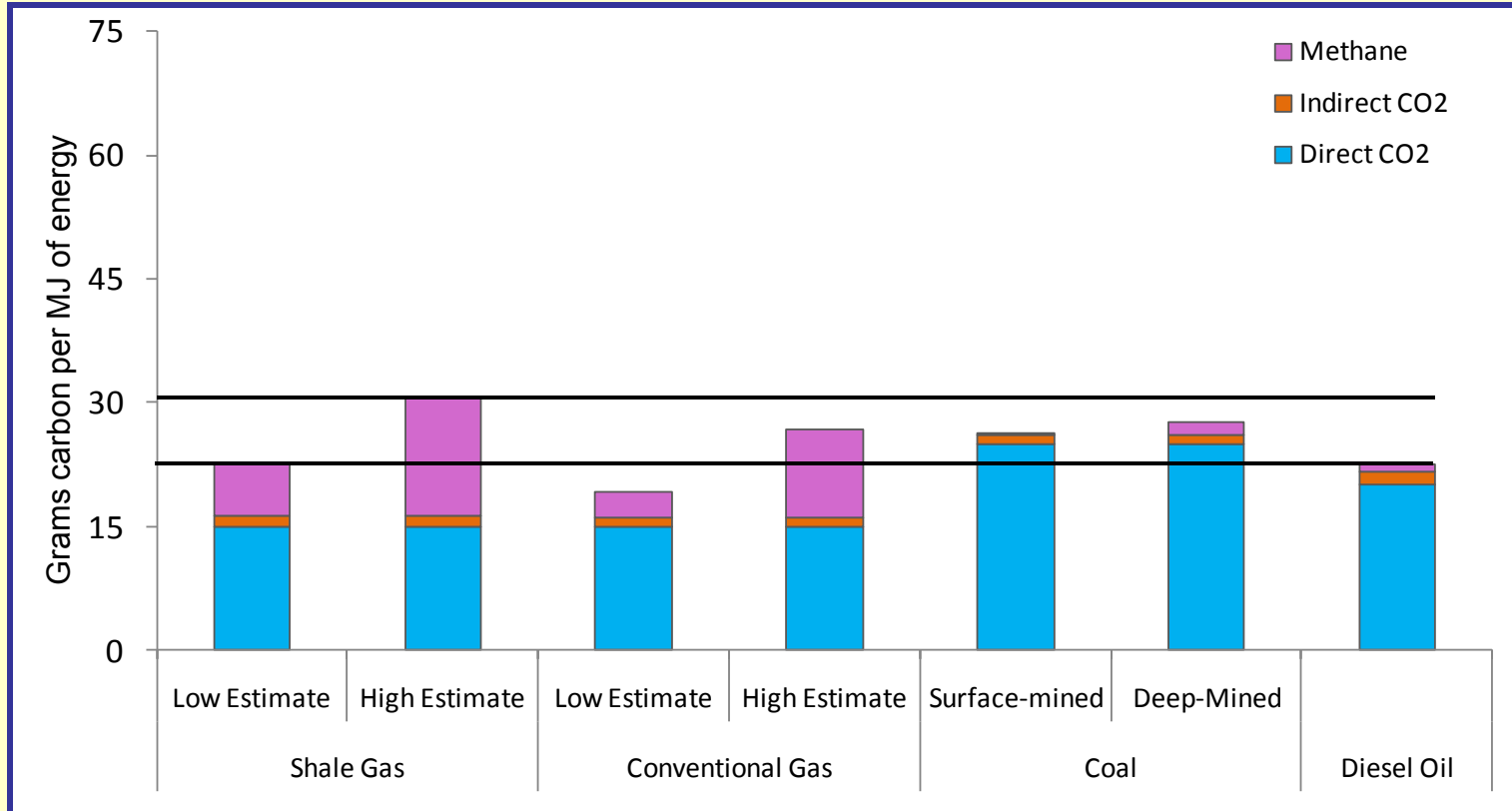
- IPCC (1995) considered only 100-year time frame;
GWP = 21
(used in all previous peer-reviewed studies, although Hayhoe et al. 2002 and Lelieveld et al. 2005 emphasized need for shorter horizons).
- IPCC (2007); GWP for 100-year horizon = 25
GWP for 20-year horizon = 72
- Shindell et al. (2009), Science: GWP for 100-year = 33
GWP for 20-year = 105

Greenhouse gas footprint of shale gas and other fossil fuels (20-year analysis; methane given in CO2 equivalents, assuming Global warming Potential = 105)



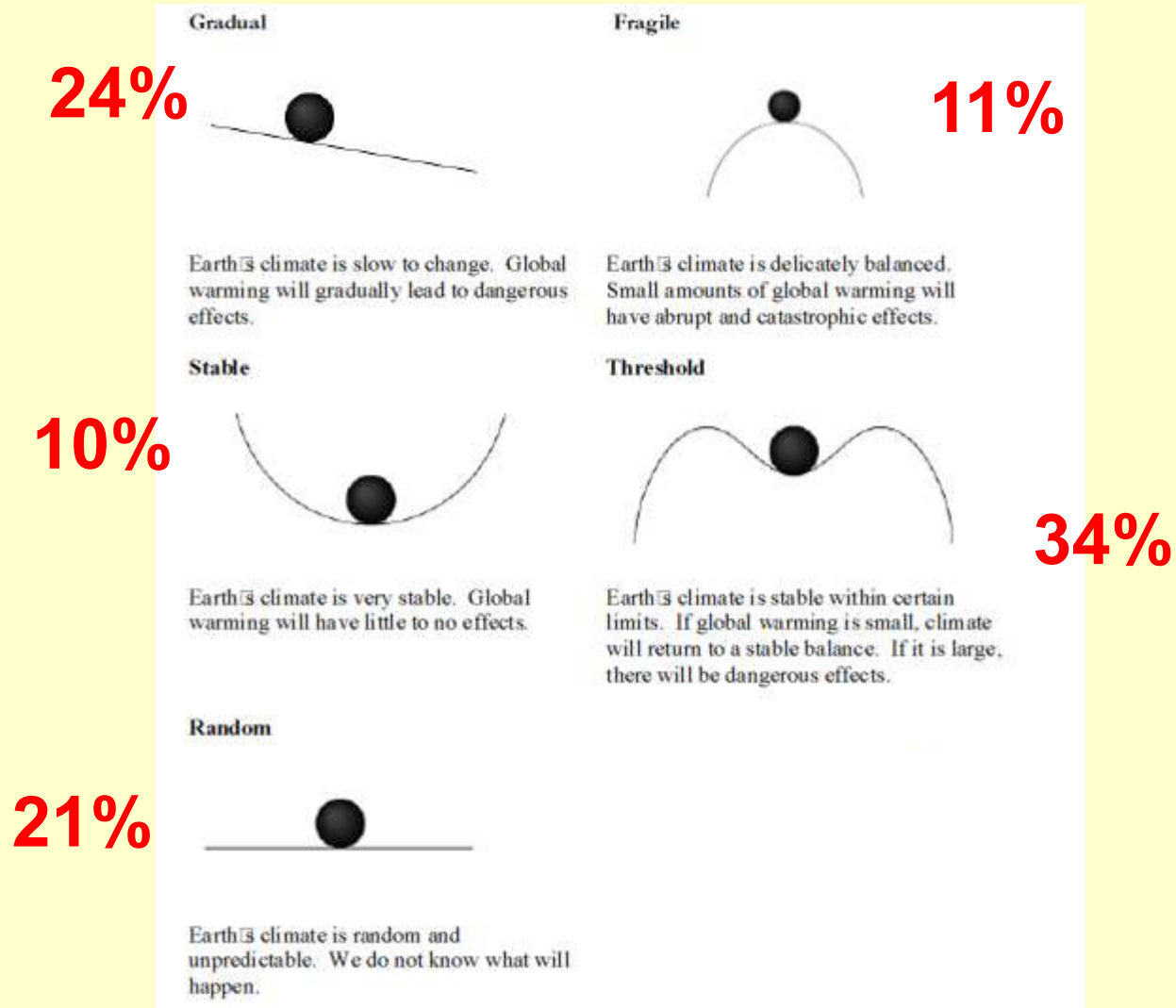
(Howarth et al. 2011)

Greenhouse gas footprint of shale gas and other fossil fuels (100-year analysis; methane given in CO2 equivalents, assuming Global warming Potential = 33)



(Howarth et al. 2011)

Stability of Earth climate system: percent beliefs of adult Americans.....



What all climate scientists think

24%

Gradual



Earth's climate is slow to change. Global warming will gradually lead to dangerous effects.

10%

Stable



Earth's climate is very stable. Global warming will have little to no effects.

21%

Random



Earth's climate is random and unpredictable. We do not know what will happen.

Earth's climate is delicately balanced. Small amounts of global warming will have abrupt and catastrophic effects.

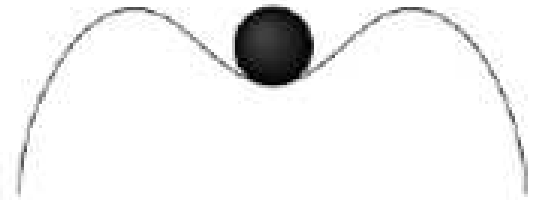
Threshold



Earth's climate is stable within certain limits. If global warming is small, climate will return to a stable balance. If it is large, there will be dangerous effects.

34%

Threshold

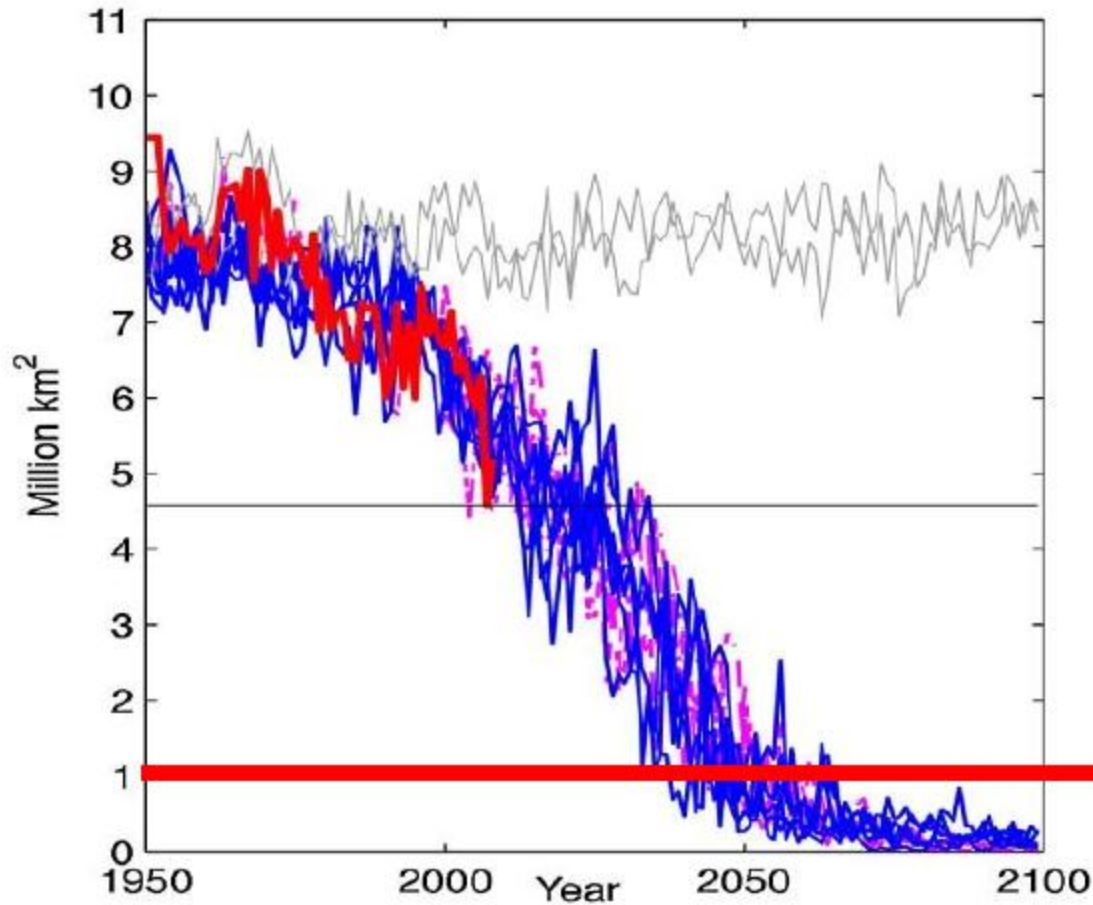


Earth's climate is stable within certain limits. If global warming is small, climate will return to a stable balance. If it is large, there will be dangerous effects.

Possible tipping points to push Earth into new climate system:

- Change in deep ocean circulation.
- Melting of Arctic Ocean ice (with reduced albedo)
- more thunderstorms in Arctic, leading to more fires
- melting of permafrost, and of methane hydrates

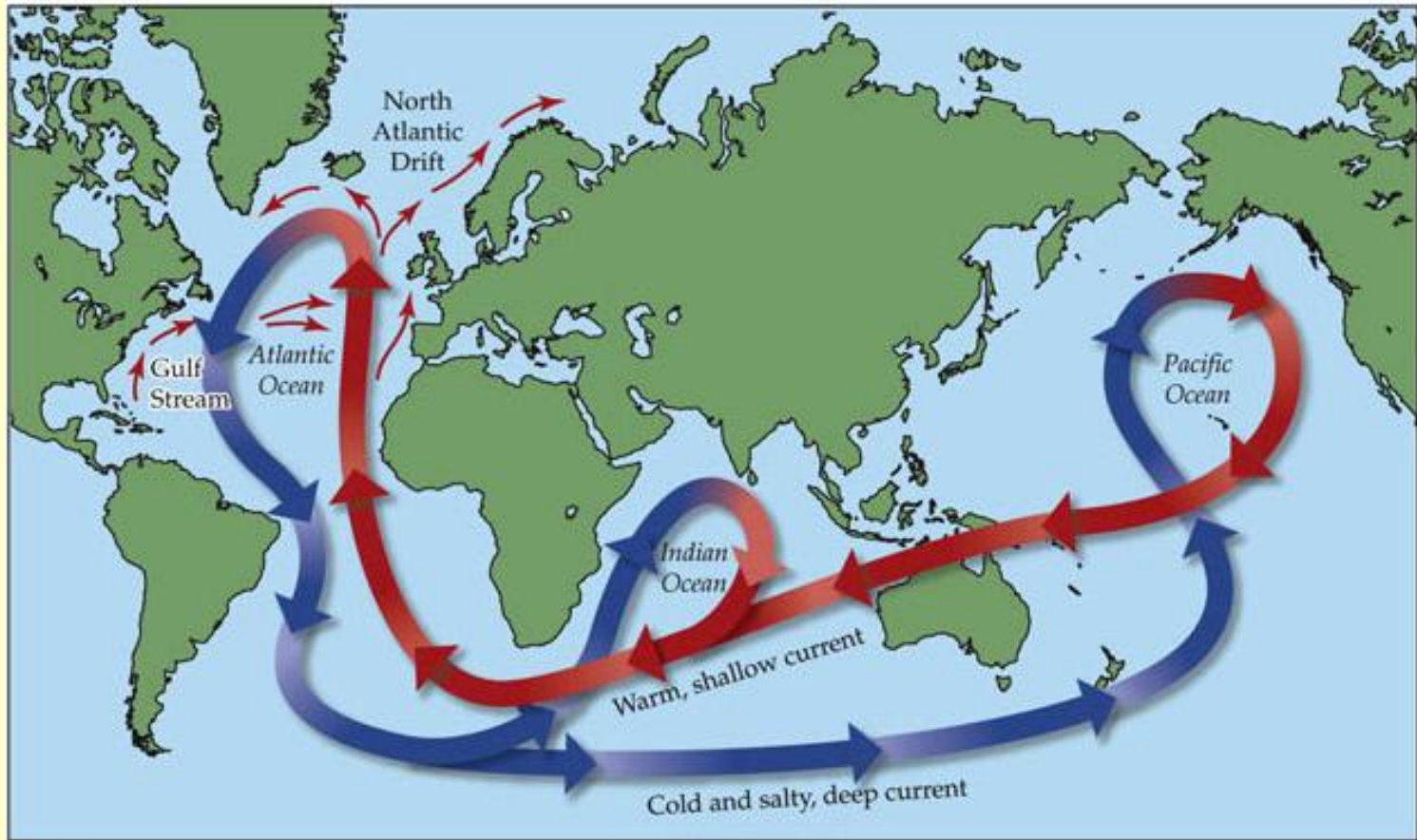
5. Rapid loss of Arctic sea ice



(Wang and Overland, 2009)

ice-free

Simplified version of Global Ocean “Conveyor” Belt



Cain et al. 2008

Tundra fire – North slope of Alaska (2007)



<http://news.discovery.com/earth/alaskas-arctic-tundra-feeling-the-heat.html>

Thermokarst ground subsidence following thawing and subsidence

CH₄

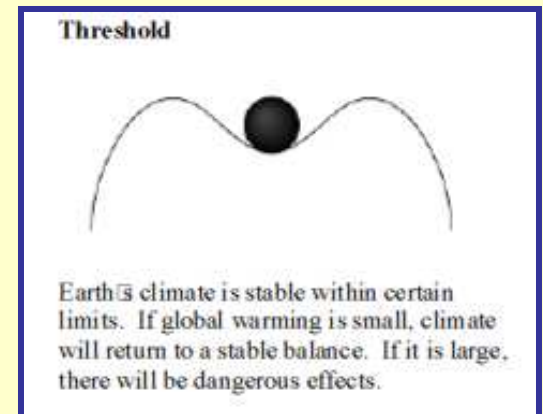
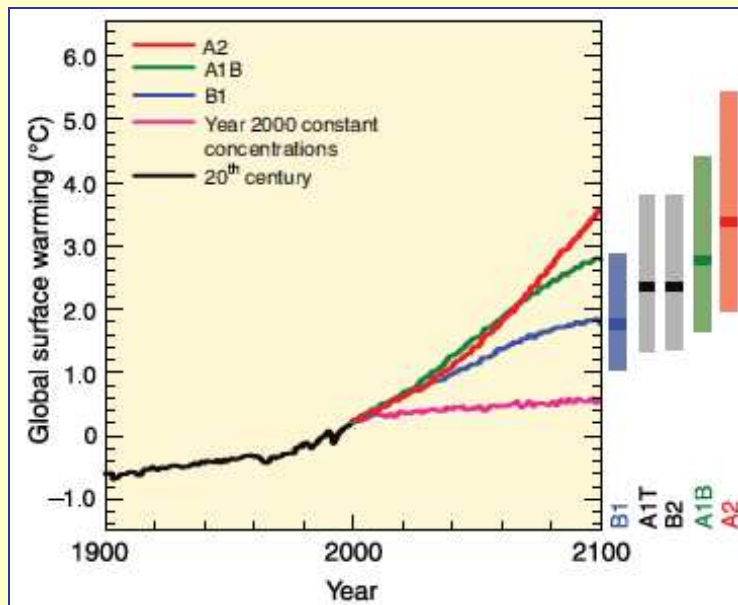
CH₄

CH₄

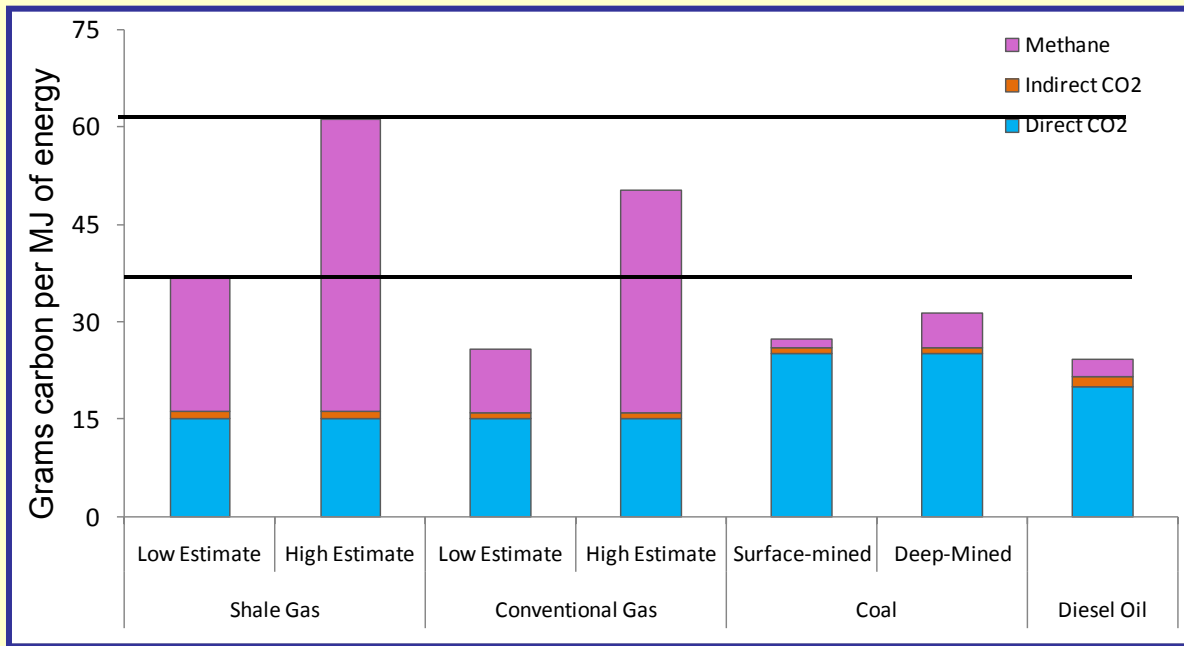
Massive emissions of ancient CH₄
(8000 – 2800 years old) due to thawing
permafrost and release of “frozen”
methane (methane hydrates)

Existing models for global warming potential (GWP) of methane only support analysis at 20-year and 100-year integrated time scales.

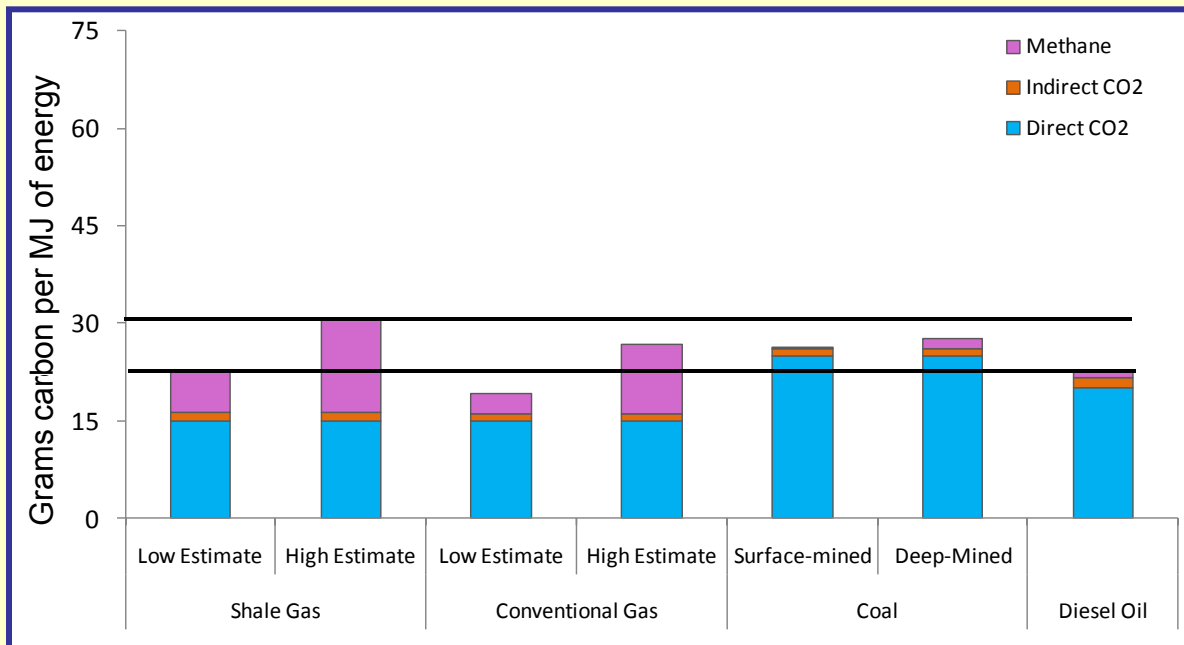
Both are important. But shorter time focus critical to minimize likelihood of surpassing tipping points and moving climate system to some new, undesirable state.



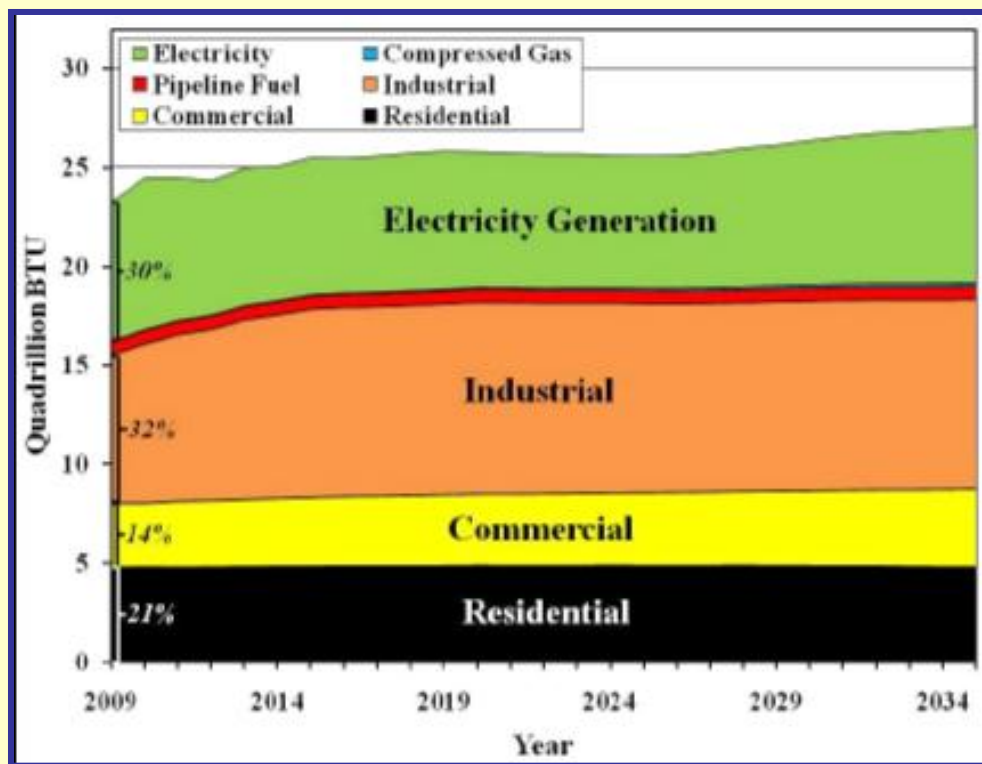
20 year



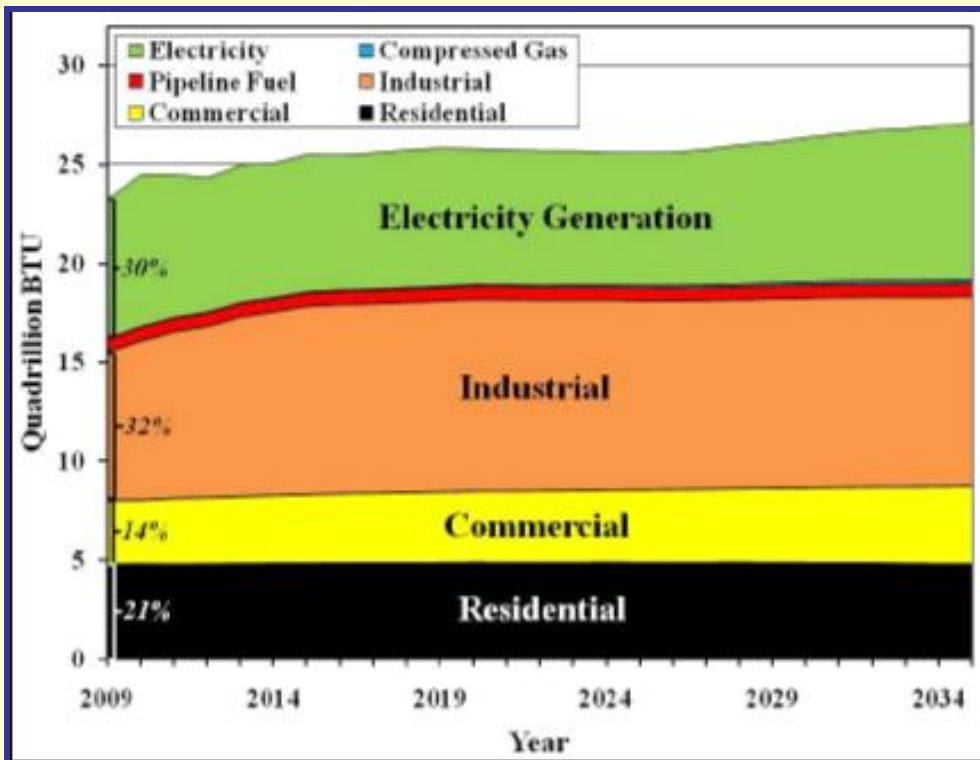
100 year



Only 30% of natural gas in the U.S. is used to generate electricity....



http://www.eia.doe.gov/forecasts/aeo/excel/aeotab_2.xls



Efficiency of use of natural gas for most uses (including transportation) is very similar to that of oil or coal.

For electricity, natural gas gains some efficiency over coal....

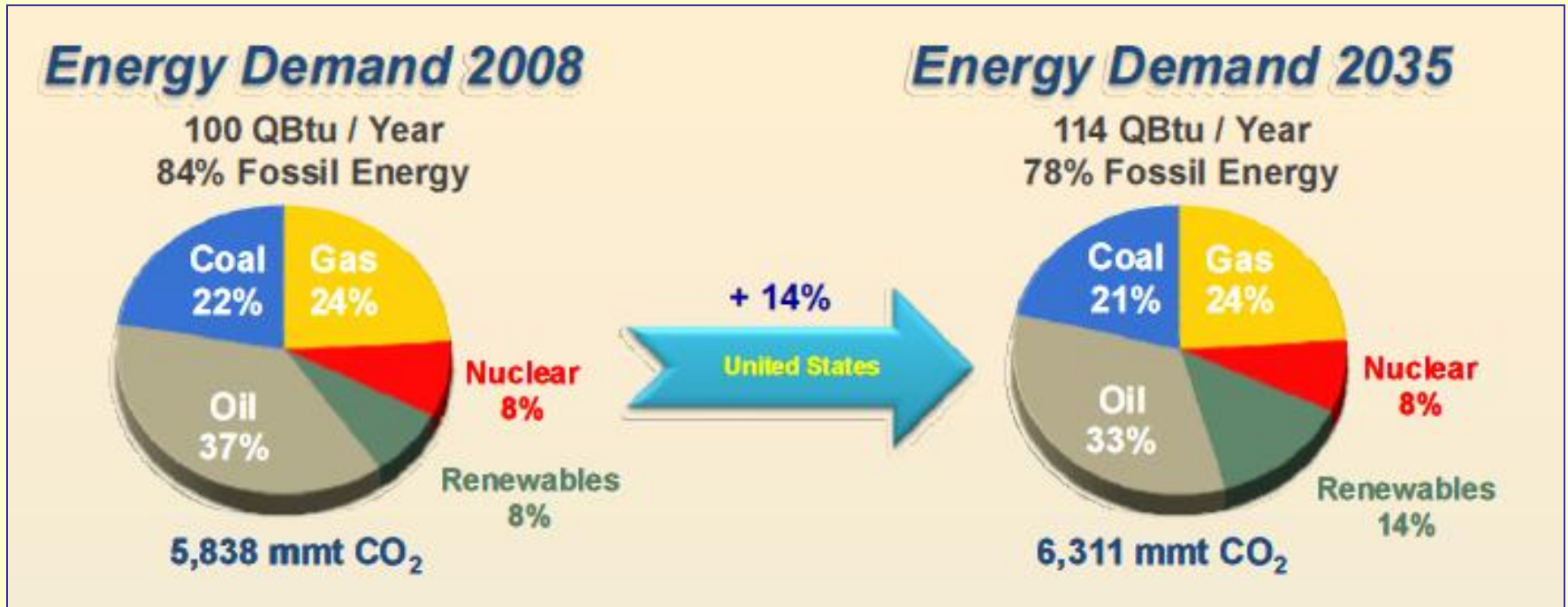
But even for electricity, GHG footprint for shale gas is similar to or worse than that for coal.

Emissions from generating electricity

(g C-CO₂ equivalents/kWatt-hr, 20-year integration)

	<u>Current average plant</u>	<u>Best technology</u>
Coal	280	220
Shale gas	320-560	270-460

Very modest growth in use of both coal and natural gas predicted.... NOT replacement of coal by natural gas.



How does natural gas fit into the national greenhouse gas inventory?

Update by US EPA on methane emissions from gas (Nov. 30, 2010):

Table 1: Comparison of Emissions Factors from Four Updated Emissions Sources

Emissions Source Name	EPA/GRI Emissions Factor	Revised Emissions Factor	Units
1) Well venting for liquids unloading	1.02	11	CH ₄ – metric tons/year-well
2) Gas well venting during completions			
<i>Conventional well completions</i>	0.02	0.71	CH ₄ – metric tons/year-completion
<i>Unconventional well completions</i>	0.02	177	CH ₄ – metric tons/year-completion
3) Gas well venting during well workovers			
<i>Conventional well workovers</i>	0.05	0.05	CH ₄ – metric tons/year-workover
<i>Unconventional well workovers</i>	0.05	177	CH ₄ – metric tons/year-workover
4) Centrifugal compressor wet seal degassing venting	0	233	CH ₄ – metric tons/year-compressor

1. Conversion factor: 0.01926 metric tons = 1 Mcf

1996

Nov. 2010

⁴ EPA did consider the data available from two new studies, TCEQ (2009) and TERC (2009). However, it was found that the data available from the two studies raise several questions regarding the magnitude of emissions

U.S. Greenhouse gas inventory (Tg CO₂ equivalents per year, 2008 base year)

	Old estimate (2010 analysis)	New estimate (2011 analysis)
Total net GHG emissions	5,916	6,020
Methane emissions (percent of total)	568 (9.6%)	677 (11%)
Methane from natural gas (percent of total)	97 (1.6%)	212 (3.5%)

Based on EPA (2011), using methane global warming potential = 21

Data from: <http://www.epa.gov/climatechange/emissions/usinventoryreport.html>

U.S. Greenhouse gas inventory

(Tg CO2 equivalents per year, 2008 base year)

	Old estimate	New estimate (2011 analysis)
Equal to 3.1% leakage of all natural gas production, well within our range of 1.7% to 6% for conventional gas		
		6,020
Methane emissions	568	677
Methane from natural gas	97	212

Based on EPA (2011), using methane global warming potential = 21

Influence of methane global warming potential assumption on U.S. greenhouse gas inventory (Tg CO₂ equivalents per year, 2008)

	GWP = 21	GWP = 33
Total net GHG emissions	6,020	6,407
Methane emissions (percent of total)	677 (11%)	1,064 (17%)
Methane from natural gas (percent of total)	212 (3.5%)	333 (5.2%)

Based on EPA (2011), using GWP from IPCC (1996) compared to Shindell et al. (2009) value

Data from: <http://www.epa.gov/climatechange/emissions/usinventoryreport.html>

Influence of methane global warming potential assumption on U.S. greenhouse gas inventory (Tg CO₂ equivalents per year, 2008)

	GWP = 21	GWP = 33 (100 yr)	GWP = 105 (20 yr)
Total net GHG emissions	6,020	6,407	8,728
Methane emissions (percent of total)	677 (11%)	1,064 (17%)	3,385 (39%)
Methane from natural gas (percent of total)	212 (3.5%)	333 (5.2%)	1,060 (12%)

Based on EPA (2011), using GWP from IPCC (1996) compared to Shindell et al. (2009) value

Data from: <http://www.epa.gov/climatechange/emissions/usinventoryreport.html>

The greenhouse gas footprint of natural gas will increase as conventional gas is further replaced by shale gas and other unconventional gas....

Using DOE (2011) projections for shale gas development and 20-year integrated GWP, the increased use of shale gas will increase the entire greenhouse gas footprint for the US by 7% by 2031 (with no increase in available gas or energy).

I am not advocating for more coal or oil, but rather to recognize full environmental costs of all fossil fuels, and to move to a truly green, renewable future as quickly as possible.



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November 2009

www.ScientificAmerican.com

The Long-Lost
Siblings of
OUR SUN
page 40



A Plan for a

Sustainable Future

How to get all energy from
wind, water and solar power
by 2030





Cornell University
College of Agriculture and Life Sciences

Thanks for the
opportunity to speak
today!



Climatic Change
DOI 10.1007/s10584-011-0061-5

LETTER

Methane and the greenhouse-gas footprint of natural gas from shale formations

A letter

Robert W. Howarth · Renee Santoro ·
Anthony Ingraffea

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Abstract We evaluate the greenhouse gas footprint of natural gas obtained by high-volume hydraulic fracturing from shale formations, focusing on methane emissions. Natural gas is composed largely of methane, and 3.6% to 7.9% of the methane from shale-gas production escapes to the atmosphere in venting and leaks over the lifetime of a well. These methane emissions are at least 30% more than and perhaps more than twice as great as those from conventional gas. The higher emissions from shale gas occur at the time wells are hydraulically fractured—as methane escapes from flow-back return fluids—and during drill out following the fracturing. Methane is a powerful greenhouse gas, with a global warming potential that is far greater than that of carbon dioxide, particularly over the time horizon of the first few decades following emission. Methane contributes substantially to the greenhouse gas footprint of shale gas on shorter time scales, dominating it on a 20-year time horizon. The footprint for shale gas is greater than that for conventional gas or oil when viewed on any time horizon, but particularly so over 20 years. Compared to coal, the footprint of shale gas is at least 20% greater and perhaps more than twice as great on the 20-year horizon and is comparable when compared over 100 years.

Keywords Methane · Greenhouse gases · Global warming · Natural gas · Shale gas · Unconventional gas · Fugitive emissions · Lifecycle analysis · LCA · Bridge fuel · Transitional fuel · Global warming potential · GWP

Electronic supplementary material The online version of this article ([doi:10.1007/s10584-011-0061-5](https://doi.org/10.1007/s10584-011-0061-5)) contains supplementary material, which is available to authorized users.

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May 4, 2010

We represent the leadership of over 1.4 million scientists in over 150 scientific disciplines. The acceleration of greenhouse gas (GHG) emissions from human activity is increasingly leading to harmful climate change and ocean acidification. Societies must act urgently to reduce these emitters to protect the life-sustaining biophysical systems of the Earth. As noted by DOE Secretary Steven Chu in his April 28, 2010 testimony to the Senate Subcommittee on Energy and Water Development, the necessary transition "will require nothing short of a new Industrial revolution." We agree with this assessment of the scale of response needed. We need to work aggressively to conserve energy and increase the efficiency of energy use, and we need rapidly to develop less polluting energy systems. Objective science has a critical role to play, and we urge that the nation fully use and incorporate the best available science in designing and implementing the energy and environmental policies necessary to guide the revolution.

America should move ahead quickly to develop a comprehensive energy policy to greatly reduce our GHG emissions. We urge that any potential approach be first evaluated in terms of the net benefits on environmental integrity, including a full analysis of GHG emissions, recognized by the Supreme Court as air pollutants, as well as other environmental concerns. The analysis of GHG emissions should include indirect land use effects and emissions of methane and nitrous oxide as well as carbon dioxide. No policy should be implemented without a full understanding of the consequences on the environment. Uncertainties will remain, which points to the necessity of also having the ability to reverse a policy action if unintended consequences are discovered.

Some energy bridges that are currently encouraged in the transition away from GHG-emitting fossil energy systems have received inadequate scientific analysis before implementation, and these may have greater GHG emissions and environmental costs than often appreciated. We find that their environmental impact studies and EPA determinations necessary to proceed are absent or inadequate. These include the production of ethanol from corn, where recent, more inclusive research concludes this is a poor option. As scientists we are concerned about the impact of the ethanol scale-up on water supply and quality, land use, GHG emissions, and net energy gain. In 2007, the nation used 27% of its corn harvest to produce 1.3% of total liquid fuels. One unintended result is greater nutrient flows down the Mississippi River, aggravating the ecological disaster underway in the Gulf of Mexico. Other biomass feedstocks produce more energy from less land, with less environmental harm. A recent report from the National Academy of Sciences lists many topics that deserve further scientific scrutiny before the nation further expands the role of ethanol as a fuel.

The production of natural gas (methane) from shales represents a major new domestic energy resource that can reduce reliance on imported crude oil. However, the development of methane from shale formations is another example where policy has proceeded adequate scientific study. Economic recovery of methane from shales requires the drilling of long-reach horizontal wells and the high-pressure injection of millions of gallons of water with chemical additives to release the gas through a process called hydrofracking. Despite the utilization of millions of gallons of water and the flow back to the surface of these injected fluids, hydrofracking is exempted from the Clean Water Act. Exploitation of the Marcellus Shale Formation in the Appalachian basin, recognized as the largest shale-gas reserve in the U.S., could occur across a five-state region. Prior, thorough science-based studies are required to evaluate the impact of massive shale development on rural land uses, water supply and quality, and full-life-cycle greenhouse gas emissions.

Sincerely,

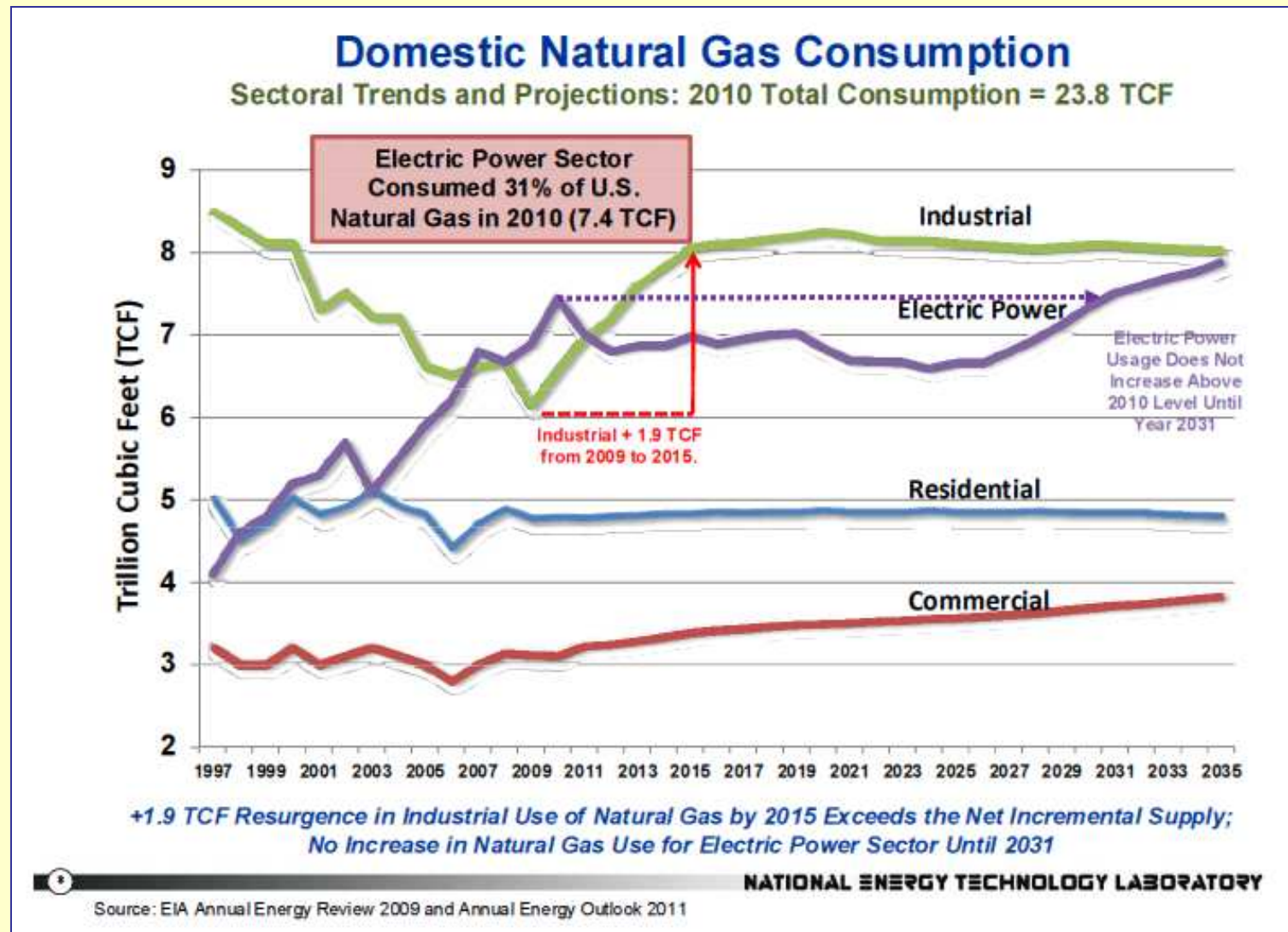
“The acceleration of greenhouse gas (GHG) emissions from human activity is increasingly leading to harmful climate change and ocean acidification. Societies must act urgently to reduce these emissions to protect the life-sustaining biophysical systems of the Earth.”

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Only 30% of natural gas in the U.S. is used to generate electricity....



U.S. Department of Energy (2011)

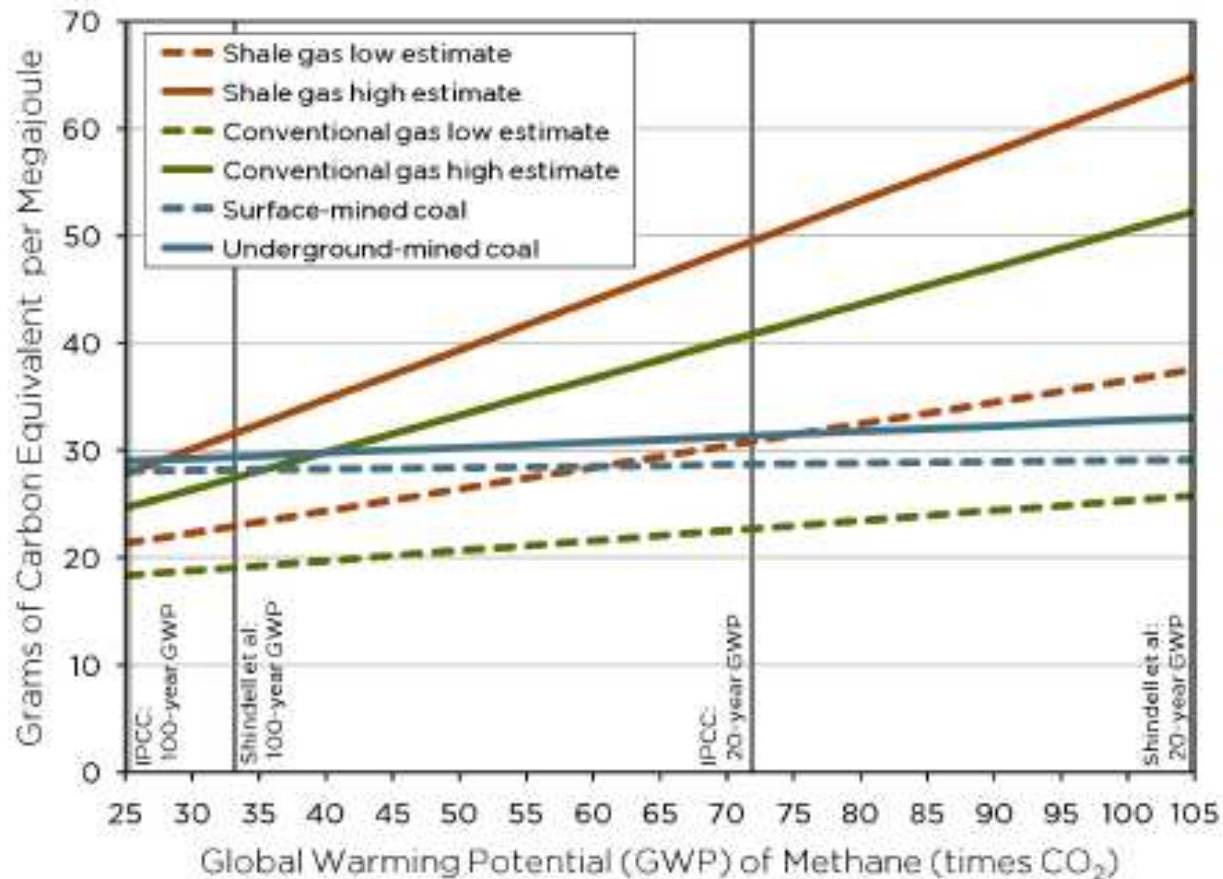


Figure 22. Comparison of Howarth et al.⁹⁴ estimates for shale gas, conventional gas and coal in terms of carbon emissions per unit of heat versus Global Warming Potential (GWP) using the estimates of the IPCC⁹⁵ and Shindell et al.⁹⁶ on 20- and 100-year timeframes.

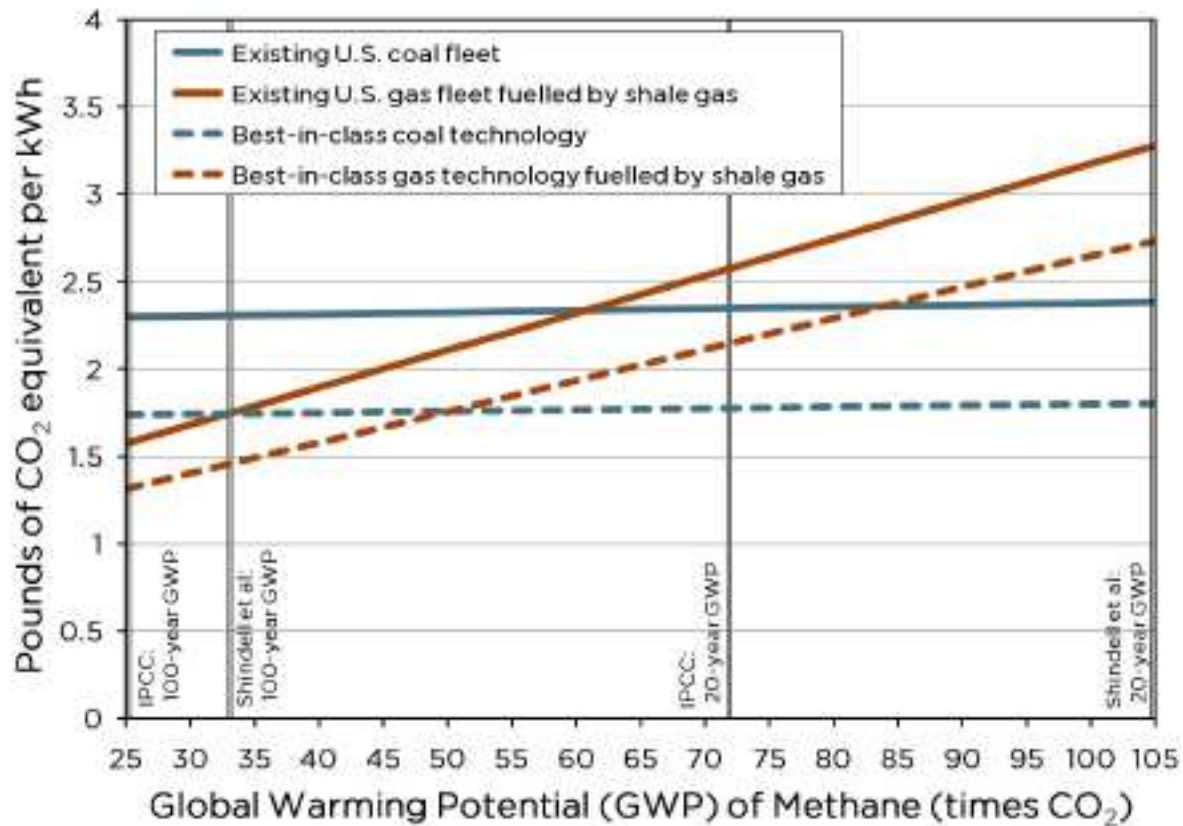


Figure 23. Comparison of CO₂ equivalent emissions per kilowatt-hour for the mean shale gas emission estimate of Howarth et al.¹¹² compared to surface-mined coal for both the existing coal and gas electricity generation fleet and best-technology coal and gas. This comparison covers the range of Global Warming Potential (GWP) highlighting the estimates of the IPCC¹¹³ and Shindell et al.¹¹⁴ on 20- and 100-year timeframes.

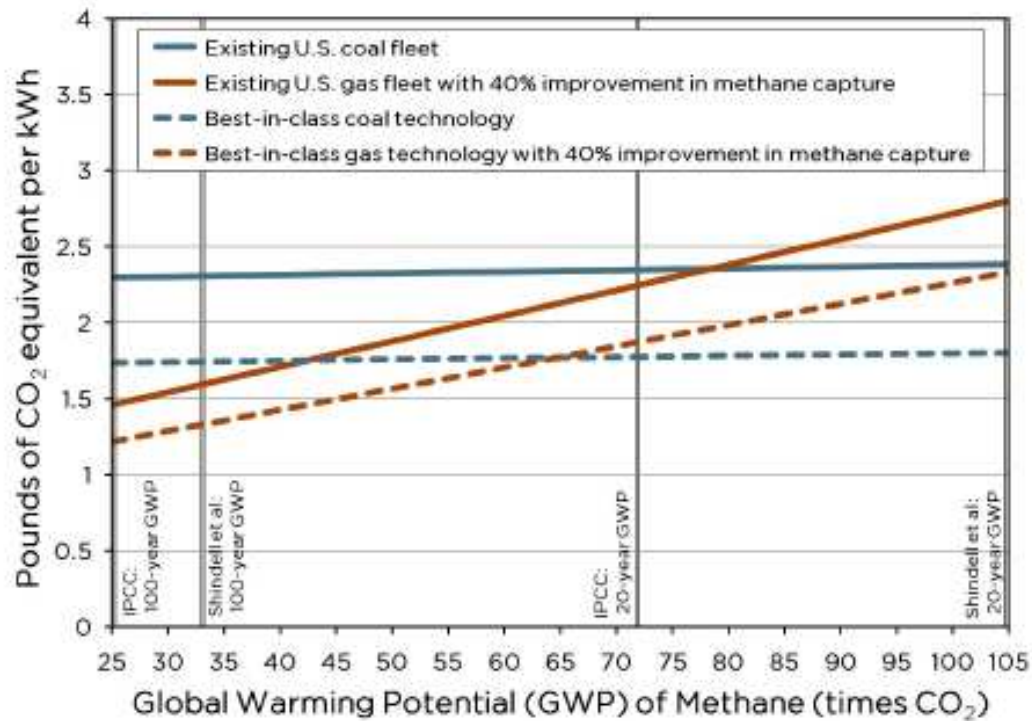


Figure 24. Comparison of future CO₂ equivalent emissions per kWh, if a 40% reduction is achieved in current methane emissions, for the mean shale gas emission estimate of Howarth et al.¹²⁰ compared to surface-mined coal for both the existing coal and gas electricity generation fleet and best-technology coal and gas. This comparison covers the range of Global Warming Potential (GWP) highlighting the estimates of the IPCC¹²¹ and Shindell et al.¹²² on 20- and 100-year timeframes.



Eben Thoma, March 2010, EPA workshop presentation