



Cornell University
College of Agriculture and Life Sciences



Developing Natural Gas in the Marcellus and other Shale Formations is likely to Aggravate Global Warming



**Bob Howarth, Renee Santoro, and
Tony Ingraffea**

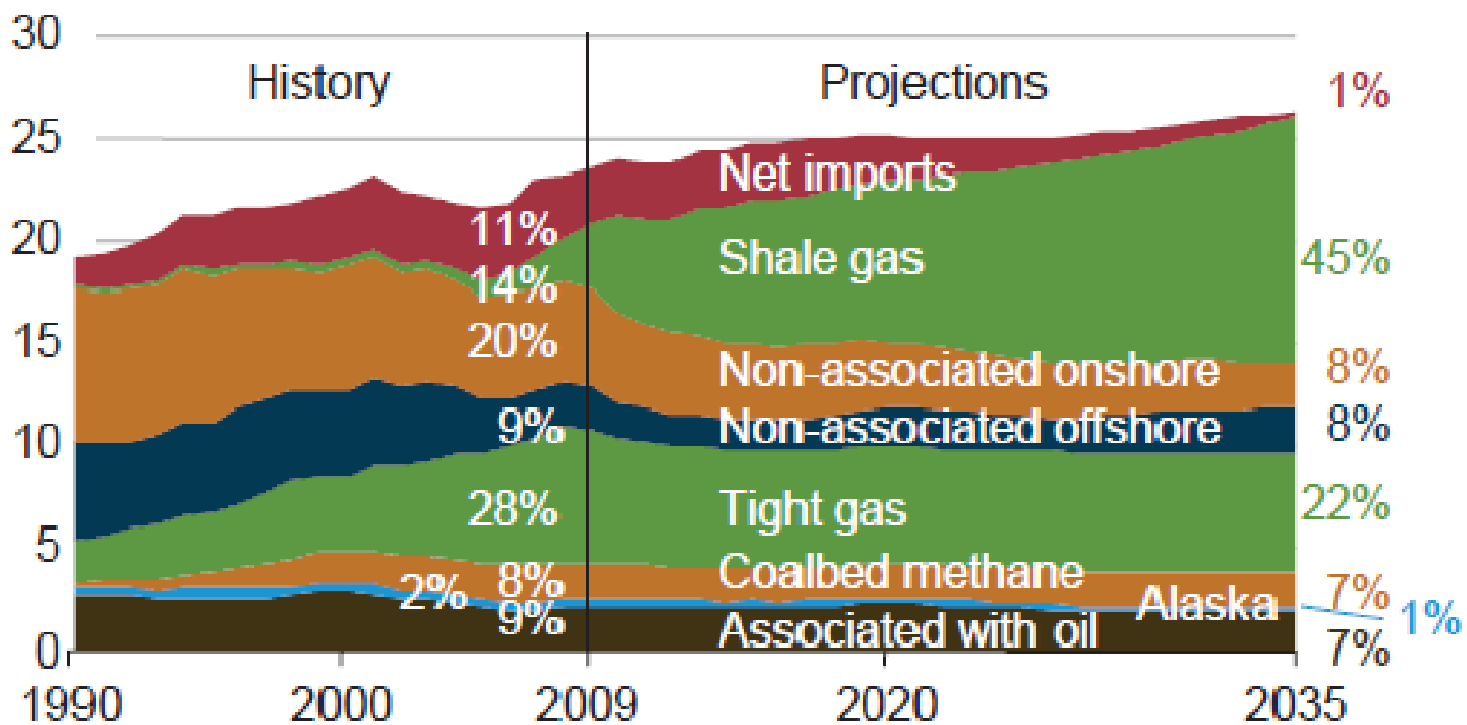
**Department of Ecology & Evolutionary Biology and
School of Civil and Environmental Engineering
Cornell University**

March 15, 2011



Figure 1. Shale gas offsets declines in other U.S. supply to meet consumption growth and lower import need

U.S. dry gas production (trillion cubic feet per year)



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

William Colton, VP of Exxon Mobil for corporate planning, NY Times, Oct. 10, 2010

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

Many others....



COUNCIL OF SCIENTIFIC SOCIETY PRESIDENTS

1155 16th Street, NW • Washington, DC 20036 • 202-872-4452 • FAX 202-872-4079

2010 EXECUTIVE BOARD

President

Martin A. Apple
Washington DC 20036-4852
mapple@sciencepres.org

Chair

Arthur Blumenthal
AMERICAN PHYSICAL SOCIETY
Stanford University
Stanford CA 94305-5055
arthur@stanford.edu

Chair-Elect

George H. Williams
SOCIETY OF TOXICOLOGISTS
Wayne State University
Detroit MI 48202-3489
gwilliams@wayne.edu

Past Chair

William F. Carroll, Jr.
AMERICAN CHEMICAL SOCIETY
Confidential Chemical Cooperation
Dallas TX 75244-100
wfc_carroll@ccco.com

Secretary

Sabine U. O'Hara
US Society for Ecological Economics
Council for the 10% Exchange of
Solutions
Washington DC 20004-3009
sohara@ciesa.org

Treasurer

John M. (Jack) Sharp, Jr.
GEOLOGICAL SOCIETY OF AMERICA
THE UNIVERSITY OF TEXAS AT AUSTIN
Austin TX 78712-0254
jms@jms@mail.utexas.edu

Past Treasurer

James G. Gilm
AMERICAN MATHEMATICAL SOCIETY
1101 UNIVERSITY STREET
SHAW BOX NY 11794-3000
gilm@amsi.sunysb.edu

Members-at-Large

Thomas L. Bohan
AMERICAN ACADEMY OF FORENSIC SCIENCES
ME Technical
Fiske Island, ME 04108
tbohan@mafmia.org

Deborah A. Bronk
AMERICAN SOCIETY OF LIMNOLOGY AND
OCEANOGRAPHY
College of William and Mary
Gloucester Park, VA 23062
dbronk@wvu.edu

Richard A. Dusch
NATIONAL ASSOCIATION FOR BIOMARKERS IN
SCIENCE SOCIETY
Pennsylvania State University
University Park, PA 16802
rod1@psu.edu

Joseph F. Francisco
AMERICAN CHEMICAL SOCIETY
Purdue University
West Lafayette, IN 47907
jfranc@acs.purdue.edu

Ralph B. James
SPE-INTERNATIONAL SOCIETY FOR OILFIELD AND
PETROLEUM
BOOKERLYN NATIONAL LABORATORY
960th, NY 11772
james@bnl.gov

Legal/Ethics Advisor
Judge Haskell Pittuck
AMERICAN ACADEMY OF FORENSIC SCIENCES
COURT HOUSE B. 40214
pittuck@aacf.net

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 emissions 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,

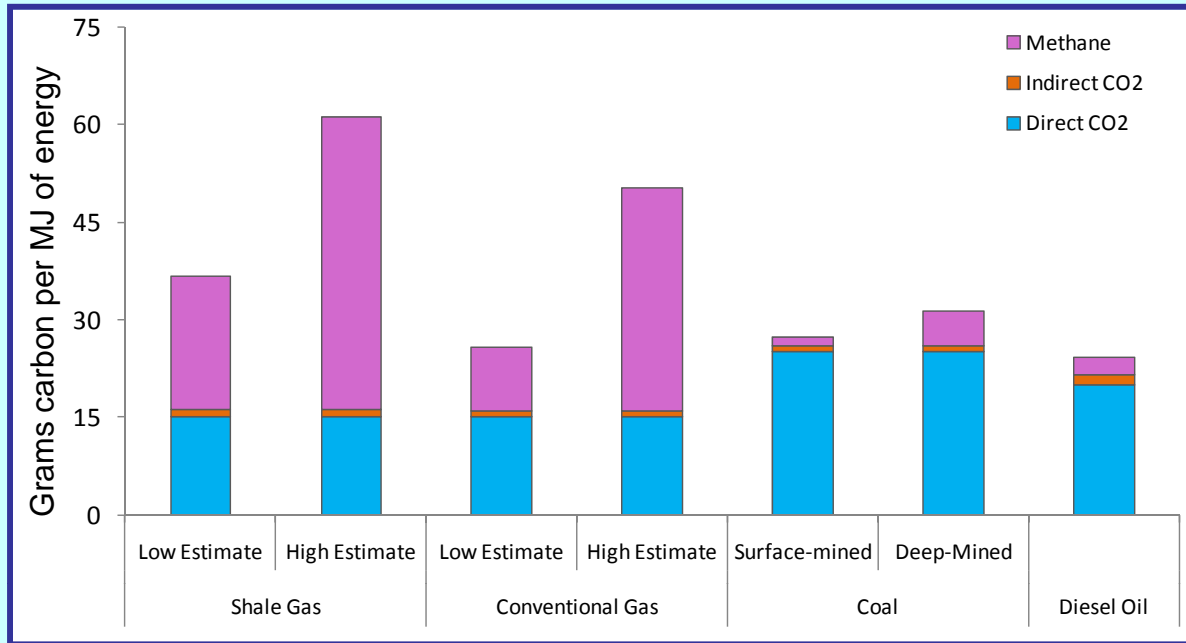
“The acceleration of greenhouse gas (GHG) emissions from human activity is increasingly leading to harmful climate change and ocean acidification. Societies must act urgently to reduce these emissions to protect the life-sustaining biophysical systems of the Earth.”

“.....the necessary transitions will require nothing short of a new industrial revolution.”

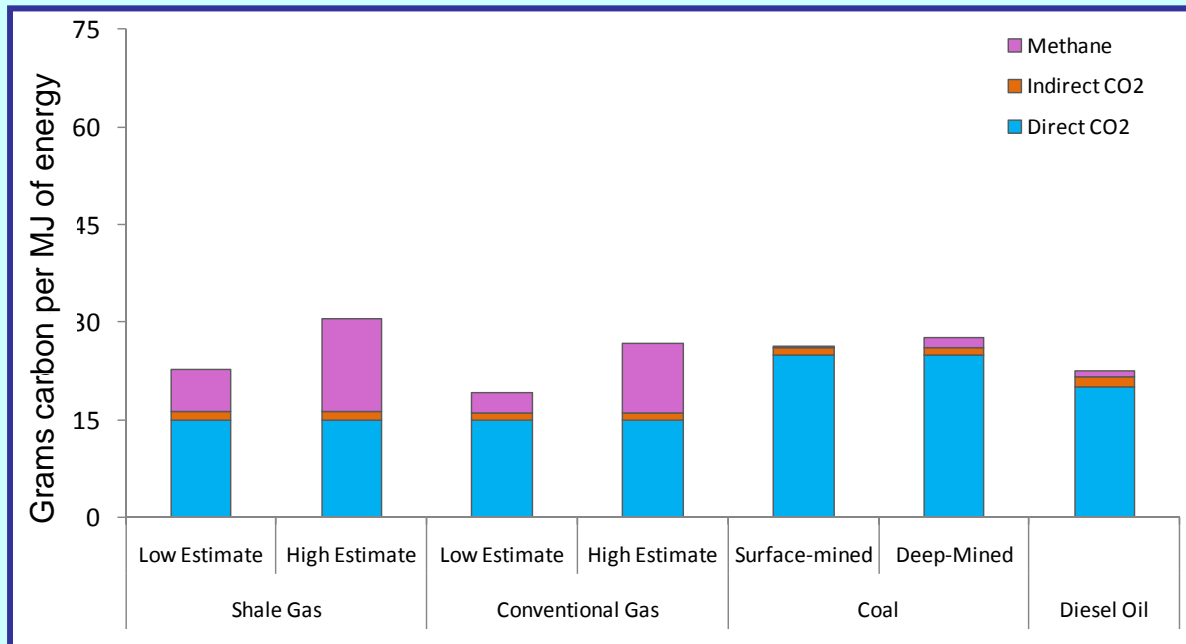
“.....some energy bridges that are currently encouraged in the transition away from GHG-emitting fossil energy systems have received inadequate scientific analysis before implementation, and these may have greater GHG emissions and environmental costs than often appreciated.”

“.... the development of methane from shale formations is another example where policy has preceded adequate scientific study.”

20 year



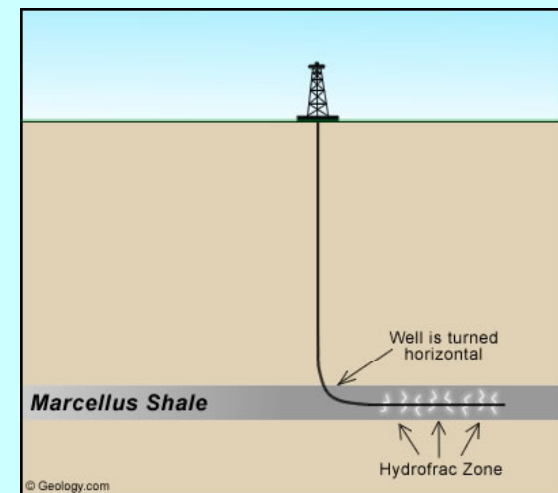
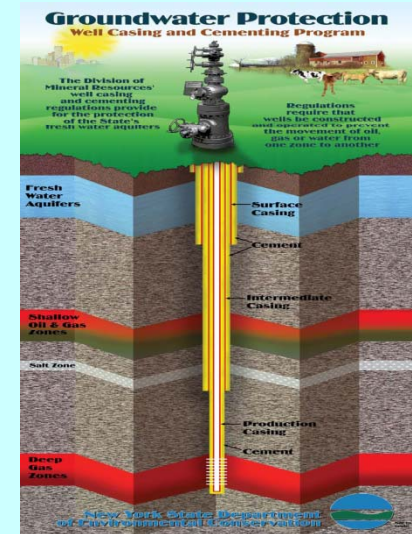
100 year



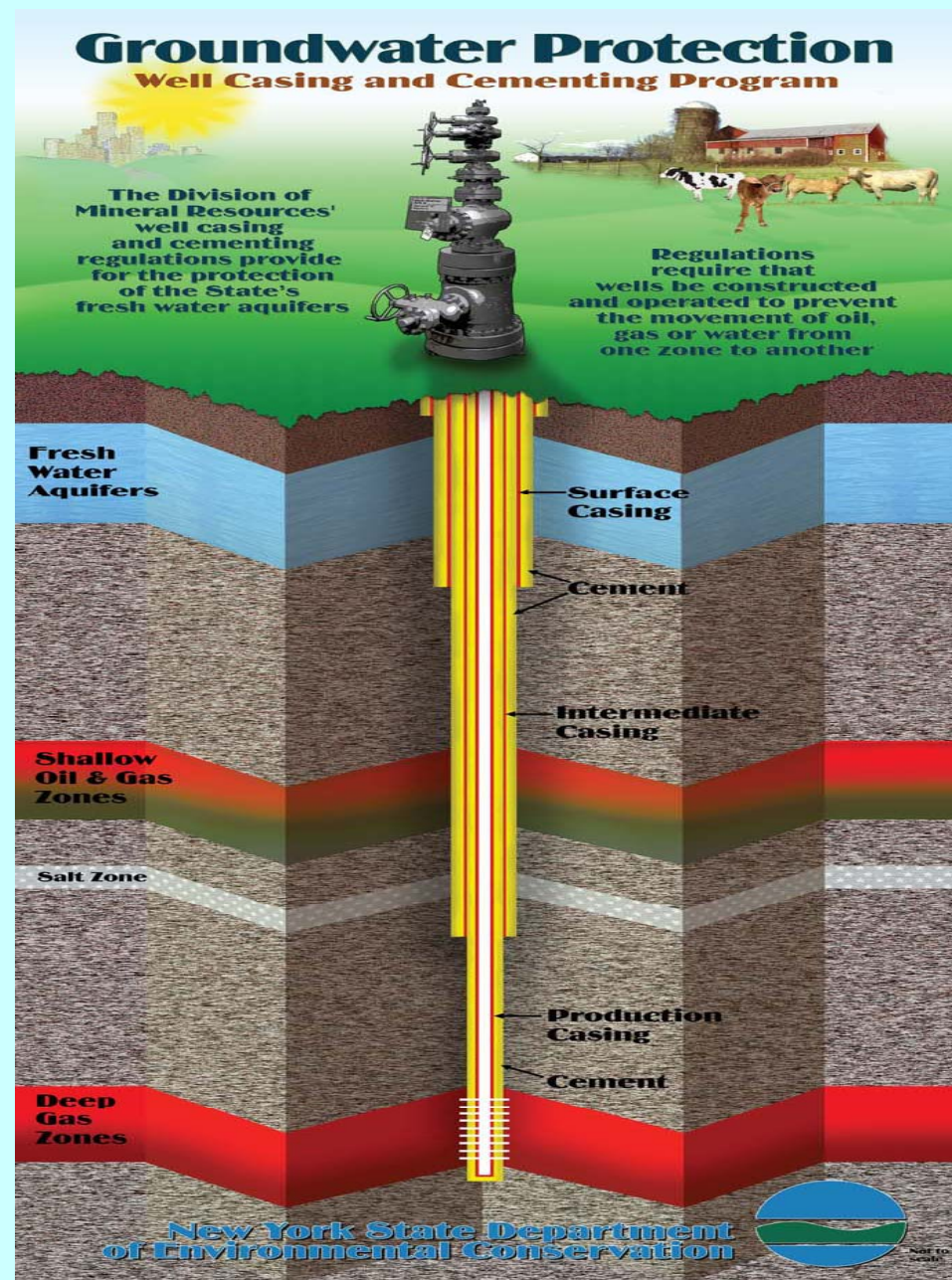
Why Are Unconventional Shale Gas Wells Different from Conventional Gas Wells?

They are “Bigger”

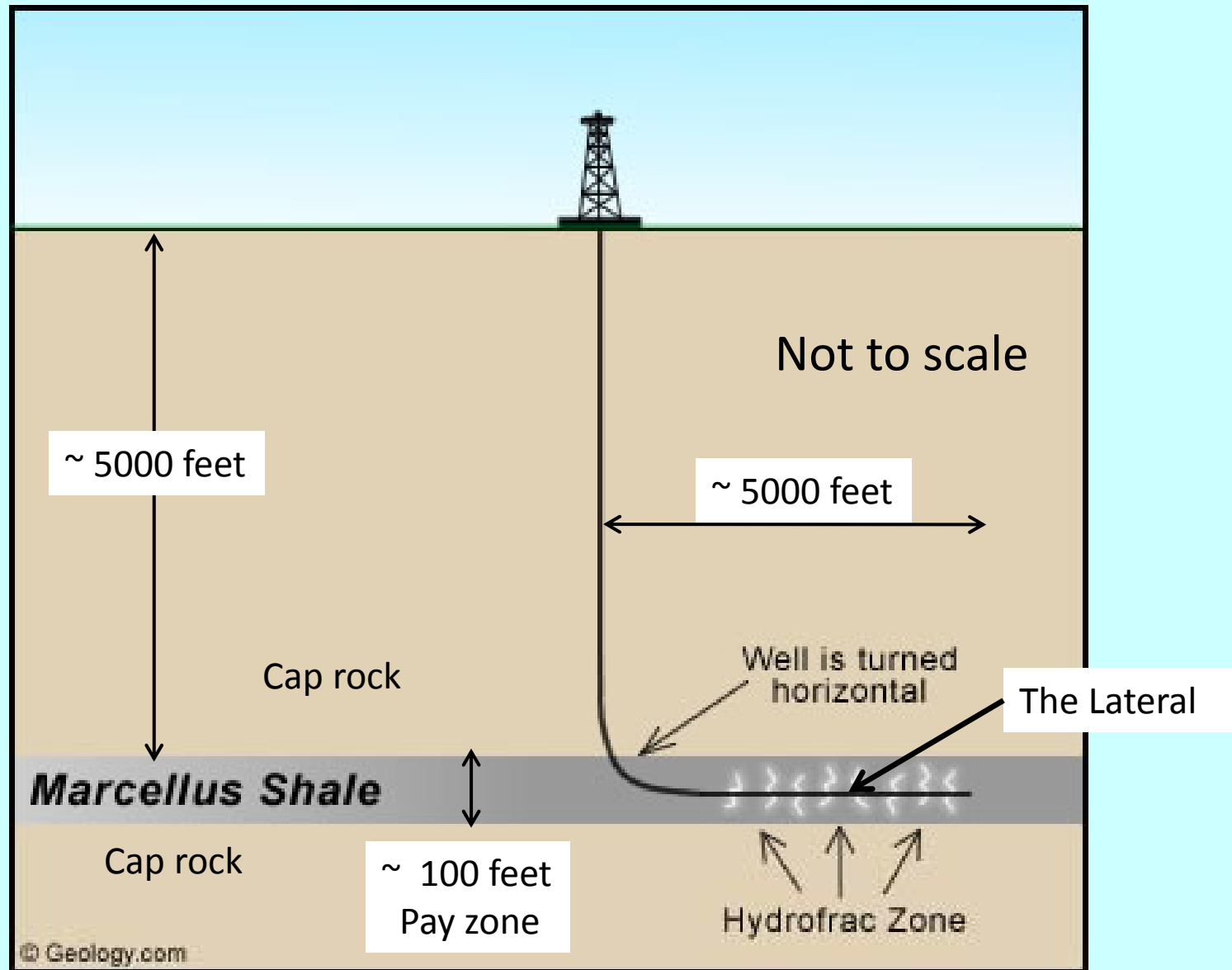
- Total Length
 - More and heavier drilling equipment
 - Longer drilling time
 - Higher probability of drilling problems
 - More venting during drilling, “making gas”
- Frac design and number of stages
 - More and heavier fracing equipment
 - More stages and volume per stage
 - More plugs and longer drill-out period
- Flowback waste, produced “water”
 - Higher volume, longer period
 - More venting and/or flaring of gas



Schematic of Typical Conventional Gas Well



Unconventional, High Volume, Fracing of Shale from Long Laterals: The Concept



Why Are Unconventional Shale Gas Wells Different from Conventional Gas Wells?

Apache Pad During Fracing, NE British Columbia, 2010



Why Are Unconventional Shale Gas Wells Different from Conventional Gas Wells?

Encana Pad During Fracing, NE British Columbia, 2010

16 wells
417 million gallons of water
78,400 tons of sand
8 million gallons of fracing chemicals
40,000 hp for fracing pumps
10,000 foot laterals
500 frac stages



Why Are Unconventional Shale Gas Wells Different from Conventional Gas Wells?

- Define a typical unconventional shale gas well
 - Reflect current PA practice (conservative)

Total Drilling Depth	8785	ft	2678	m
Lateral length	3938	ft	1200	m
BHP	5000	psi	340.22	atm
BHT	250	F	121	C
Casing detail				
	d (in)	L (ft)	Wt (lb)	Grade
Conductor	16	60		
Surface	9.625	1000	40	J-55
Production	5.5	8785	20	P-110
Cement detail				
	Grade	ID (in)	OD (in)	% excess
Cond -Surf		16	9.625	100
Surf - Prod	Class A inhibited	9.625	5.5	15

Sample well specifications (Source: Chesapeake 2009).

Why Are Unconventional Shale Gas Wells Different from Conventional Gas Wells? More CO₂ Emissions

Combustion equipment at well site

<i>Stationary Combustion</i>	<i>number</i>	<i>Sub Total</i>	<i>hp rating</i>	<i>load</i>	<i>hr/yr^b</i>
Drilling	1	Prime Mover/ Drawworks (1000 hp)	1000	0.50	504
	2	Mud Pumps (750 hp each)	1500	0.50	504
	1	Generators (1200 hp)	1200	0.50	504
	2	Air package (30hp)	60	0.50	504

Fracturing pumps 10 @(50.5 bpm, 7500 psi: min hhp = 9283.1) 9300 hp 70hr

	1	Generators (1200 hp)	1200	0.50	70
--	---	----------------------	------	------	----

<i>Mobile Combustion</i>		<i>truckloads</i>	<i>load</i>	<i>trips</i>
Equipment trucks	Total	280	0.50	2
	Drill pad and road construction	45	0.50	2
	Drilling rig	30	0.50	2
	Drilling equipment	50	0.50	2
	Completion equipment	5	0.50	2
	Fracture stimulation equipment	150	0.50	2
Fluids trucks	Total	1069	0.50	2
	Water trucks	729	0.50	2
	Chemical Trucks	4	0.50	2
	Flowback trucks	322	0.50	2
	Production water trucks	14	0.50	2

<i>Site Clearing mobile combustion^c</i>		<i>Joules/ha</i>
	<i>Bulldozers (grading purpose: 335 net hp)</i>	1.24E+12
	<i>large excavator (mid-level: 159 net hp)</i>	9.77E+10

Why Are Unconventional Shale Gas Wells Different from Conventional Gas Wells?

More CH₄ Emissions

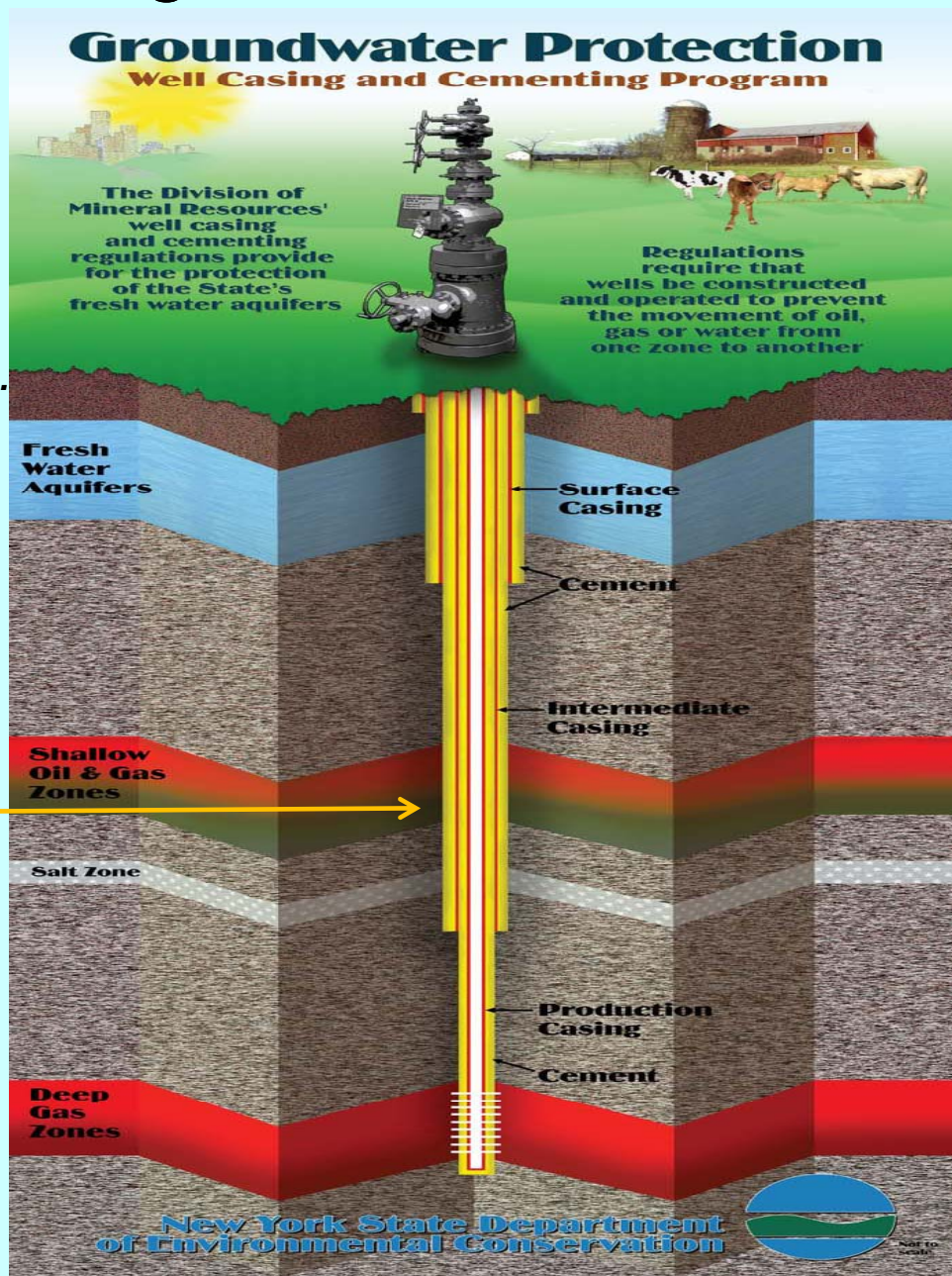
- During Drilling
 - “Shallow” gas shows: vented
- During Flowback after each Frac Stage
 - Production not yet possible: vented or flared
- During Plug Drill-out after all Fracing
 - Production not yet possible: vented or flared

New York State does not currently regulate gas disposal during well completion (NYSDEC, 2009).
We include both venting and flaring emission estimates.
We conservatively assume 50% venting and 50% flaring.

Venting During Drilling: Not Included in Our Study

We also do not include venting from blowouts or gas migration.

Gas show vented during drilling



Flowback Gas Generated from Typical Unconventional Sources

Basin	Type	Avg reservoir pressure ^a (psi)	Flow-back time ^b (d)	Daily FB gas (1000 m ³ /d)	IP24 ^c (1000 m ³)	FB gas generated ^d (1000 m ³)
Haynesvilles (LA)	Gas-shale	9,000	10	676.4	641.2	6763.7
Piceance (CO)	Tight-sand	4,000	8	88.4	54.5	707.5
Barnett (TX)	Gas-shale	3,500	9	40.9	36.8	367.9
Uinta (UT)	Tight-sand	NA	5	50.9	42.5	254.7
Den-Jules (CO)	Tight-sand	3,750	12	11.6	10.5	138.7
Marcellus <i>est.</i> (NY) ^e	Gas-shale	NA	10	NA	121.7	1272.3

Flowback/Drill Out to Open Pit



http://www.epa.gov/OGWDW/uic/pdfs/cbmstudy_attach_uic_ch04_hyd_frac_fluids.pdf

Flowback/Drill Out to Tank Farm



Tanks can be vented, or piped to flare

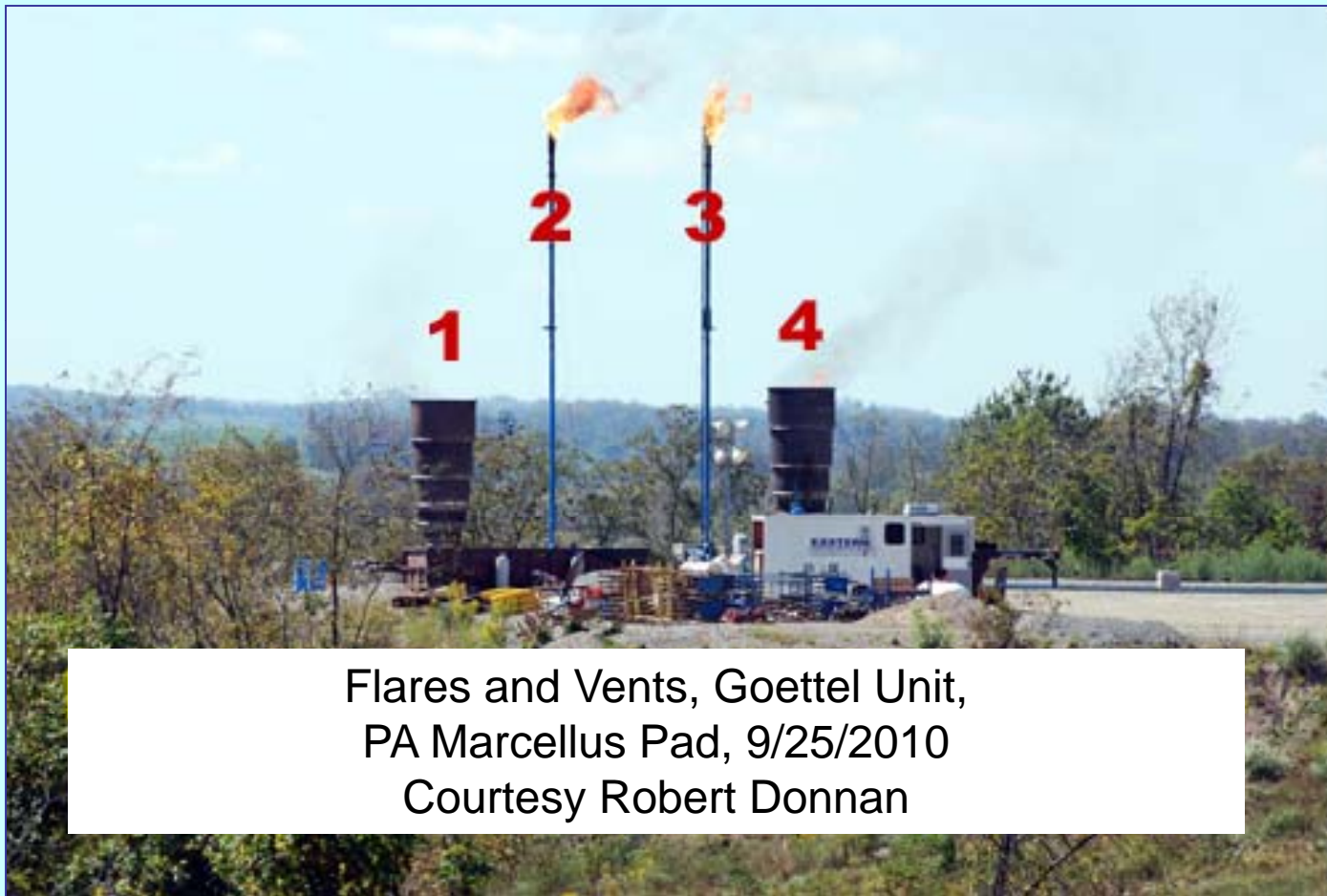
<http://pubs.usgs.gov/fs/2009/3032/>

Flaring During Flowback/Drill Out



Courtesy Robert Donnan

Vent and Flare Stacks



Flares and Vents, Goettel Unit,
PA Marcellus Pad, 9/25/2010
Courtesy Robert Donnan

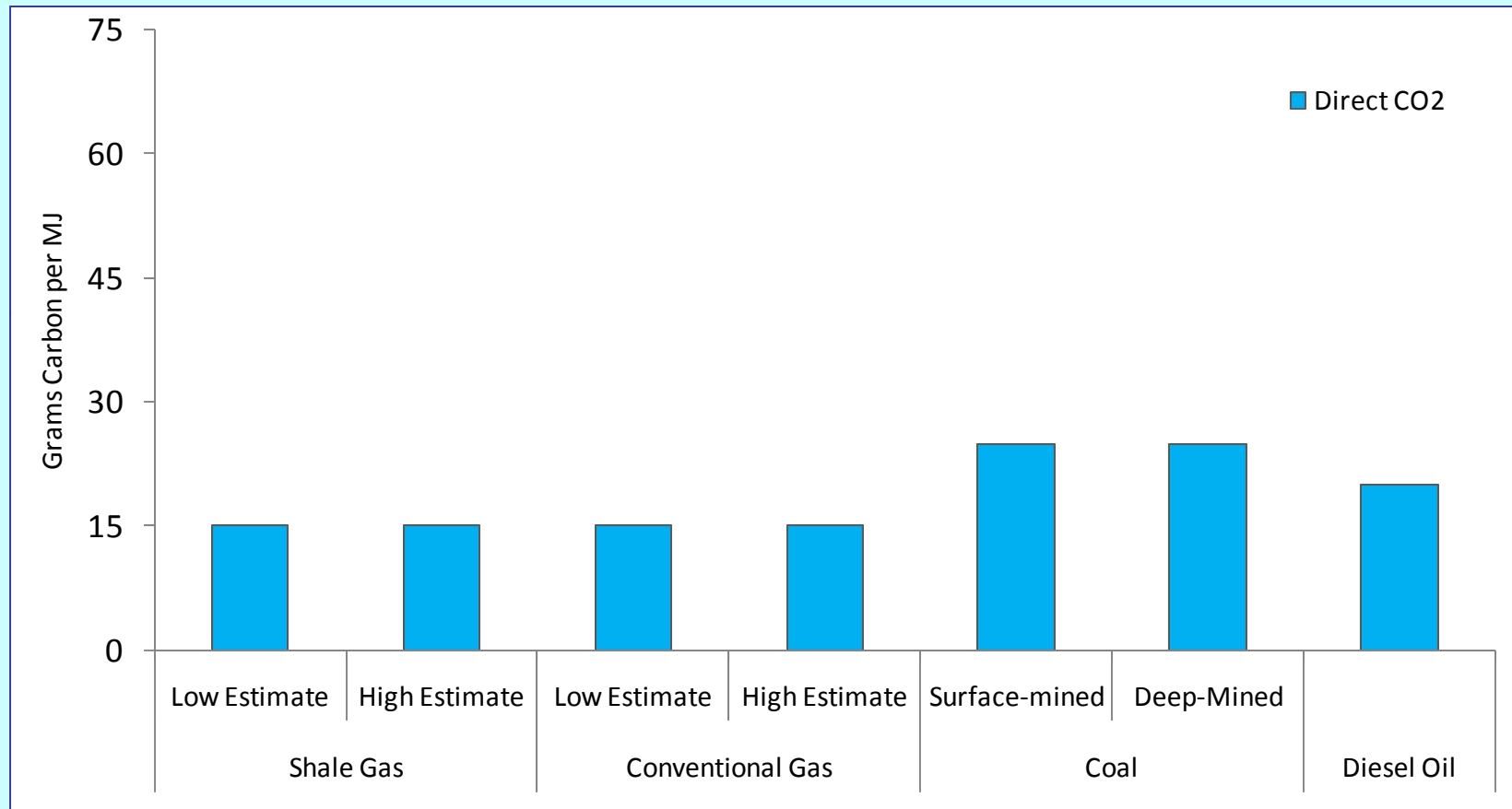
Sources of Methane During Well Development Plug Drill-Out (Removal) Process



Emissions Per Unit Energy Produced Expressed by High and Low Heat Value

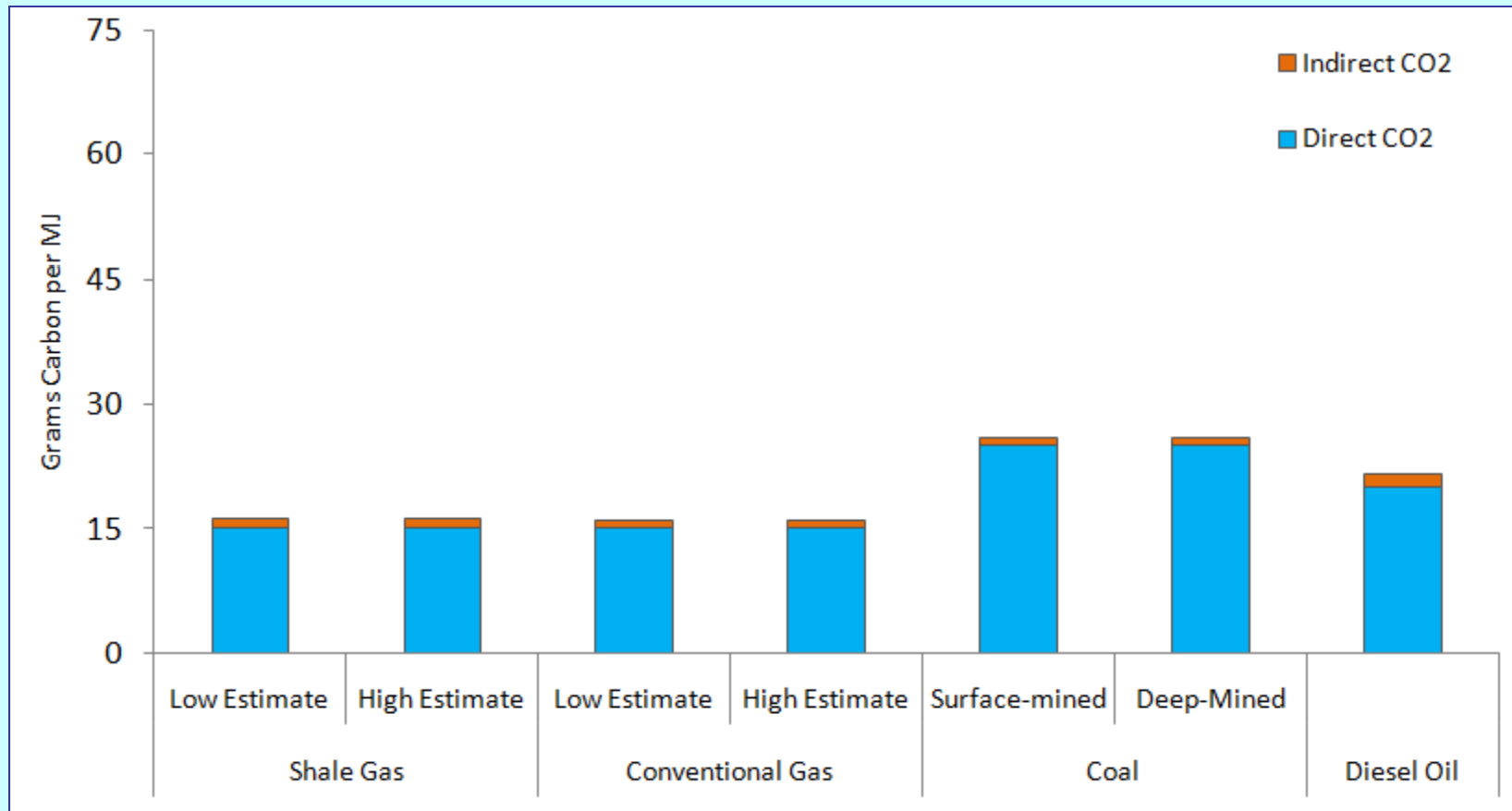
	HHV			LHV ^a		
	g C-CO ₂ /MJ	g C-CH ₄ /MJ	g N ₂ O/MJ	g C-CO ₂ /MJ	g C-CH ₄ /MJ	g N ₂ O/MJ
Indirect emissions	0.15	0.00	0.00	0.16	0.00	0.00
disturbance	0.01	x	x	0.01	x	x
land clearing	0.00	< 0.01	< 0.01	>0.01	< 0.01	< 0.01
Resource consumption	0.14	< 0.01	x	0.15	< 0.01	x
Exploration & Development	0.25 - 0.44	0.19-0.37	0.00	0.26-0.46	0.20-0.37	0.00
Drilling combustion - RIG + FRAC	0.17	< 0.01	< 0.01	0.18	< 0.01	< 0.01
Drilling combustion - MOBILE	0.08	< 0.01	< 0.01	0.08	< 0.01	< 0.01
Completion - 100% VENT	x	0.37	x	x	0.37	x
Completion - 50% FLARE	0.19	0.19	x	0.20	0.19	x
Gas Production	0.54	0.11	0.00	0.57	0.11	0.00
combustion ^b	0.54	x	x	0.57	x	x
brine tank	x	< 0.01	x	x	< 0.01	x
misc fugitives (continuous)	x	0.11	x	x	0.11	x
Processing^c	0.58	0.02	0.00	0.61	0.03	0.00
<i>combustion</i>	<i>0.49</i>	<i>< 0.01</i>	<i>x</i>	<i>0.52</i>	<i>< 0.01</i>	<i>x</i>
<i>fugitives</i>	<i>0.09</i>	<i>0.02</i>	<i>x</i>	<i>0.09</i>	<i>0.02</i>	<i>x</i>
Transmission & Distribution^d	0.14	0.14	0.00	0.15	0.14	0.00
compressors	0.14	0.01	x	0.15	0.01	x
Transmission fugitives	< 0.01	0.13	x	< 0.01	0.14	x
Distribution fugitives	x		x	x		x
upstream combustion	0.79	< 0.01	< 0.01	0.83	< 0.01	< 0.01
upstream fugitives	0.19	0.29	x	0.20	0.30	x
midstream combustion	no process	no process	no process	no process	no process	no process
midstream fugitives	no process	no process	no process	no process	no process	no process
downstream combustion	0.14	0.01	x	0.14	0.01	x
downstream fugitives	0.00	0.13	x	0.00	0.14	x
end-use combustion	13.70	x	x	15.00	x	x
Total Direct Emissions	14.82	0.44	0.00	16.17	0.45	0.00
TOTAL (incl. indirect)	14.97	0.44	<0.01	16.33	0.45	<0.01

Direct carbon dioxide emissions during combustion of fossil fuels



Howarth et al. (2011)

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



Howarth et al. (2011)

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.**

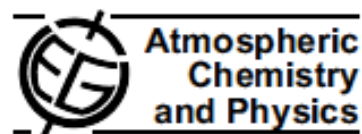
New report from the US EPA, 30 November 2010:

**GREENHOUSE GAS EMISSIONS REPORTING FROM THE
PETROLEUM AND NATURAL GAS INDUSTRY**

BACKGROUND TECHNICAL SUPPORT DOCUMENT

“The EPA/GRI (1996) study used the best available data and somewhat restricted knowledge of industry practices at the time to provide estimates of emissions from each source in the various segments of the natural gas industry. In addition, this study was conducted at a time when CH₄ emissions were not a significant concern in the discussion about GHG emissions. **Over the years, new data and increased knowledge of industry operations and practices have highlighted the fact that emissions estimates from the EPA/GRI study are outdated and potentially understated for some emissions sources.**”

Atmos. Chem. Phys., 7, 2141–2149, 2007
www.atmos-chem-phys.net/7/2141/2007/
© Author(s) 2007. This work is licensed
under a Creative Commons License.



The atmospheric cycling of radiomethane and the “fossil fraction” of the methane source

K. R. Lassey¹, D. C. Lowe¹, and A. M. Smith²

¹National Institute of Water and Atmospheric Research, P.O. Box 14-901, Wellington, New Zealand

²Australian Nuclear Science and Technology Organisation, PMB 1, Menai NSW 2234, Australia

Received: 6 April 2006 – Published in Atmos. Chem. Phys. Discuss.: 21 June 2006

Revised: 12 December 2006 – Accepted: 10 April 2007 – Published: 2 May 2007

Abstract. The cycling of $^{14}\text{CH}_4$ (“radiomethane”) through the atmosphere has been strongly perturbed in the industrial era by the release of ^{14}C -free methane from geologic reservoirs (“fossil methane” emissions), and in the nuclear era,

measurement has provided another tool for understanding the global methane cycle because of the discriminative ^{14}C content among methane sources. In particular, methane originating from geologic reservoirs whose carbon has been isolated

30% of global methane comes from fossil sources, twice as much as in IPCC (2007) and other inventories.

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**

Table 1. Methane emissions from flow-back fluids and initial production rates for 5 unconventional wells.

Basin	Methane emission during flow-back (10^3 m^3)	Methane emission per day during flow-back ($10^3 \text{ m}^3 \text{ d}^{-1}$)	Initial gas production upon well completion ($10^3 \text{ m}^3 \text{ d}^{-1}$)	Life-time production of well (10^6 m^3)	Flow-back emissions as % of life-time production
Haynesville (LA)	6,800	680	640	210	3.2%
Barnett (TX)	370	41	37	35	1.1%
Piceance (CO)	710	79	57	55	1.3%
Uinta (UT)	255	51	42	40	0.6%
Den-Jules (CO)	140	12	11	?	?

(Howarth et al. 2011)

Table 1. Methane emissions from flow-back fluids and initial production rates for 5 unconventional wells.

Basin	Methane emission during flow-back (10^3 m^3)	Methane emission per day during flow-back ($10^3 \text{ m}^3 \text{ d}^{-1}$)	Initial gas production upon well completion ($10^3 \text{ m}^3 \text{ d}^{-1}$)	Life-time production of well (10^6 m^3)	Flow-back emissions as % of life-time production
Haynesville (LA)	6,800	680	640	210	3.2%
Barnett (TX)	370	41	37	35	1.1%
Piceance (CO)	710	79	57	55	1.3%
Uinta (UT)	255	51	42	40	0.6%
Den-Jules (CO)	140	12	11	?	?

(Howarth et al. 2011)

Much higher pressure in basin, leading to higher initial gas production and more methane in flow-back waters.

Table
for 5

initial production rates

Basin	Methane emission during flow-back (10^3 m^3)	Methane emission per day during flow-back ($10^3 \text{ m}^3 \text{ d}^{-1}$)	Initial gas production upon well completion ($10^3 \text{ m}^3 \text{ d}^{-1}$)	Life-time production of well (10^6 m^3)	Flow-back emissions as % of life-time production
Haynesville (LA)	6,800	680	640	210	3.2%
Barnett (TX)	370	41	37	35	1.1%
Piceance (CO)	710	79	57	55	1.3%
Uinta (UT)	255	51	42	40	0.6%
Den-Jules (CO)	140	12	11	?	?

(Howarth et al. 2011)

Table 1. Methane emissions from shale gas basins during flow-back fluids and initial production rates

**Shortest duration for flow back
– 5 days, vs. 8 to 12 for the
other basins**

Basin	emission during flow-back (10^3 m^3)	emission per day during flow-back ($10^3 \text{ m}^3 \text{ d}^{-1}$)	initial gas production upon well completion ($10^3 \text{ m}^3 \text{ d}^{-1}$)	Life-time production of well (10^6 m^3)	Flow-back emissions as % of life-time production
Haynesville (LA)	6,800	680	640	210	3.2%
Barnett (TX)	370	41	37	35	1.1%
Piceance (CO)	710	79	57	55	1.3%
Uinta (UT)	255	51	42	40	0.6%
Den-Jules (CO)	140	12	11	?	?

(Howarth et al. 2011)

Table 1. Methane emissions from flow-back fluids and initial production rates for 5 unconventional wells.

Limited data, poor documentation (Powerpoint slides from EPA workshops).

We have chosen to use the mean emission percentage of 1.6%

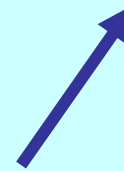
	Flow-back emissions as % of life-time production
Barnett (TX)	3.2%
Piceance (CO)	1.1%
Uinta (UT)	1.3%
Den-Jules (CO)	0.6%
	?

Barnett (TX)	370	41	37	33
Piceance (CO)	710	79	57	55
Uinta (UT)	255	51	42	40
Den-Jules (CO)	140	12	11	?

(Howarth et al. 2011)

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%



1.6% from flow-back fluids, plus 0.3% from drill-out following hydraulic fracturing (0.6% equally likely, but we are being conservative).

Source: EPA (2010) plus numerous industry reports and presentation.

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%

0.3% reflects use of best technology

Note that routine leaks and emissions occur continuously over 7-10 year life-time of the well, contrasting with the initial drilling and completion leaks that occur in just a few weeks.

Source for routine leaks and emissions at well = GAO (2010)

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%

Source for venting during liquid unloading = GAO (2010)

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%

Source for emissions during processing = Shires et al. (2009) (API)

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%

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%

Methane emissions from shale gas are 80% to 7.1-fold greater.

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%

But, this is only part of the story, as the gas has to be delivered to consumers.

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

Naked eye

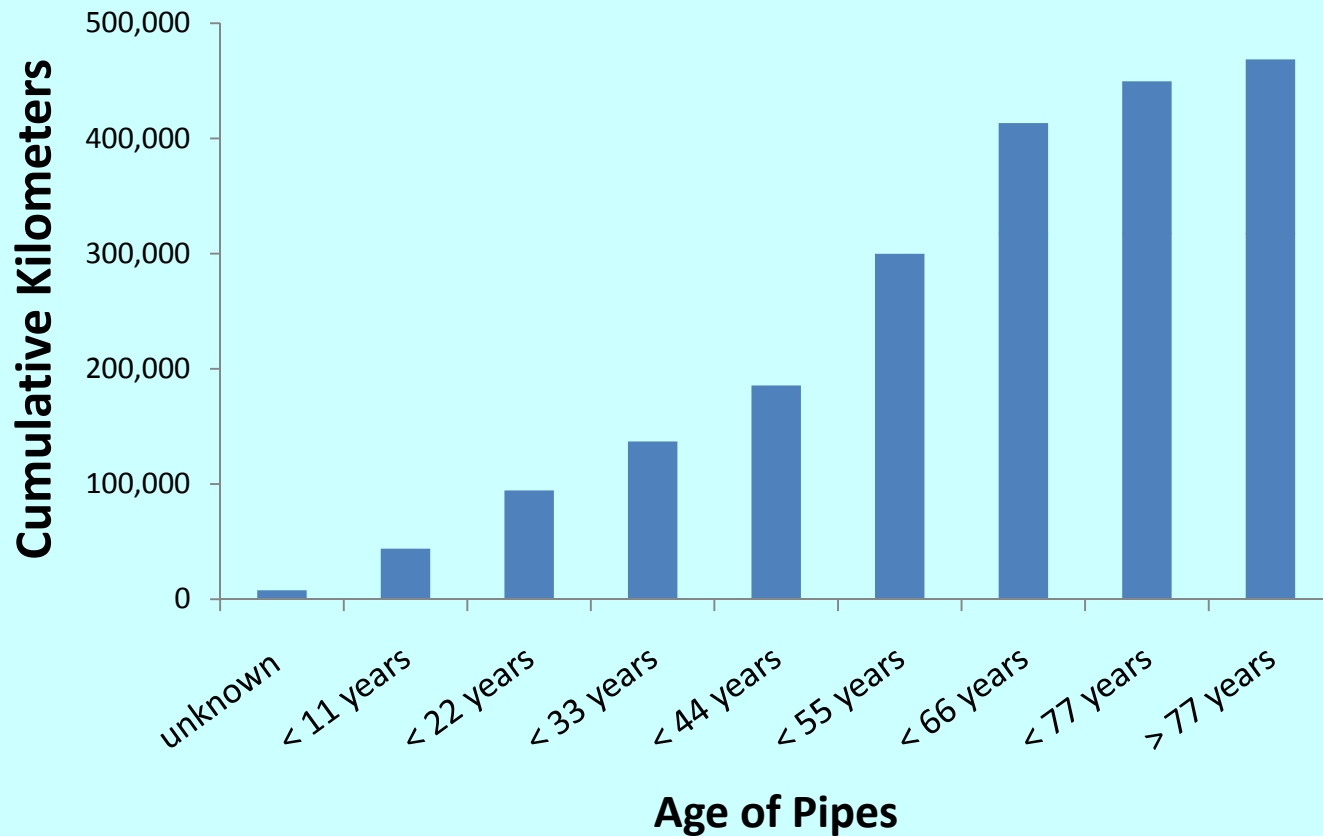


Infra-red ⁽⁴²⁾



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%

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%

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%

30% to 2.1-fold greater emissions from shale gas

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.**

Our estimates rely heavily on materials also used in November 30, 2010 EPA report, and are broadly consistent with the EPA report.

Our estimates and those from the EPA (2010) report for emissions during flow-back period are 2 orders of magnitude greater than those from EPA (1996).

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

2) We can compare our estimates for conventional gas with 3 other peer-reviewed papers.

- Hayhoe et al. (2002), *Climatic Change*: range of 0.7% to 10.%; “best estimate” = 3% emission rate (compared to our range of 1.7% to 6%)
- Lelieveld et al. (2005), *Nature*: transportation, storage, and distribution only = 1.4% (compared to our range of 1.4% to 3.6%) (based partly on EPA 1996, now superseded by EPA 2010 report)
- Jamarillo et al. (2007), *ES&T* = 1.1% emission rate (based entirely on EPA 1996 report).

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.

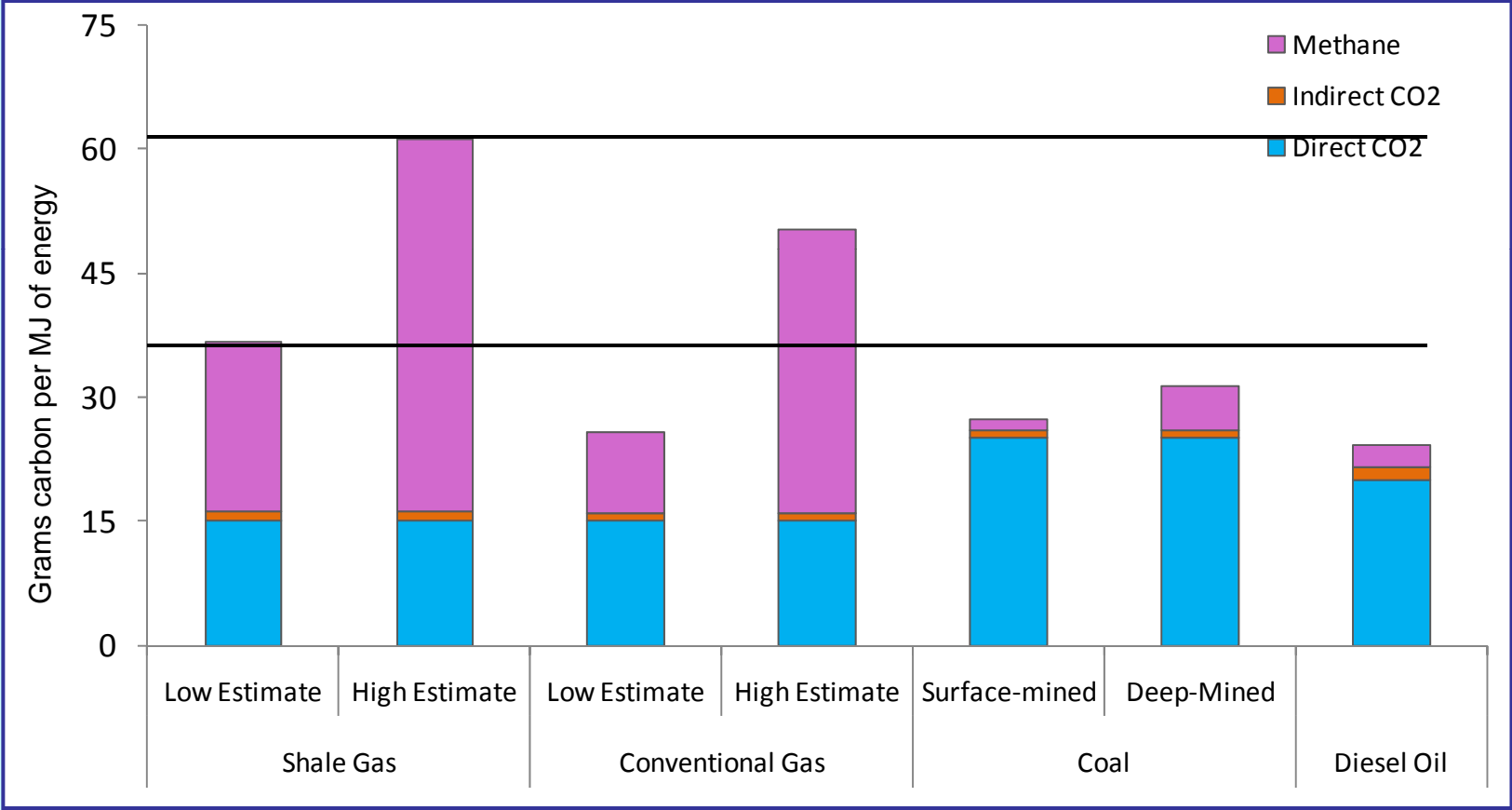
*To whom correspondence should be addressed. E-mail: drew.t.shindell@nasa.gov

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

- IPCC (1995) considered only 100-year time frame;
GWP = 21
(used in all 3 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

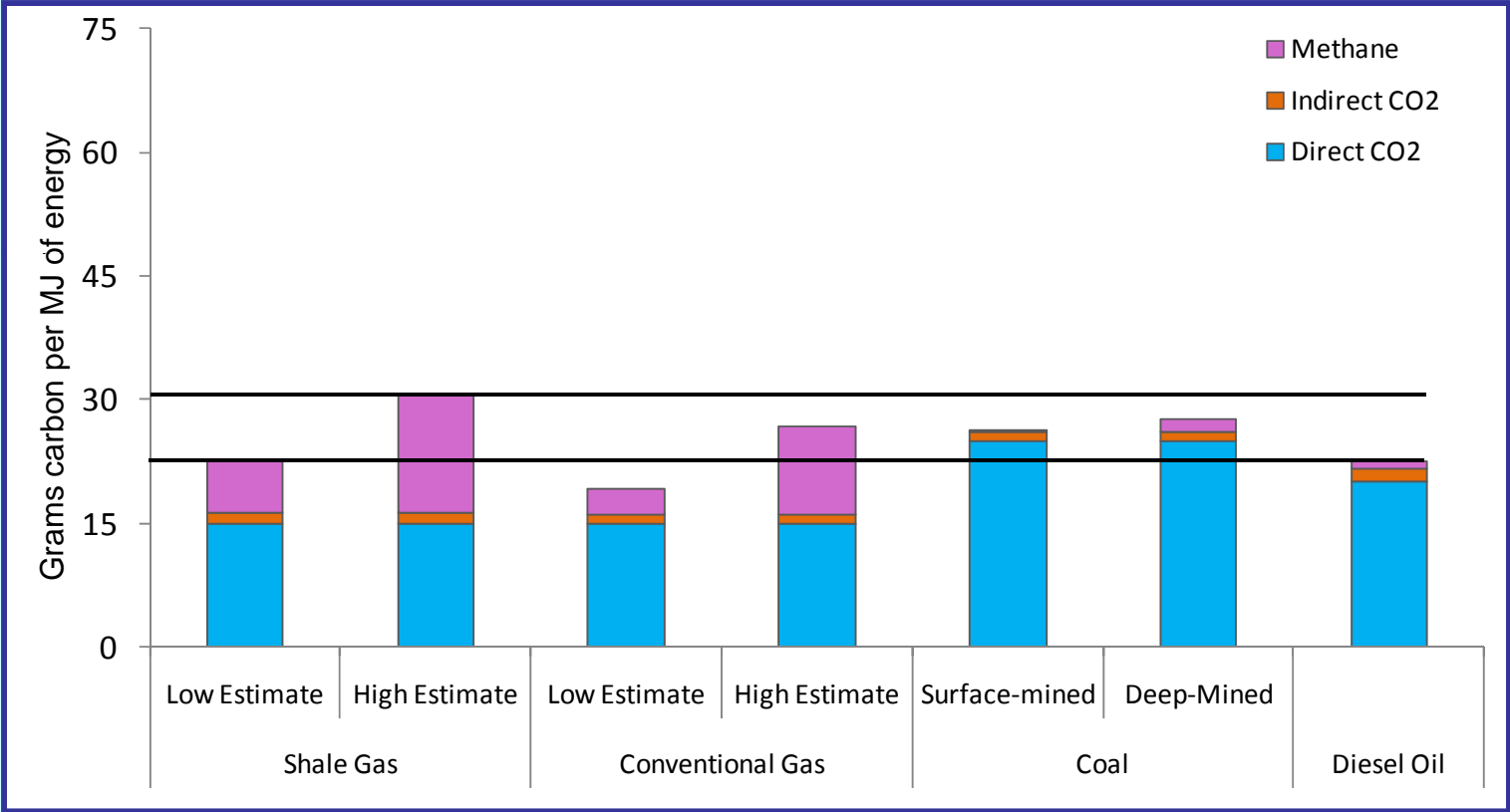
Greenhouse gas footprint of shale gas and other fossil fuels

(20-year analysis; methane given in CO2 equivalents, assuming Global warming Potential = 105)



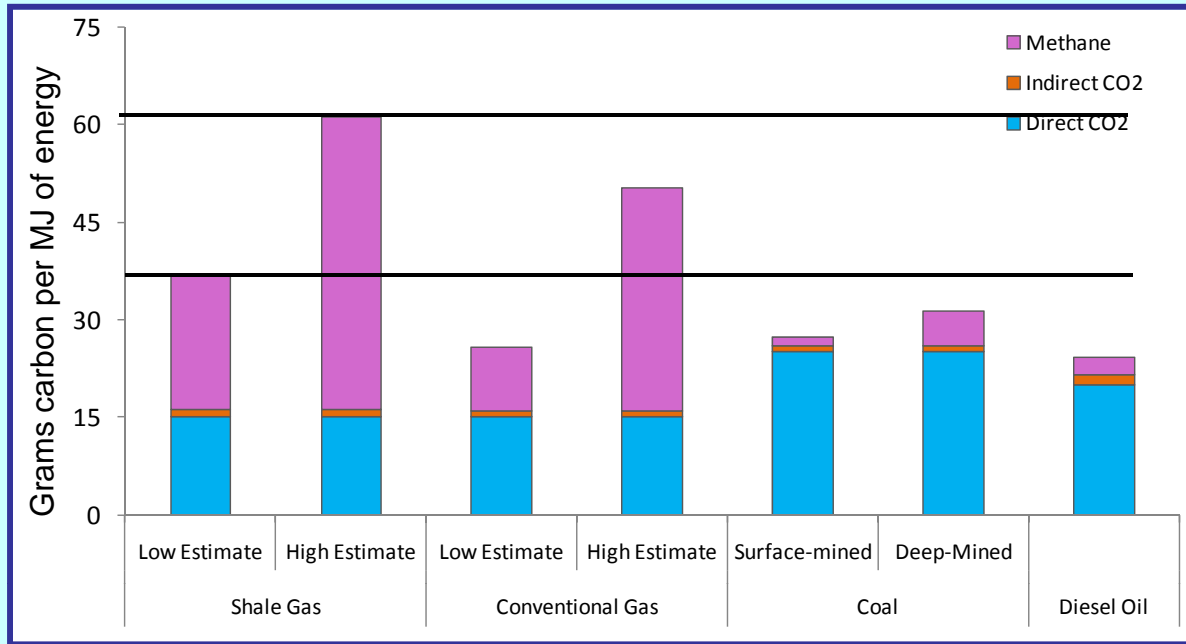
(Howarth et al. 2011)

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

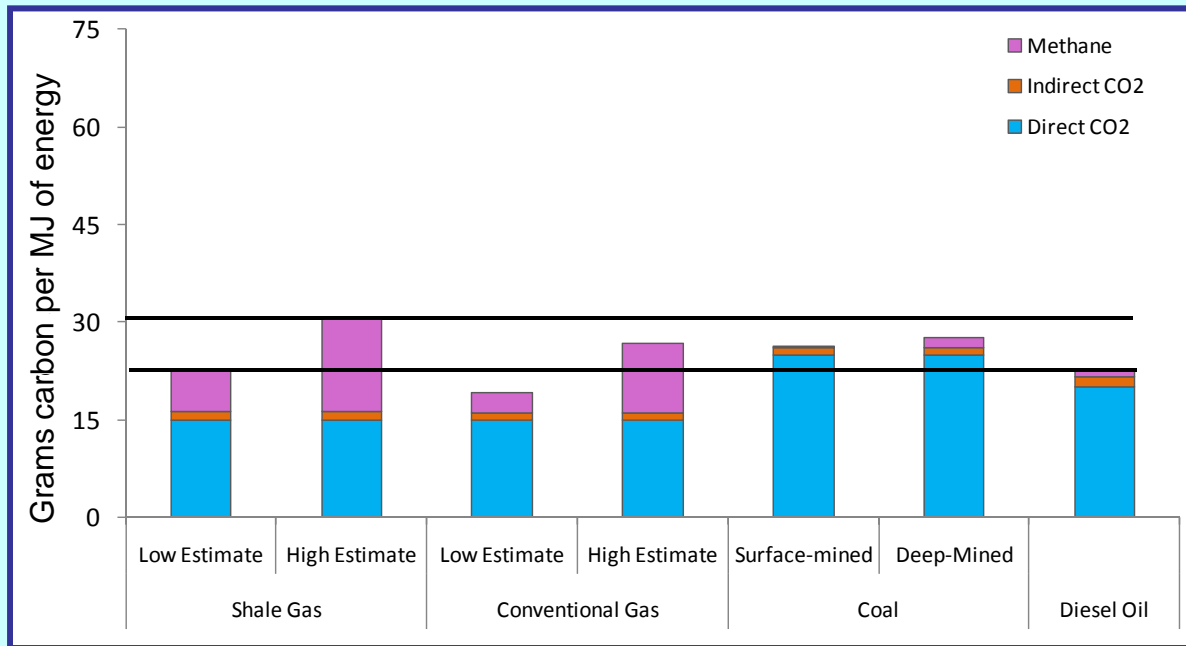


(Howarth et al. 2011)

20 year



100 year



We are not advocating for more coal or oil, but rather to move to a truly green, renewable future as quickly as possible.





**Methane and the Greenhouse-Gas Footprint of Natural Gas
from Shale Formations**

Robert W. Howarth^{1*}, Renee Santoro¹, and Anthony Ingraffea²

1. Department of Ecology & Evolutionary Biology, Cornell University, Ithaca, NY
14853 USA.

1. School of Civil and Environmental Engineering, Cornell University, Ithaca, NY
14853 USA.

* corresponding author's e.mail: howarth@cornell.edu

Climatic Change Letters
In press

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

**Summary, references, and supporting technical report available at:
http://www.eeb.cornell.edu/howarth/Howarth_EnergyandEnvironment.html**



Cornell University
College of Agriculture and Life Sciences



Funding from the Park Foundation and the David R. Atkinson Professorship of Ecology & Environmental Biology.