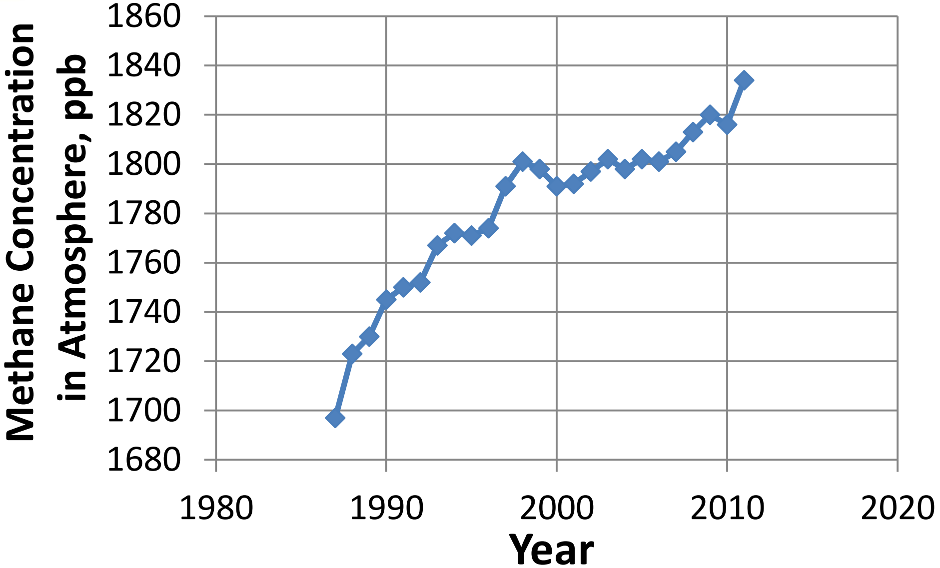


Unconventional Development of Natural Gas from Shale Formations: Impacts on Water and Climate

A. R. Ingraffea

Dwight C. Baum Professor

Cornell University, and

Physicians, Scientists, and Engineers for Sustainable and Healthy Energy, Inc.

Scientific and Technical Advisory Committee

State College, PA

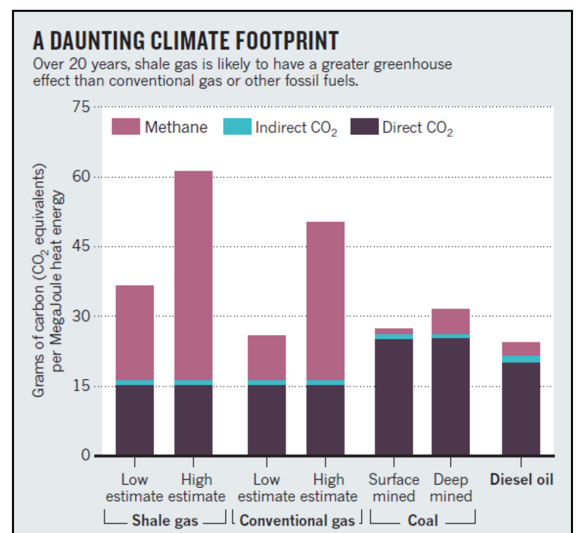
April 11, 2012

Impacts on Water and Climate

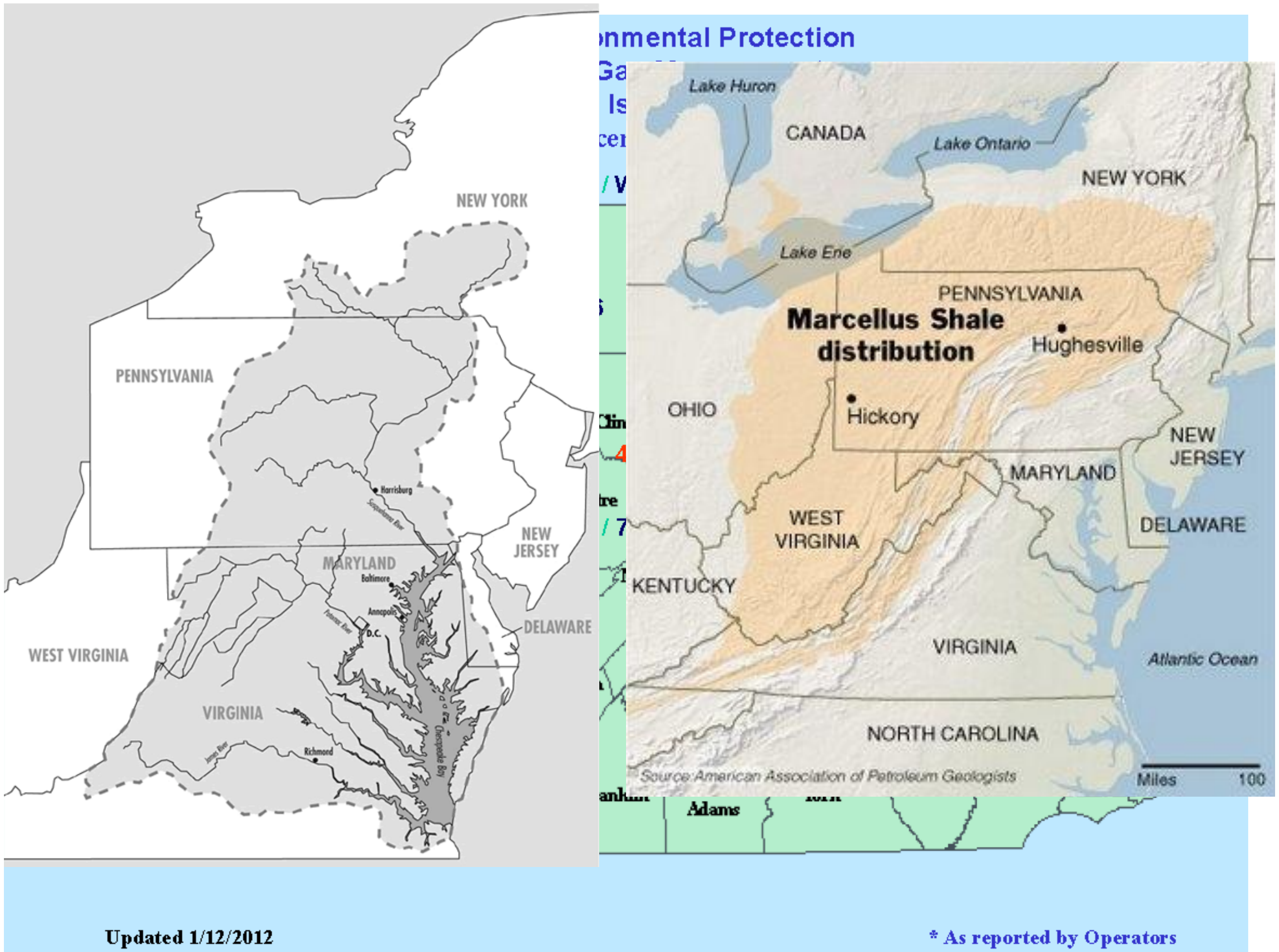
- Contamination of USDW

- Waste disposal

- Methane emissions



Unconventional Development of Natural Gas from Shale Formations Is Spatially Intense



PA Marcellus Wells Drilled

2008 – 195
2009 – 768
2010 – 1454
2011 – 1937
2012 – 262+

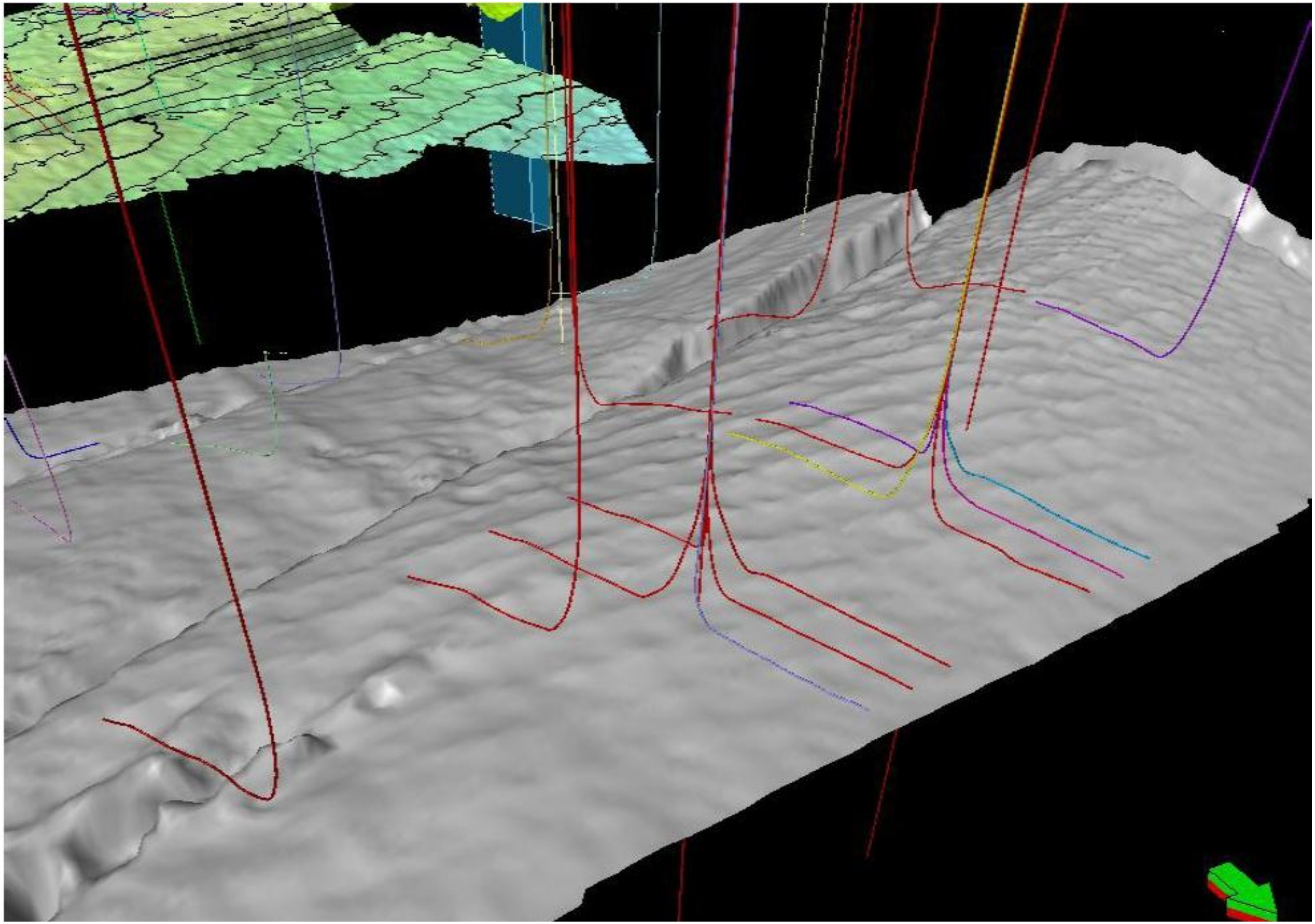
No Shale Wells Yet
In NY, VA and MD

Estimated # of Marcellus Wells in Chesapeake Watershed at Buildout:

50,000

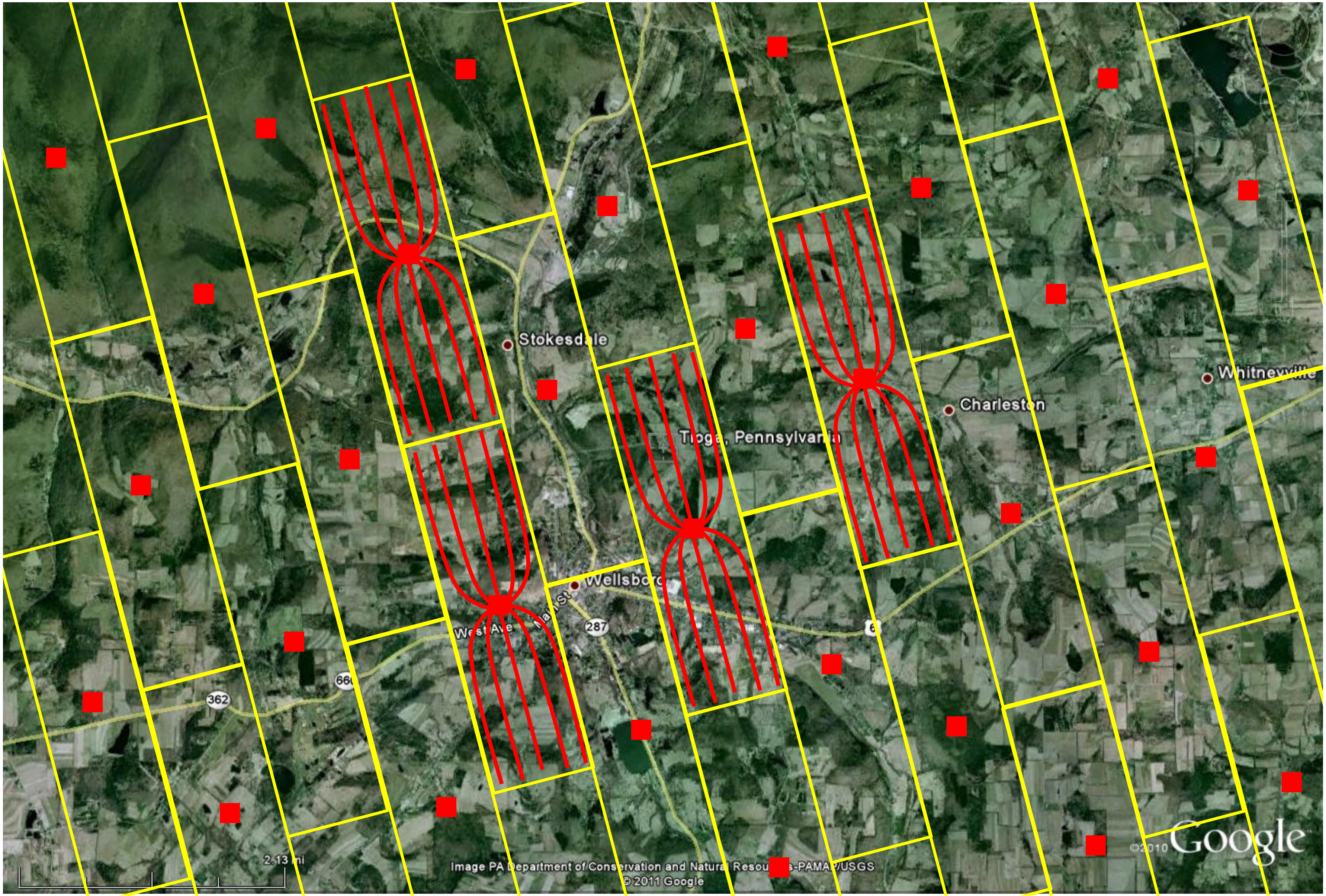
Marcellus shale gas development has only just begun

Spatial Intensity Via Multiple, “Horizontal” Wells from Clusters of Pads

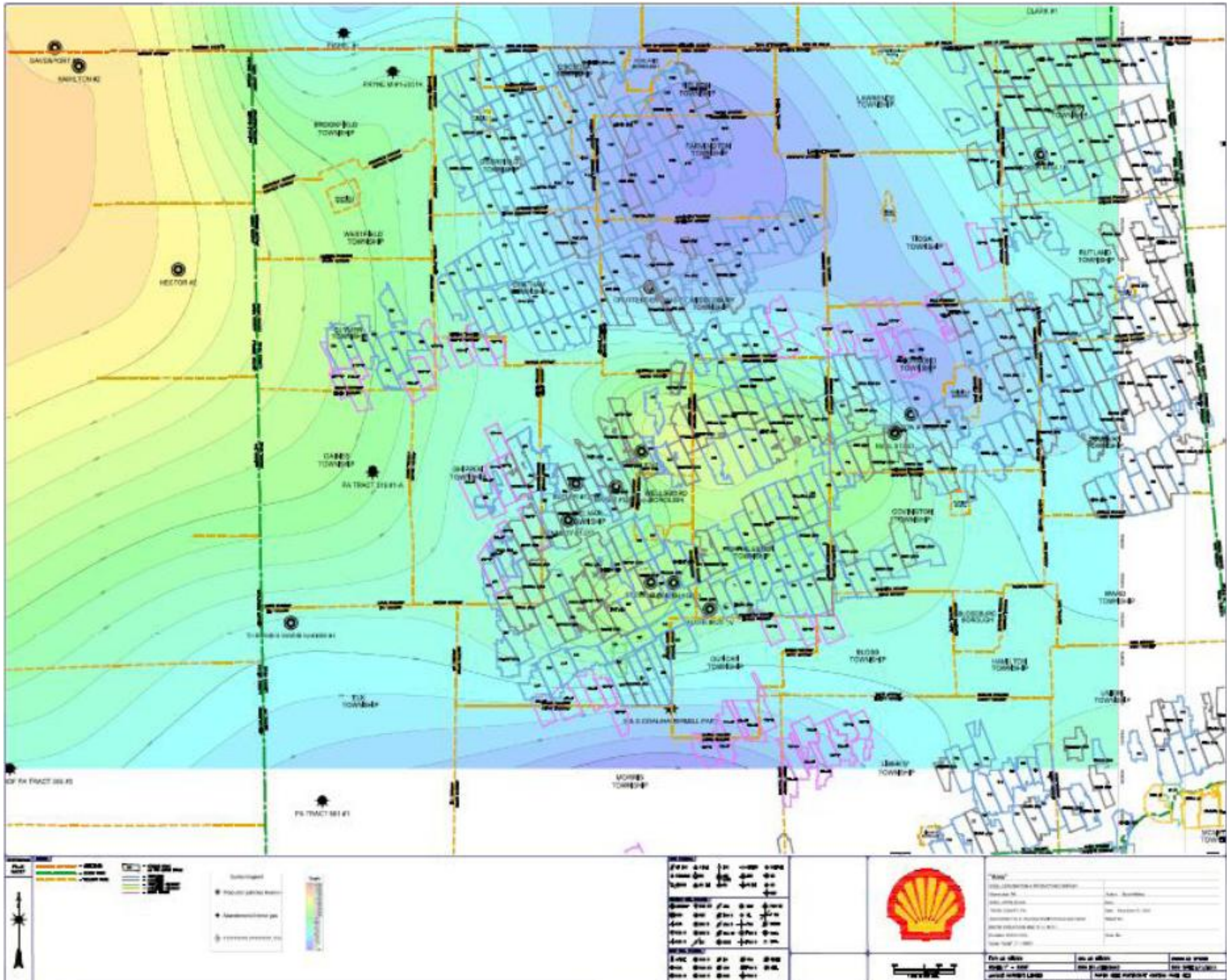


From Cody Teff, Shell Appalachia, WELL CONSTRUCTION PRACTICES IN THE MARCELLUS

An Industrial-Ideal Pad/Well Buildout Scenario



Clustering of Pads in Tioga County, PA



Impacts on Water and Climate

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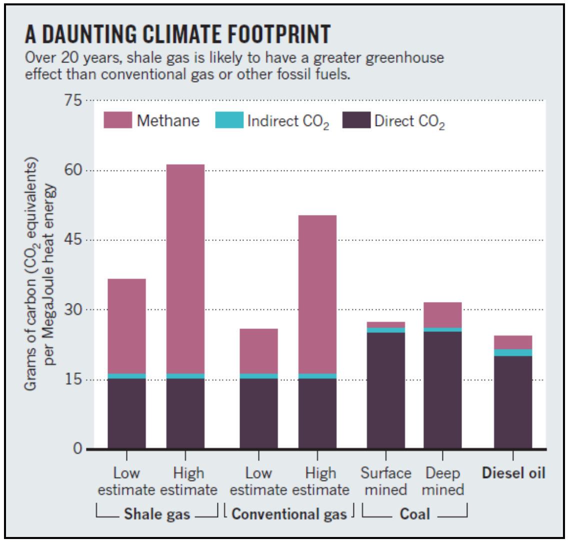
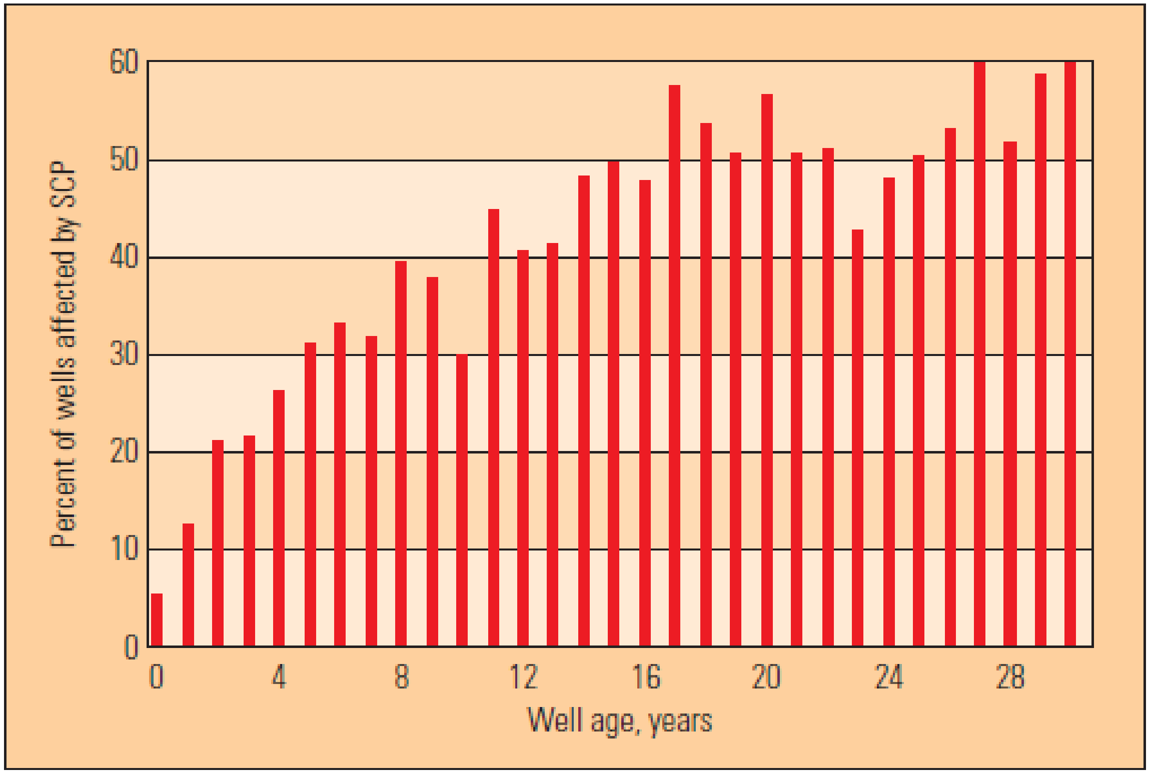
- Waste disposal

- Methane emissions



“Since the earliest gas wells, uncontrolled migration of hydrocarbons to the surface has challenged the oil and gas industry.”



^ Wells with SCP by age. Statistics from the United States Mineral Management Service (MMS) show the percentage of wells with SCP for wells in the outer continental shelf (OCS) area of the Gulf of Mexico, grouped by age of the wells. These data do not include wells in state waters or land locations.

SCP=Sustained Casing Pressure. Also called sustained annular pressure in one or more of the casing annuli.

- About 5% of wells fail soon
- More fail with age
- Most fail by maturity

Brufatto *et al.*, *Oilfield Review*, Schlumberger, Autumn, 2003

Sustained Casing Pressure and Gas Migration Are Chronic Problems

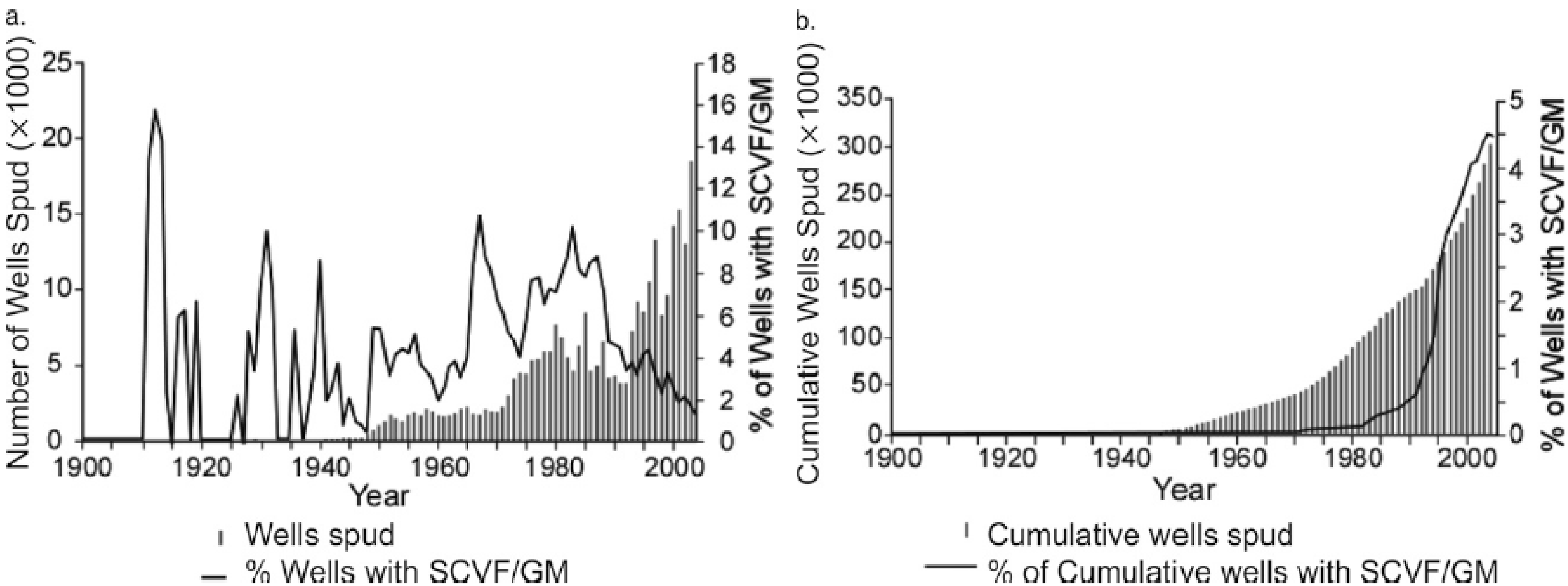


Fig. 8—Historical levels of drilling activity and SCVF/GM occurrence in Alberta: (a) by year of well spud and (b) by cumulative wells drilled.

Watson and Bachu, SPE 106817, 2009.

Bubbling in Muncy Creek, Lycoming County, PA: Example of Migration of Hydrocarbons

Video Courtesy of Ralph Kisberg, Responsible Drilling Alliance

PA DEP Compliance Database:
Violations for Methane Migration from Faulty Wells

	OPERATOR	REGION	INSPECTION ID	INSPECTION DATE
1	OPERATOR	REGION	INSPECTION ID	INSPECTION DATE
2	CABOT OIL & GAS CORP	EP DOGO NCDO Dstr Off	1947248	01/05/2011
3	CABOT OIL & GAS CORP	EP DOGO NCDO Dstr Off	1947533	01/05/2011
4	CABOT OIL & GAS CORP	EP DOGO NCDO Dstr Off	1947546	01/05/2011
5	SENECA RESOURCES CORP	EP DOGO NWDO Dstr Off	1999373	08/17/2011
6	SENECA RESOURCES CORP	EP DOGO NWDO Dstr Off	1999378	08/17/2011
7	CARRIZO (MARCELLUS) LLC	EP DOGO NCDO Dstr Off	1985316	06/27/2011

…ATION …DE	Issue	VIOLATION TYPE	VIOLATION COMMENT
ailure to cement nt s into ater	casing	Environmental Health & Safety	78.81(a)(2)&(3) - 0.1 psi at 9 5/8 annulus & 0.2 psi at 5 1/2 annulus, 25% gas at 9 5/8 annulus & 90% gas at 5 1/2 annulus
ailure to cement nt s into ater	casing	Environmental Health & Safety	78.81(a)(2)&(3) - 0.0 psi at 9 5/8 annulus & 0.6 psi at 5 1/2 annulus, 75% peak and sustained 40% gas at 9 5/8 annulus & 90% peak gas at 5 1/2 annulus
ailure to cement nt s into ater	casing	Environmental Health & Safety	78.81(a)(2)&(3) - 0.0 psi at 9 5/8 annulus & 0.4 psi at 5 1/2 annulus, 0.5% gas peaked at 9 5/8 annulus & 90% gas peaked at 5 1/2 annulus
ailure to cement nt s into ater	casing	Environmental Health & Safety	Written reply by September 23, 2011. Seneca notified Scott Motter via emil on 8/16/2011 of leaks. NOV vacated
ailure to cement nt s into ater	casing	Environmental Health & Safety	Written reply by September 23, 2011.seneca notified DEP via email of the leaks on August 16, 2011. NOV vacated
ailure to control or of or waste to pollution aters of wealth.	emissions	Environmental Health & Safety	

1,454 wells drilled in 2010.
90 well failures.
6.2% rate of failure.

1,937 wells drilled in 2011.
121 well failures.
6.2% rate of failure.

262 wells drilled in Jan/Feb 2012
19 well failures
7.2% rate of failure

Consistent with previous industry data, and not improving.

http://www.deprepo … _Gas/OG_Compliance

Impacts on Water and Climate

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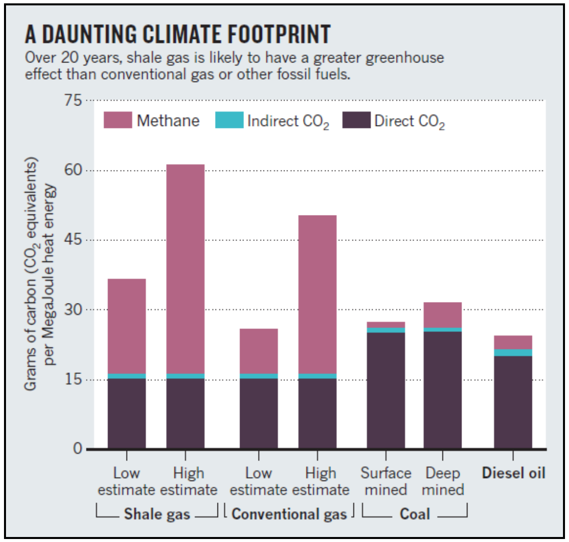
- Waste disposal
- Methane emissions



Flowback* Disposal Possibilities

- EPA-regulated Class II “brine” injection well
- Sewage treatment plant (POTW)
- Industrial waste treatment facility
- Road spreading
- Recycling/Reuse

* “Brine” and “Produced Water” are still “flowback” from shale gas wells

PA DEP Waste Production Database:

<u>38 %</u> of Frac Fluid Recycled in 2011

Well Permit #	Well #	Waste Type	Waste Quantity	Units	Disposal Method	Waste Facility Permit #	Waste Facility Name	Facility City	Facility State
129-28463	3H	FRAC FLUID	360	Bbl	BRINE OR INDUSTRIAL WASTE TREATMENT PLT	253723/PA025723	APPALACIAN WATER SERVICES LLC	CONNELLSVILLE	PA
129-28463	3H	FRAC FLUID	21294.3	Bbl	REUSE OTHER THAN ROAD SPREADING		REUSED IN DRILLING OR PLUGGING JOB		PA
129-28512	8446H	FRAC FLUID	100	Bbl	BRINE OR INDUSTRIAL WASTE TREATMENT PLT	PA0254185	RESERVED ENVIRONMENTAL SERVICES	MOUNT PLEASANT	PA
129-28515	22H	FRAC FLUID	605	Bbl	REUSE OTHER THAN ROAD SPREADING		REUSED IN DRILLING OR PLUGGING JOB		PA
129-28516	23H	FRAC FLUID	605	Bbl	REUSE OTHER THAN ROAD SPREADING		REUSED IN DRILLING OR PLUGGING JOB		PA
129-28524	NE 1-1	FRAC FLUID	895.2	Bbl	BRINE OR INDUSTRIAL WASTE TREATMENT PLT	PA0254185	RESERVED ENVIRONMENTAL SERVICES	MOUNT PLEASANT	PA
129-28558	3H	FRAC FLUID	3153.25	Bbl	REUSE OTHER THAN ROAD SPREADING		REUSED IN DRILLING OR PLUGGING JOB		PA
129-28559	4H-A	FRAC FLUID	688.25	Bbl	REUSE OTHER THAN ROAD SPREADING		REUSED IN DRILLING OR PLUGGING JOB		PA
129-28596	1-2H	FRAC FLUID	48372.35	Bbl	BRINE OR INDUSTRIAL WASTE TREATMENT PLT	PA0254185	RESERVED ENVIRONMENTAL SERVICES	MOUNT PLEASANT	PA
129-28604	1-6H	FRAC FLUID	100	Bbl	BRINE OR INDUSTRIAL WASTE TREATMENT PLT	PA0254185	RESERVED ENVIRONMENTAL SERVICES	MOUNT PLEASANT	PA
129-28611	1-9H	FRAC FLUID	[illegible]	Bbl	BRINE OR INDUSTRIAL WASTE TREATMENT PLT	PA0254185	RESERVED ENVIRONMENTAL SERVICES	MOUNT PLEASANT	PA
129-28649	1-6H	F						EASANT	PA
129-28674	1-10H	F						EASANT	PA
131-20038	1	F							PA
131-20049	1H	F							
131-20055	1H	F							
131-20058	5H	F							
131-20062	2H	F							
131-20081	2H	F							
131-20096	2H	FRAC FLUID	7114	Bbl	REUSE OTHER THAN ROAD SPREADING		REUSE OF BRINE TO FRAC A WELL		
131-20121	2H	FRAC FLUID	3901	Bbl	REUSE OTHER THAN ROAD SPREADING		REUSE OF BRINE TO FRAC A WELL		
131-20125	4H	FRAC FLUID	1305	Bbl	REUSE OTHER THAN ROAD SPREADING		REUSE OF BRINE TO FRAC A WELL		
131-20138	6h	FRAC FLUID	1305	Bbl	REUSE OTHER THAN ROAD SPREADING		REUSE OF BRINE TO FRAC A WELL		
131-20143	P&G3#1	FRAC FLUID	5155	Bbl	REUSE OTHER THAN ROAD SPREADING		REUSE OF BRINE TO FRAC A WELL		
131-20147	1H	FRAC FLUID	7773	Bbl	REUSE OTHER THAN ROAD SPREADING		FRAC WATER REUSE		PA
131-20156	1H	FRAC FLUID	3130	Bbl	REUSE OTHER THAN ROAD SPREADING		FRAC WATER REUSE		PA
131-20157	1H	FRAC FLUID	4050	Bbl	REUSE OTHER THAN ROAD SPREADING		FRAC WATER REUSE		PA
131-20158	P&G32	FRAC FLUID	4704	Bbl	REUSE OTHER THAN ROAD SPREADING		REUSE OF BRINE TO FRAC A WELL		
131-20160	4H	FRAC FLUID	12620	Bbl	REUSE OTHER THAN ROAD SPREADING		FRAC WATER REUSE		PA
131-20161	5H	FRAC FLUID	600	Bbl	BRINE OR INDUSTRIAL WASTE TREATMENT PLT	EPA ID: 748-163	PATRIOT WATER TREATMENT	WARREN	OH
131-20164	2H	FRAC FLUID	140	Bbl	REUSE OTHER THAN ROAD SPREADING		FRAC WATER REUSE		PA
131-20175	2H	FRAC FLUID	20	Bbl	REUSE OTHER THAN ROAD SPREADING		FRAC WATER REUSE		PA
131-20181	2H	FRAC FLUID	1328	Bbl	REUSE OTHER THAN ROAD SPREADING		REUSE OF BRINE TO FRAC A WELL		
		Total liquid waste	**31,329,760**	**Bbl**					
		% recycled	**35.2**						
		Total Frac fluid	**15,604,210**	**Bbl**					
		% recycled	**37.8**						

Industry claims of “nearly 100% recycling” are not supported by DEP data

Impacts on Water and Climate

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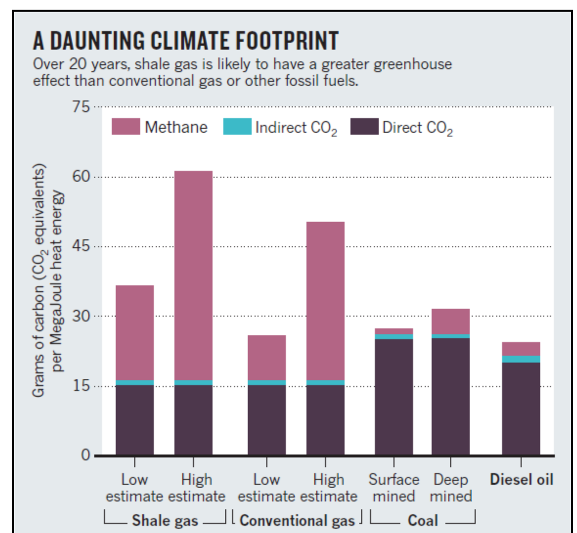
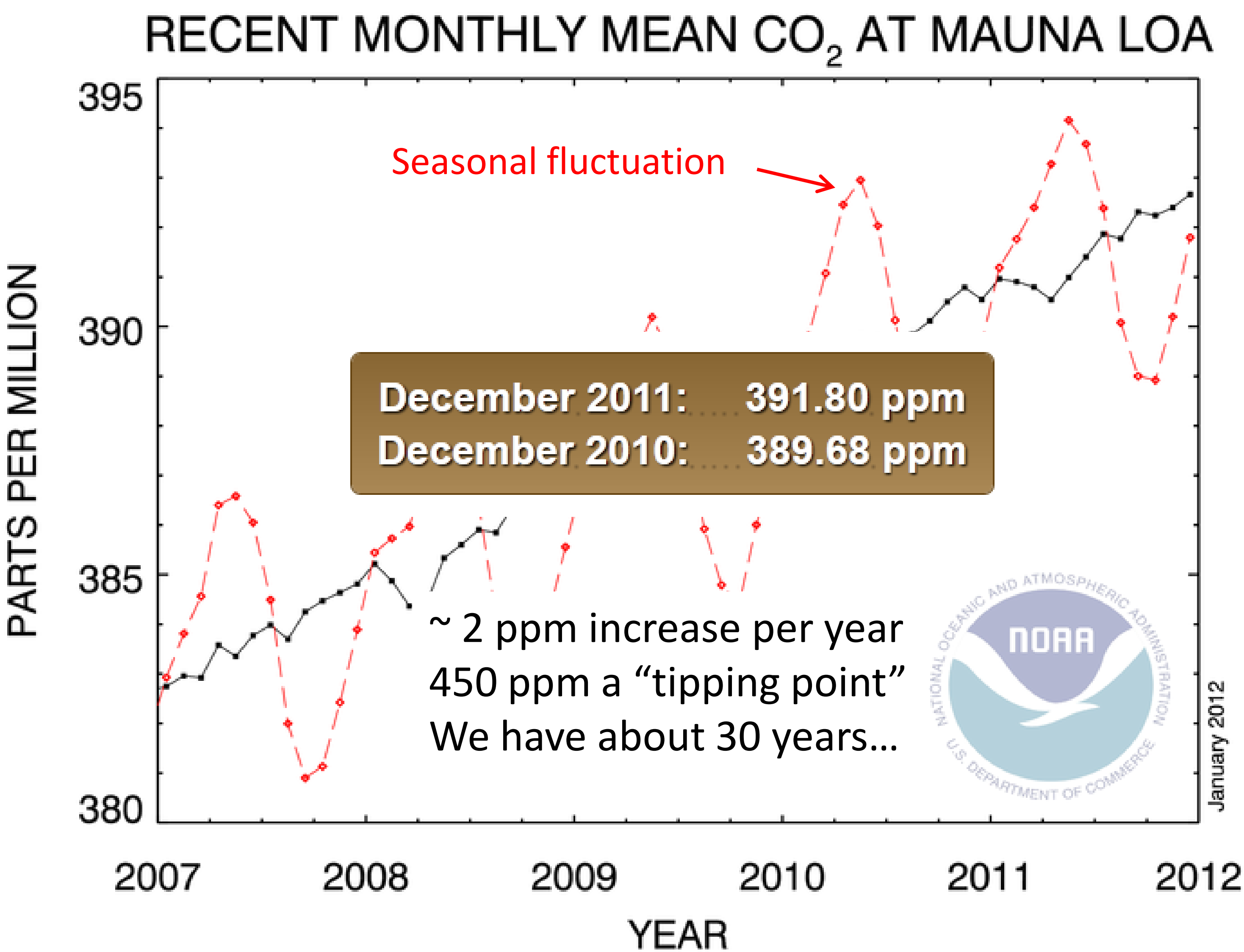
- Waste disposal

- Methane emissions



CO_2 Concentration in the Atmosphere: NOAA



Methane Concentration in the Atmosphere: Historical Record

GWP of CH_4

100 year time frame: 33
20 year time frame: 105

Shindell et al. 2009

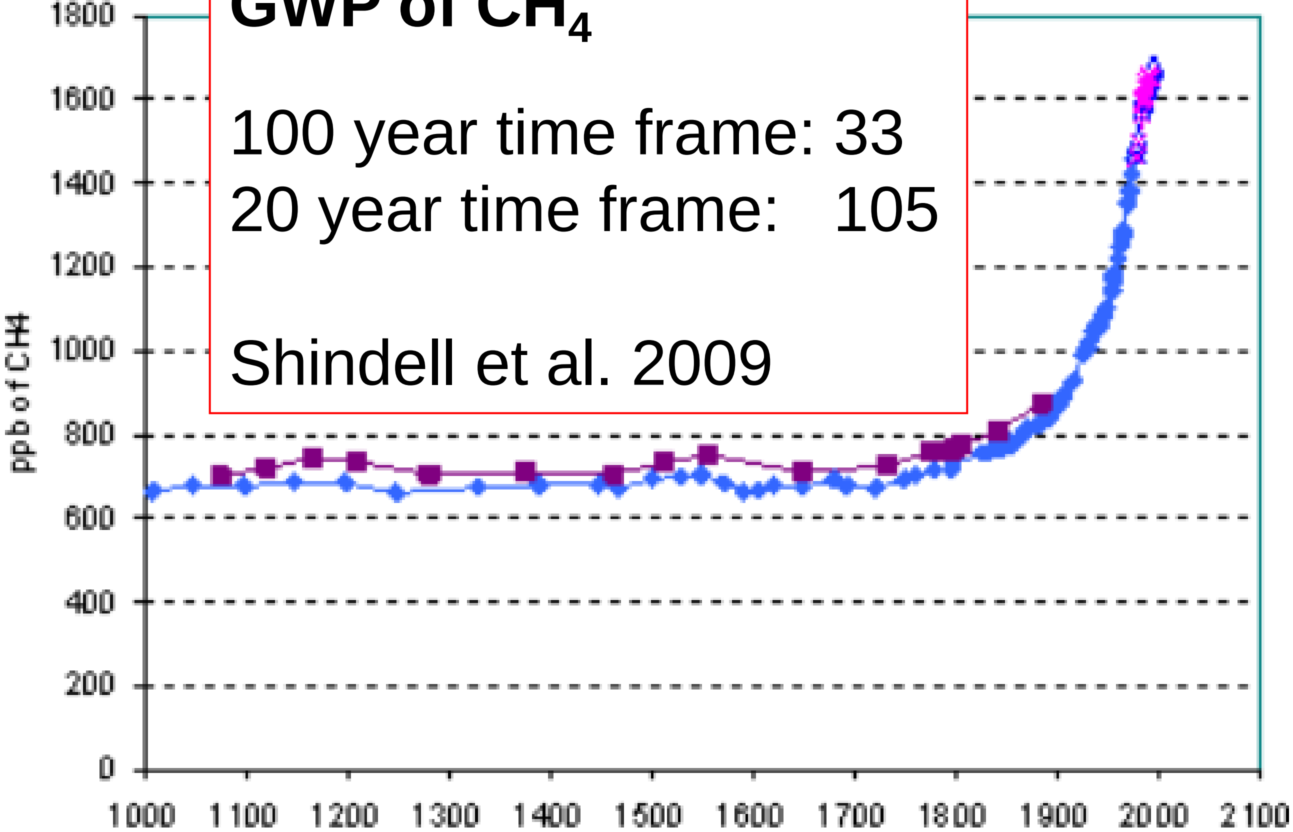
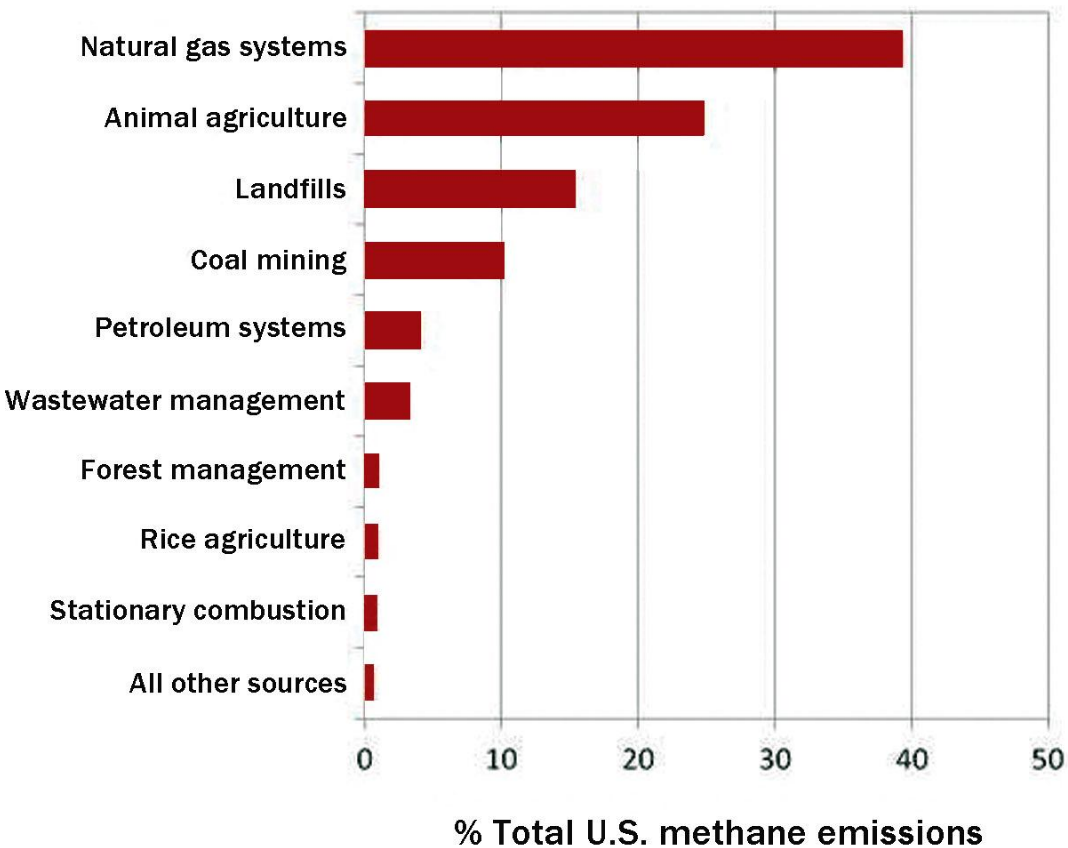
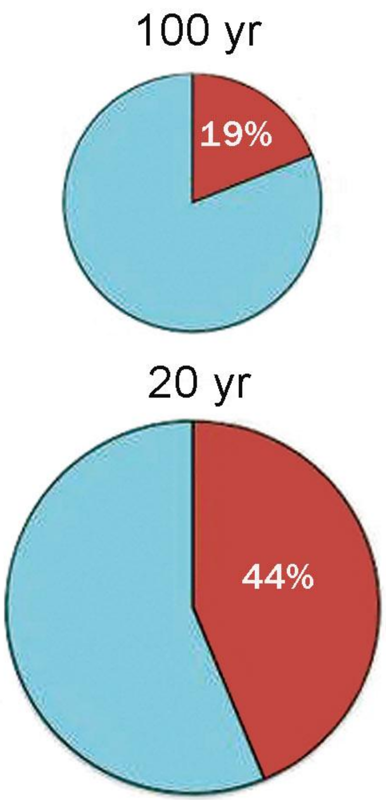


Figure 1: Methane content in the atmosphere obtained from measurements in glaciers in Antarctic and Greenland and in environmental samples collected in Tasmania.

http://www.ecen.com/eee55/eee55e/growth_of%20methane_concentration_in_atmosphere.htm

Natural Gas Systems Now Produce 39% of Total U.S. Methane Emissions

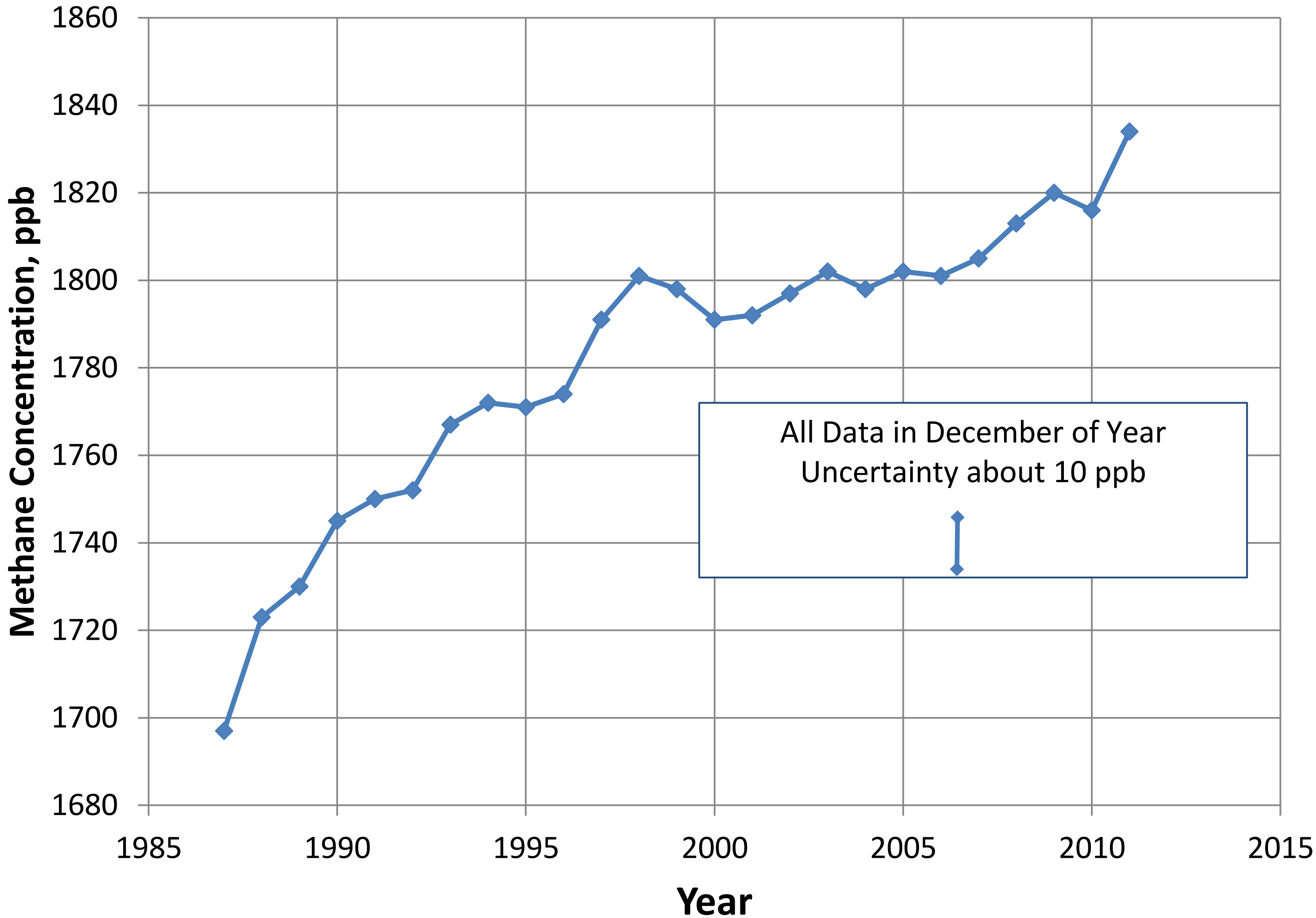




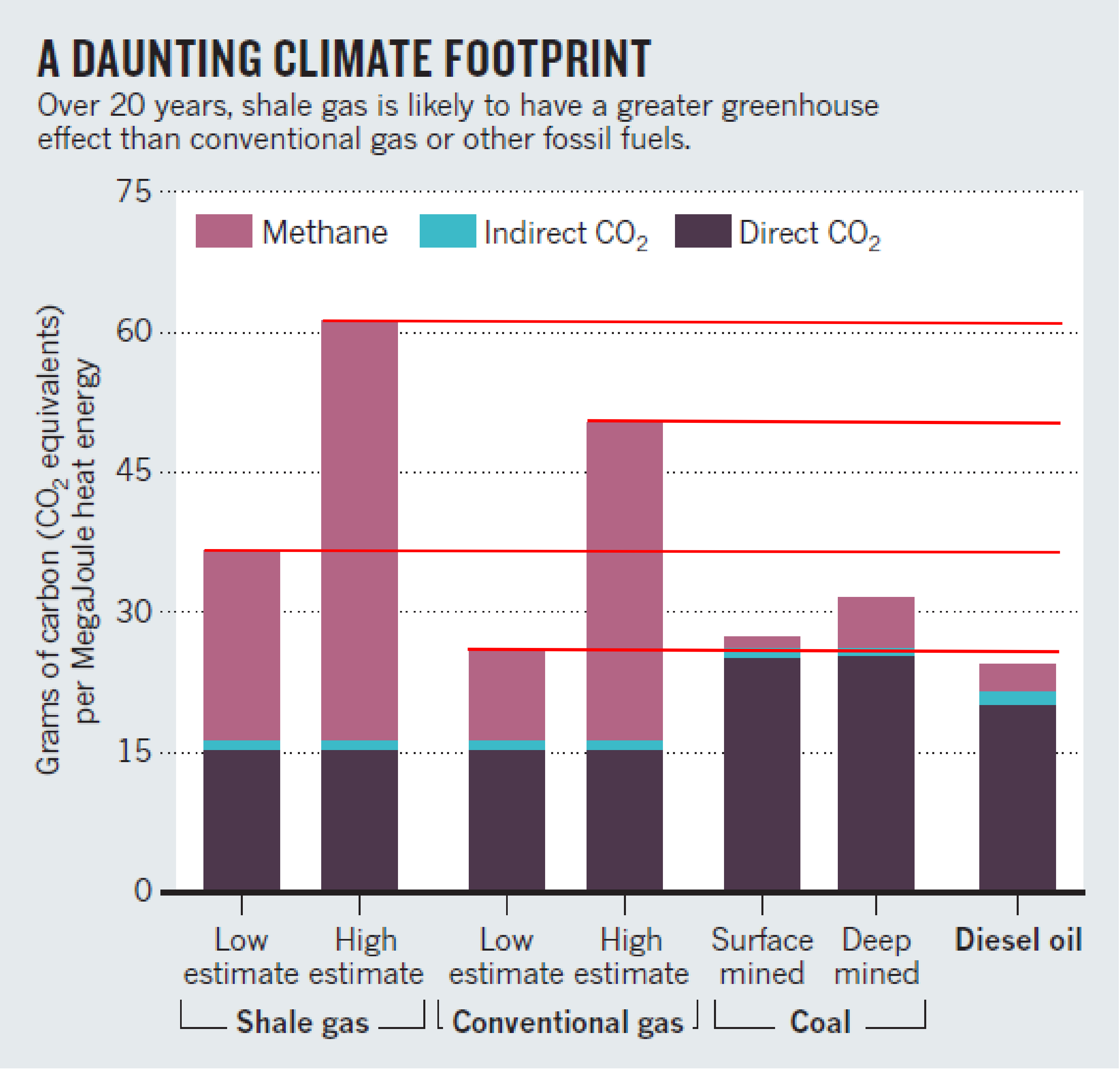
Methane contribution to entire greenhouse gas inventory

(Howarth et al. 2012, based on 2011 EPA data for 2009)

Recent Measured Methane Concentration in the Atmosphere: NOAA

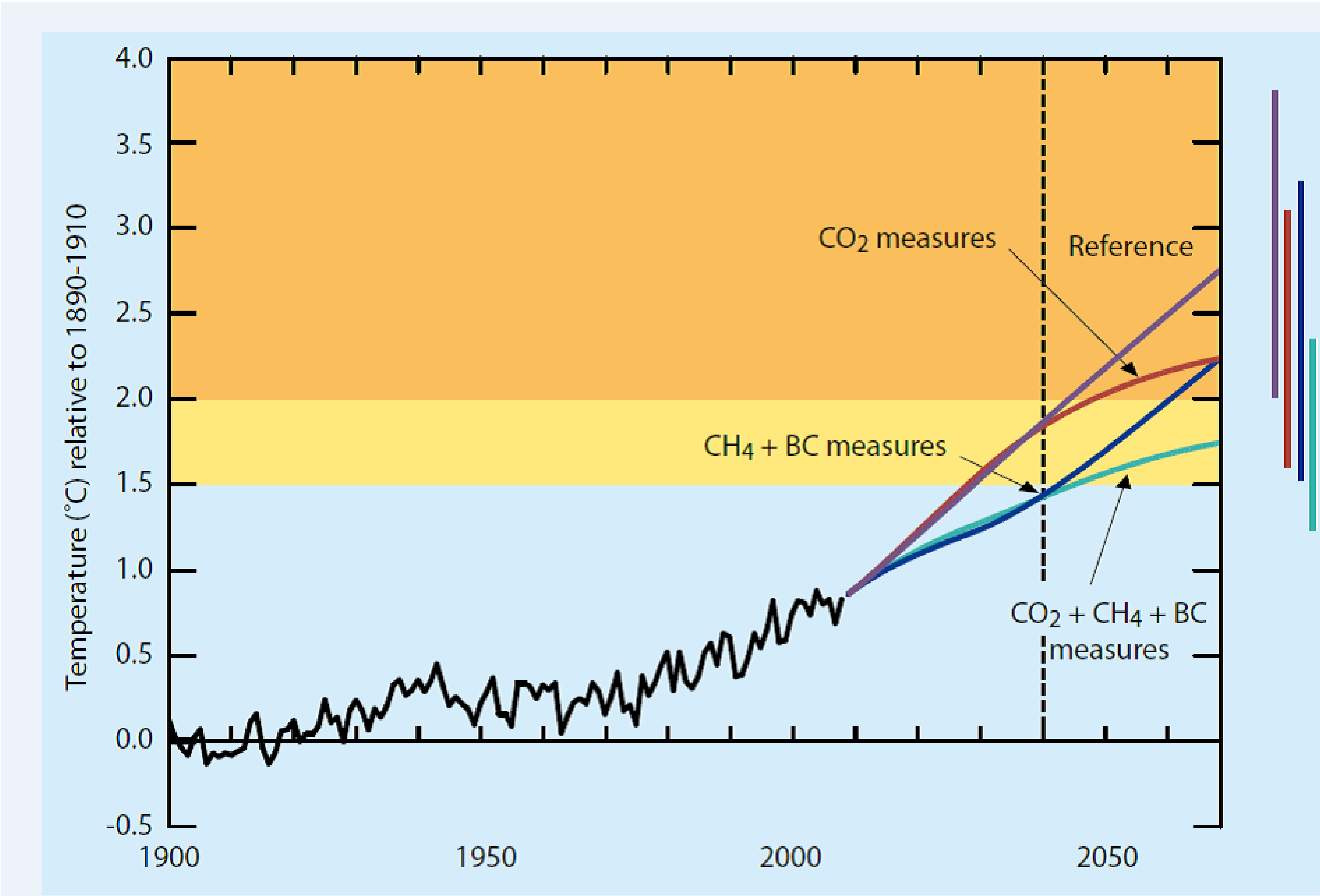


ftp://ftp.cmdl.noaa.gov/ccg/ch4/in-situ/mlo/ch4_mlo_surface-insitu_1_ccgg_month.txt



Howarth & Ingraffea, *Nature*, 15 September 2011

Why Is Controlling Methane (CH_4) Emission So Important?



Shindell, *et al. Science* ***335, 183 (2012)***

Thank You for Attending and Participating Today

Physicians Scientists & Engineers for Healthy Energy

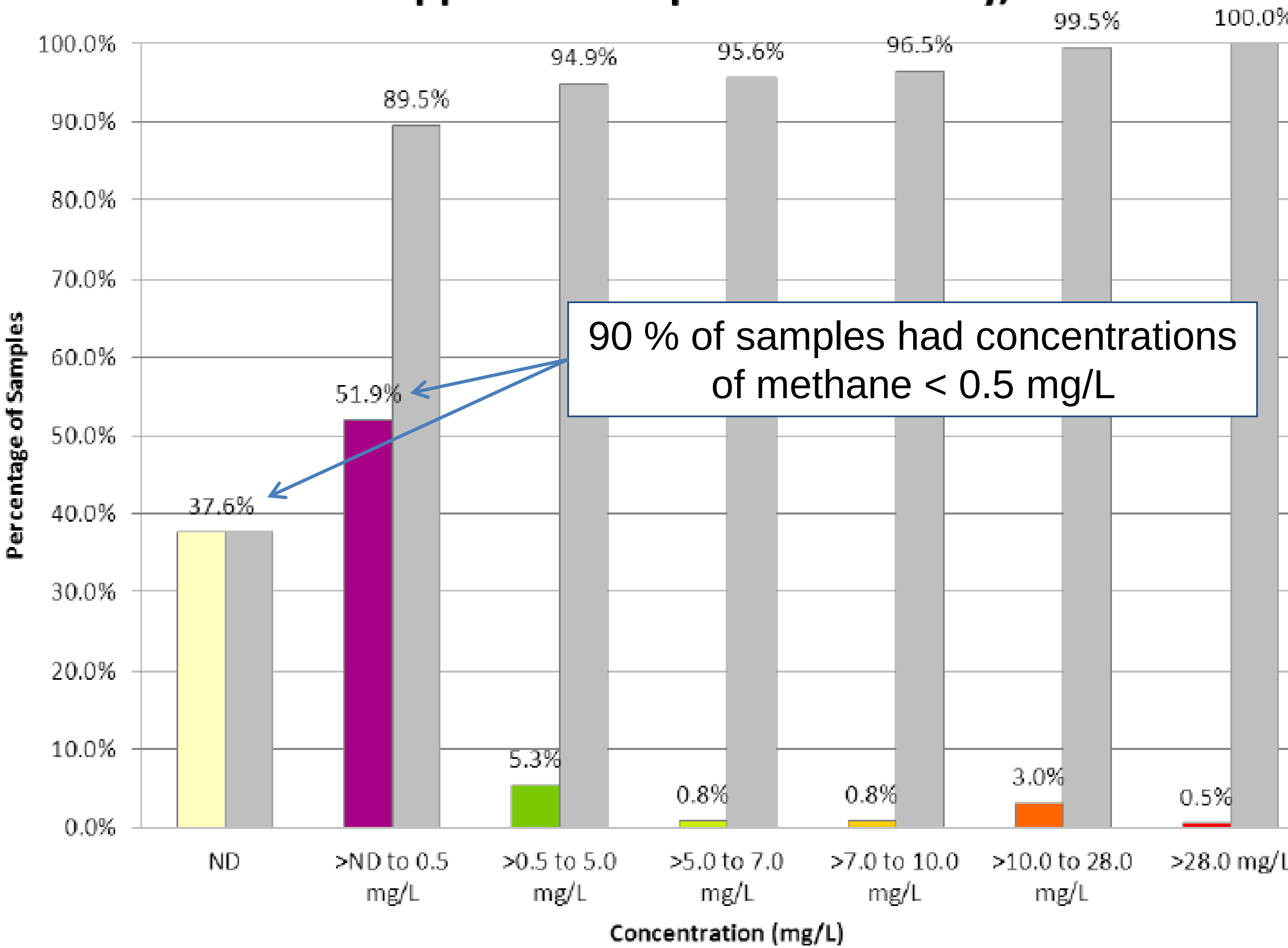
www.psehealthyenergy.org

Potential Impacts on Chesapeake Bay from Shale Gas Development: Loss of Forest Cover

"Forests.
By 2030, a range of between 34,000 to 82,000 acres of forest cover could be cleared by new Marcellus gas development in the state."

Pennsylvania Energy Impacts Assessment
Report 1: Marcellus Shale Natural Gas and Wind
November 15, 2010

Frequency Distribution of Methane Concentration in Water Supplies in Susquehanna County, PA

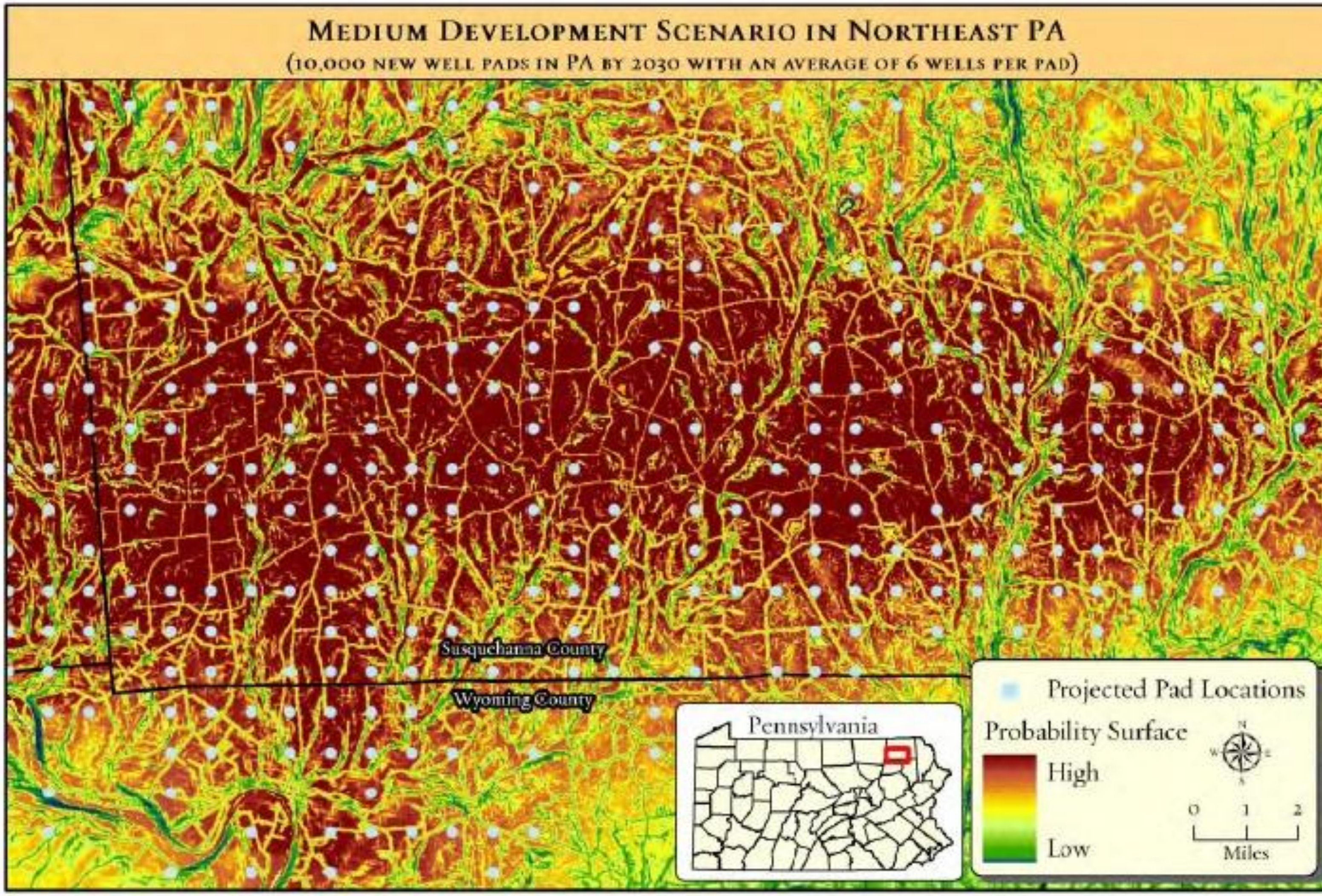


Data Courtesy of Seth Pelepko, Subsurface Activities Section, PA DEP

Last Time I Spoke, I Was Challenged….

Photos Courtesy
of Bob Donnan

A Nearby, Consistent Projection



Map showing projected location of new Marcellus well pads in southern Susquehanna County under the medium development scenario.

www.nature.org/media/pa/tnc_energy_analysis.pdf

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			
Conventional well completions	0.02	0.71	CH_4 – metric tons/year-completion
Unconventional well completions	0.02	177	CH_4 – metric tons/year-completion
3) Gas well venting during well workovers			
Conventional well workovers	0.05	0.05	CH_4 – metric tons/year-workover
Unconventional well workovers	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


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

Received: 12 November 2010 / Accepted: 13 March 2011

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 life-time 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

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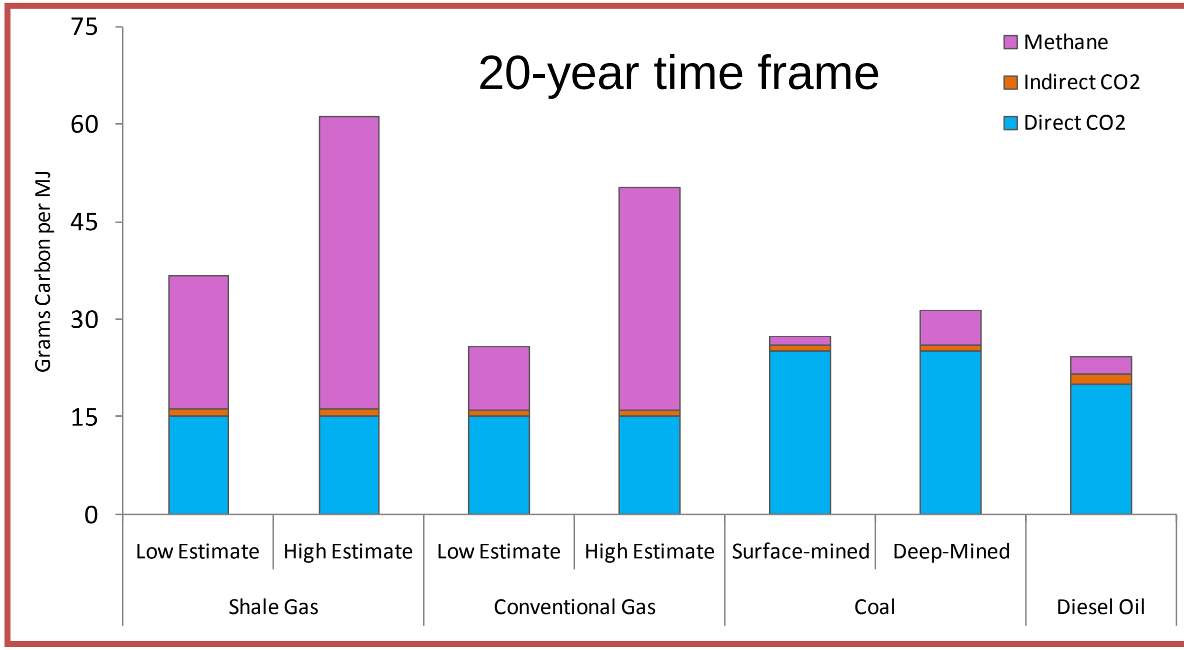

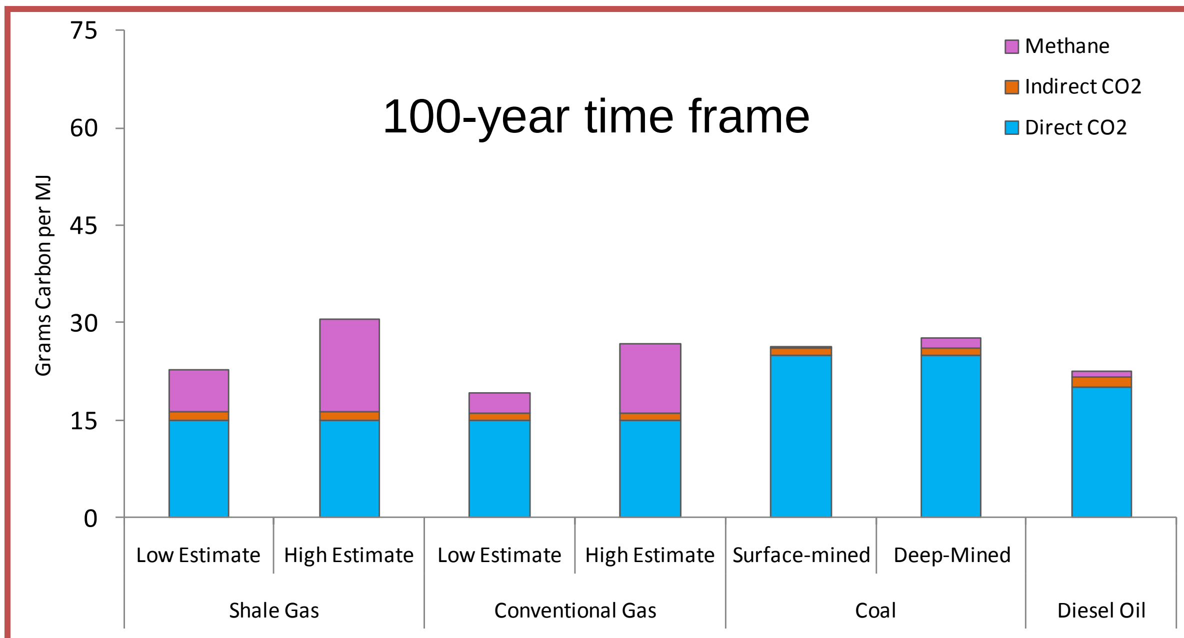

Published in April 2011

Comparison of published estimates for methane emissions from conventional and shale gas development, expressed per unit of Lower Heating Value ($gC\ MJ^{-1}$).

	Conventional gas	Shale gas
Hayhoe et al. (2002)	0.57	*
Jamarillo et al. (2007)	0.15	*
Howarth et al. (2011)	0.26 - 0.96	0.55 - 1.2

* Estimates not provided in these papers and reports.

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Very good agreement

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Low, since based on old and low emissions factors from a 1996 EPA study

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Roughly 40% more methane

* Estimates not provided in these papers and reports.

Papers and reports since April 2011:

- EPA (2011-a)
- Hughes (2011)
- Venkatesh et al. (2011)
- Jiang et al. (2011)
- Wigley (2011)
- EPA (2011-b)
- Fulton et al. (2011)
- Stephenson et al. (2011)
- Hultman et al. (2011)
- Skone et al. (2011)
- Burnham et al. (2011)
- Cathles et al. (2012)
- Howarth et al. (2012-a)
- Howarth et al. (2012-b)
- Petron et al. (2012)

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EPA (2011a)	0.38	0.60
Hughes (2011a)	0.26 - 0.96	0.55 - 1.2
Venkatesh et al. (2011)	0.34	*
Jiang et al. (2011)	*	0.30
Fulton et al. (2011)	0.38	*
Stephenson et al. (2011)	0.07	0.10
Hultman et al. (2011)	0.35	0.57
Skone et al. (2011)	0.27	0.37
Burnham et al. (2011)	0.39	0.29
Cathles et al. (2012)	0.14 - 0.36	0.14 - 0.36

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Stephenson et al. (2011)	0.07	0.10
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Stephenson et al. (2011)	0.07	0.10
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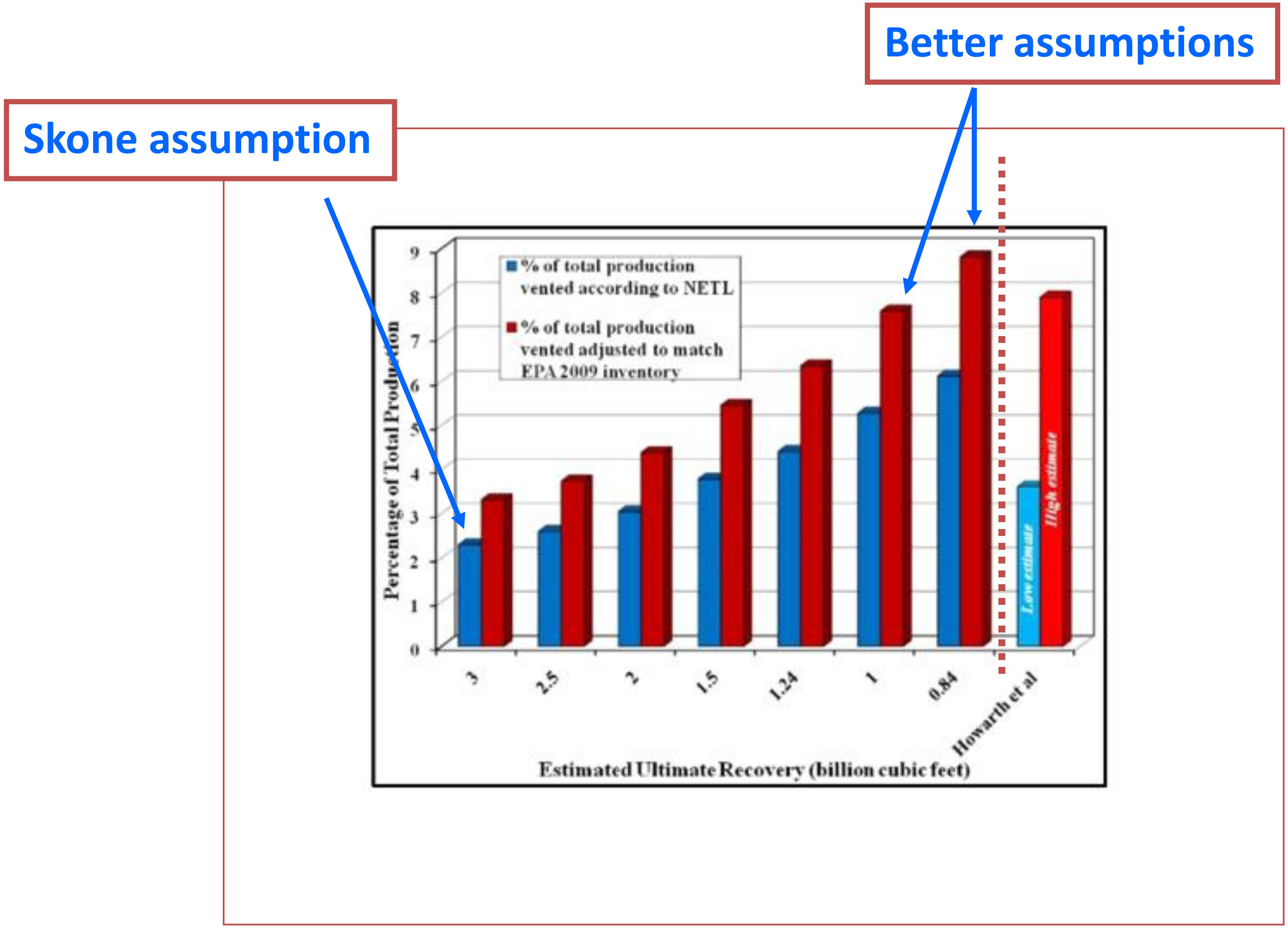
Skone et al. (2011)	0.27	0.37
Burnham et al. (2011)	0.39	0.29
Cathles et al. (2012)	0.14 - 0.36	0.14 - 0.36



Skone estimates may be low, when normalized to energy, since gas production for well was likely over-estimated (Hughes 2011).

Comparison of published estimates for methane emissions from conventional and shale gas development, expressed per unit of Lower Heating Value ($gC\ MJ^{-1}$).

	Conventional gas	Shale gas
Hayhoe et al. (2002)	0.57	*
Jamarillo et al. (2007)	0.15	*
Howarth et al. (2011)	0.26 - 0.96	0.55 - 1.2
EPA (2011a)	0.38	0.60
Hughes (2011a)	0.26 - 0.96	0.55 - 1.2
Venkatesh et al. (2011)	0.34	*
Jiang et al. (2011)	*	0.30
Fulton et al. (2011)	0.38	*
Stephenson et al. (2011)	0.07	0.10
Hultman et al. (2011)	0.35	0.57
Skone et al. (2011)	0.27	0.37
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Howarth et al. (2012-b) – Background paper for National Climate Assessment

Table 2. Conventional natural gas, estimates of methane emissions from upstream (at the well site) plus midstream (at gas processing plants), expressed as the percentage of methane produced over the lifecycle of a well. Studies are listed chronologically by date of publication. Modified from Howarth et al. (2012).

Hayhoe et al. (2002)	1.2 %	("best estimate")
Howarth et al. (2011)	1.4 %	(mean; range = 0.2% to 2.4%)
EPA (2011)*	1.6 %	
Hultman et al. (2011)	1.3 %	
Venkatesh et al. (2011)	1.8 %	
Burnham et al. (2011)	2.0 %	
Stephenson et al. (2011)	0.4 %	
Cathles et al. (2012)	0.9 %	

Emissions at well site… conventional gas

* The EPA (2011) estimate is as calculated in Howarth et al. (2012), using national emissions from EPA reports and national gas production data from US Department of Energy reports.

Howarth et al. (2012-b) – Background paper for National Climate Assessment

Table 1. Estimates of methane emission from downstream emissions (transmission pipelines and storage and distribution systems) expressed as the percentage of methane produced over the lifecycle of a well. Studies are listed chronologically by date of publication. Modified from Howarth et al. (2012).

Hayhoe et al. (2002)	2.5 %	("best estimate;" range = 0.2% – 10%)
Lelieveld et al. (2005)	1.4 %	("best estimate;" range = 1.0% – 2.5%)
Howarth et al. (2011)	2.5 %	(mean; range = 1.4% – 3.6%)
EPA (2011)*	0.9 %	
Jiang et al. (2011)	0.4 %	
Hultman et al. (2011)	0.9 %	
Ventakesh et al. (2011)	0.4 %	
Burnham et al. (2011)	0.6 %	
Stephenson et al. (2011)	0.07 %	
Cathles et al. (2012)	0.7 %	

Downstream emissions (storage, transmission pipelines, distribution systems)

* The EPA (2011) estimate is as calculated in Howarth et al. (2012), using national emissions from EPA reports and national gas production data from US Department of Energy reports.

Bruce Gellerman, “Living on Earth,” Jan. 13, 2012, based on work of Prof. Nathan Phillips

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