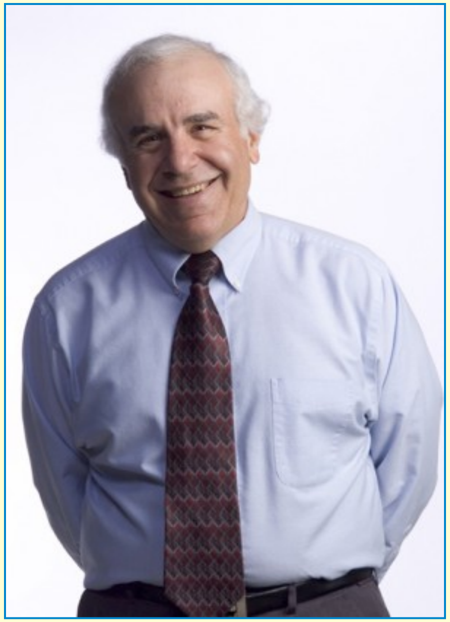
Cornell University
College of Agriculture and Life Sciences

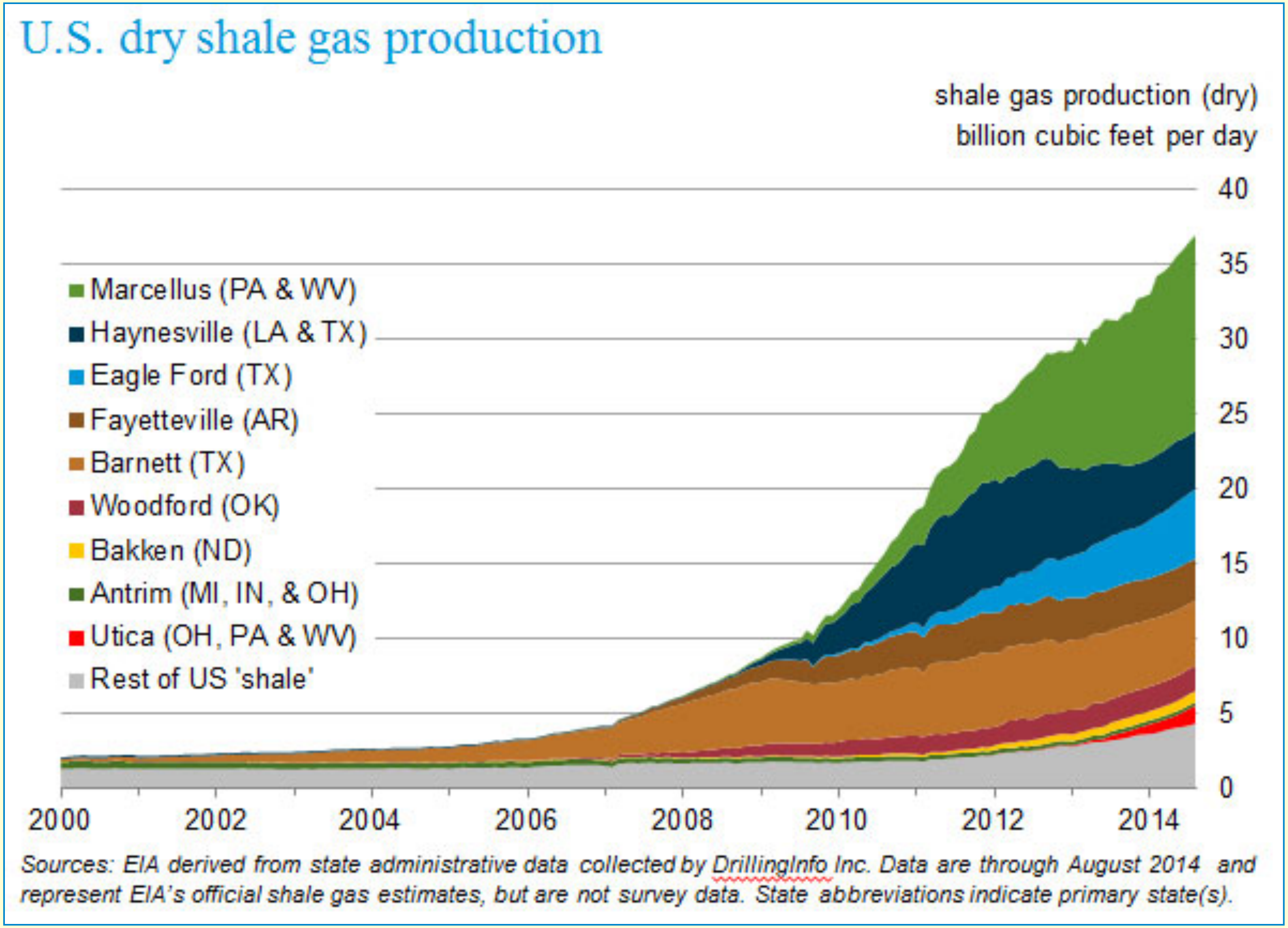
Methane emissions make shale gas a bridge to nowhere

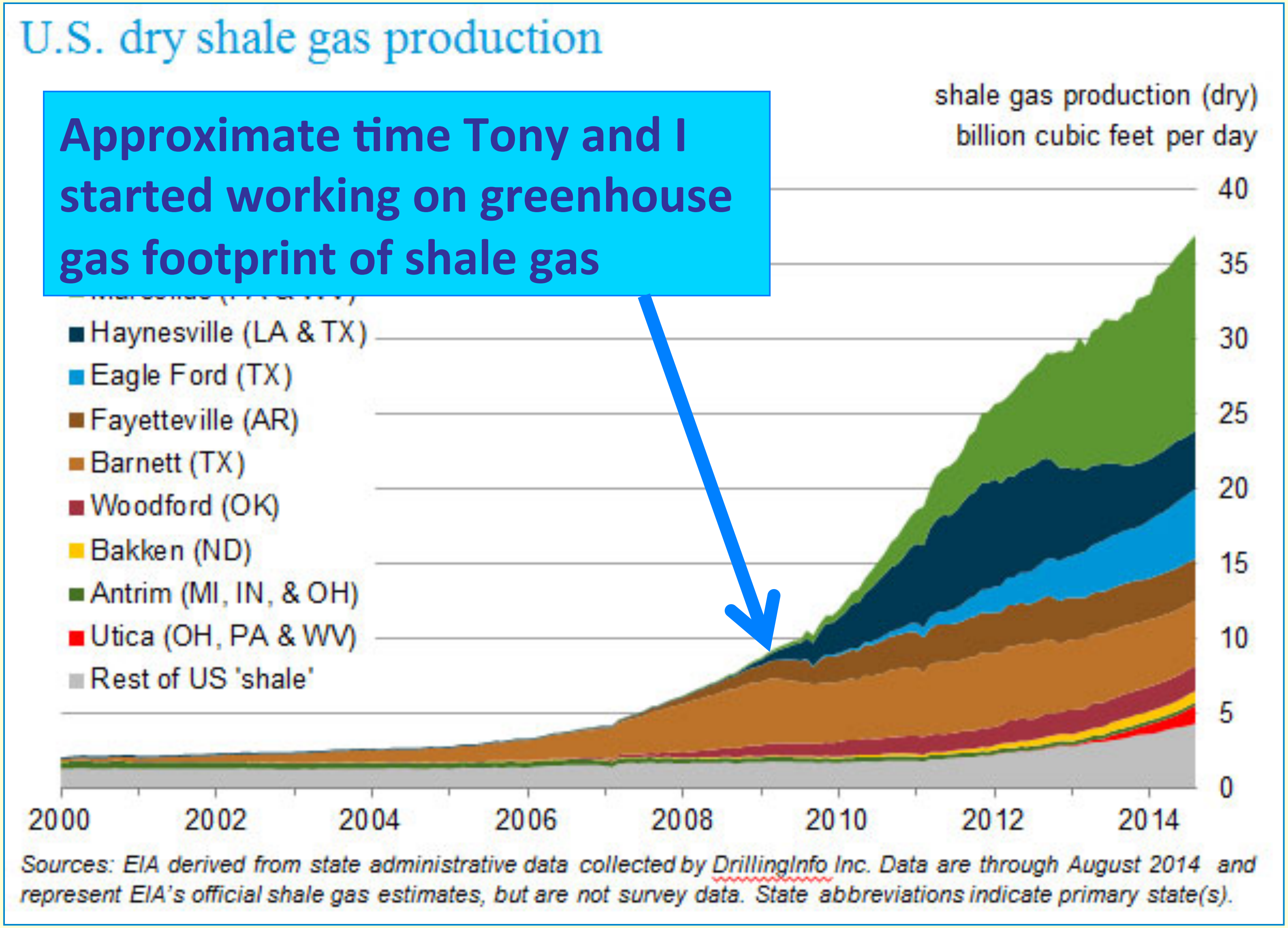
Robert Howarth
The David R. Atkinson Professor of Ecology & Environmental Biology
Cornell University, Ithaca, NY USA

Symposium to Honor Prof. Tony Ingraffea
Cornell University
September 27, 2014

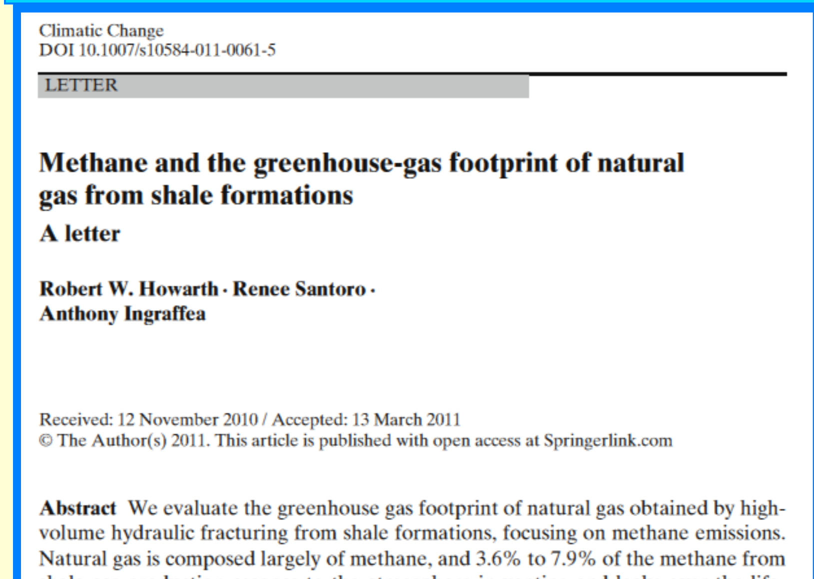


Shale gas is new, the science behind it is new .....




U.S. dry shale gas production
Approximate time Tony and I started working on greenhouse gas footprint of shale gas
shale gas production (dry)
billion cubic feet per day
40
35
30
25
20
15
10
5
0
Haynesville (LA & TX)
Eagle Ford (TX)
Fayetteville (AR)
Barnett (TX)
Woodford (OK)
Bakken (ND)
Antrim (MI, IN, & OH)
Utica (OH, PA & WV)
Rest of US 'shale'
2000
2002
2004
2006
2008
2010
2012
2014
Sources: EIA derived from state administrative data collected by DrillingInfo Inc. Data are through August 2014 and represent EIA's official shale gas estimates, but are not survey data. State abbreviations indicate primary state(s).

Publication of first peer-reviewed paper on any aspect of environmental risk of shale gas (Howarth, Santoro, & Ingraffea 2011)


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

LETTER

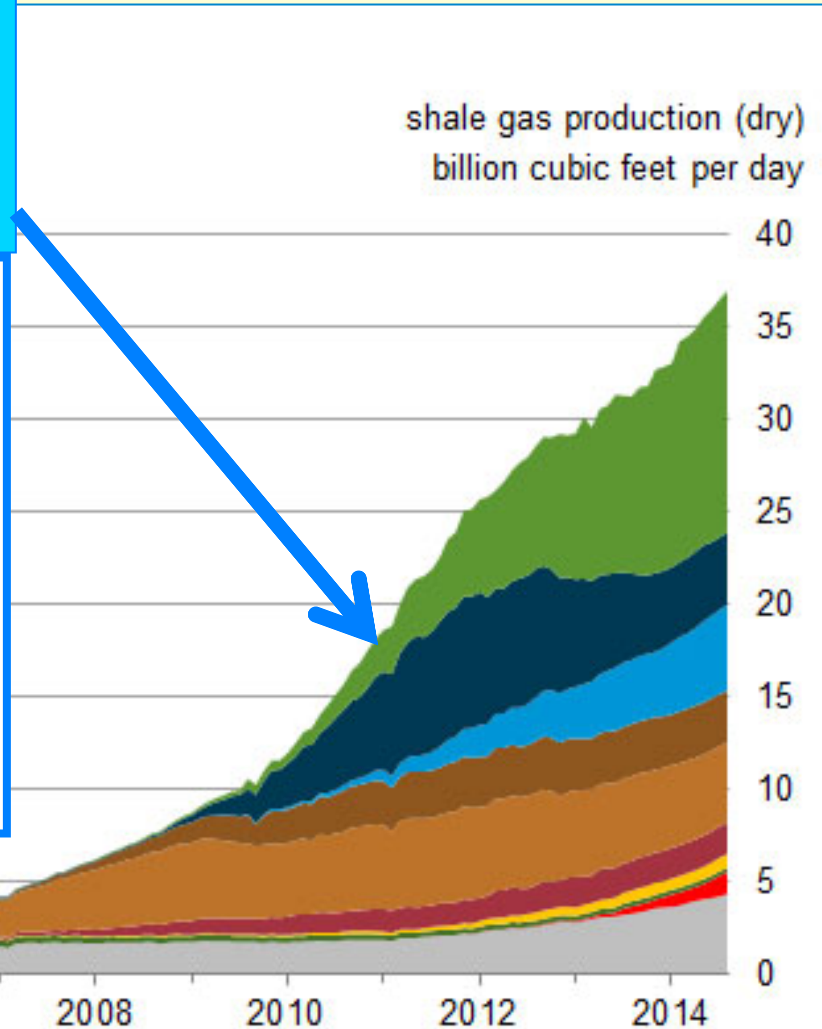
Methane and the greenhouse-gas footprint of natural gas from shale formations

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



Sources: EIA derived from state administrative data collected by DrillingInfo Inc. Data are through August 2014 and represent EIA's official shale gas estimates, but are not survey data. State abbreviations indicate primary state(s).

Howarth, Santoro, & Ingraffea. 2011. Methane and the greenhouse gas footprint of natural gas from shale formations. ***Climatic Change Letters***

Howarth & Ingraffea. 2011. Should fracking stop? Yes, it is too high risk. ***Nature***

Howarth, Santoro, & Ingraffea. 2012. Venting and leakage of methane from shale gas development: Reply to Cathles et al. ***Climatic Change***

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Jacobson, et al. 2013. Examining the feasibility of converting New York State's all-purpose energy infrastructure to one using wind, water, and sunlight. ***Energy Policy***

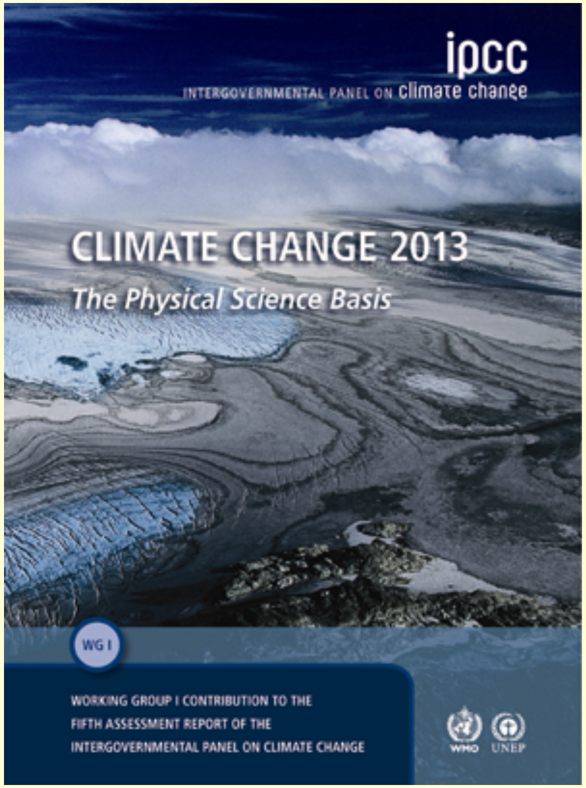
Howarth and Ingraffea. 2013. Shale gas: Time to go slow. **World Energy Monitor**, United Nations.

Caulton et al. 2014. Toward a better understanding and quantification of methane emissions from shale gas development. ***Proceedings of the National Academy of Sciences***

Jacobson et al. 2014. A roadmap for repowering California for all purposes with wind, water, and sunlight. ***Energy***

Ingraffea et al. 2014. Assessment and risk analysis of casing and cement impairment in oil and gas wells in Pennsylvania, 2000–2012. ***Proceedings of the National Academy of Sciences***

Howarth 2014. A bridge to nowhere: Methane emissions and the greenhouse gas footprint of natural gas. ***Energy Science & Engineering***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WORKING GROUP I CONTRIBUTION TO THE
FIFTH ASSESSMENT REPORT OF THE
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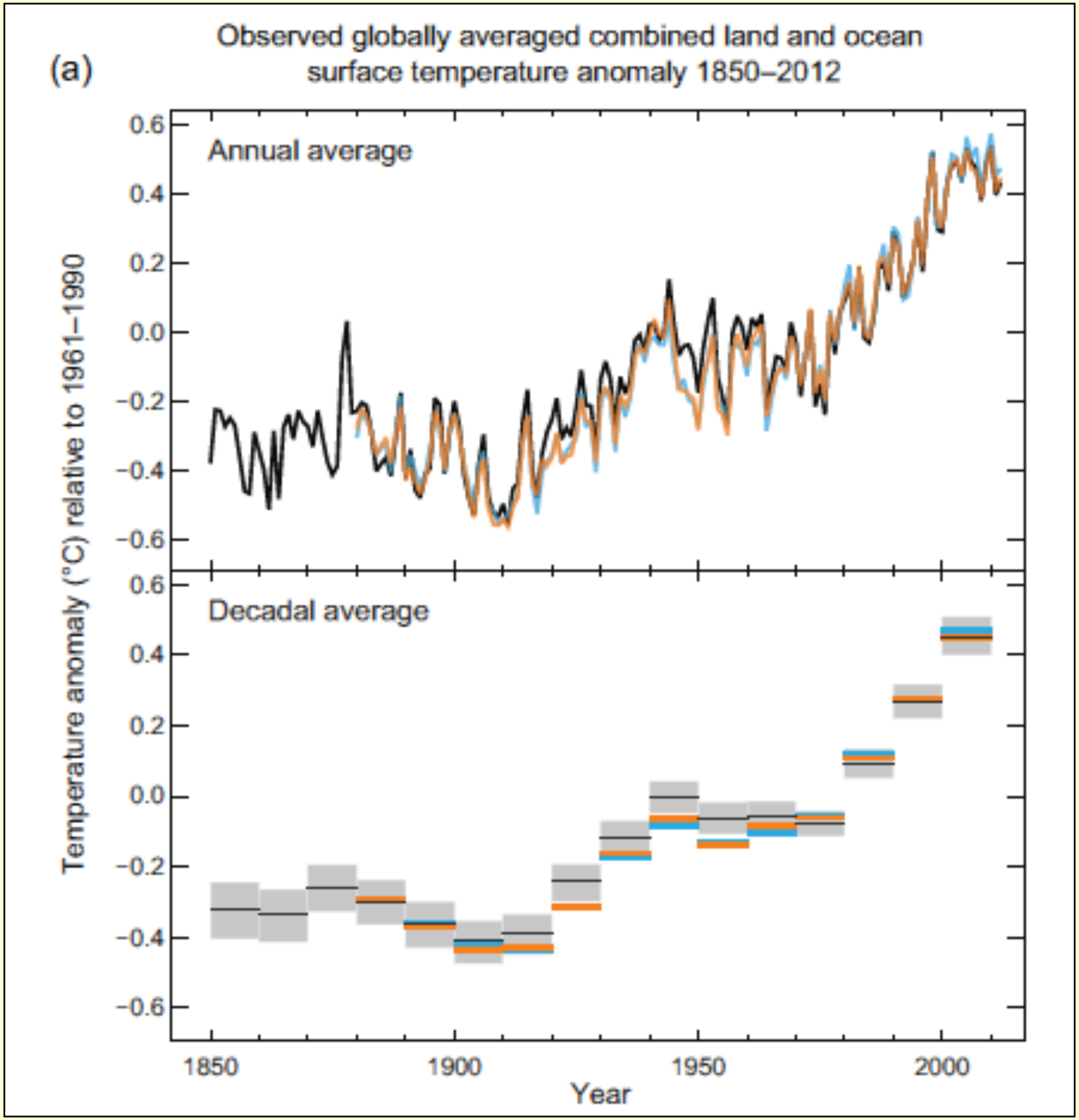
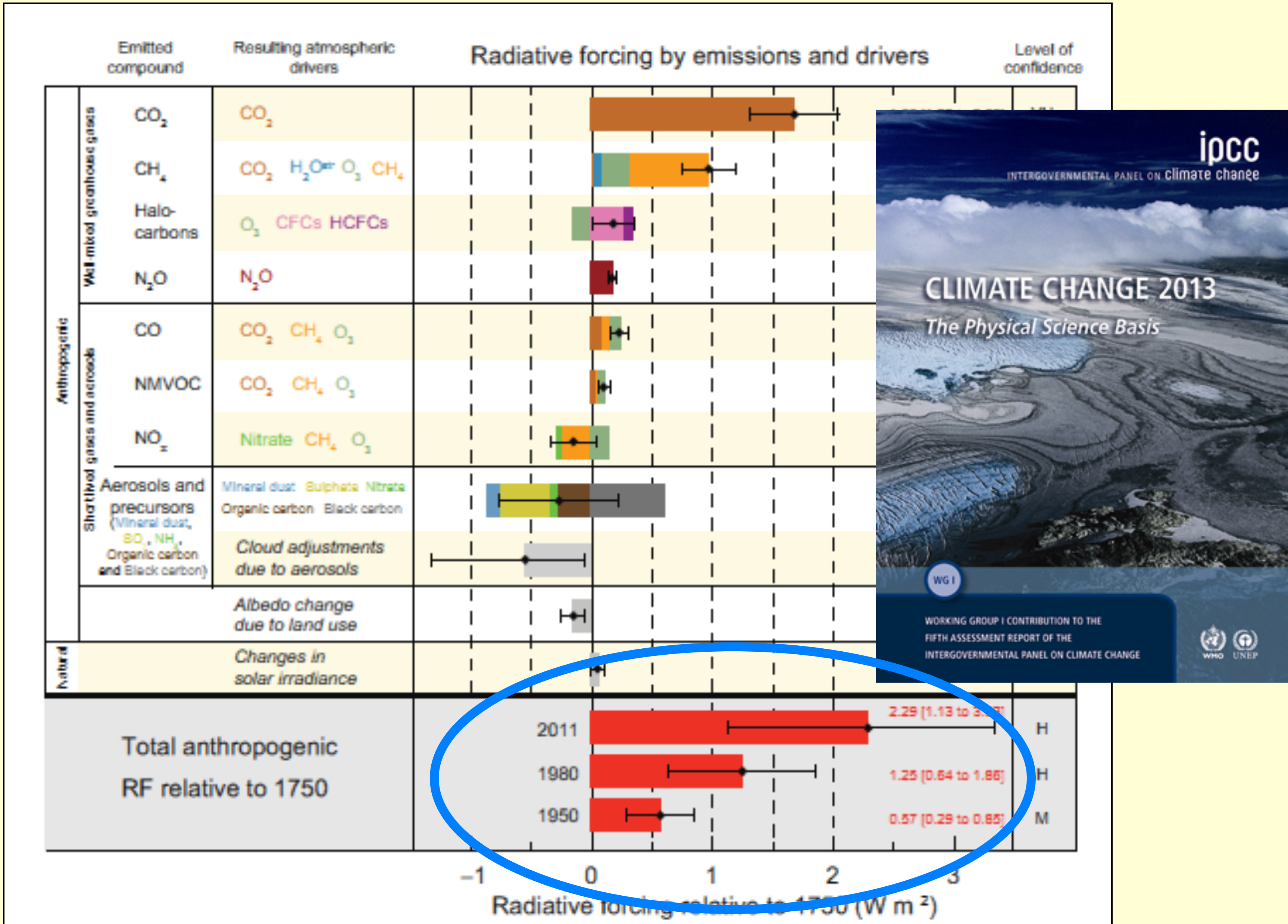

(a)
Observed globally averaged combined land and ocean
surface temperature anomaly 1850–2012
Annual average
Decadal average
Temperature anomaly (°C) relative to 1961–1990
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
1850
1900
1950
2000
Year


Emitted compound
Resulting atmospheric drivers
Radiative forcing by emissions and drivers
Level of confidence
Anthropogenic
Well-mixed greenhouse gases
CO_2
CO_2
CH_4
CO_2 H_2O^{str} O_3 CH_4
Halo-carbons
O_3 CFCs HCFCs
N_2O
N_2O
Short lived gases and aerosols
CO
CO_2 CH_4 O_3
NMVOC
CO_2 CH_4 O_3
NO_x
Nitrate CH_4 O_3
Aerosols and precursors (Mineral dust, SO_2, NH_3, Organic carbon and Black carbon)
Mineral dust Sulphate Nitrate Organic carbon Black carbon
Cloud adjustments due to aerosols
Albedo change due to land use
Natural
Changes in solar irradiance
Total anthropogenic RF relative to 1750
2011
1980
1950
2.29 [1.13 to 3.
1.25 [0.64 to 1.86]
0.57 [0.29 to 0.85]
H
H
M
−1
0
1
2
3
Radiative forcing relative to 1750 (W m⁻²)
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Is natural gas a "bridge fuel?"

For just the release of carbon dioxide during combustion.....

	g C of CO_2 MJ^{-1} of energy
Natural gas	15
Diesel oil	20
Coal	25

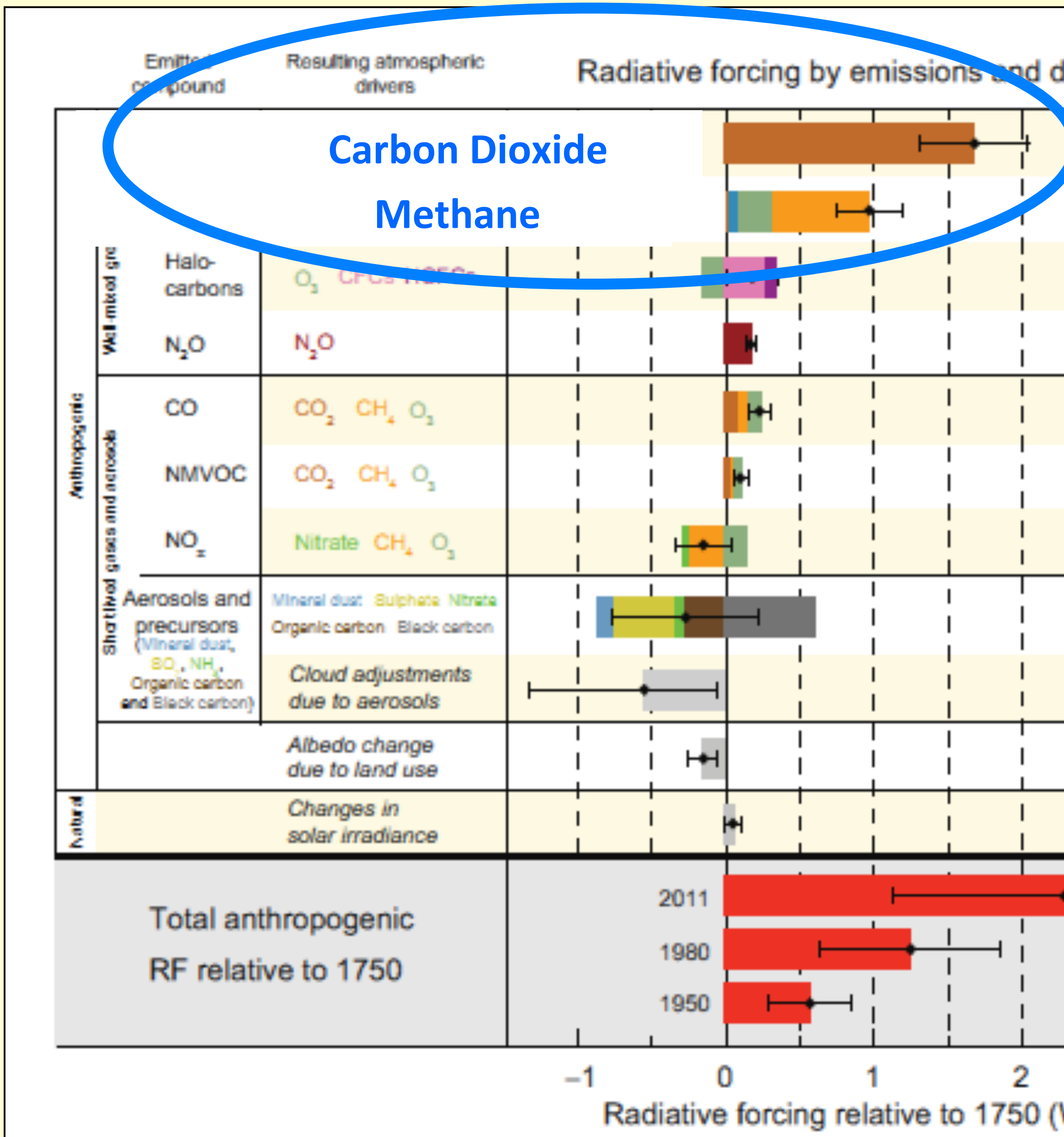
(Hayhoe et al. 2002)

Methane emissions – the Achilles' heel of natural gas

- Natural gas is mostly methane.

- Methane is 2nd most important gas behind human-caused global warming.

- Methane is much more potent greenhouse gas than carbon dioxide, so even small emissions matter.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Radiative forcing by emissions and drivers
Level of confidence
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Methane
Halo-carbons
O_3
N_2O
N_2O
Well mixed gre
CO
CO_2 CH_4 O_3
NMVOC
CO_2 CH_4 O_3
NO_x
Nitrate CH_4 O_3
Short lived gases and aerosols
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M
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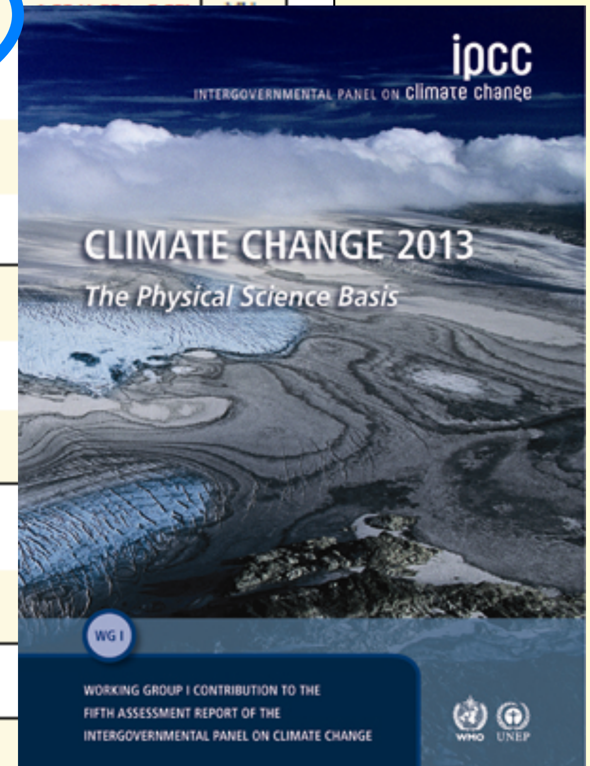
0
1
2
3
Radiative forcing relative to 1750 (W m⁻²)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WHO
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In fall 2009, Tony Ingraffea, Renee Santoro, and I took on as research questions:

1) The role of methane emissions in the greenhouse gas footprint of natural gas.

2) Evaluation of methane emissions from shale gas in comparison to conventional natural gas.

Methane emissions

(full life-cycle, well site to consumer), shown chronologically by date of publication (% of life-time production of well)

	Conventional gas	Shale gas
EPA (1996, through 2010)	1.1 %	-----
Hayhoe et al. (2002)	3.8 %	-----
Jamarillo et al. (2007)	1.0 %	-----

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Good agreement, with largely independent data sources

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Clearly too low, based on Lelieveld et al. (2005) and GAO (2010)

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50% greater emissions from shale gas, based on estimates of venting during frack-return flow back

Methane emissions

One of our major conclusions in Howarth et al. (2011): pertinent data were extremely limited, and poorly documented.

Great need for better data, conducted by researchers free of industry control and influence.

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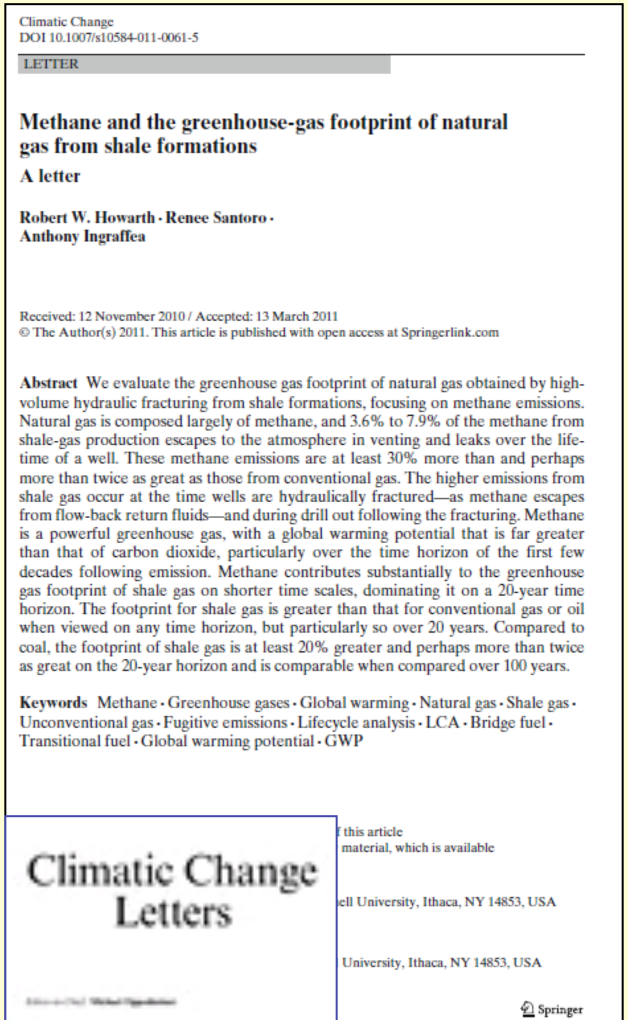
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Abstract We evaluate the greenhouse gas footprint of natural gas obtained by high-volume hydraulic fracturing from shale formations, focusing on methane emissions. Natural gas is composed largely of methane, and 3.6% to 7.9% of the methane from shale-gas production escapes to the atmosphere in venting and leaks over the 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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material, which is available

ell University, Ithaca, NY 14853, USA

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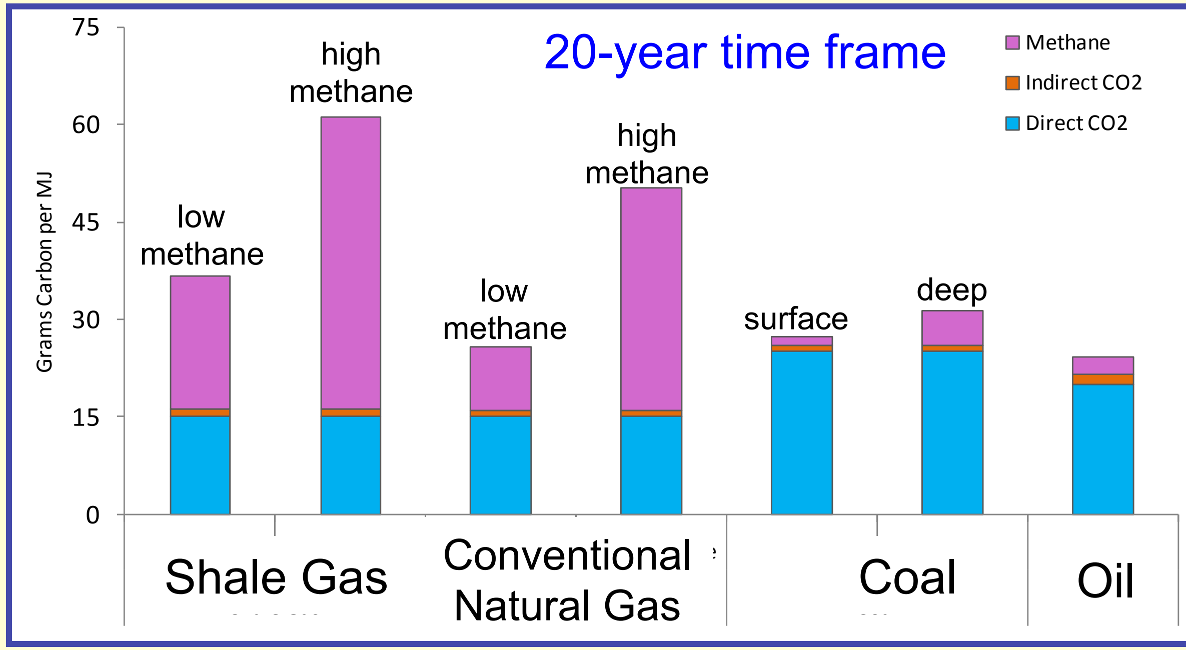
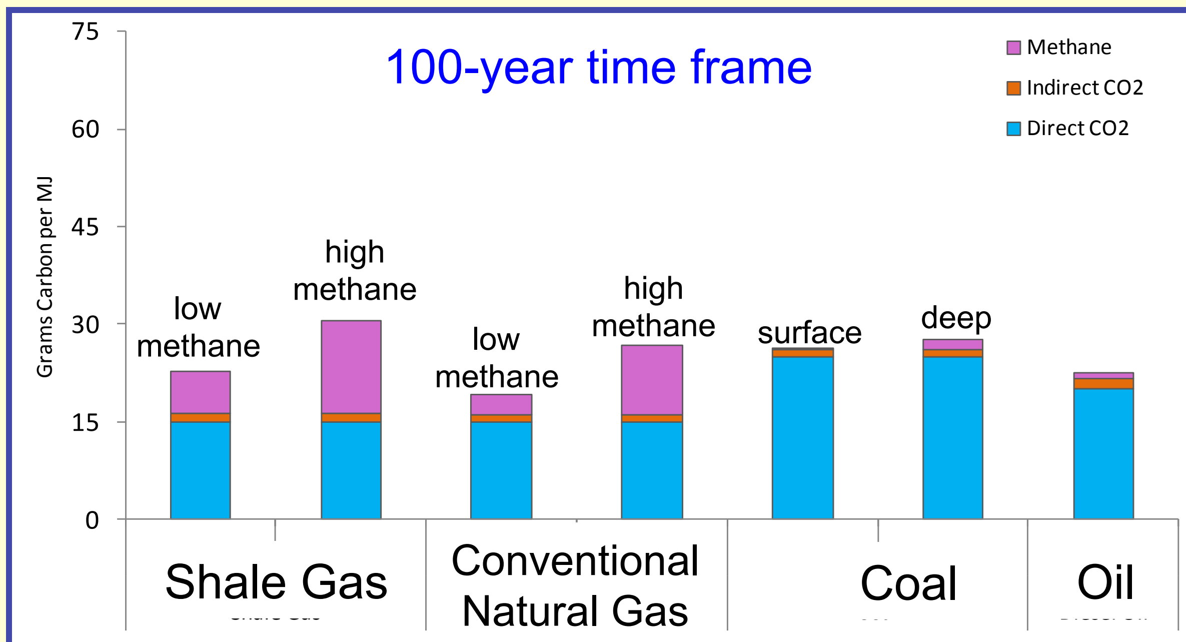
Springer

April 2011





TIME Person of the Year

People who Mattered

Mark Ruffalo, Anthony Ingraffea, Robert Howarth
By Bryan Walsh Wednesday, Dec. 14, 2011

The biggest environmental issue of 2011 — at least in the U.S. — wasn't global warming. It was hydraulic fracturing, and these three men helped represent the determined opposition to what's more commonly known as fracking. **Anthony Ingraffea** is an engineer at Cornell University who is willing to go anywhere to talk to audiences about the geologic risks of fracking, raising questions about the threats that shale gas drilling could pose to water supplies. **Robert Howarth** is his colleague at Cornell, an ecologist who produced one of the most controversial scientific studies of the year: **a paper arguing that natural gas produced by fracking may actually have a bigger greenhouse gas footprint than coal. That study — strenuously opposed by the gas industry and many of Howarth's fellow scientists — undercut shale gas's major claim as a clean fuel**. And while he's best known for his laidback hipster performances in films like *The Kids Are All Right*, Mark Ruffalo emerged as a tireless, serious activist against fracking — especially in his home state of New York.

TIME **Person** *of the* **Year**

People who Mattered

Mark Ruffalo, Anthony Ingraffea, Robert Howarth
By Bryan Walsh Wednesday, Dec. 14, 2011

Other "People who Mattered" in 2011:

Newt Gingrich, Osama bin Laden, Joe Paterno, Adele, Mitt Romney, Muammar Gaddafi, Barack Obama, Bill McKibben, Herman Cain, Rupert Murdoch, Vladimir Putin, Benjamin Netanyahu…

Methane emissions

(% of life-time production of well)

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Howarth et al. (2011)	3.8 %	5.8 %
EPA (2011)	2.5 %	3.9 %
Venkatesh et al. (2011)	2.2 %	----
Jiang et al. (2011)	----	2.0 %
Stephenson et al. (2011)	0.5 %	0.7 %
Hultman et al. (2011)	2.3 %	3.8 %
Burnham et al. (2011)	2.6 %	1.9 %
Cathles et al. (2012)	1.8 %	1.8%

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Many things to critique here….

But fundamentally, these are all just reinterpretations of the same pretty limited data set.

Methane emission estimates:

	Upstream (well site)	Downstream (storage, distribution, etc.)	Total
Hayhoe et al. (2002), conventional	1.3 %	2.5 %	3.8 %
EPA (2010), US average for 2009	0.16 %	0.9 %	1.1 %
Howarth et al. (2011), US average	1.7 %	2.5 %	4.2 %
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Petron et al. (2012), Colorado field	4.0 %	------	-----
EPA (2013), US average for 2009	0.88 %	0.9 %	1.8 %
Karion et al. (2013), Utah field	9.0 %	------	-----
Allen et al. (2013), US average	0.42 %	------	-----
Miller et al. (2013), US average	-----	------	> 3.6 %
Brandt et al. (2014), US average	-----	------	5.4 %
Schneising et al. (2014), average shale gas	9.6 %	_____	_____

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First re-analysis by EPA since 1996

Re-analyzed again, under pressure from industry, and ignoring Petron et al. (2012)

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Low-end, best-case estimate from Howarth et al. (2011) for US average for 2009 = 0.5%

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Range for shale gas in Howarth et al. (2011) = 2.2 % to 4.3%

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[illegible]	[illegible]		-----
[illegible]	[illegible]		~~1.8 %~~
[illegible]	[illegible]		-----
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Miller et al. (2013) PNAS national analysis for methane from all sources, 2007 – 2008, based on all monitoring data on methane in atmosphere (12,694 observations). EPA (2013) estimate at least 2-X too low…

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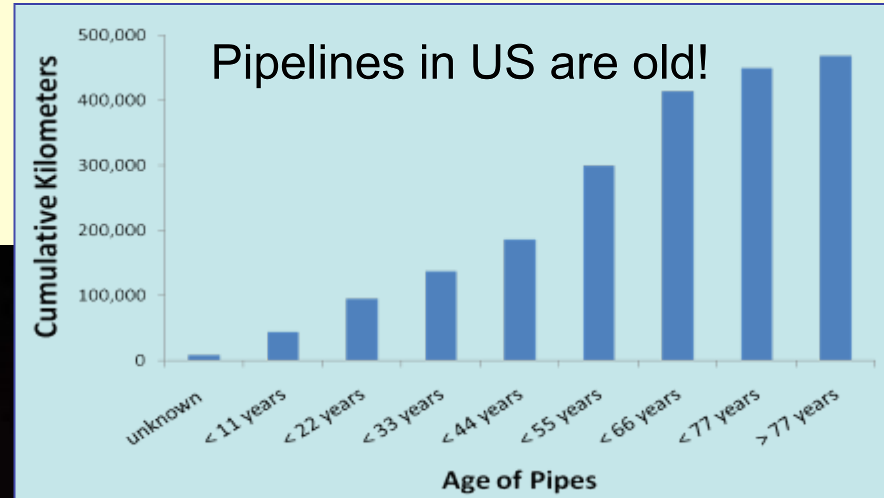
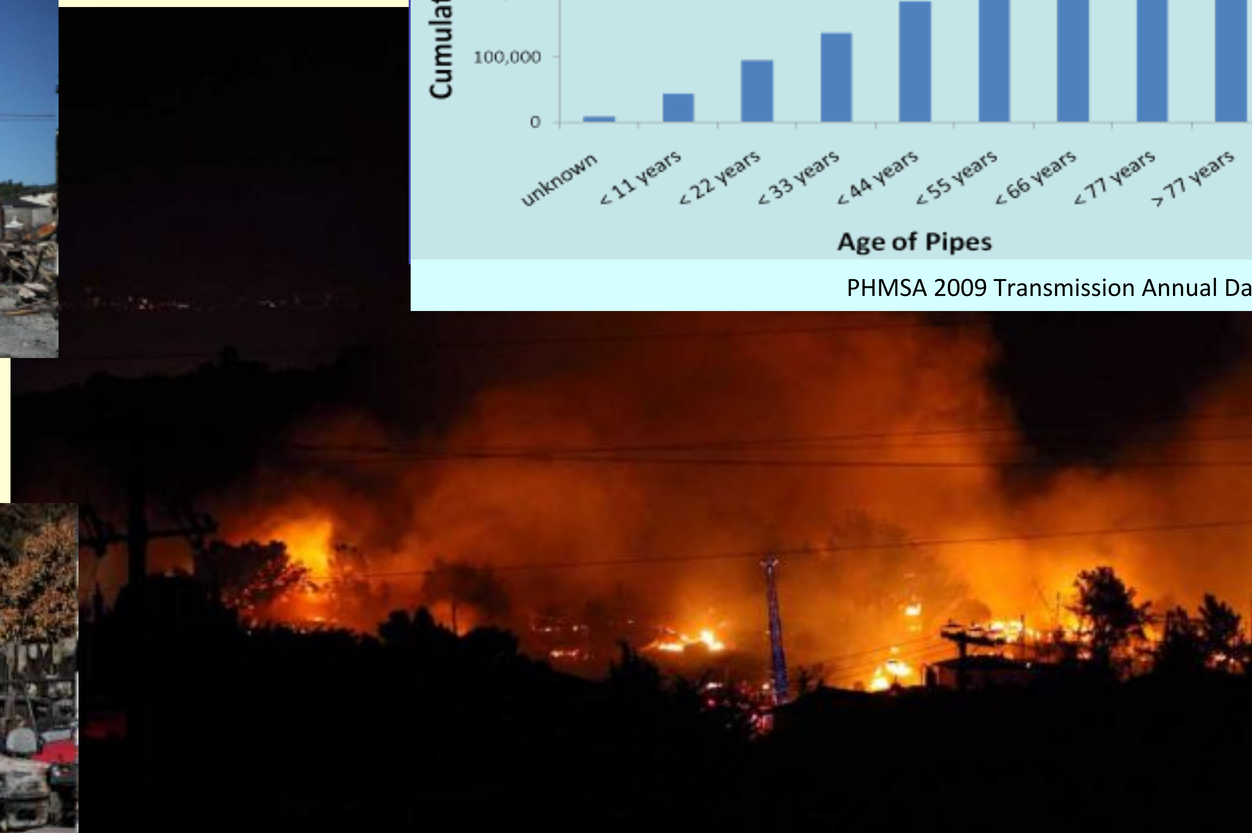
Bruce Gellerman, “Living on Earth,” Jan. 13, 2012, based on work of Nathan Phillips

http://www.loe.org/shows/segments.html?programID=12-P13-00002&segmentID=3

Pipeline accidents and explosions happen, due to large leaks….
….. small leaks are ubiquitous.

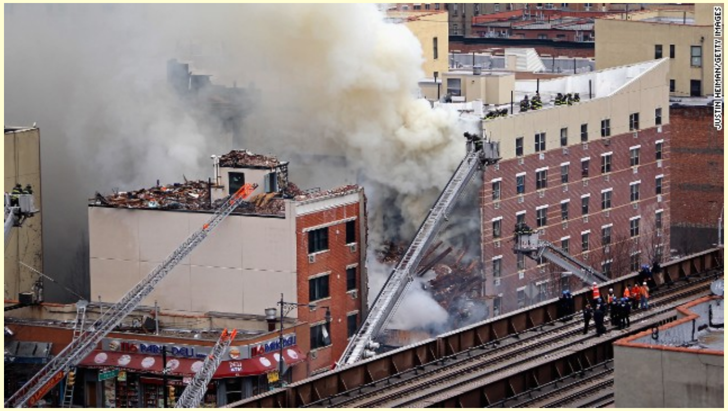


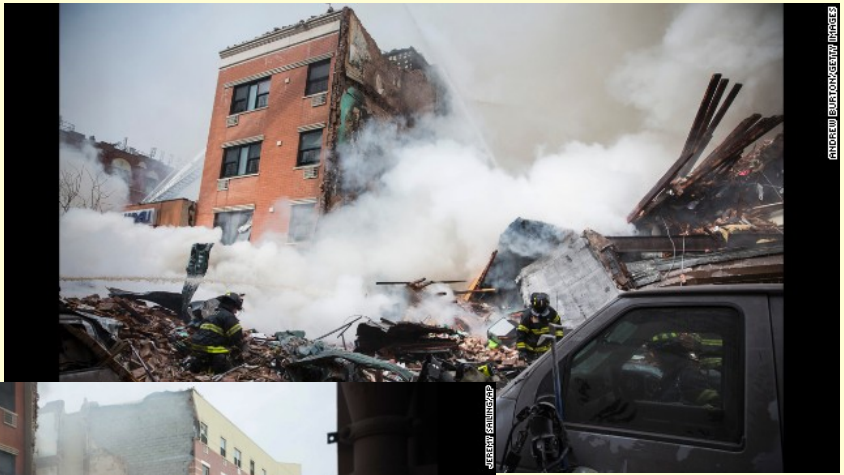
PHMSA 2009 Transmission Annual Data



Flames consume homes during a massive fire in a residential neighborhood September 9, 2010 in San Bruno, California. (Photo by Ezra Shaw/Getty Images)

March 12, 2014 – 7 killed in explosion in NYC
(127-year old gas mains)





Methane emission estimates:

	Upstream (well site)	Downstream (storage, distribution, etc.)	Total
Hayhoe et al. (2002), conventional	1.3 %	2.5 %	3.8 %
EPA (2010), US average for 2009	0.16 %	0.9 %	1.1 %
Howarth et al. (2011), US average	1.7 %	2.5 %	4.2 %
conventional gas	1.3 %	2.5 %	3.8 %
shale	[illegible]	[illegible]	5.8 %
EPA (2011), US			2.7 %
conv			2.5 %
shale	[illegible]	[illegible]	3. 9 %
Petron et al. (2012), Colorado field	4.0 %	------	-----
EPA (2013), US average for 2009	0.88 %	0.9 %	1.8 %
Karion et al. (2013), Utah field	9.0 %	------	-----
Allen et al. (2013), US average	0.42 %	------	-----
Miller et al. (2013), US average	-----	------	> 3.6 %
Brandt et al. (2014), US average	-----	------	5.4 %
Schneising et al. (2014), average shale gas	9.6 %	_____	_____

5.4 % (+/- 1.8%) is best estimate for average US methane emissions from natural gas BEFORE the shale gas revolution

Methane emission estimates:

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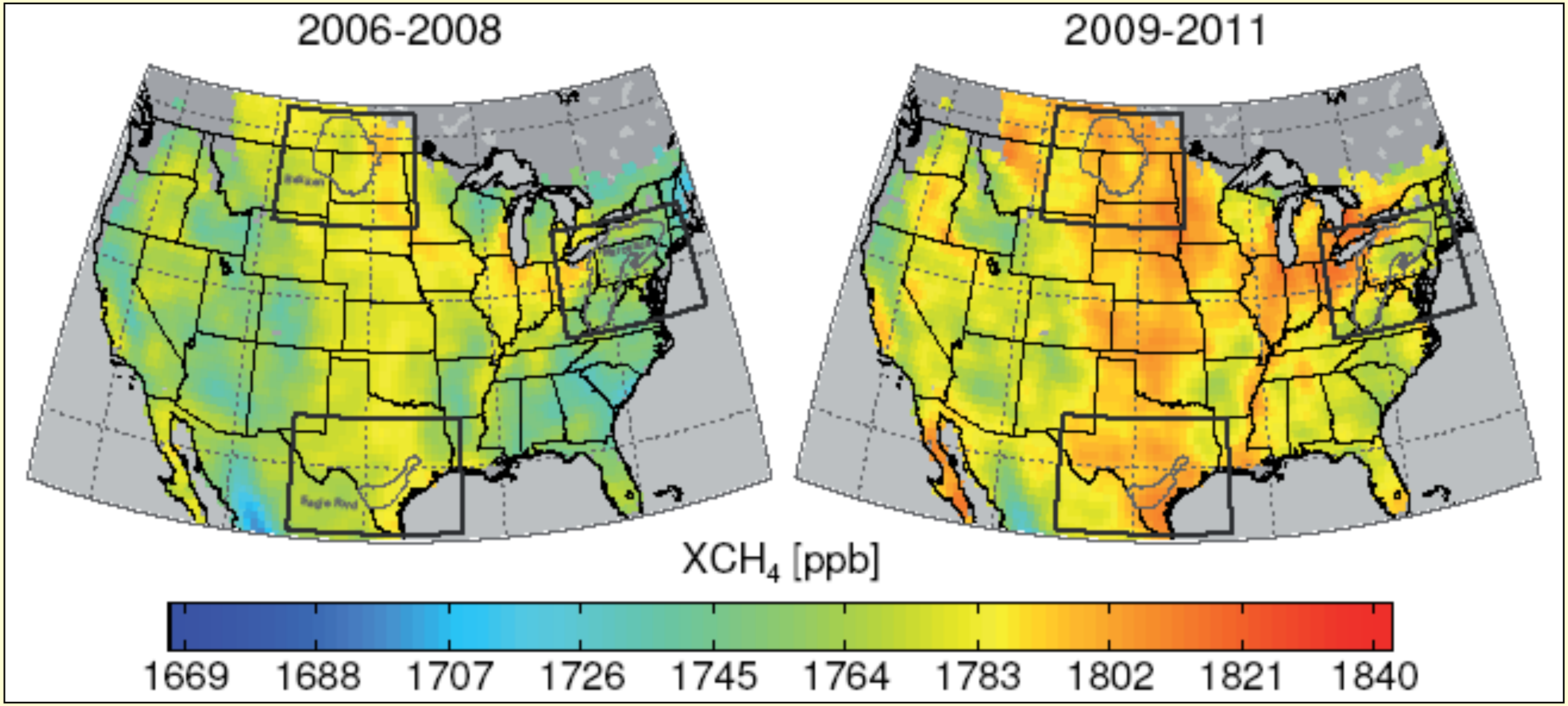
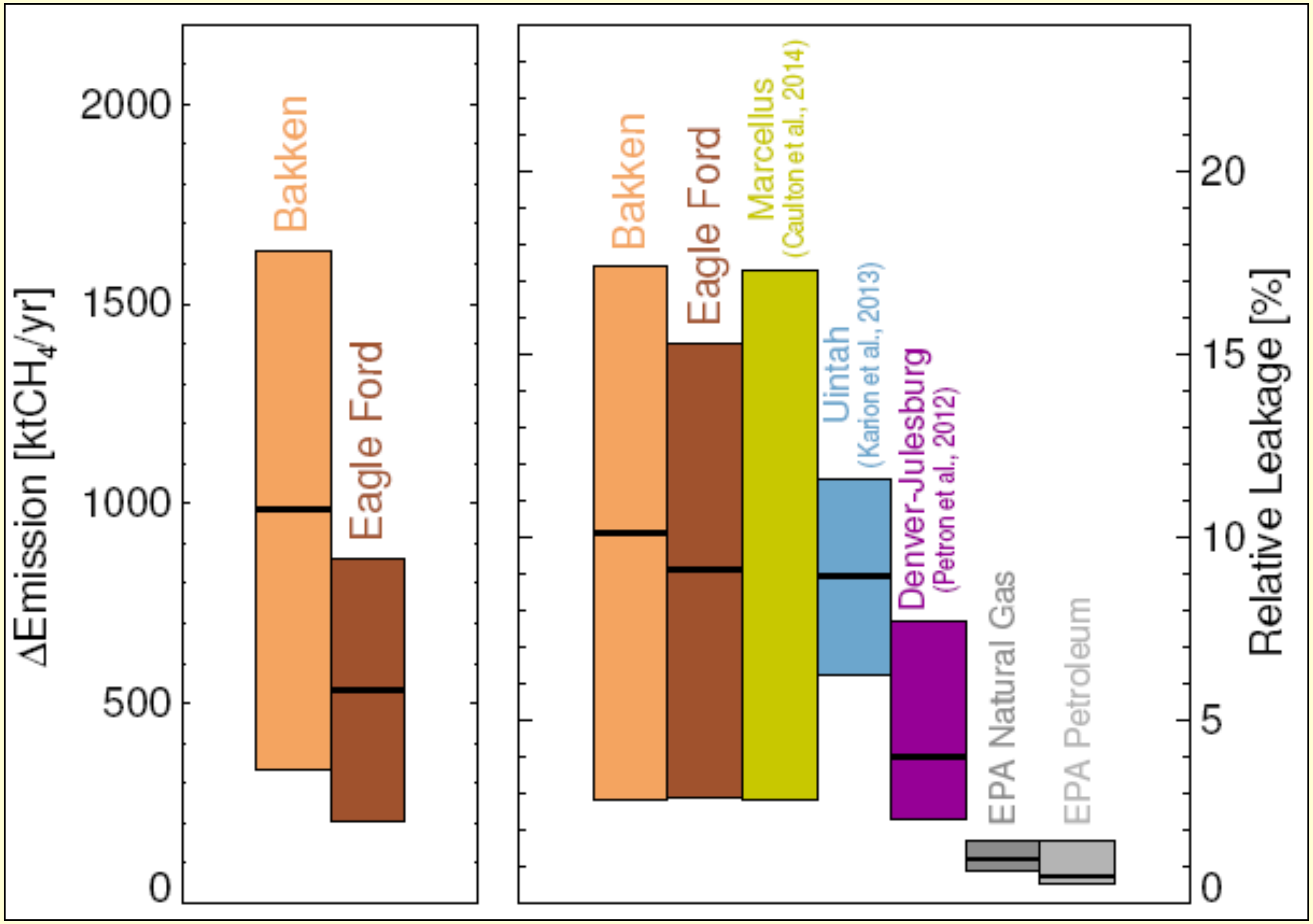
Perhaps 12% (+/- 8%) for shale gas, including downstream emissions?

Schneising et al. (2014) – "Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations"



Schneising et al. (2014) – "Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations"



Time frame for comparing methane and carbon dioxide:

• Hayhoe et al. (2002)	0 to 100 years
• Lelieveld et al. (2005)	20 & 100 years
• Jamarillo et al. (2007)	100 years
• Howarth et al. (2011)	20 & 100 years
• Hughes (2011)	20 & 100 years
• Venkatesh et al. (2011)	100 years
• Jiang et al. (2011)	100 years
• Wigley (2011)	0 to 100 years
• Fulton et al. (2011)	100 years
• Stephenson et al. (2011)	100 years
• Hultman et al. (2011)	100 years
• Skone et al. (2011)	100 years
• Burnham et al. (2011)	100 years
• Cathles et al. (2012)	100 years
• Alvarez et al. (2012)	0 to 100 years

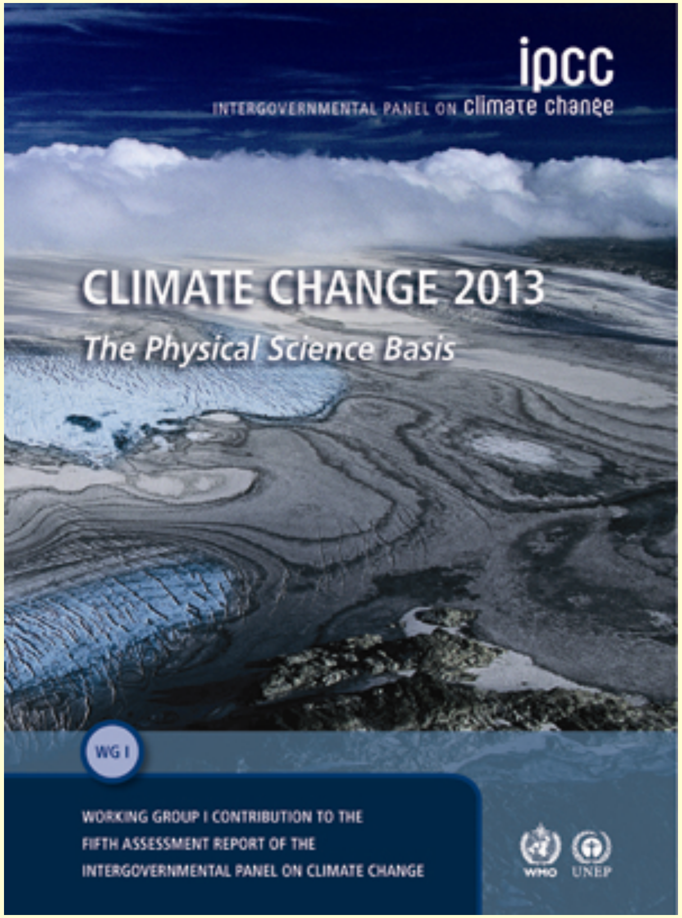
Global Warming Potential (GWP):

-- the integrated effect of radiative forcing of a greenhouse gas relative to carbon dioxide over a defined period of time

-- usually expressed in terms of total masses (ie, mass of methane relative to mass of carbon dioxide)

GWP values for methane:

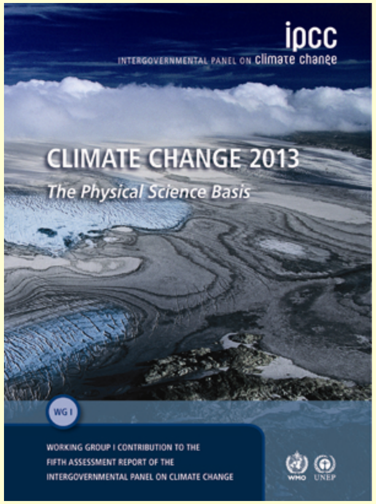
	20 year	100 year
IPCC 1996	56	21
IPCC 2007	72	25
Shindell et al. 2009	105	33
IPCC 2013	86	34

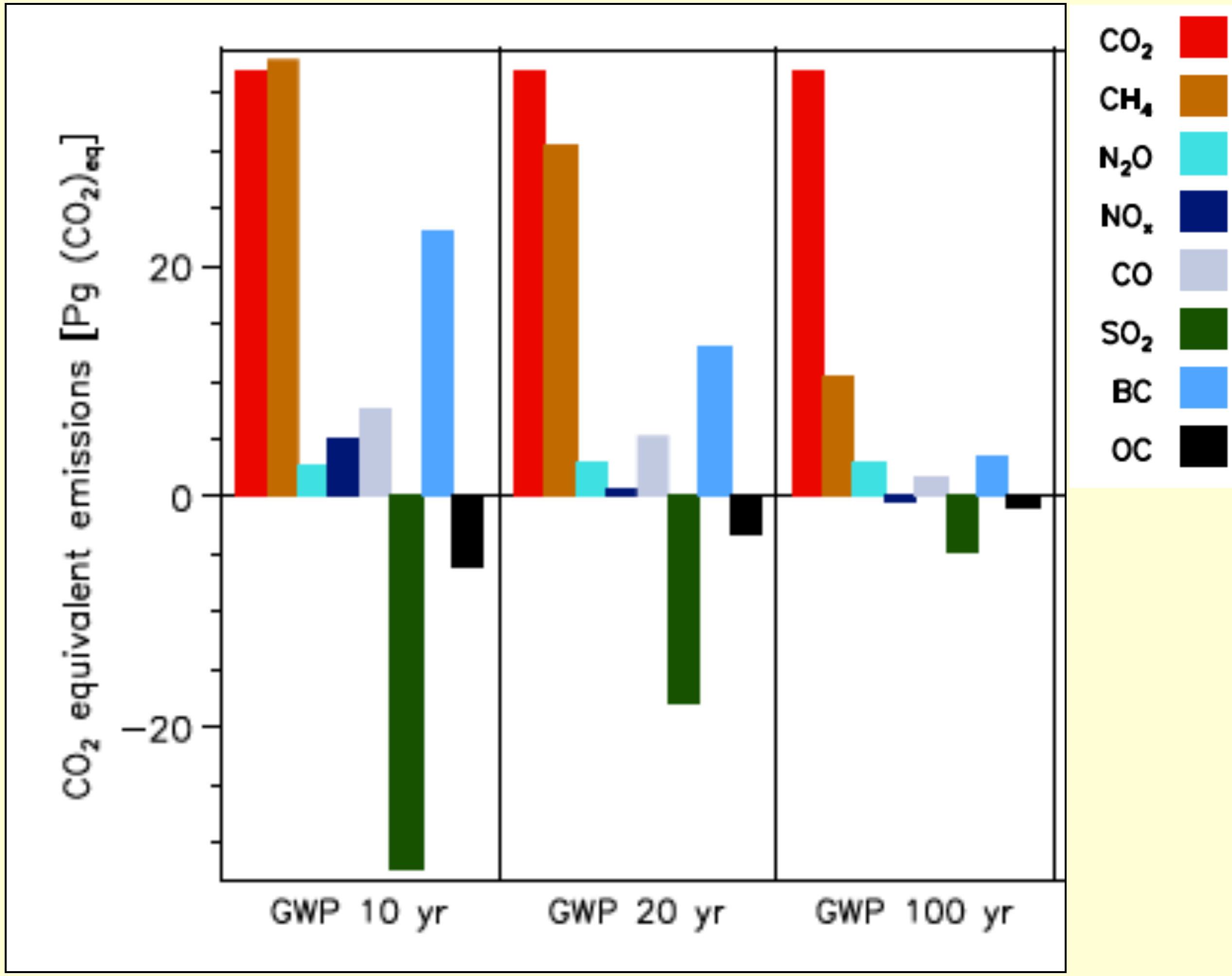


IPCC (2013): "There is no scientific argument for selecting 100 years compared with other choices."

"The choice of time horizon …. depends on the relative weight assigned to the effects at different times."

Global greenhouse gas emissions, weighted by global warming potentials

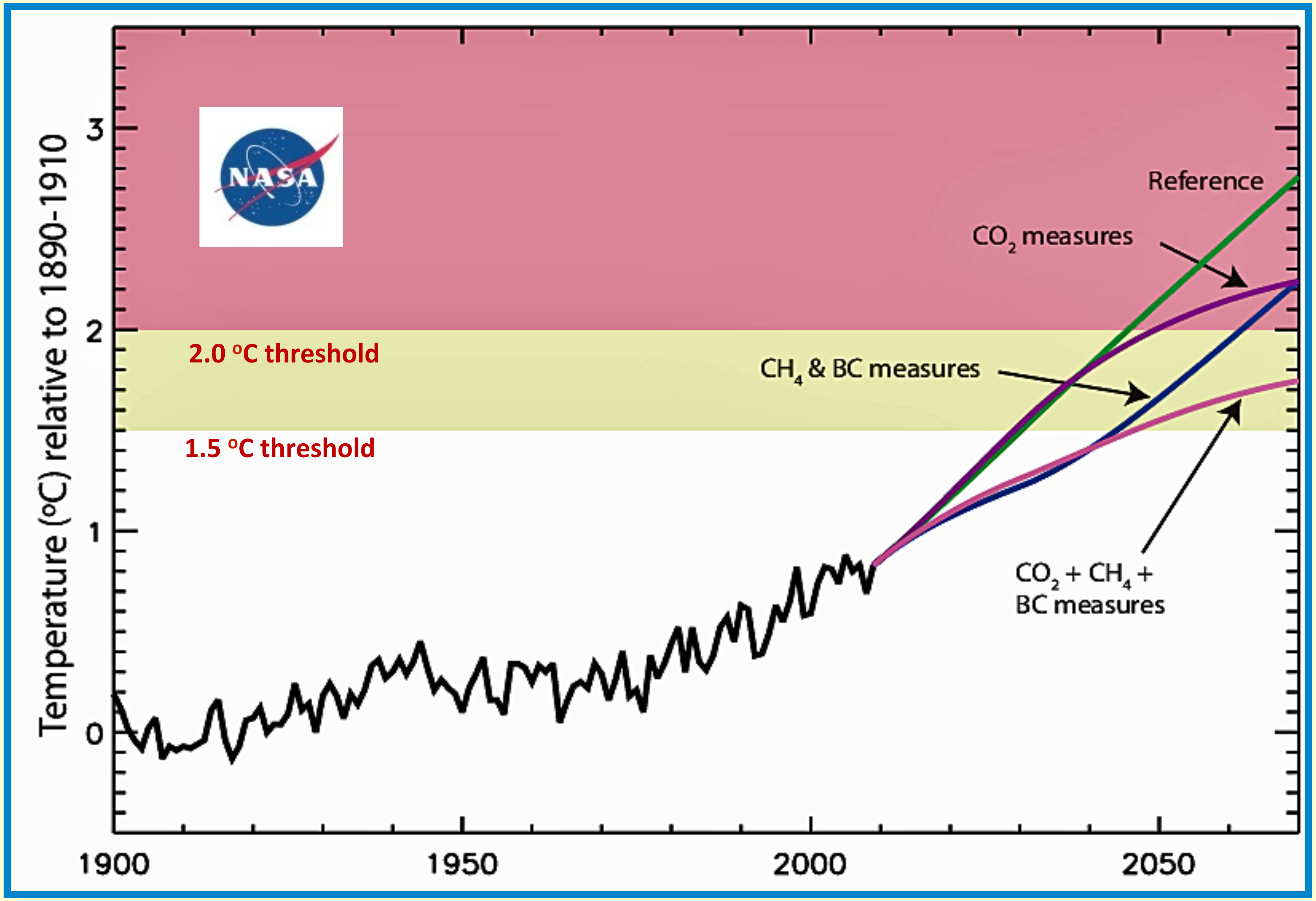




IPCC 2013

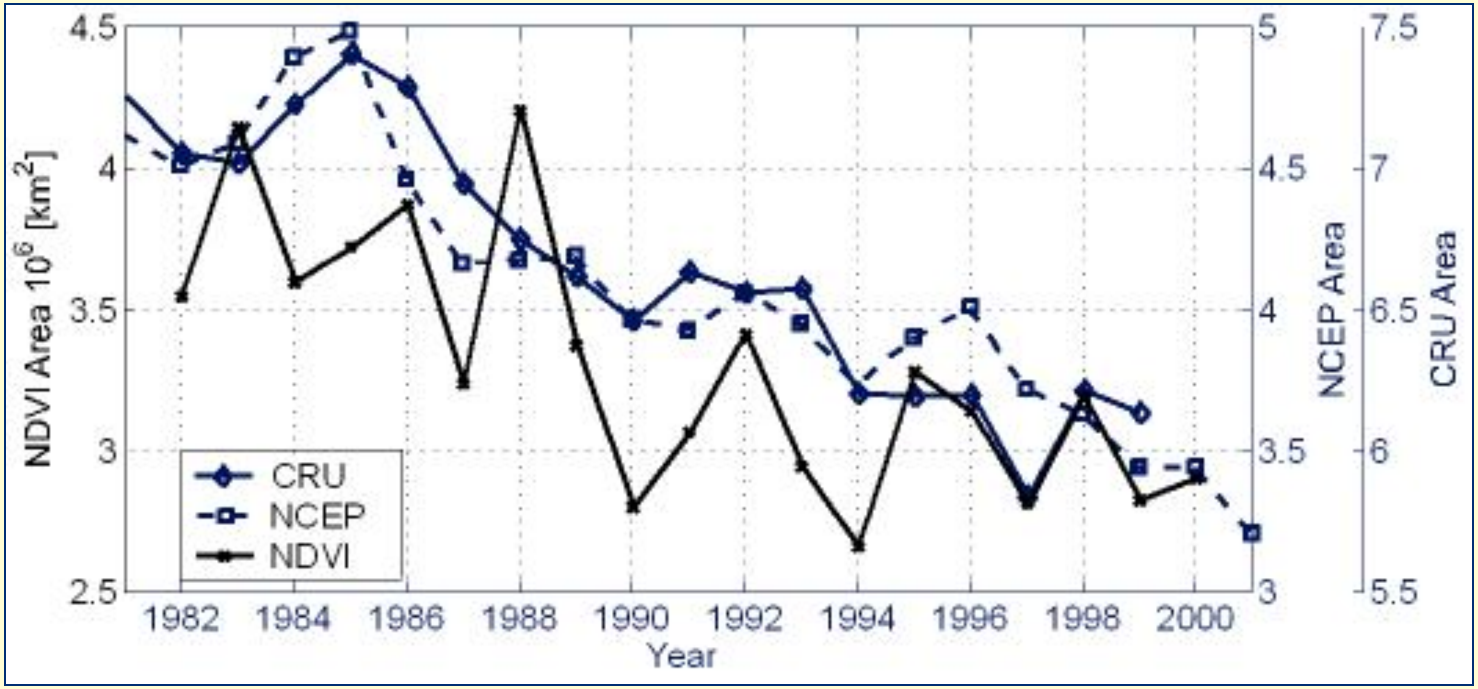
Dangerous tipping points may be only 15 to 35 years into the future.

Controlling methane is ***CRITICAL*** to the solution!



Shindell et al. 2012

The global area of tundra decreased 18% in past 20 years (Wang et al. 2004)



http://www.arctic.noaa.gov/detect/land-tundra.shtml

(downloaded June 9, 2014)

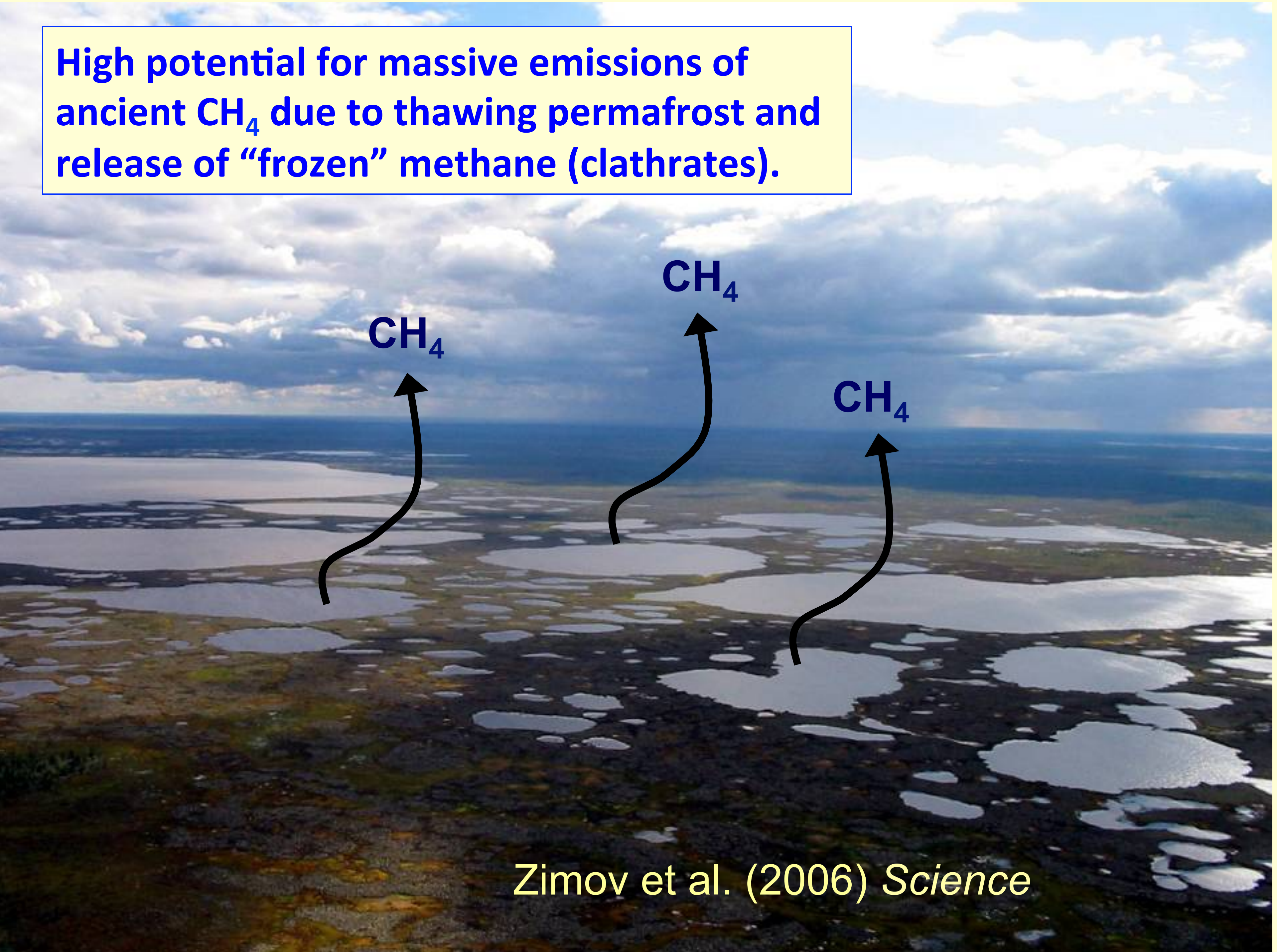
Same location in Alaska, showing transition from tundra to wetlands over the last 20 years

http://www.arctic.noaa.gov/detect/land-tundra.shtml

(downloaded June 9, 2014)

(Torre Jorgenson)

High potential for massive emissions of ancient CH_4 due to thawing permafrost and release of "frozen" methane (clathrates).



PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

Phil. Trans. R. Soc. A (2007) **365**, 1925–1954
doi:10.1098/rsta.2007.2052
Published online 18 May 2007

Climate change and trace gases

By James Hansen[1,*], Makiko Sato[1], Pushker Kharecha[1], Gary Russell[1], David W. Lea[2] and Mark Siddall[3]

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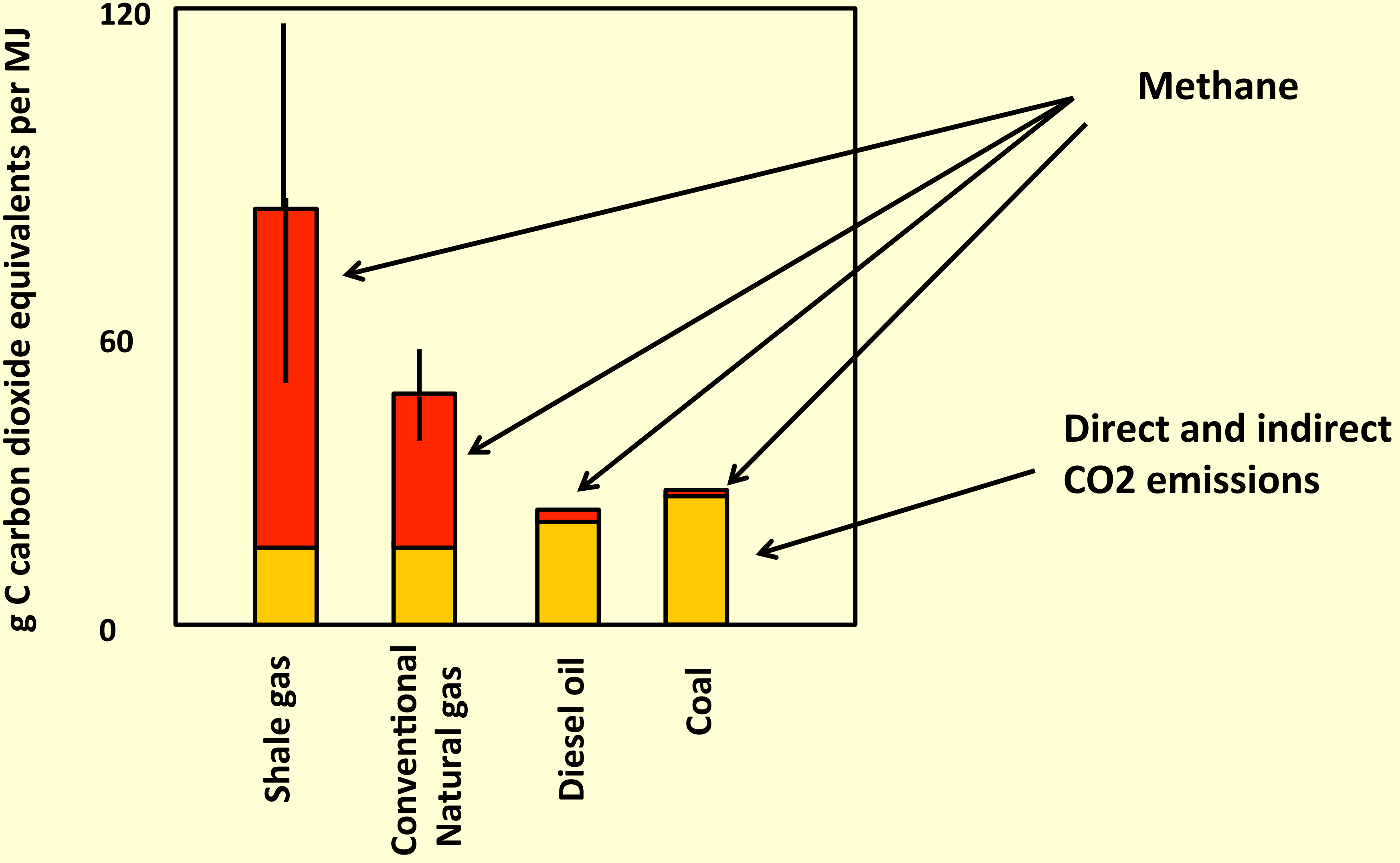
[2]*Department of Earth Science, University of California, Santa Barbara, CA 93106, USA*
[3]*Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA*

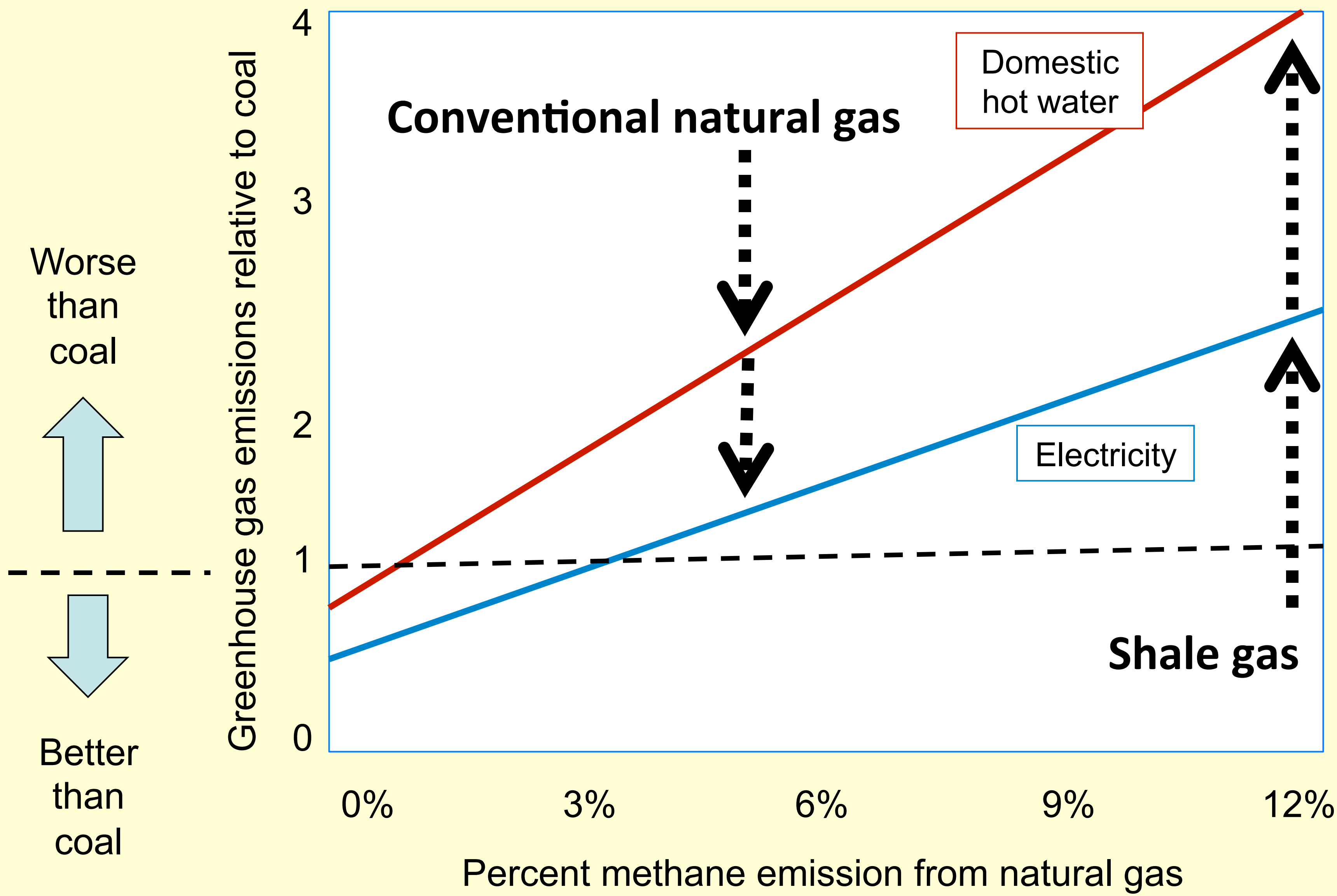
Hansen et al. (2007) suggested critical threshold in climate system, to avoid melting of natural methane hydrates, at ~ 1.8^{o} C.

Greenhouse gas footprints per unit of heat generated, with methane converted to CO2 equivalents using 20-year GWP from IPCC (2013)

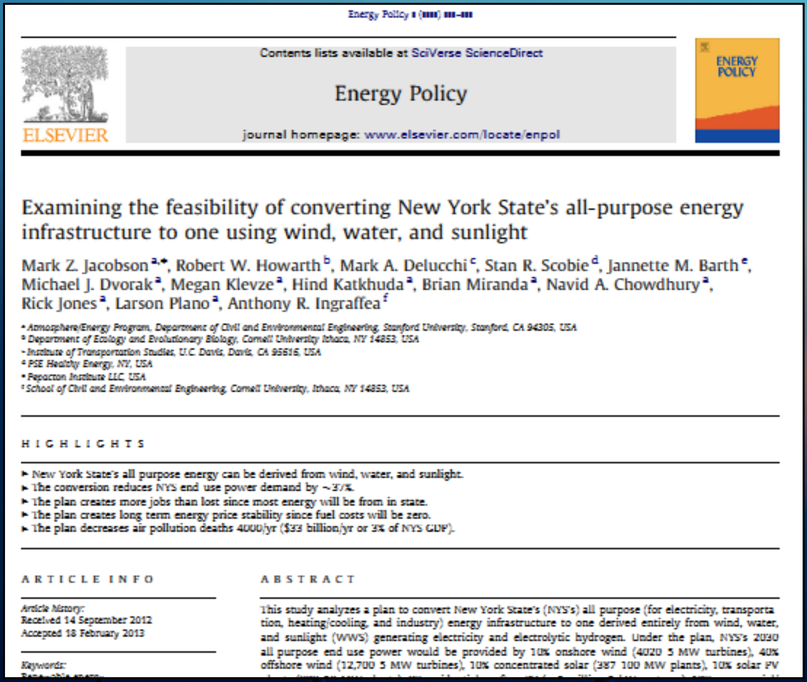


Greenhouse gas consequences for natural gas compared to coal

(compared over integrated 20-year time frame)



Powering New York and California with no fossil fuels, largely by 2030, using only current technologies



Energy Policy ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at SciVerse ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

ELSEVIER

Examining the feasibility of converting New York State's all-purpose energy infrastructure to one using wind, water, and sunlight

Mark Z. Jacobson [a,*], Robert W. Howarth [b], Mark A. Delucchi [c], Stan R. Scobie [d], Jannette M. Barth [e], Michael J. Dvorak [a], Megan Klevze [a], Hind Katkhuda [a], Brian Miranda [a], Navid A. Chowdhury [a], Rick Jones [a], Larson Plano [a], Anthony R. Ingraffea [f]

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[b] Department of Ecology and Evolutionary Biology, Cornell University Ithaca, NY 14853, USA
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[d] PSE Healthy Energy, NY, USA
[e] Pepacton Institute LLC, USA
[f] School of Civil and Environmental Engineering, Cornell University, Ithaca, NY 14853, USA

HIGHLIGHTS

- New York State's all purpose energy can be derived from wind, water, and sunlight.
- The conversion reduces NYS end use power demand by ~37%.
- The plan creates more jobs than lost since most energy will be from in state.
- The plan creates long term energy price stability since fuel costs will be zero.
- The plan decreases air pollution deaths 4000/yr ($33 billion/yr or 3% of NYS GDP).

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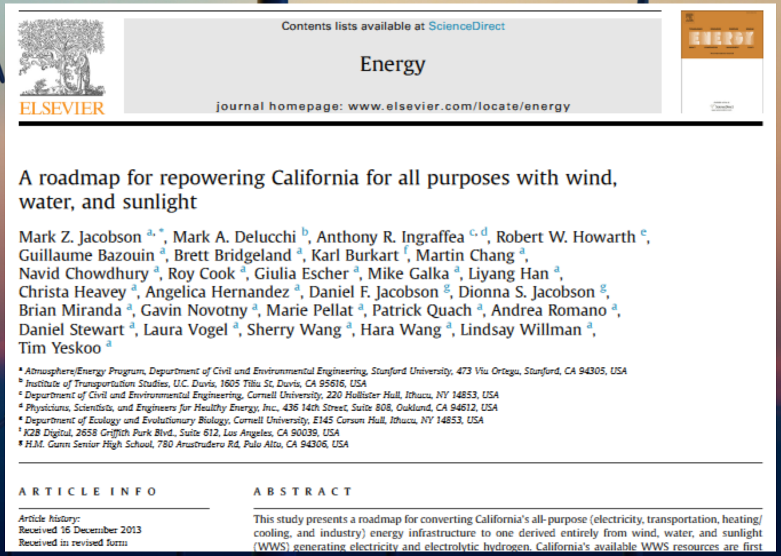
ABSTRACT

This study analyzes a plan to convert New York State's (NYS's) all purpose (for electricity, transportation, heating/cooling, and industry) energy infrastructure to one derived entirely from wind, water, and sunlight (WWS) generating electricity and electrolytic hydrogen. Under the plan, NYS's 2030 all purpose end use power would be provided by 10% onshore wind (4020 5 MW turbines), 40% offshore wind (12,700 5 MW turbines), 10% concentrated solar (387 100 MW plants), 10% solar PV



Contents lists available at ScienceDirect

Energy

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ELSEVIER

A roadmap for repowering California for all purposes with wind, water, and sunlight

Mark Z. Jacobson [a,*], Mark A. Delucchi [b], Anthony R. Ingraffea [c,d], Robert W. Howarth [e], Guillaume Bazouin [a], Brett Bridgeland [a], Karl Burkart [f], Martin Chang [a], Navid Chowdhury [a], Roy Cook [a], Giulia Escher [a], Mike Galka [a], Liyang Han [a], Christa Heavey [a], Angelica Hernandez [a], Daniel F. Jacobson [g], Dionna S. Jacobson [g], Brian Miranda [a], Gavin Novotny [a], Marie Pellat [a], Patrick Quach [a], Andrea Romano [a], Daniel Stewart [a], Laura Vogel [a], Sherry Wang [a], Hara Wang [a], Lindsay Willman [a], Tim Yeskoo [a]

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[c] Department of Civil and Environmental Engineering, Cornell University, 220 Hollister Hall, Ithaca, NY 14853, USA
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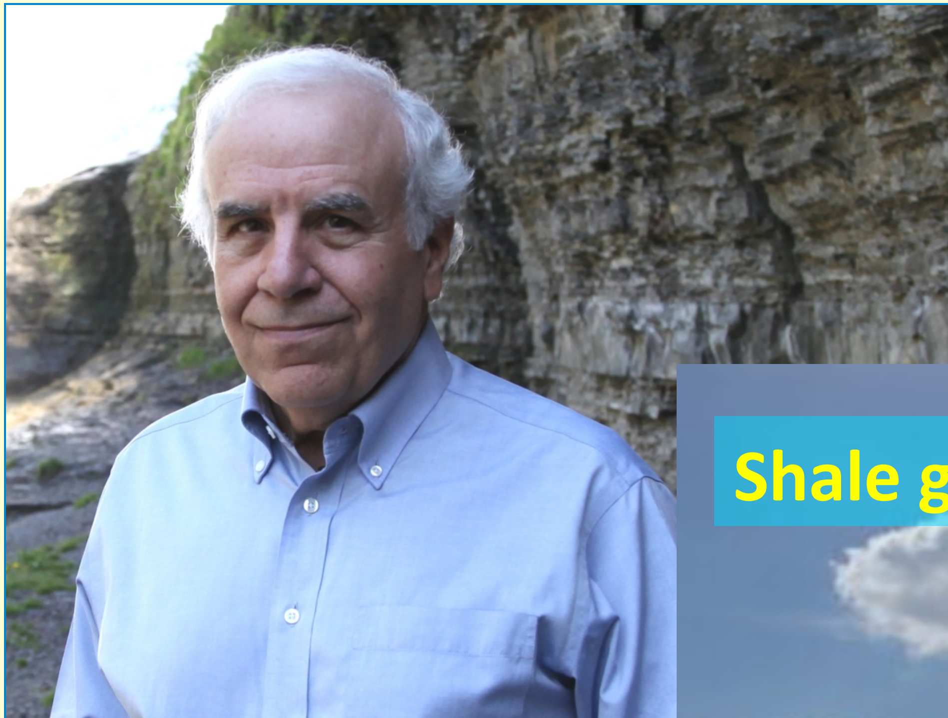
ABSTRACT

This study presents a roadmap for converting California's all-purpose (electricity, transportation, heating/cooling, and industry) energy infrastructure to one derived entirely from wind, water, and sunlight (WWS) generating electricity and electrolytic hydrogen. California's available WWS resources are first

Cornell University
College of Agriculture and Life Sciences



Funding:

- Park Foundation
- Wallace Global Fund
- Cornell University

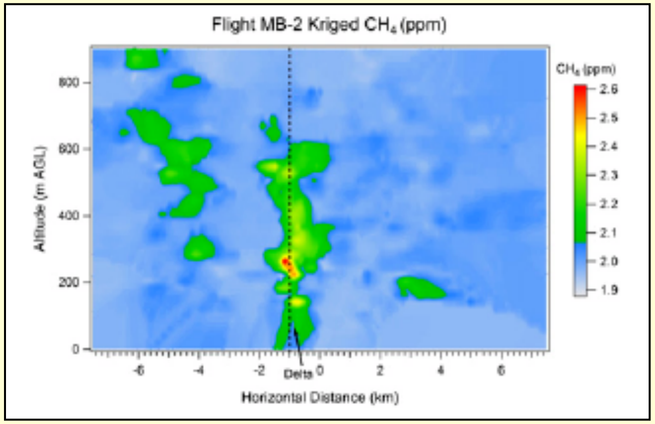
Gas pipelines in Manhattan: NY Times, March 24, 2014

http://www.nytimes.com/2014/03/24/nyregion/beneath-cities-a-decaying-tangle-of-gas-pipes.html?_r=1

Are methane emissions from shale gas greater than from conventional gas?

1)Large potential for venting from shale gas wells at time of flow-back following hydraulic fracturing. New EPA regulations address this, but allow some exceptions. And enforcement? And what about other countries?

2)Caulton et al. (PNAS, April 2014): very high methane emissions from some shale gas wells in southwestern Pennsylvania during drilling phase…. A result of going back into an area with a long history of gas and coal development?



BUT most importantly, shale gas is the future of natural gas, and natural gas in general is problematic.