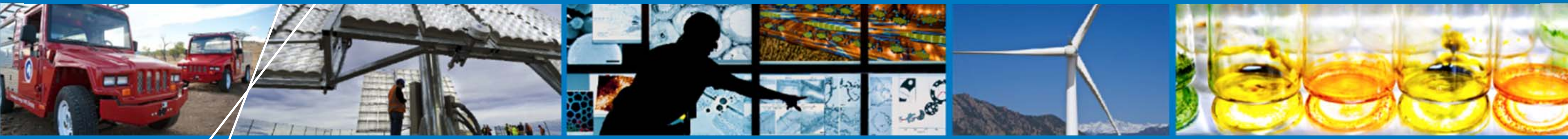
U.S. Natural Gas System Methane Emissions: State of Knowledge from LCAs, Inventories, and Atmospheric Measurements



Mechanical Engineering Seminar
Colorado State University (CSU)

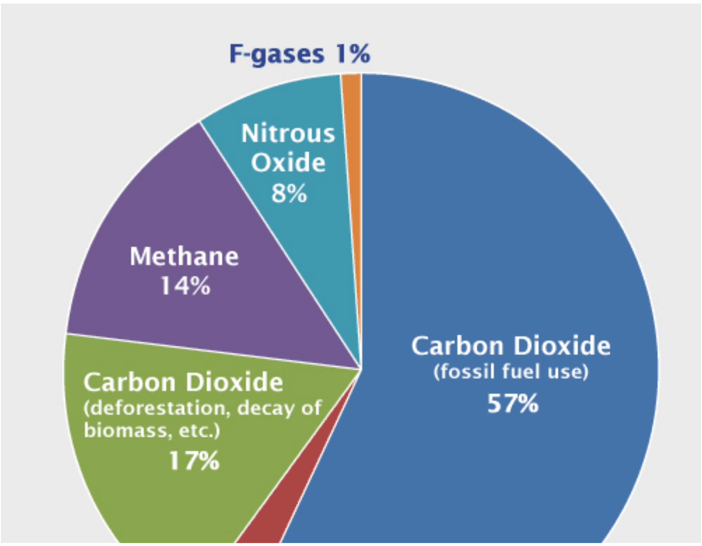
Dr. Garvin Heath
National Renewable Energy Laboratory

April 7, 2014
Fort Collins, Colorado

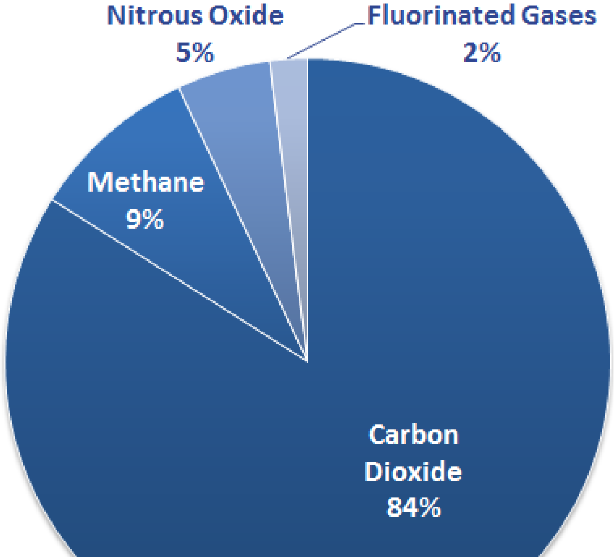
NREL/PR-6A20-61686

Methane (CH_4) Is an Important GHG

Global



USA

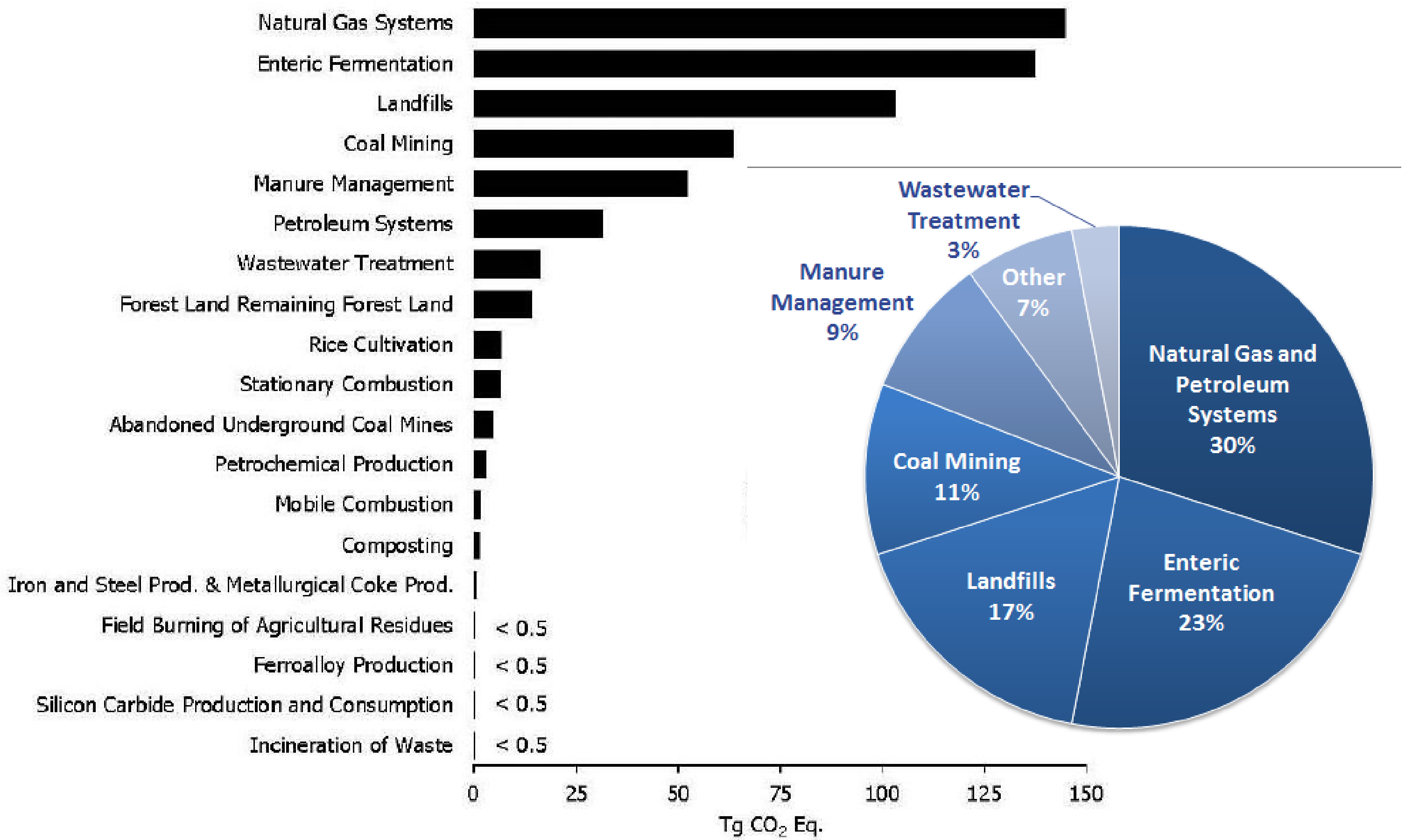


IPCC AR5 (2013): "Of note is an increase in the average growth rate of atmospheric CH_4 from ~0.5 ppb/yr during 1999–2006 to ~6 ppb/yr [+12x] from 2007 through 2011."

Note: Assumes AR3 GWPs.
Methane = 21 (AR4 = 25, AR5 = 28-30);
N_2O = 310 (AR5 = 265).

U.S. GHG Inventory: "NG system CH_4 emissions decreases 1990-2011 by 16.5 Tg CO_2e (-10%)"

2011 Methane Emissions – ~587 MMt (Tg) CO_2e



Source: EPA (2013) GHG Inventory

Note: Methane is also emitted from a number of natural sources. Wetlands are the largest natural source. Smaller sources include termites, oceans, sediments, volcanoes, and wildfires.

U.S. GHG Inventory: “NG system CH_4 emissions decreases 1990-2011 by 16.5 Tg CO_2e (-10%)”

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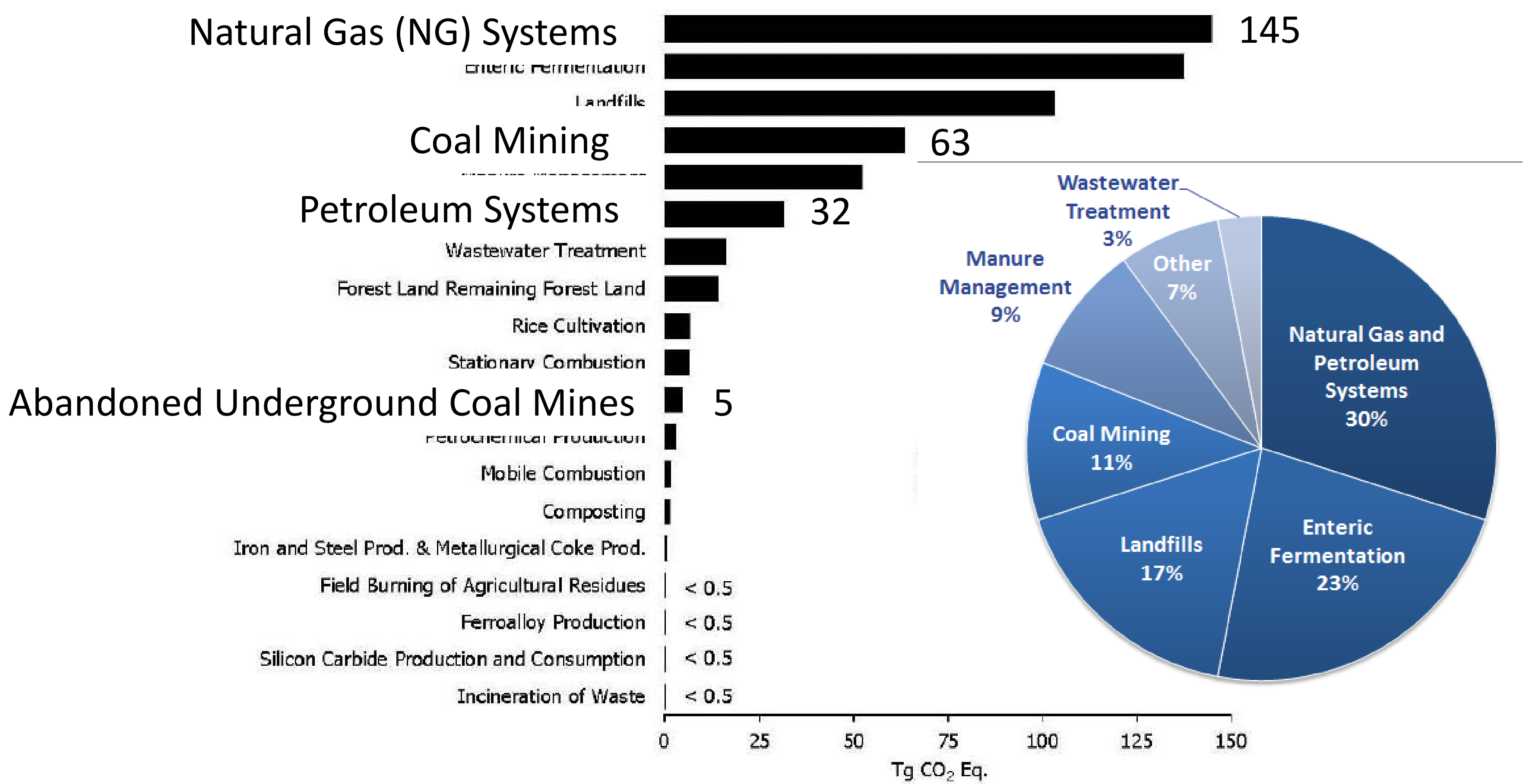
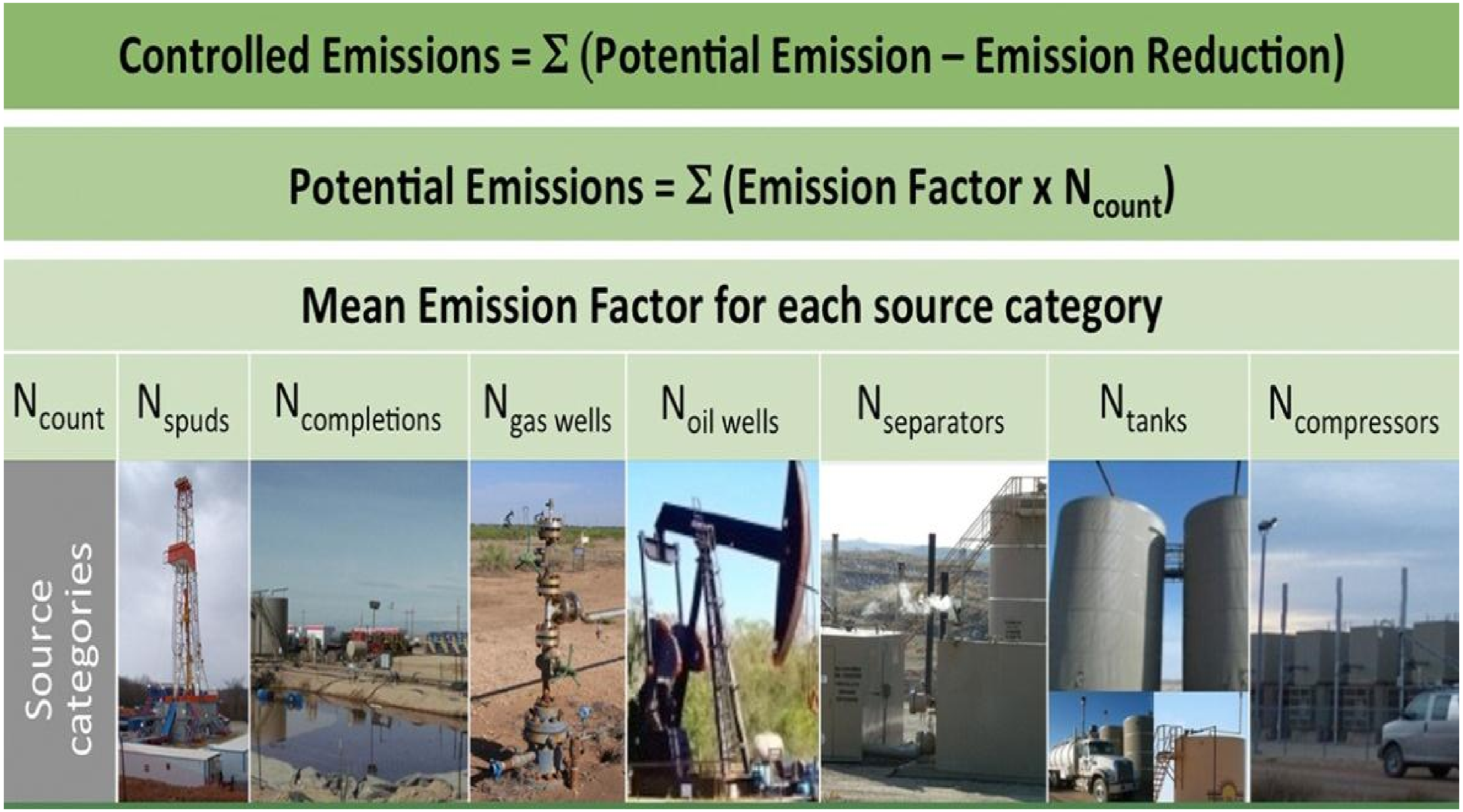


Source: EPA (2013) GHG Inventory

Note: Methane is also emitted from a number of natural sources. Wetlands are the largest natural source. Smaller sources include termites, oceans, sediments, volcanoes, and wildfires.

Inventory Method

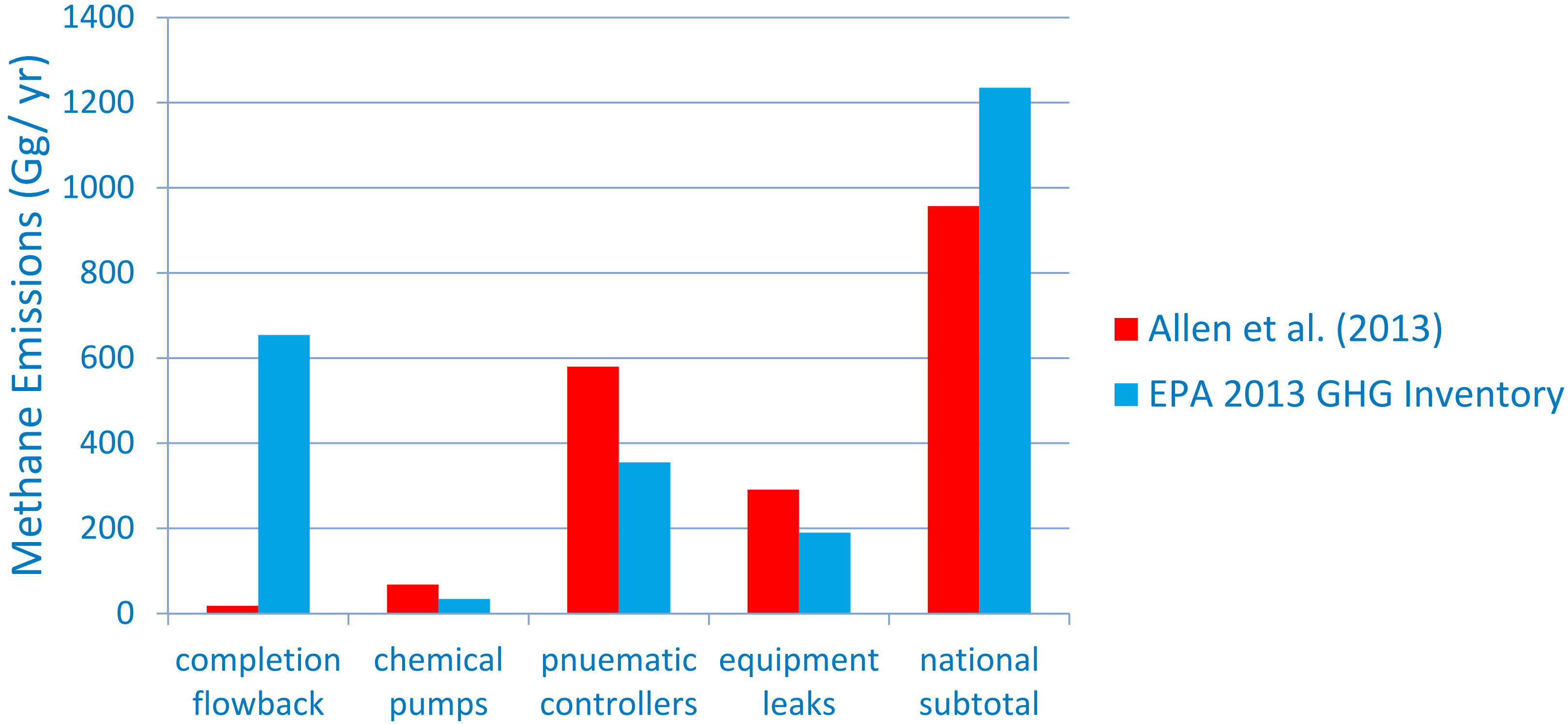


Source: NREL

- *Temporal boundary*: typically 1 year
- *Spatial boundary*: global, national, sub-national.

Challenge: Measurements ≠ Inventory

Example: Most recent component/activity measurement study: Allen et al. (2013).



Conclusion: Some sources overestimated by inventory, some underestimated, with errors compensating to result in similar national estimate.

Measurements ≠ Inventory

- **Consistently true at all scales**
- **Next slides will summarize our recent meta-analysis of 20 years of measurements.**

"Methane leaks from North American natural gas systems"
Science, February 14, 2014
Brandt, Heath, et al.

- **Organized by Novim (UCSB)**
- **Funded by: Cynthia and George Mitchell Foundation**
- **Slides in crimson credit to: Adam Brandt, Stanford University.**

Result: Inventories underestimate CH_4 emissions

- Evidence from numerous studies suggests that total U.S. CH_4 emissions are larger than those estimated by EPA inventory

- National-scale atmospheric studies[1] suggest that CH_4 emissions are 50% higher than EPA estimates (uncertainty range = 25 – 75% higher)
  - 14 million tonnes of excess CH_4 per year (range 7 to 21)[2]

- Excess CH_4 emissions from the NG industry are very likely to contribute to the total excess, but exact contribution is still uncertain.

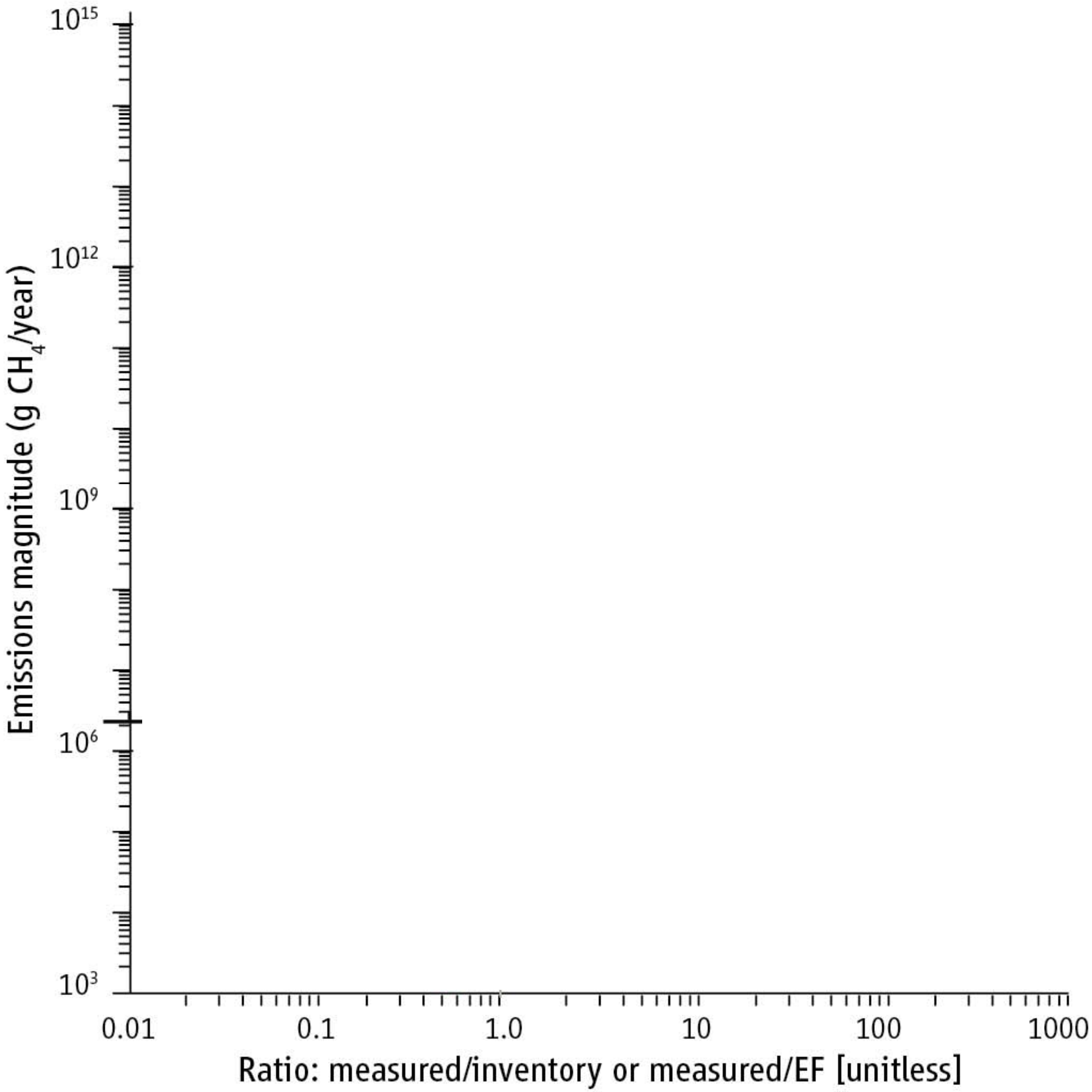
Additional notes:

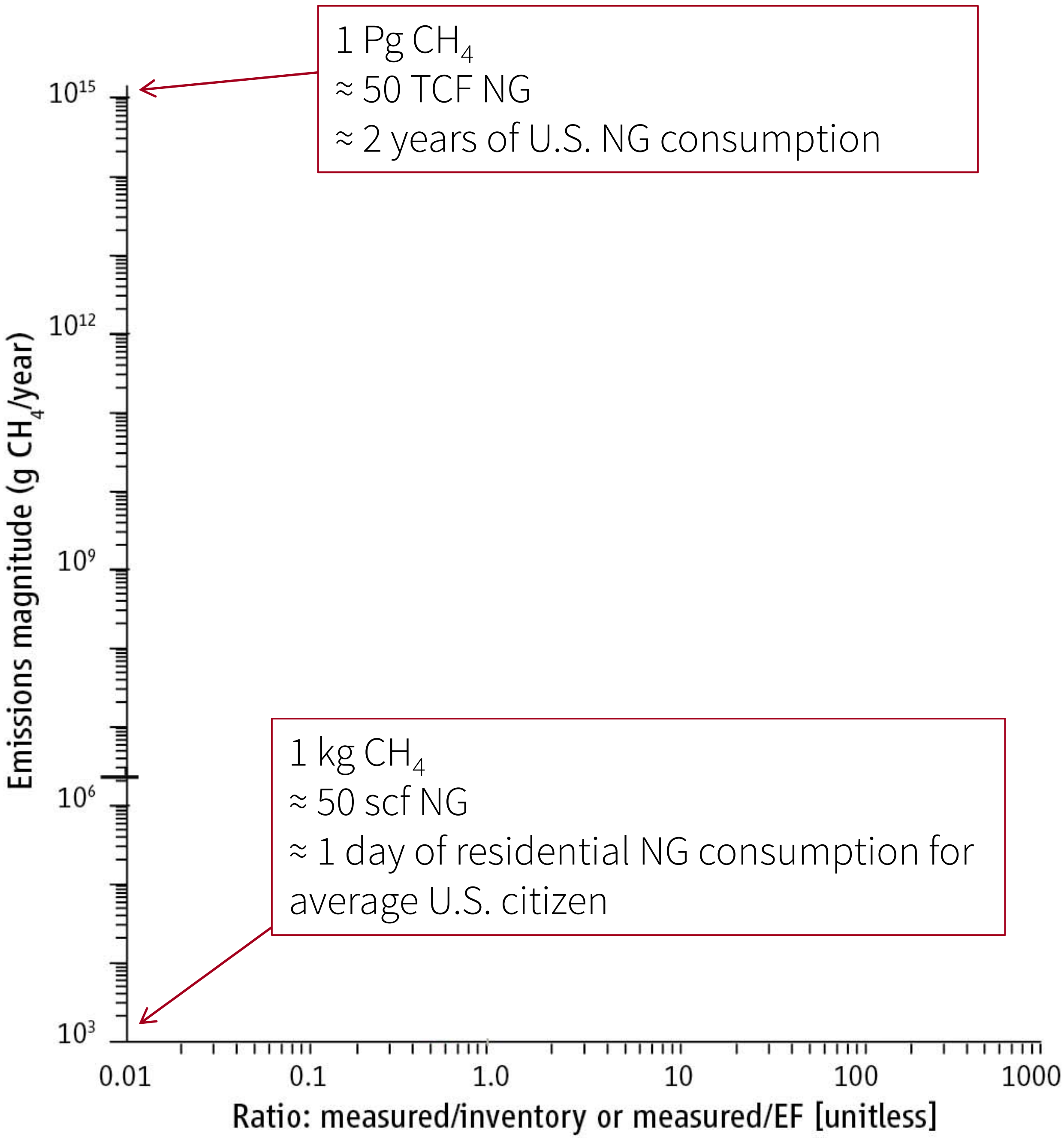
[1]National-scale studies include Kort et al. (2008), Xiao et al. (2008), Miller et al. (2013), Wang et al. (2004).

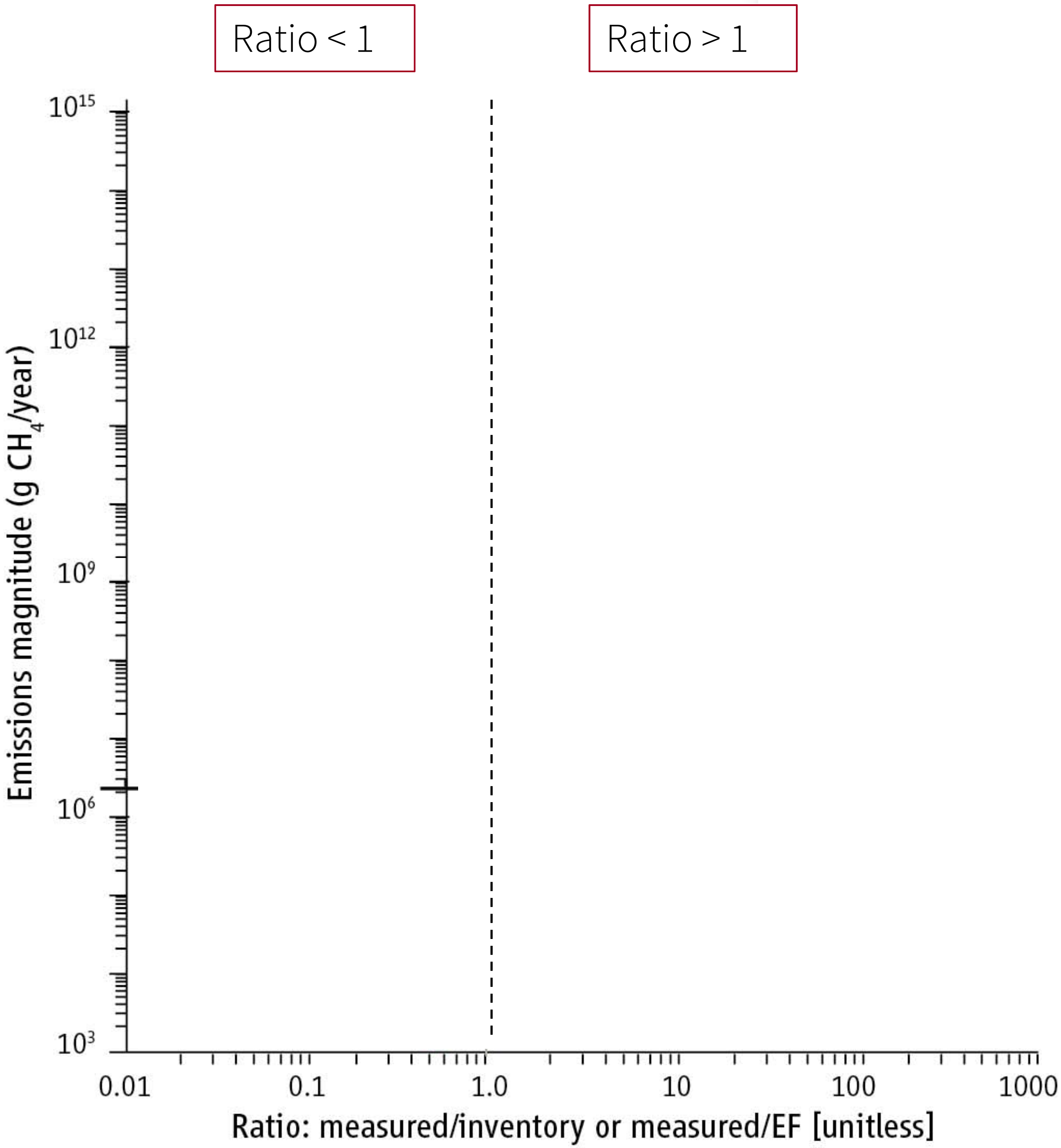
[2] ~14 Tg (+/- 7 Tg) of excess methane.

Figure 1: What is evidence for excess CH_4?

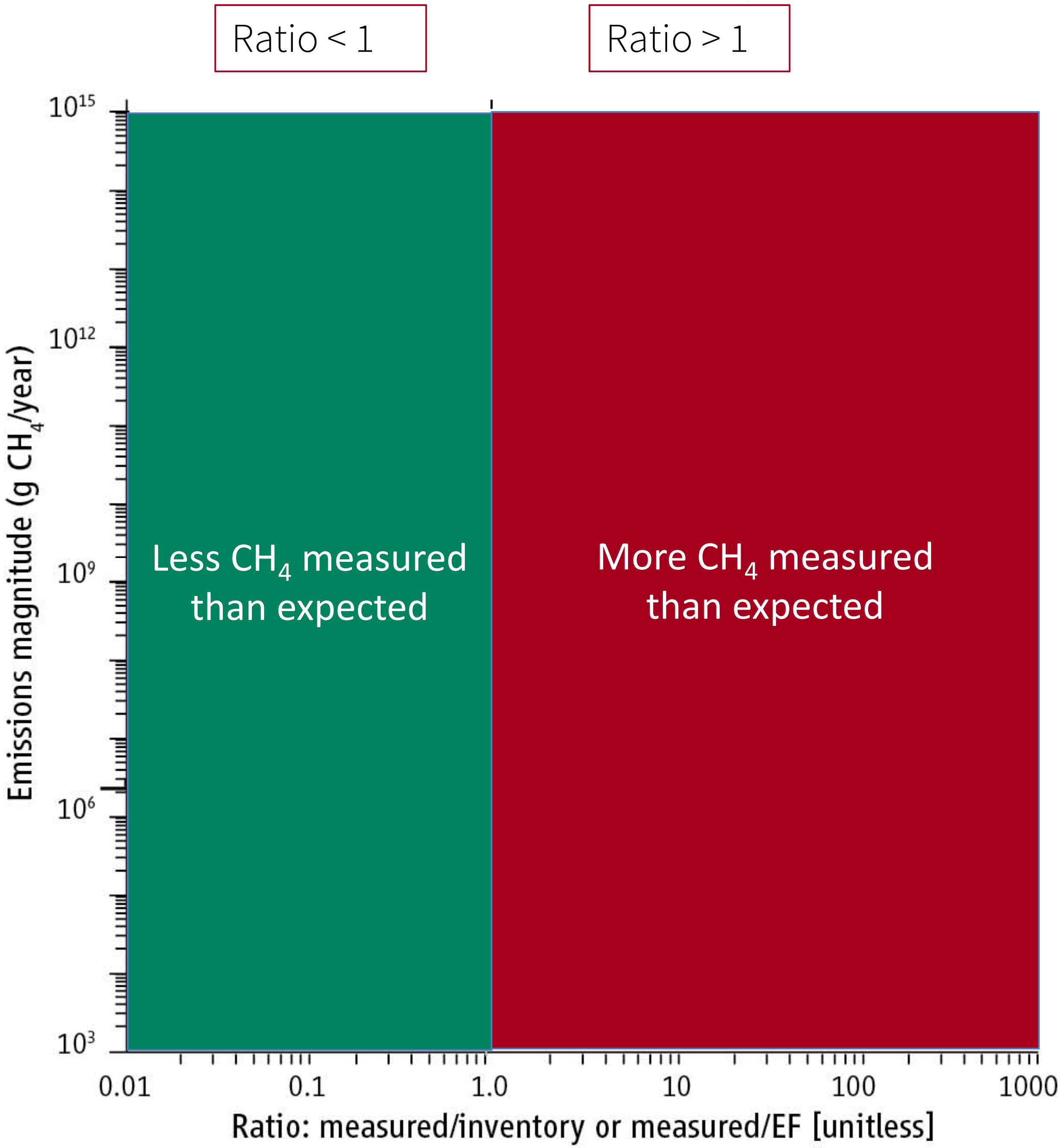
- In Figure 1, we collect and compare evidence from all studies we could locate which:
  - Generated original observations
  - Computed an emissions flux and compared to a published inventory.


Emissions magnitude (g CH4/year)
10^15
10^12
10^9
10^6
10^3
0.01
0.1
1.0
10
100
1000
Ratio: measured/inventory or measured/EF [unitless]

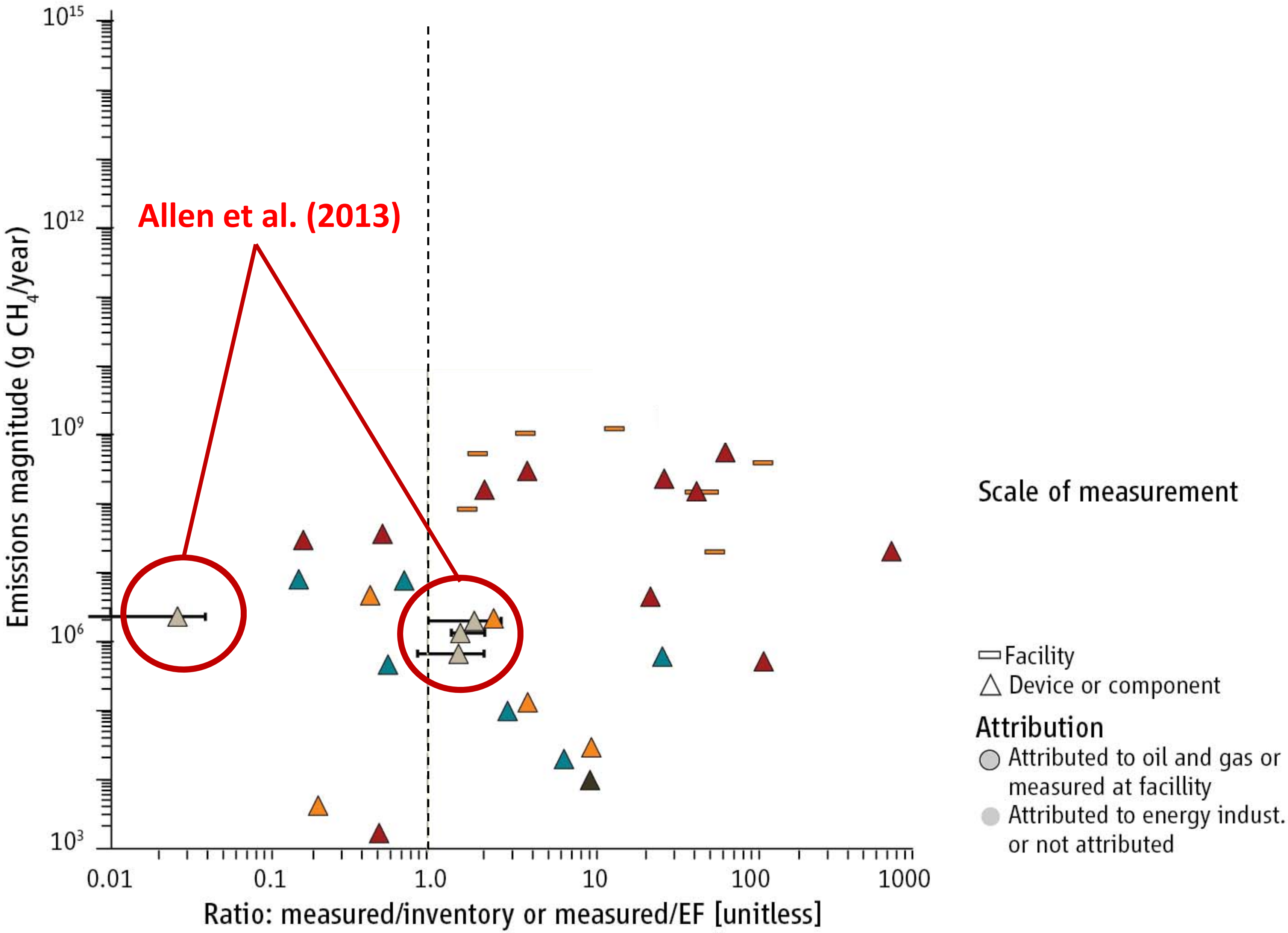

1 Pg CH_4
≈ 50 TCF NG
≈ 2 years of U.S. NG consumption
1 kg CH_4
≈ 50 scf NG
≈ 1 day of residential NG consumption for average U.S. citizen
10^{15}
10^{12}
10^{9}
10^{6}
10^{3}
Emissions magnitude (g CH_4/year)
0.01
0.1
1.0
10
100
1000
Ratio: measured/inventory or measured/EF [unitless]



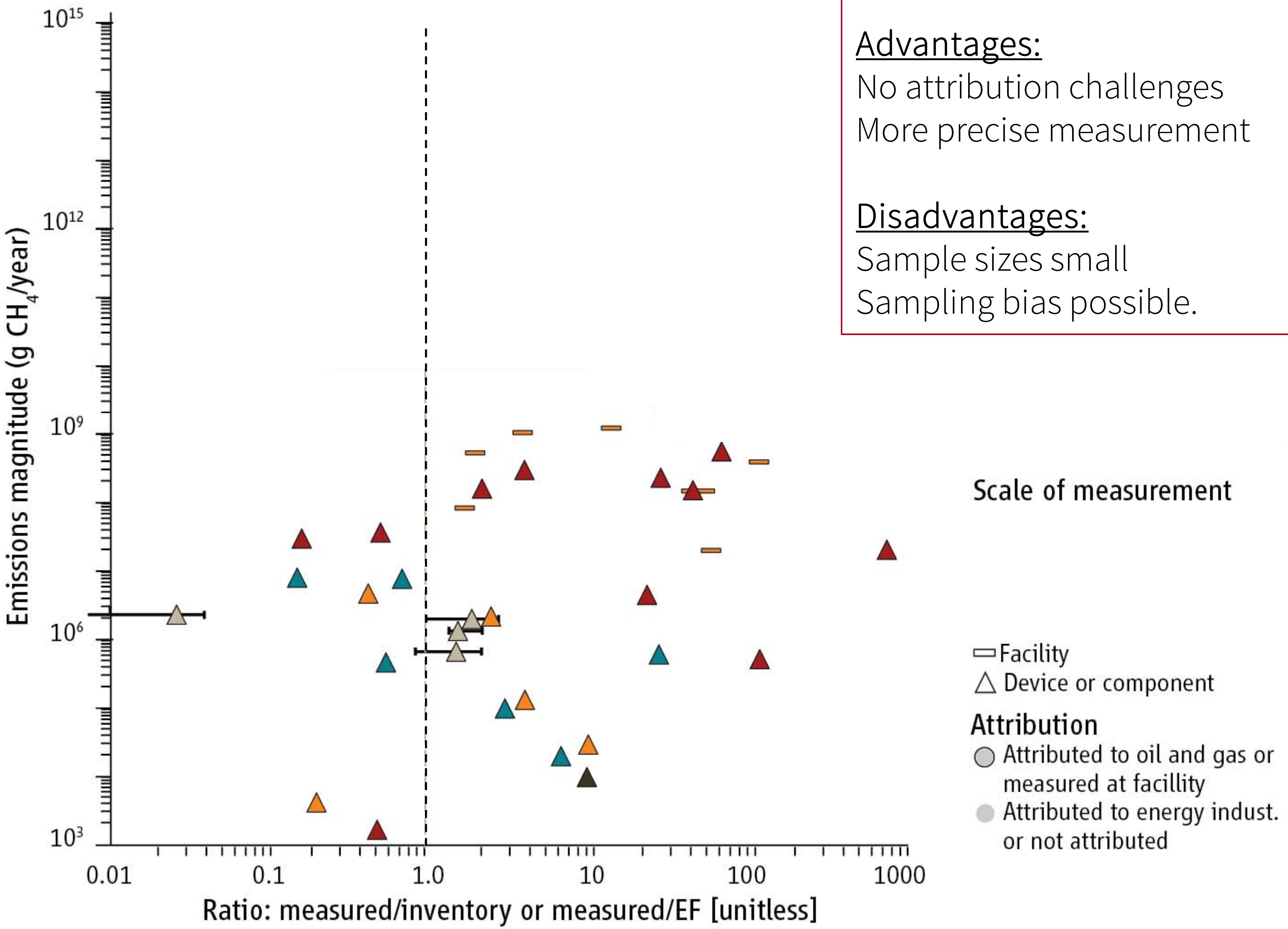
Ratio < 1
Ratio > 1
Emissions magnitude (g CH_4/year)
10^{15}
10^{12}
10^{9}
10^{6}
10^{3}
0.01
0.1
1.0
10
100
1000
Ratio: measured/inventory or measured/EF [unitless]



Ratio < 1
Ratio > 1
Less CH_4 measured than expected
More CH_4 measured than expected
10^{15}
10^{12}
10^{9}
10^{6}
10^{3}
Emissions magnitude (g CH_4/year)
0.01
0.1
1.0
10
100
1000
Ratio: measured/inventory or measured/EF [unitless]



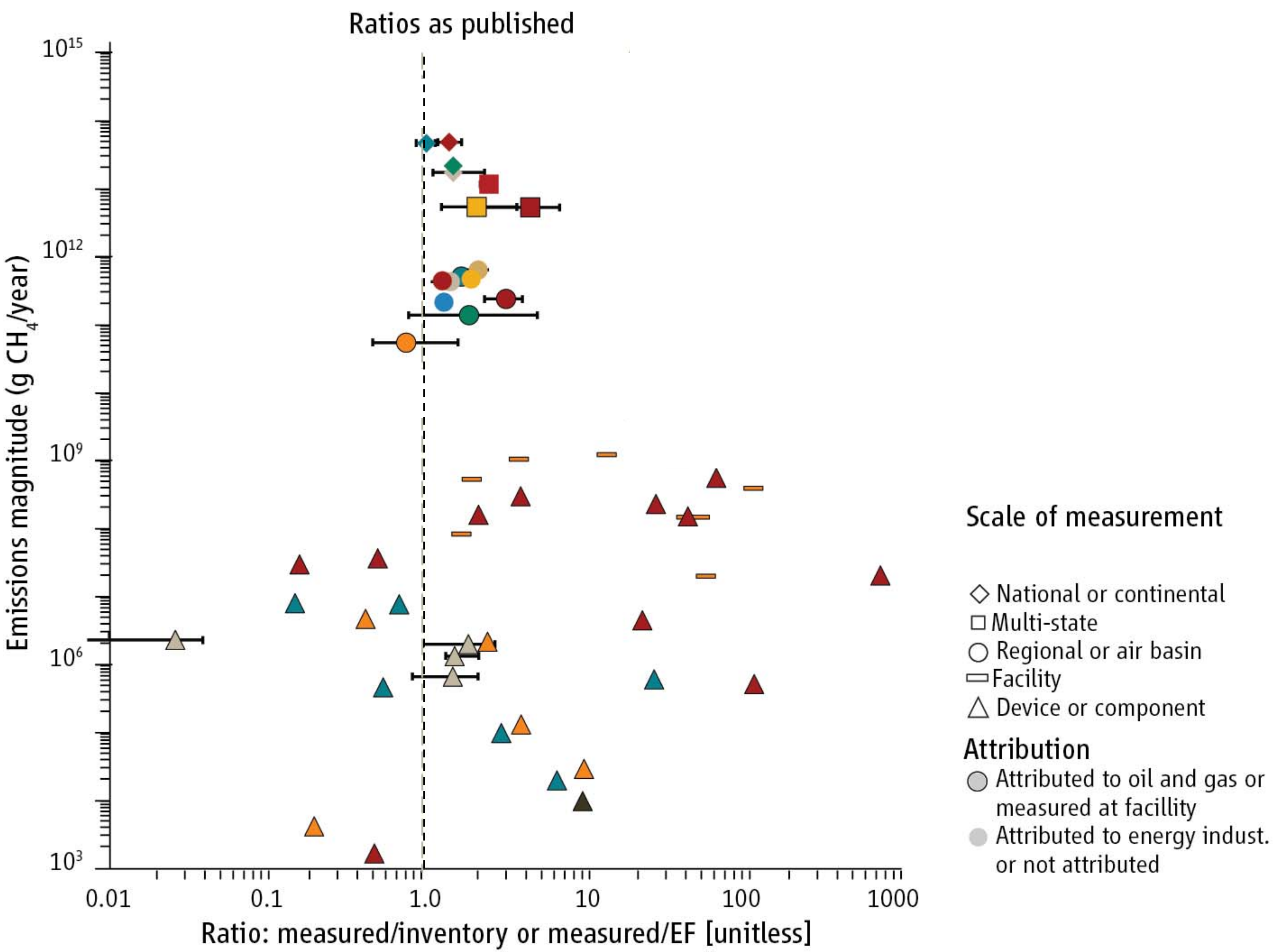
Allen et al. (2013)
Emissions magnitude (g CH4/year)
10^15
10^12
10^9
10^6
10^3
0.01
0.1
1.0
10
100
1000
Ratio: measured/inventory or measured/EF [unitless]
Scale of measurement
Facility
Device or component
Attribution
Attributed to oil and gas or measured at facillity
Attributed to energy indust. or not attributed



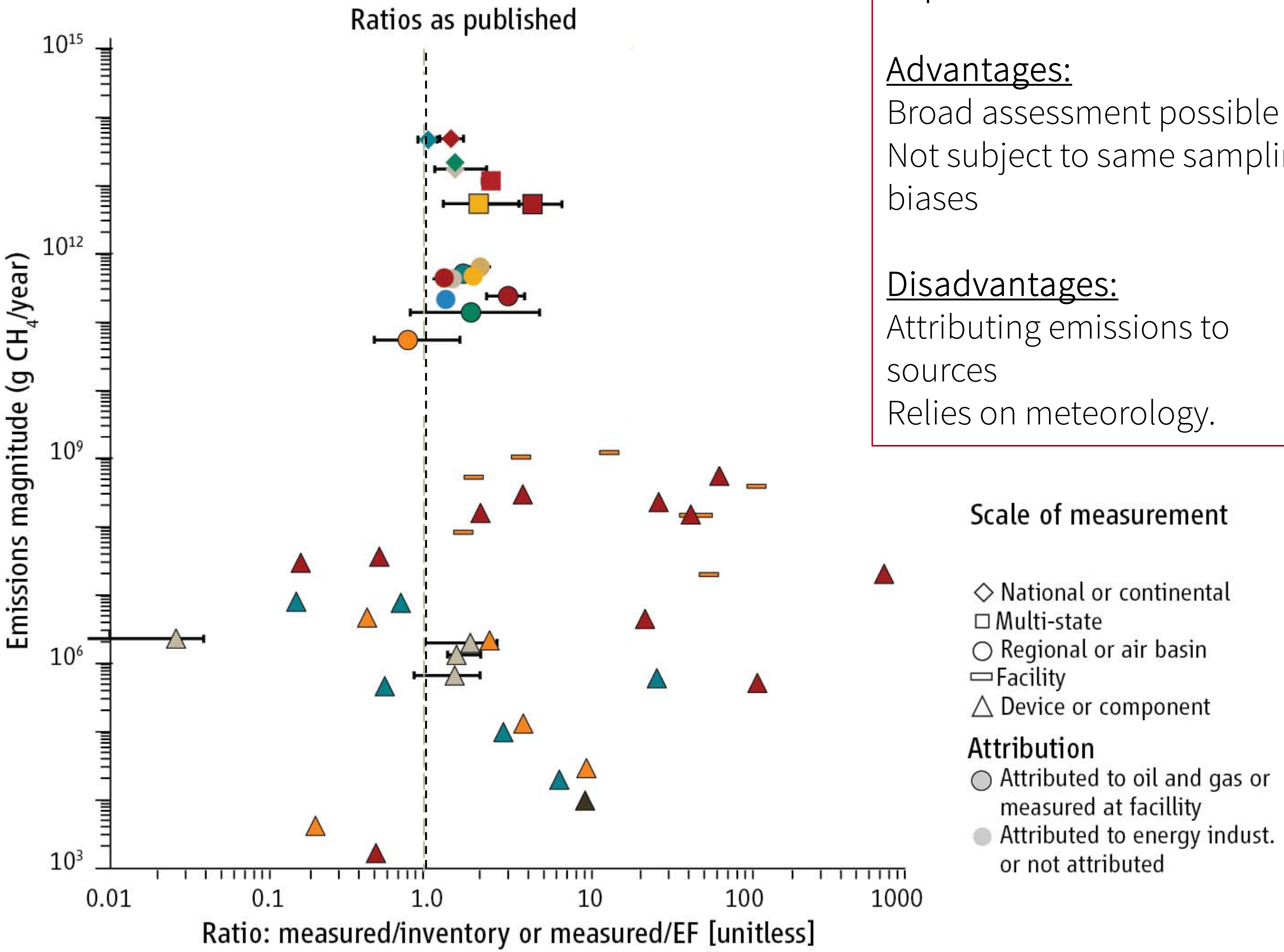
Bottom-up studies

Advantages:
No attribution challenges
More precise measurement

Disadvantages:
Sample sizes small
Sampling bias possible.



Ratios as published
Emissions magnitude (g CH4/year)
10^15
10^12
10^9
10^6
10^3
0.01
0.1
1.0
10
100
1000
Ratio: measured/inventory or measured/EF [unitless]
Scale of measurement
National or continental
Multi-state
Regional or air basin
Facility
Device or component
Attribution
Attributed to oil and gas or measured at facillity
Attributed to energy indust. or not attributed



Top-down studies

Advantages:
Broad assessment possible
Not subject to same sampling biases

Disadvantages:
Attributing emissions to sources
Relies on meteorology.

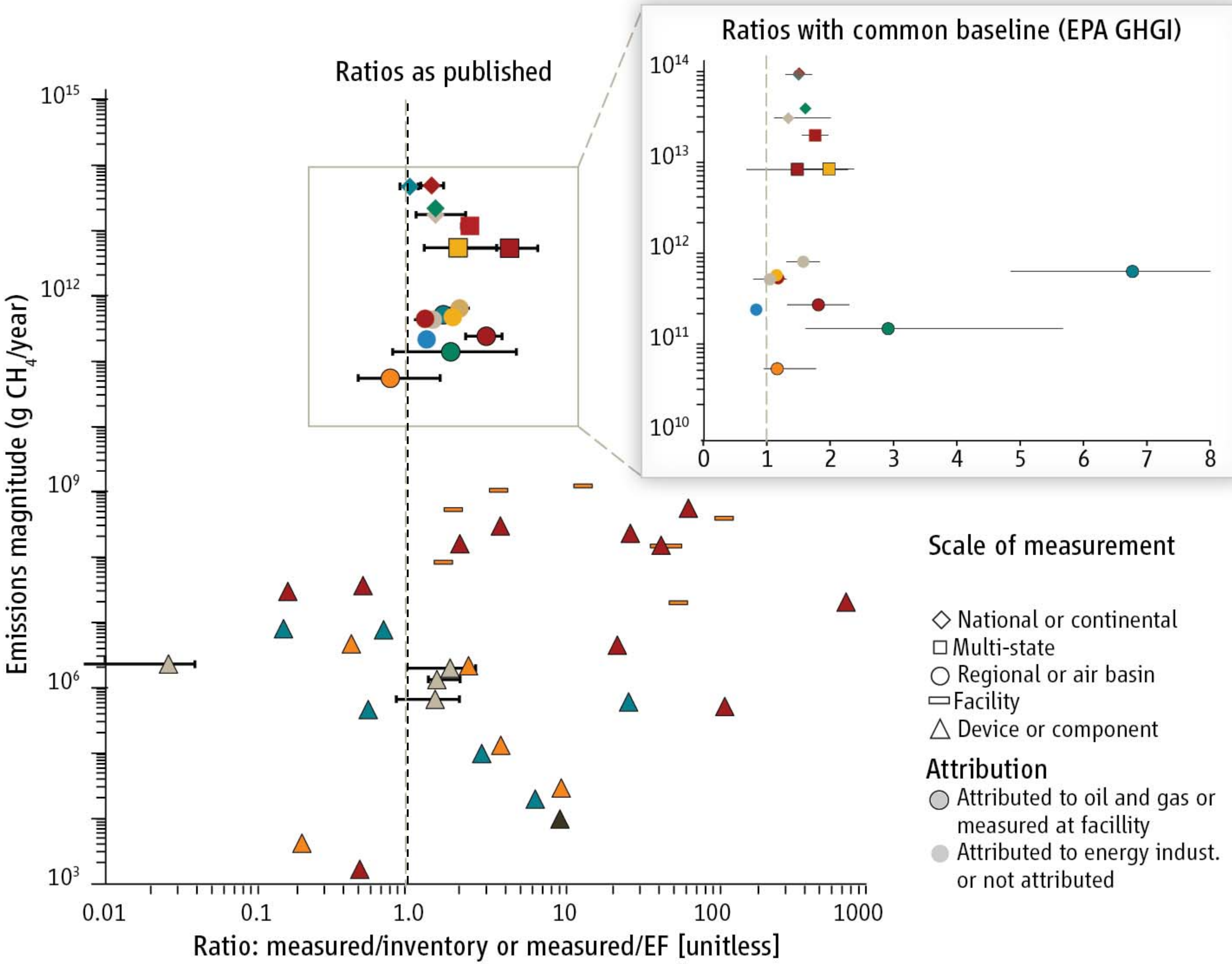
Challenge of differing baselines

- Nearly all bottom-up studies compare their results to EPA GHGI[1] emissions factors
- Top-down studies compare to a variety of baselines
  - Putting studies on consistent basis yields more robust insights
  - For each study, we scaled 2013 EPA GHGI for the region and sectors.[2]

Additional notes:

[1]One exception: Chambers (2004, 2006) compares his results to CAPP methods.

[2]See supplemental worksheet, sheet 'Calc – Figure 1 – Inset' for full computation.



Ratios as published
Ratios with common baseline (EPA GHGI)
Emissions magnitude (g CH_4/year)
10^{15}
10^{12}
10^{9}
10^{6}
10^{3}
0.01
0.1
1.0
10
100
1000
Ratio: measured/inventory or measured/EF [unitless]
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
0
1
2
3
4
5
6
7
8
Scale of measurement
National or continental
Multi-state
Regional or air basin
Facility
Device or component
Attribution
Attributed to oil and gas or measured at facillity
Attributed to energy indust. or not attributed

Summary results: Figure 1

- Normalized top-down studies suggest overall emissions of CH_4 of ~1.5 (1.25-1.75) times those of EPA estimates
- NG-specific studies also find excess
  - Both top-down and bottom-up tend > 1
  - Wider range and more scatter
- We cannot say how much of the overall excess is due to the NG system.

Causes of the Gap – Some Examples

Many possible reasons for inventory underestimation

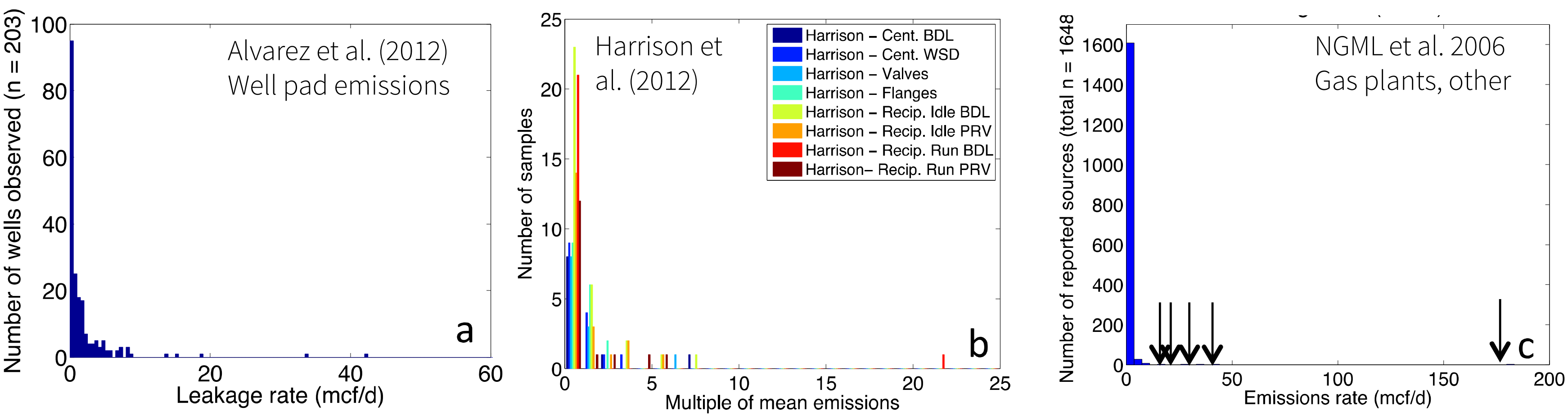
- Inventories not from same time period as measurements
- Emission factors low/unrepresentative of current technology
- Inaccurate counts
- Missing sources
- Average emission factors do not consider fat tails distribution ("super-emitters")

Also challenges for top-down studies

- Mixture of methane sources – how attribute?
  - Oil and gas
  - Agriculture
  - Natural seeps
- Meteorology
- Measurements at specific times compared to annual inventories.

Results: Variability and “super-emitters”

- Bottom-up studies[1] suggest that unintentional leakage rates vary greatly between devices
  - Most devices do not leak
  - A small fraction of devices leak excess gas
  - A **very** small fraction (<<1%) leak a large amount. These sources often contribute a large fraction of the total leakage.



Additional notes:

[1]See Table S6 in paper SM for tabular evidence of “super-emitters”, and Figure S2.

Results: Variability and "super-emitters"

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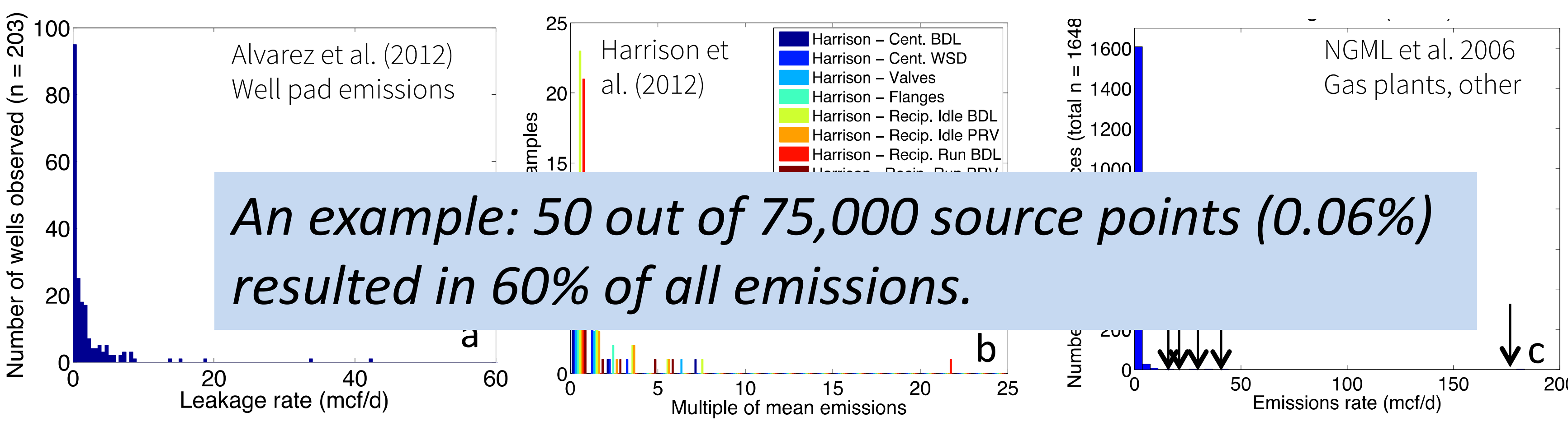
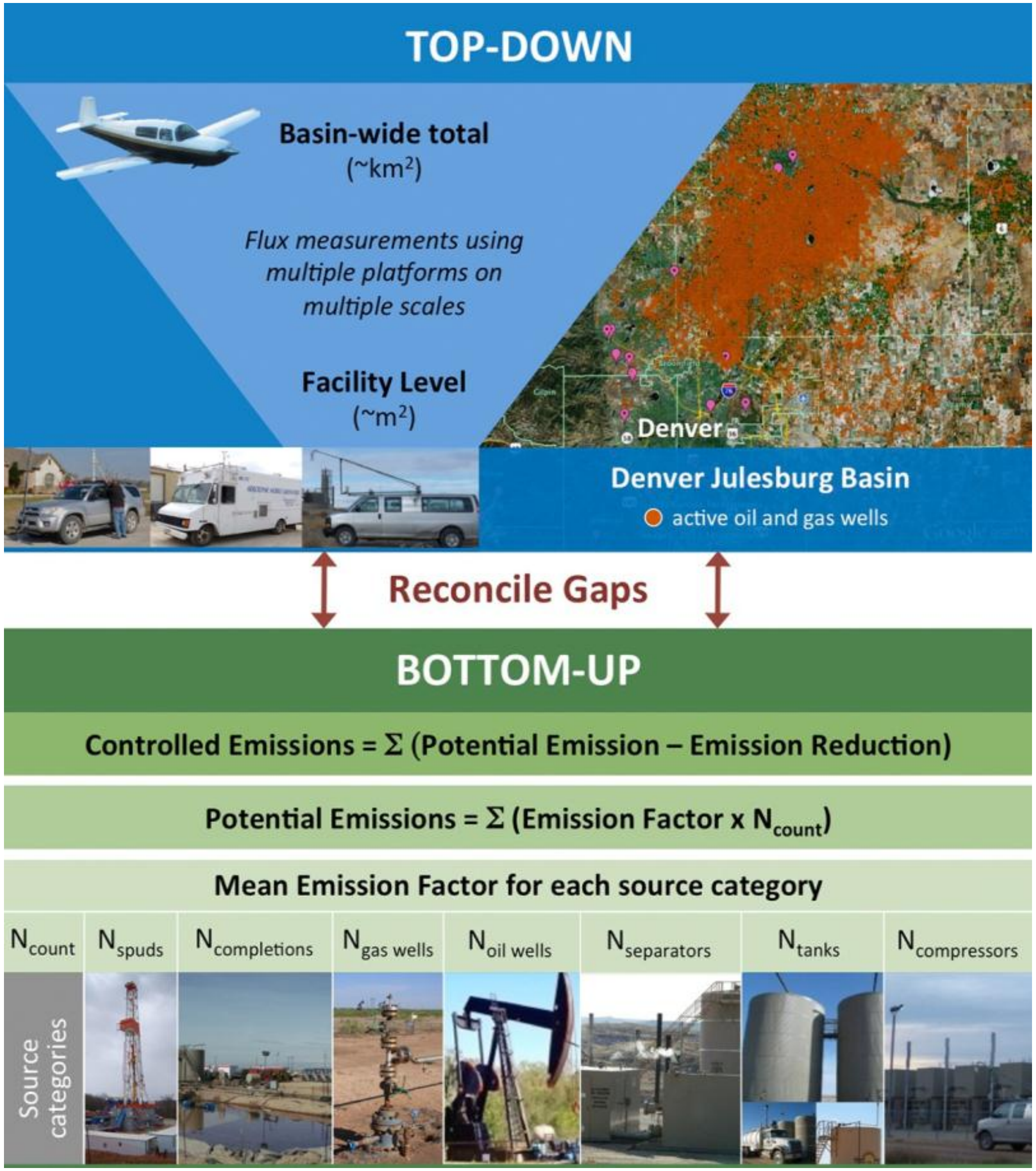


An example: 50 out of 75,000 source points (0.06%) resulted in 60% of all emissions.

Additional notes:

[1]See Table S6 in paper SM for tabular evidence of "super-emitters", and Figure S2.

Research Needs



Top-down:

- Source sector differentiation
- Representative sampling
- Accuracy
- Gas composition profiles
- Downscaling to sources

Reconcile Gaps

Bottom-up:

- “Fat tails” emission distribution
- Missing sources
- Representative samples
- Activity data
- Uncertainty characterization.

Source: NREL

Results: NG fuel substitution

- Leakage rates from the NG system are unlikely to be high enough to disfavor coal to NG substitution for electricity generation (100 year global warming potentials)
  - To favor coal: high estimate of undercounted emissions (1.75x EPA); all excess CH_4 from NG industry.
  - We know other sources contribute (e.g., livestock).

- Climate benefits from using NG in transportation are uncertain (for gasoline cars) or unlikely (for heavy-duty diesel vehicles), but this conclusion is based on key assumptions that need to be updated.

Additional notes:
[1]Fuel switching benefits defined using cutoff percentages from Alvarez et al. (2012).

Opportunities to solve the problem

- Leakage detection and repair programs have been shown to be profitable
- Super-emitting sources: if we can find them cheaply and quickly, they are profitable to fix
- EPA Inventory is a critical resource that should be improved to provide better policy guidance.

Thank you!

Collaborators:

- **Science paper co-authors**
- **Proposal team** (CSM (Nummedal), NOAA (Petron), CSU (Zimmerle), ENVIRON (Bar-Ilan), WRAP (Moore))
- **NREL/JISEA** (Doug Arent, Morgan Bazilian, Jeff Logan, Ethan Warner, Maggie Mann, Dan Steinberg).

Funding from:

- JISEA
- DOE (EERE, EPSA)
- Novim.

Contact and links

Garvin.Heath@nrel.gov

www.nrel.gov/harmonization

www.jisea.org/natural_gas.cfm

www.novim.org/projects/natural-gas

Supplementary Slides

Changing EPA Inventory Estimates

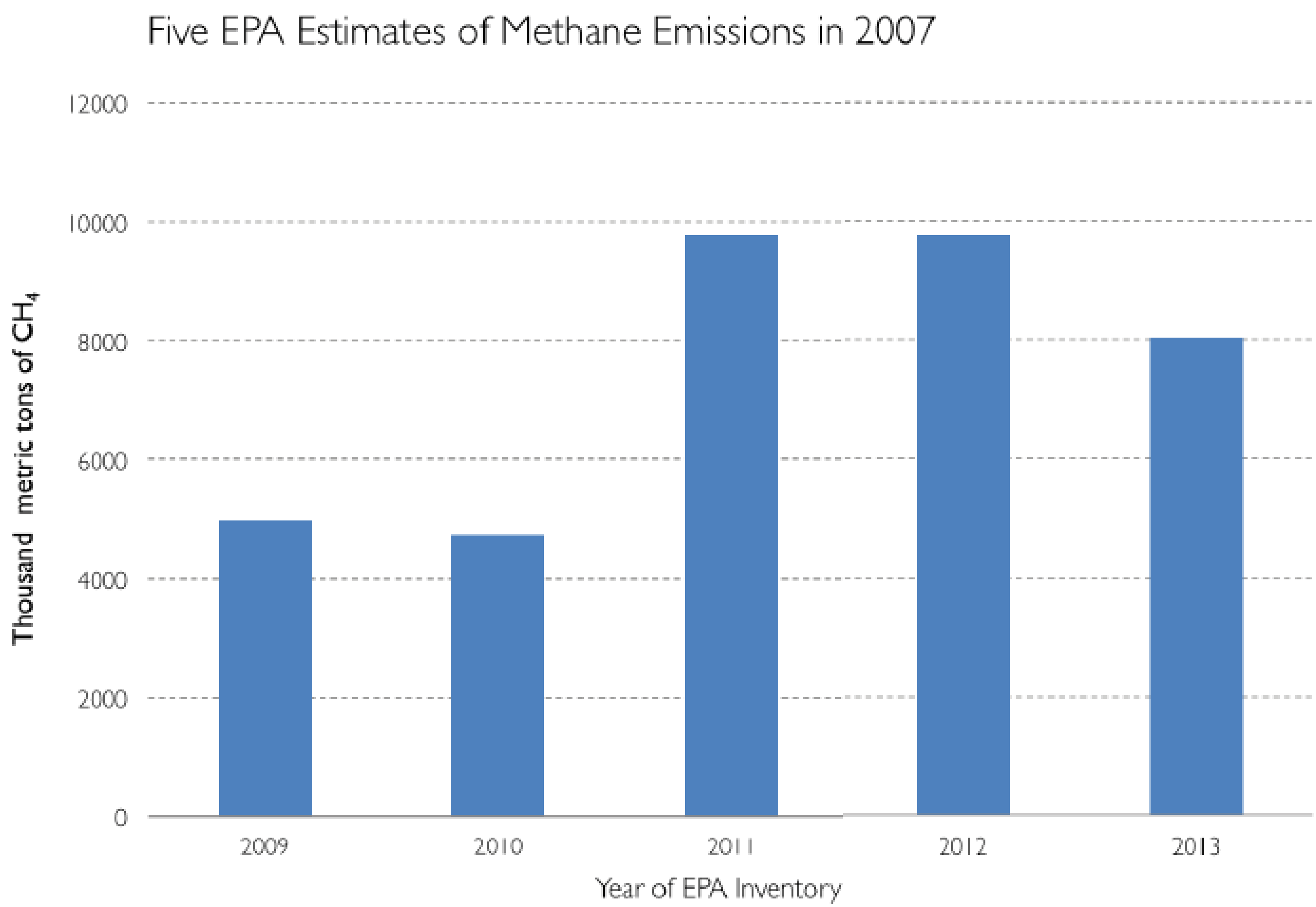


Figure 17. Methane emissions from the natural gas supply system for 2007, as estimated in five different EPA Emission Inventories. Differences in data sources and methodologies account for the differences in estimated emissions.[27]

US GHG Inv.

<u>2011 vs. 2010</u>

1. **>2x production segment emissions**
2. **+10x liquids unloading emission factor (EF) (conv. gas)**
3. **EFs for unconv.:**
   - Completions
   - Workovers
4. **Centrifugal compressors**

<u>2013 vs. 2011</u>

1. **Liquids unloading -~80%.**

Source: Larsen (2013)

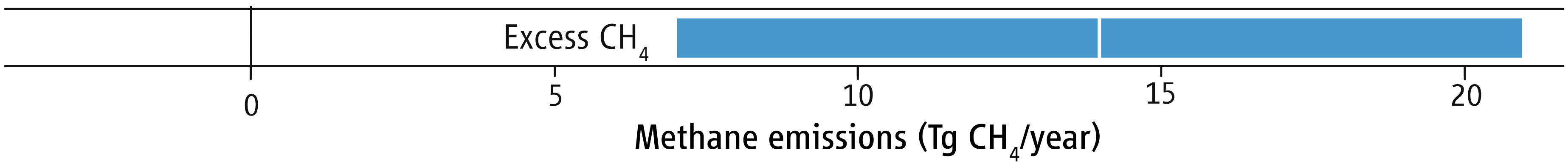
Fuel switching analysis caveats

- **We use 100-year climate assessment period**
- **We rely on Alvarez et al. (2012) analysis and assumptions**
  - Leakage rates assumed for NG vehicle refueling and vehicle efficiencies were from a single, 1992 study
  - Global warming potentials for CH_4 have since increased
- **System boundary alignment between inventories and LCAs is poor**
  - EPA GHGI methods attribute CH_4 emissions from coproducing NG systems to the NG sector, rather than apportion some emissions to liquids
  - EPA GHGI methods attribute CH_4 emissions from associated gas production to petroleum sector.
- **Does not consider technological change or reductions in leakage**

Figure 2: What might be causing excess CH_4?

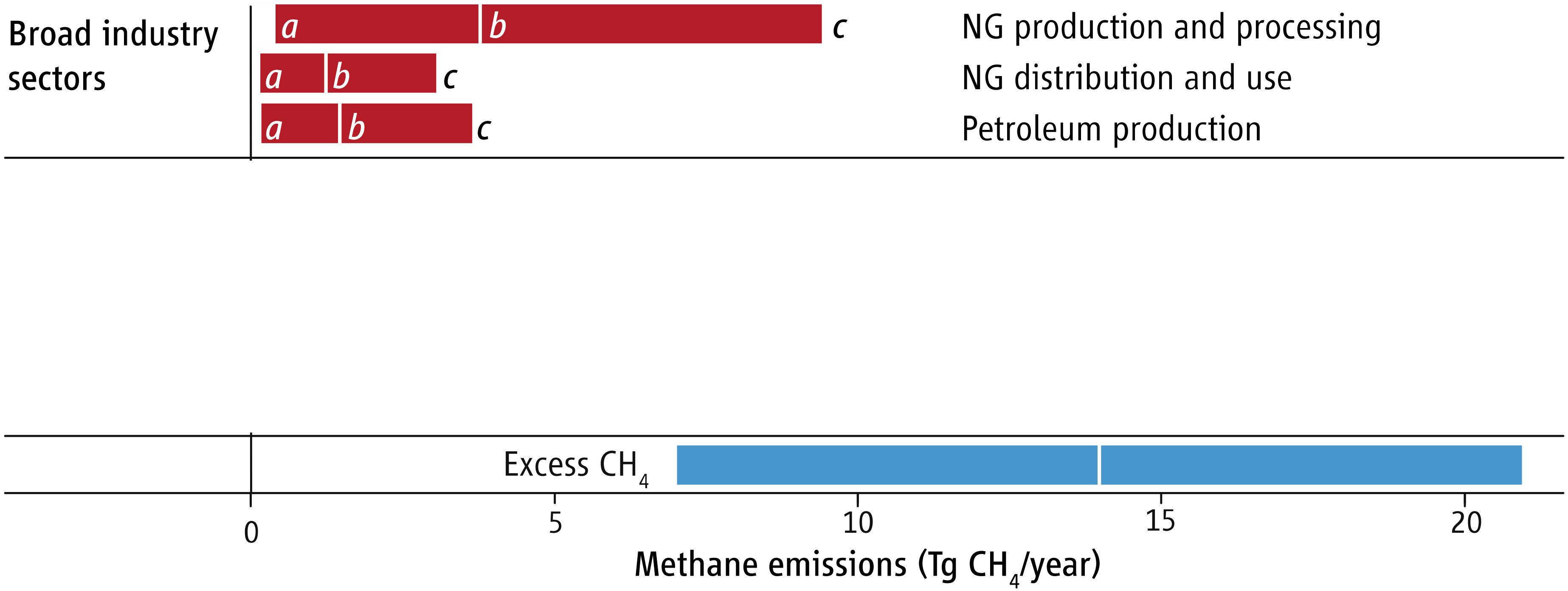
- In Figure 2, we perform a thought experiment on some possible causes of excess CH_4, given evidence available
  - What sources might be responsible for excess CH_4?
- We focus on NG sources and sources that might be mistaken for NG
  - Sources that could “look like” NG by chemical or isotopic signature.


0
5
10
15
20
Methane emissions (Tg CH_4/year)



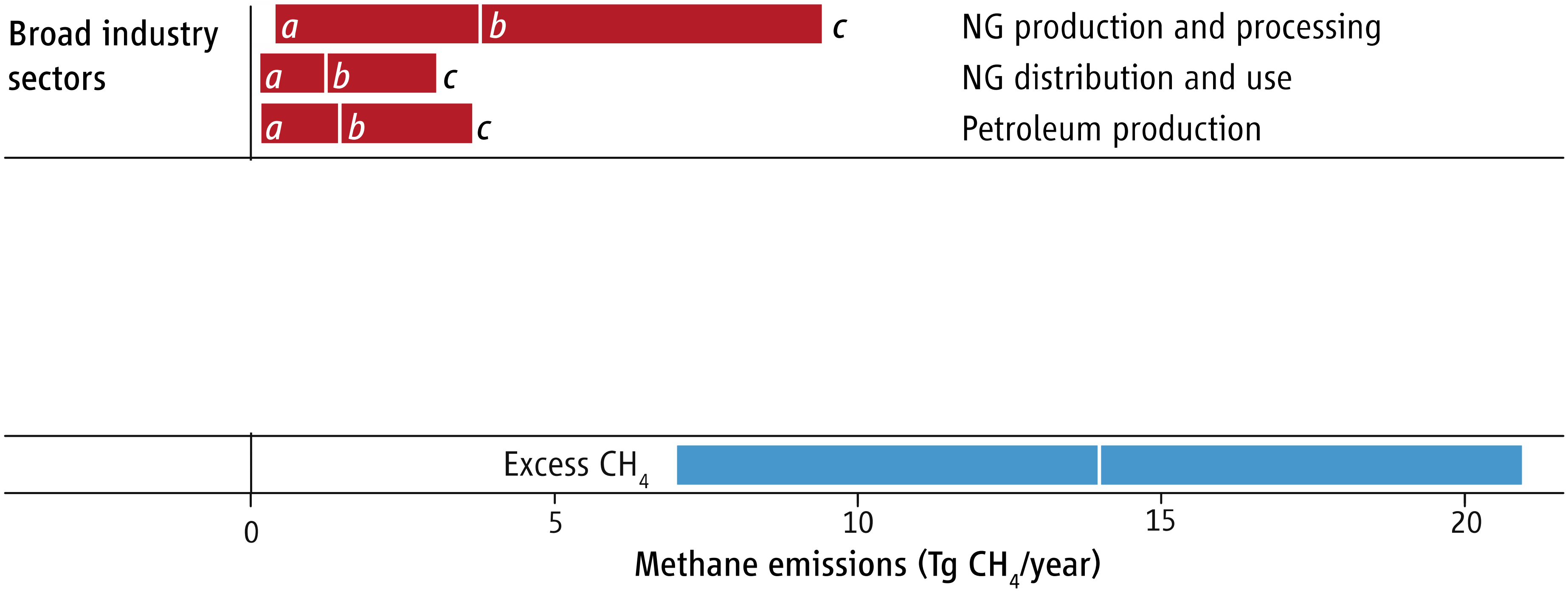
Range of total excess CH_4 (based on normalized Figure 1 results)

= 50% (25-75%) above EPA GHGI
= 14 Tg CH_4/y (7- 21 Tg CH_4/y).



<u>Broad industry sectors</u>

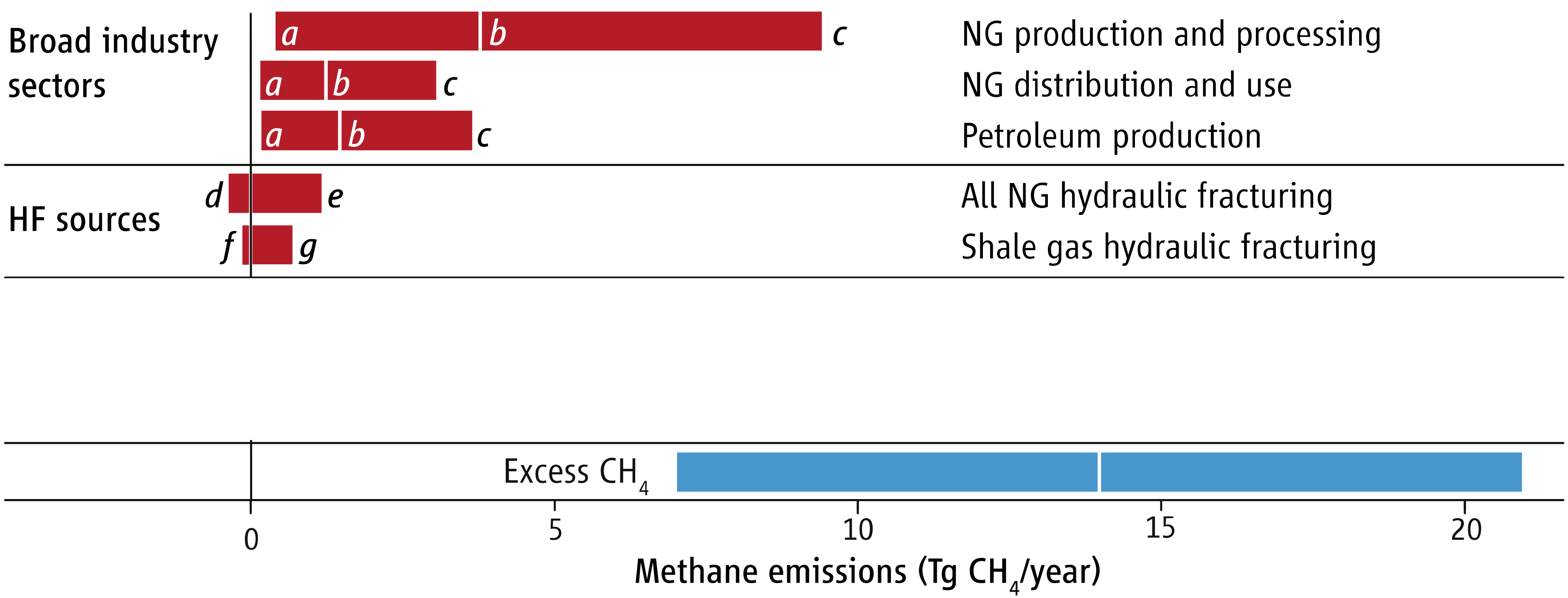
- Top-down studies give us emissions estimates for a region (or NG industry sub-sectors)
- They do not tell us **how common** these emissions rates are
- So we construct "illustrative prevalence scenarios"
    - Take leakage rate observations from the literature
    - Apply these to a set fraction of activity (*a* = 1%, *b* = 10%, *c* = 25%) while the rest of activity remains at EPA average.



Broad industry sectors

- Example: NG production and processing:
    - Leakage rate of 9% (Karion et al. (2013) data from Uintah Basin UT)
    - Apply this to 1%, 10% and 25% of U.S. gas production, compute excess.

- **Result:** High emissions rates from recent atmospheric studies (UT, LA) are not the norm. If so, we would see more methane from the continental/national atmospheric studies.



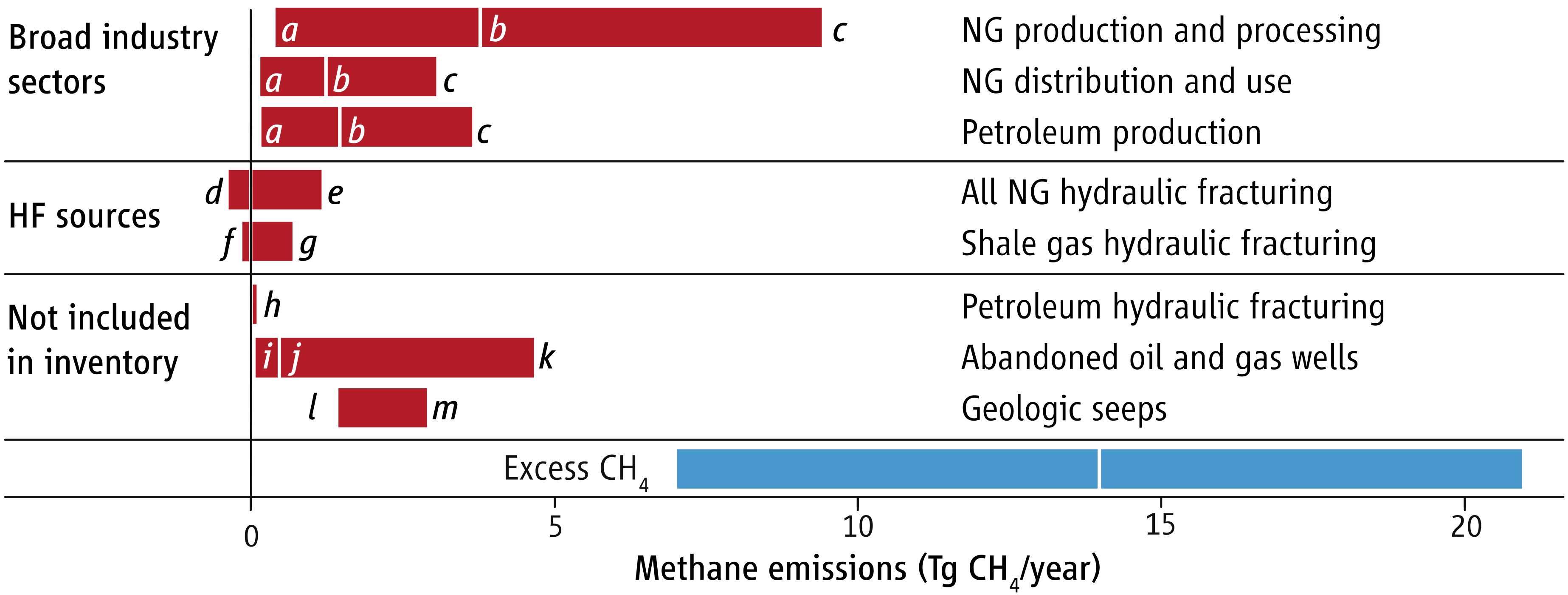
Hydraulic fracturing

Emissions rates during flowback are uncertain

Shale gas HF:

- Examine “Big 5” shale gas plays, use method from O’Sullivan and Paltsev (2012)
- Low (*f*) is “current practice” emissions rate: 56 Mg CH_4/well
- High (*g*) is “all vented” emissions rate: 234 Mg CH_4/well

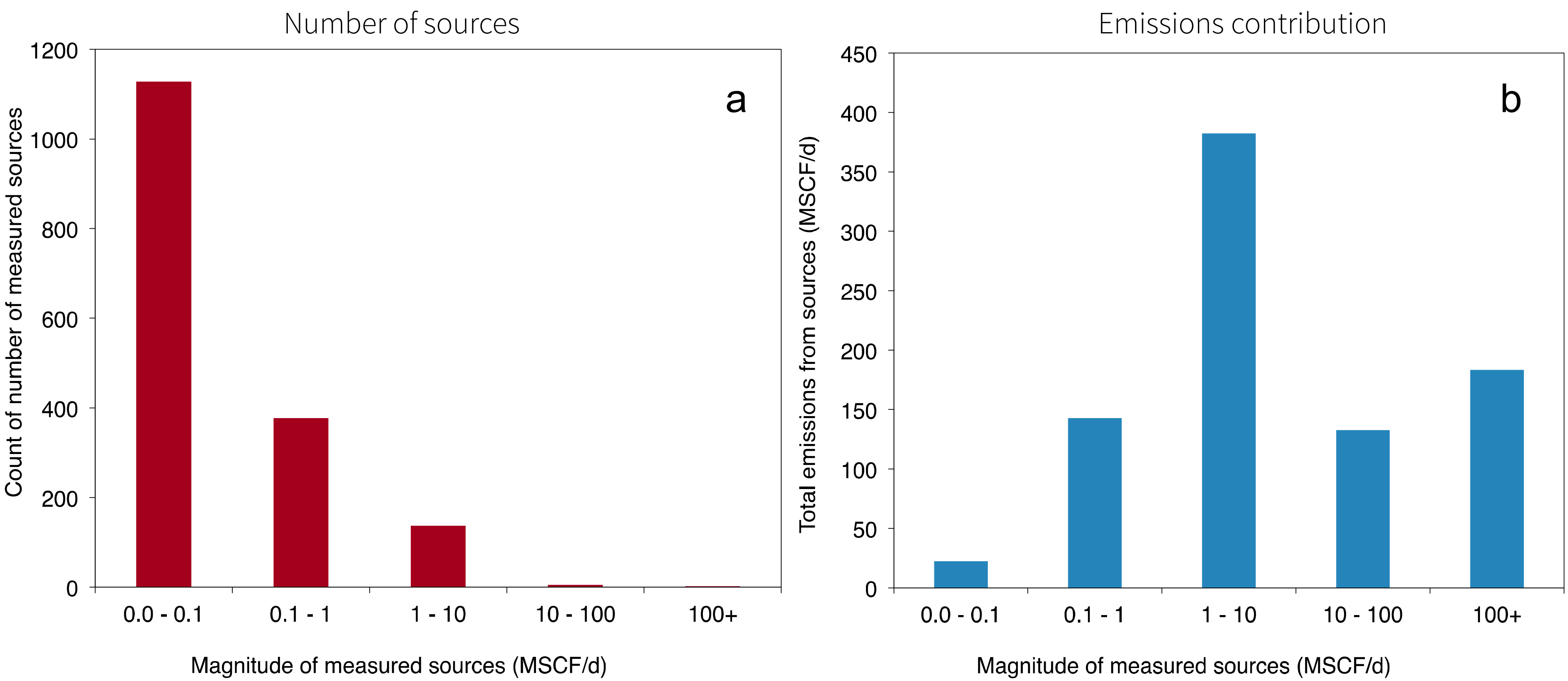
Result: HF may contribute if uncontrolled flowback is the norm. However, results suggests that HF is not the dominant contributor to overall excess CH_4.



Sources not included in inventory

- **Petroleum HF not likely a major source.**
- **Abandoned wells could contribute, but requires assuming high leakage rates.**
- **Geologic seeps could confound, but some studies (e.g., Miller et al. 2013) already account for this.**

Emissions share by emissions rate



Footnotes:
[1]See Figure S3 in paper SM. Data from NGML, IES, Clearstone (2006) report for EPA. Measurements at gas plants, well pads, other sources.

The challenge of attribution

- How do we attribute what we see in the atmosphere to the NG industry?
  - Focus on regions with natural gas production
  - Model atmospheric transport (wind) to assign sources
  - Use chemical signatures to determine fossil origin
  - Use chemical signatures to assign to a given sub-sector (e.g., processed gas or raw gas).

Misalignment: inventories, LCAs, measurements

- A still-entangled problem: methodologies can (and often do) have different system boundaries
- Ideal comparisons require understanding congruence (or lack thereof) between LCA, inventories, and experimental evidence
- Examples:
  - Peischl et al. (2013) gas vs. petroleum
  - EPA sector divisions vs. LCA methods.

Quantifying Attributable Impacts

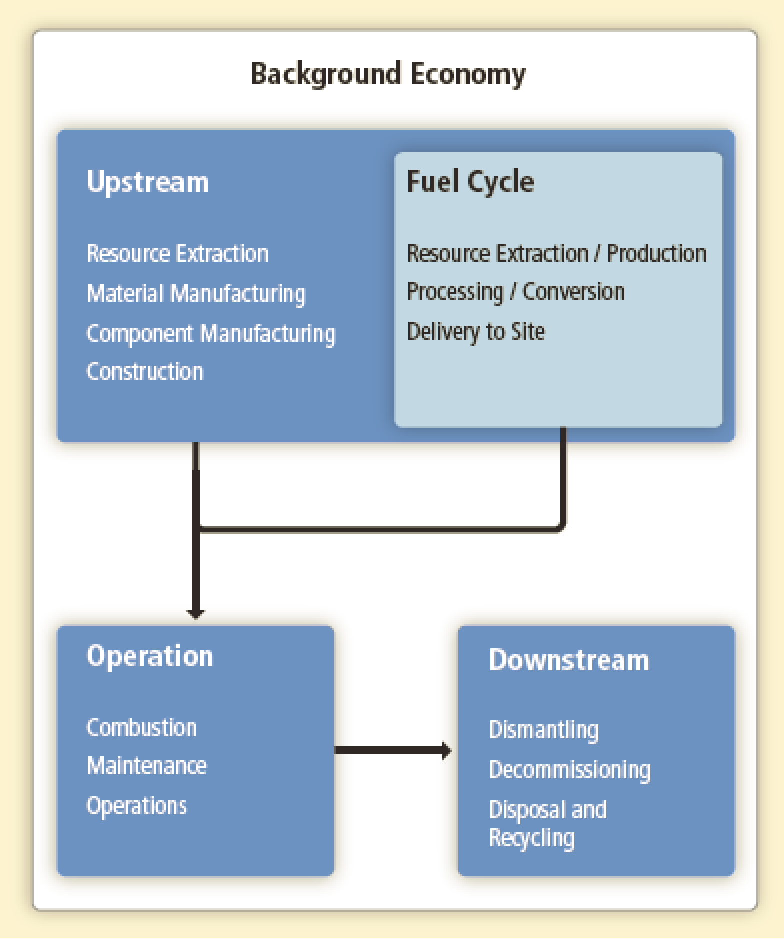
Life cycle assessment (LCA) – quantifies resource consumption, energy use, and emissions, from cradle-to-grave.

- Practiced for 40 years
- Methods codified in standards (e.g., ISO) and guidelines, though some methodological issues persist.

Selected by IPCC as most appropriate basis for consistent comparison of renewable and conventional energy technologies in *Special Report on Renewables.*

Metrics

- **GHG emissions**
- **Water consumption and discharges**
- **Energy use**
- **Petroleum use**
- **Raw material consumption**
- **Air pollutant emissions**
- **Solid waste.**

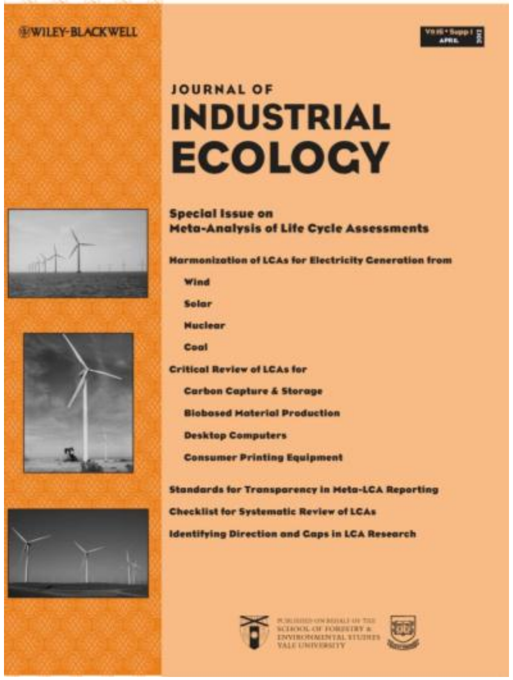


Source: IPCC SRREN

LCA Harmonization Project

Six articles in Special Issue of *Journal of Industrial Ecology* on **Meta-Analysis of LCA** (May, 2012)

- Coal
- Nuclear
- Wind
- Concentrating solar power
- Crystalline silicon PV
- Thin-film PV.



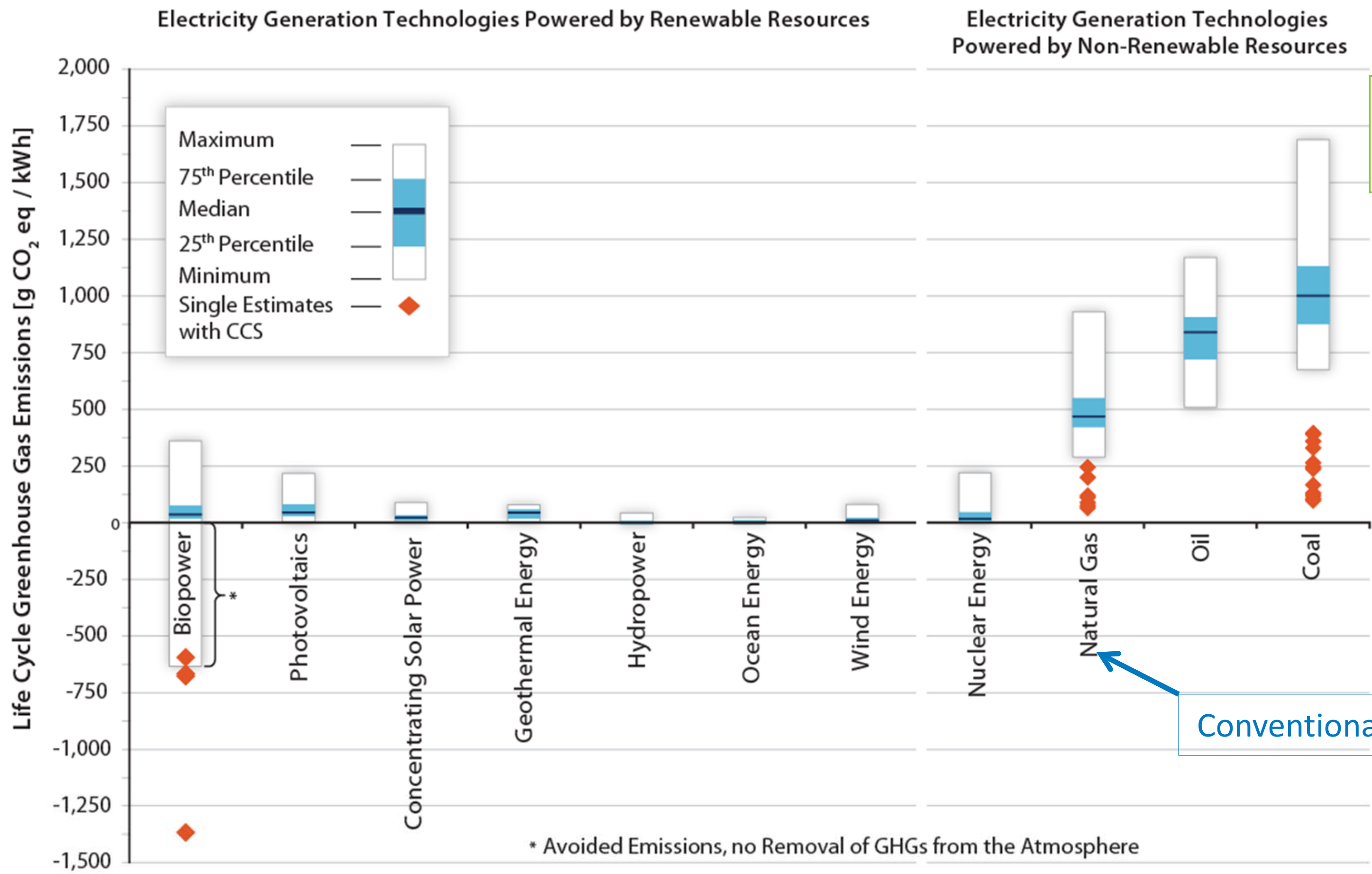
- **In press: Conventional Natural Gas**
- **In review: Unconventional Natural Gas.**

www.nrel.gov/harmonization

NG Life Cycle GHG Emissions in Context

(pre-2011 published LCAs)

IPCC SRREN SPM Fig. 8



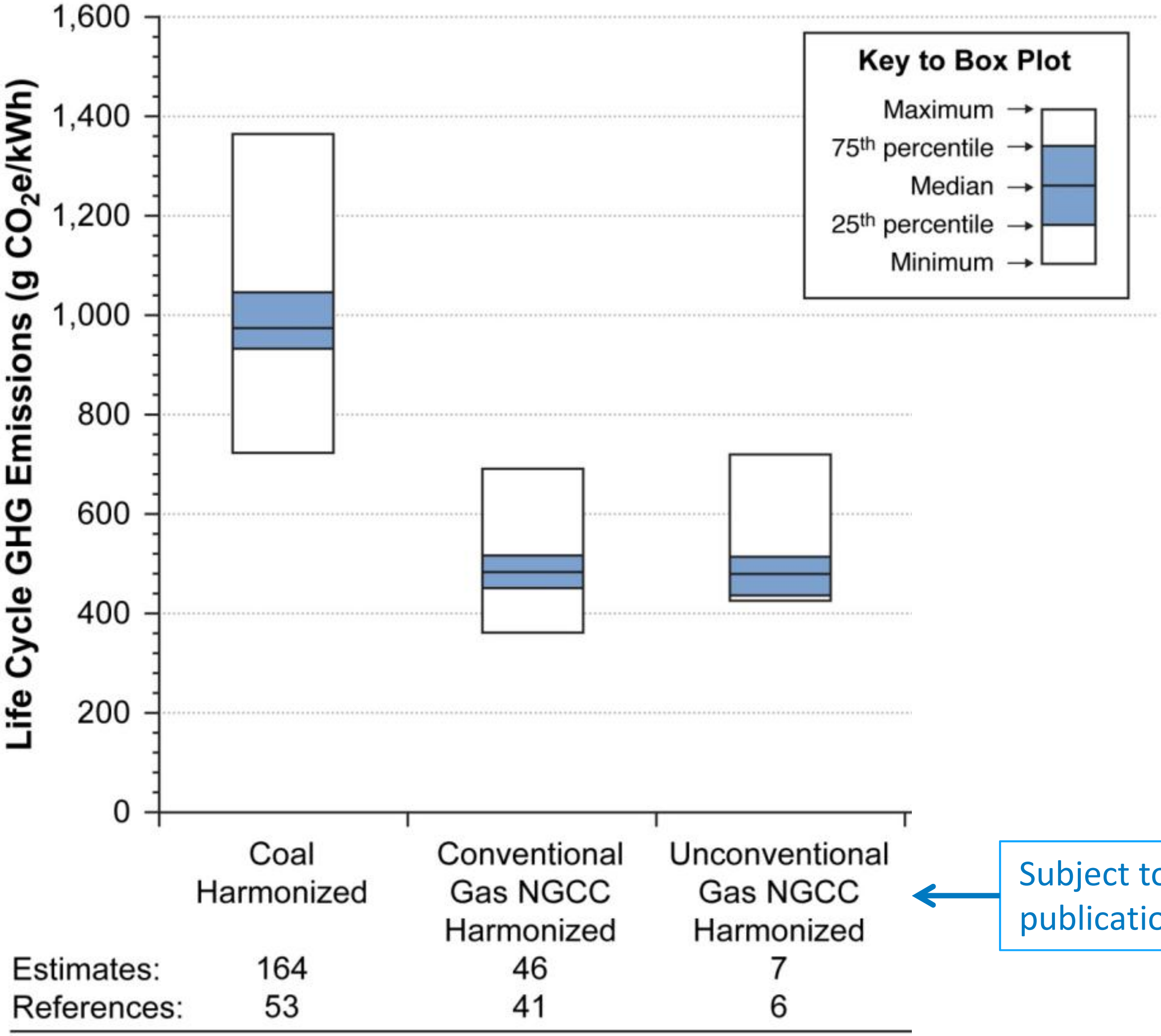
	Biopower	Photovoltaics	Concentrating Solar Power	Geothermal Energy	Hydropower	Ocean Energy	Wind Energy	Nuclear Energy	Natural Gas	Oil	Coal
Count of Estimates	222(+4)	124	42	8	28	10	126	125	83(+7)	24	169(+12)
Count of References	52(+0)	26	13	6	11	5	49	32	36(+4)	10	50(+10)

Shale (Unconventional) Gas LCAs Emerging…

Study	Headline result
1. Howarth et al. (2011)	1. NG > coal
2. Jiang et al. (2011)	2. Marcellus < domestic gas (conv. + unconv.), both < coal
3. Skone et al. (2011) (since updated, adding Marcellus)	3. Barnett Shale > conventional (except onshore), both < coal
4. Hultman et al. (2011)	4. Unconv. < conv., both < coal
5. Stephenson et al. (2011)	5. Shale > conventional, both < coal
6. Burnham et al. (2012)	6. Conv. > shale, both < coal
7. Heath et al. (2012)	7. Shale ~ conv., both < coal.

All rely heavily on inventory results, data sources and assumptions

Preliminary Results of Gas LCA Meta-analysis (Harmonization)

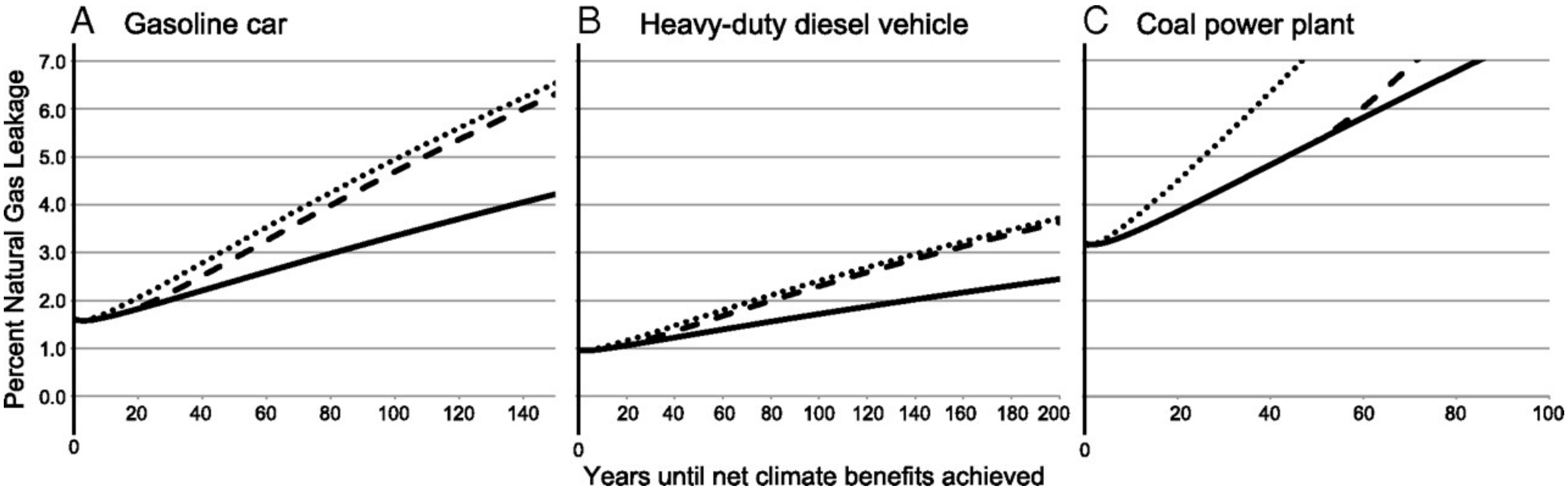


Subject to change during publication process

Sources: Figure from JISEA (2013). Conventional results – O'Donoughue, P.; Heath, G.; Dolan, S. Vorum M.; (2014). *Journal of Industrial Ecology*; Unconventional results – Heath. G.; O'Donoughue, P.; Arent, D.; Bazilian, M. (in review). Coal: Whitaker et al. (2012).
NGCC = natural gas combined cycle.

Methane Leakage Rate: A Framing Concept

Maximum "well-to-wheels" natural gas leak rate as a function of the number of years needed to achieve net climate benefits [from fuel switching to] NG

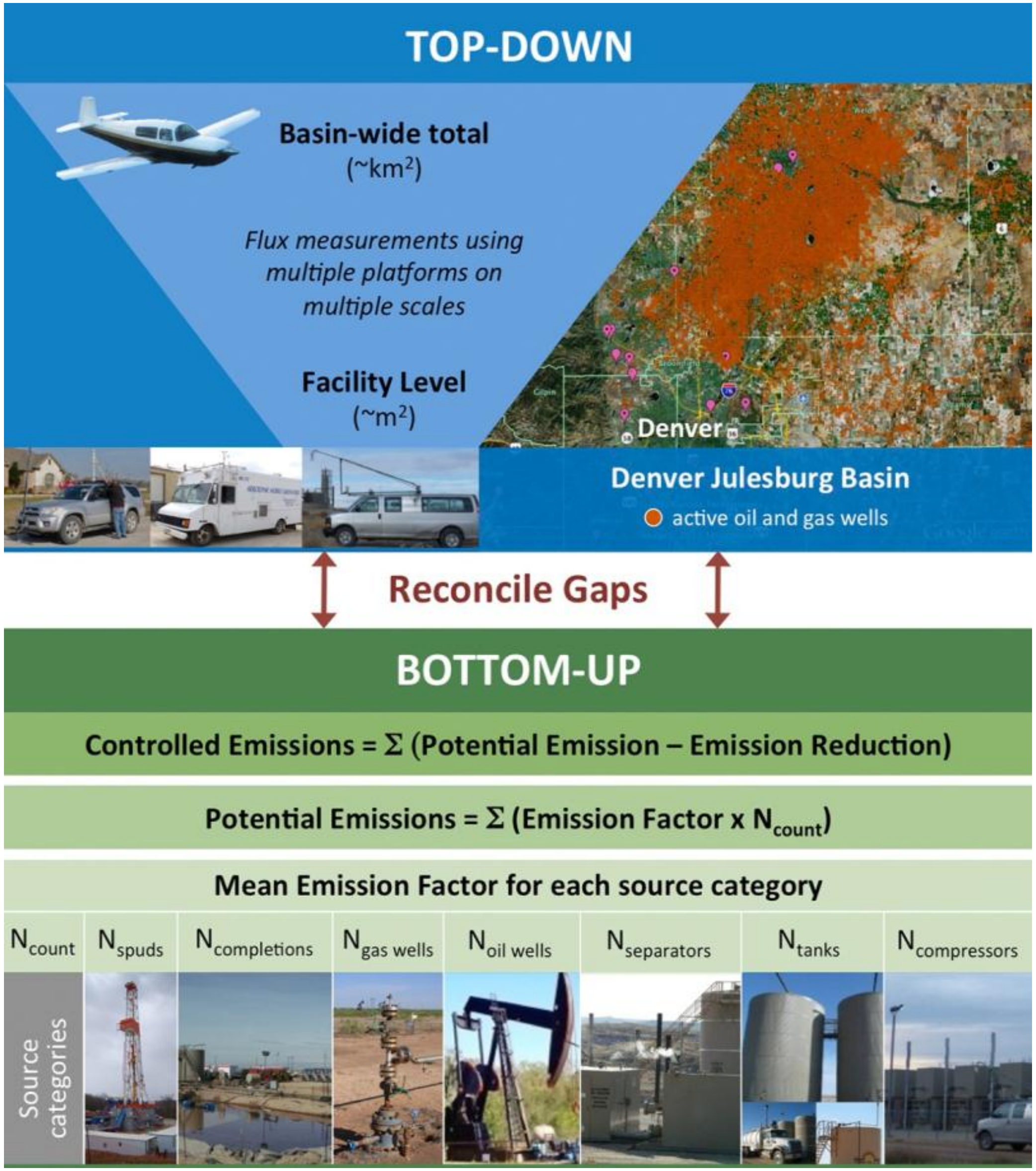


Dotted lines: single emissions pulses
Dashed lines: the service life of a vehicle or a power plant, 15 or 50 years, respectively
Solid lines: a permanent fleet conversion.

Alvarez et al. (2012). PNAS. (109); pp. 6435-6440.

PNAS

Next Step: Contemporaneous, State of the Science Bottom-up Plus Top-down Empirical Assessment



Reconciling Top-down and Bottom-up GHG and Air Pollutant Emission Estimates from Unconventional Gas Development in the Denver-Julesburg Basin

Colorado has some of the world's leading institutions and researchers on all aspects of this challenge!