Environmental Impacts of Renewable Electricity Generation Technologies: A Life Cycle Perspective

Presenter: Garvin Heath, Ph.D.

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18th Conference on Atmospheric Chemistry

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NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Outline

1. National Renewable Energy Laboratory (NREL) overview
2. Sustainability analysis and life cycle assessment (LCA)
3. Review of environmental impacts of electricity generation technologies
   - Greenhouse gas (GHG) emissions, with a case study on natural gas
   - Water use
   - Land use
4. Career opportunities.

NREL Snapshot

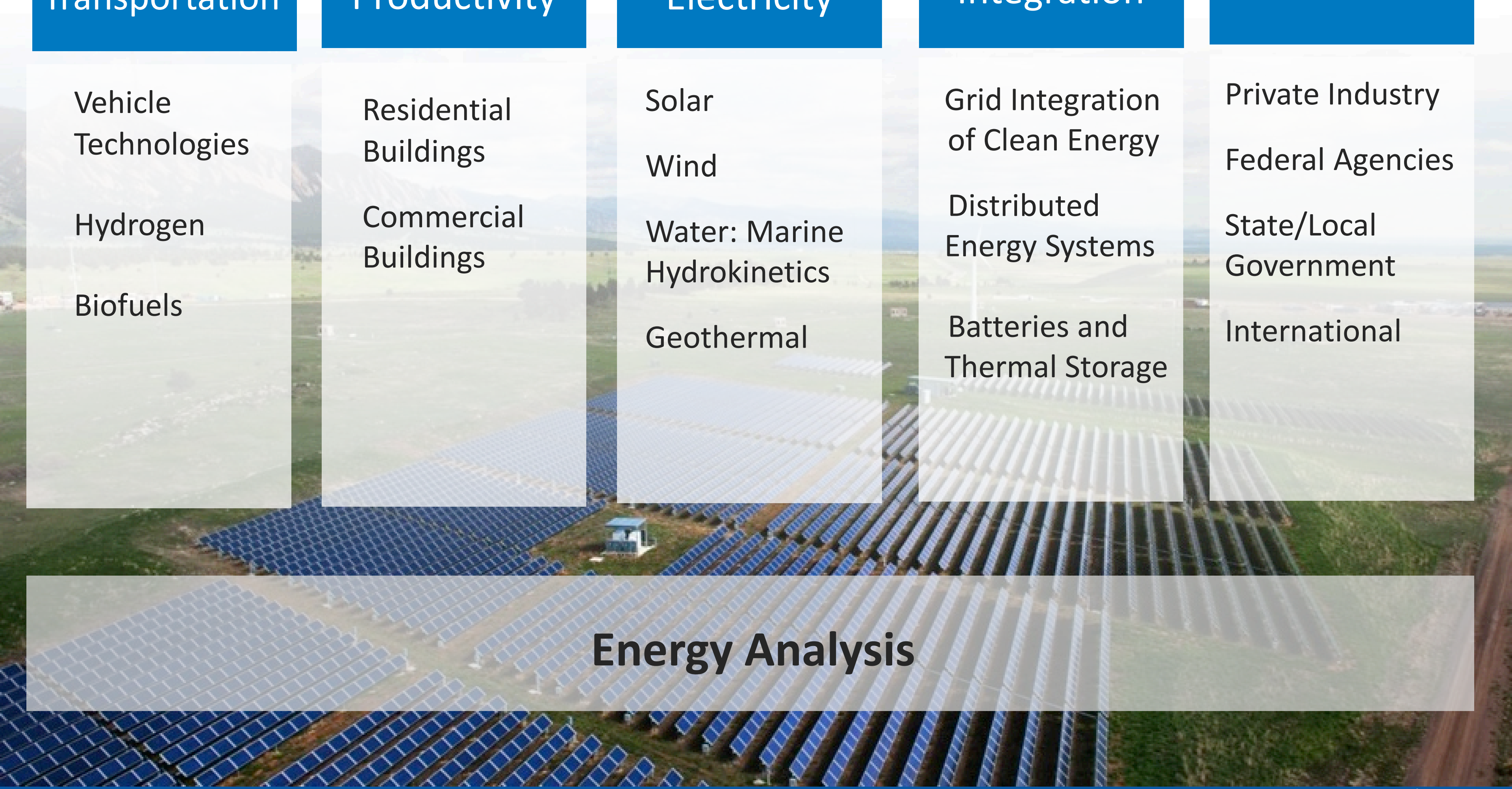
Only national laboratory dedicated solely to energy efficiency and renewable energy

- Leading clean energy innovation for more than 37 years
- 1,763 employees with world-class facilities
- Campus is a living model of sustainable energy
- Economic impact at $872M nationwide
- Owned by the Department of Energy (DOE)
- Operated by the Alliance for Sustainable Energy.

Scope of Mission

Sustainable Transportation	Energy Productivity	Renewable Electricity	Systems Integration	Partners
Vehicle Technologies	Residential Buildings	Solar	Grid Integration of Clean Energy	Private Industry
Hydrogen	Commercial Buildings	Wind	Distributed Energy Systems	Federal Agencies
Biofuels		Water: Marine Hydrokinetics	Batteries and Thermal Storage	State/Local Government
		Geothermal		International

Energy Analysis



Photovoltaic Pioneer

- NREL invented the first commercially viable multijunction solar cell, the gallium indium phosphide (GaInP)/gallium arsenide (GaAs) tandem, which forms the basis for every solar cell used by the space and concentrator photovoltaic (PV) industries
- NREL invented the inverted metamorphic multijunction (IMM) solar cell and demonstrated a 45.7% efficiency for this technology, which is on the near-term product roadmaps of major multijunction cell manufacturers

Airfoil and Turbine Research

- NREL-patented airfoil designs improved blade efficiency and simplified over-speed controls, helping launch the wind industry
    - Currently holds 20 patents in wind technologies
- Drivetrain and blade testing improved turbine reliability and lowered costs
- Aerodynamic and structural models guided U.S. industry product development
- On-going research in reliability, efficiency, and controls for multi-megawatt wind turbines and entire wind farms; also developing offshore wind and water power technologies

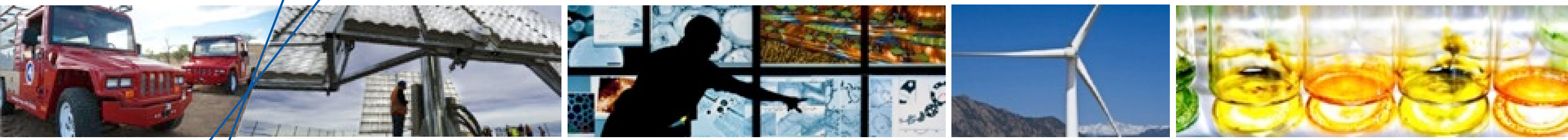
Sustainable Transportation

NREL's transportation RD&D accelerates widespread adoption of energy-efficient vehicles and clean alternative fuels with:

- Computer-aided engineering tools to design better electric vehicle batteries faster
- Platooned trucks that demonstrate ~6.4% fuel savings
- Recruitment of more than 200 businesses for the Workplace Charging Challenge
- Climate control configurations to reduce electric vehicle energy use by ~66.5%
- R&D 100 Award-winning calorimeters that provide the most accurate measurement of battery thermal performance

Analyses, Models, and Tools

- NREL analyzed high penetrations of renewable energy in the eastern and western U.S. power grids for benefits, impacts, and mitigation strategies
- The OpenEI website links and shares energy data worldwide
- NREL's System Advisor Model (SAM) determines the economic value of proposed solar, wind, and geothermal projects
- LCA Harmonization Study—consistent basis to compare life cycle GHG emissions for energy technologies.



Life Cycle Assessment (LCA) Background

Bottom-up Engineering-based Methods for Environmental Assessment

Inventory

Cross-sectional:

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

Controlled Emissions = Σ (Potential Emission – Emission Reduction)

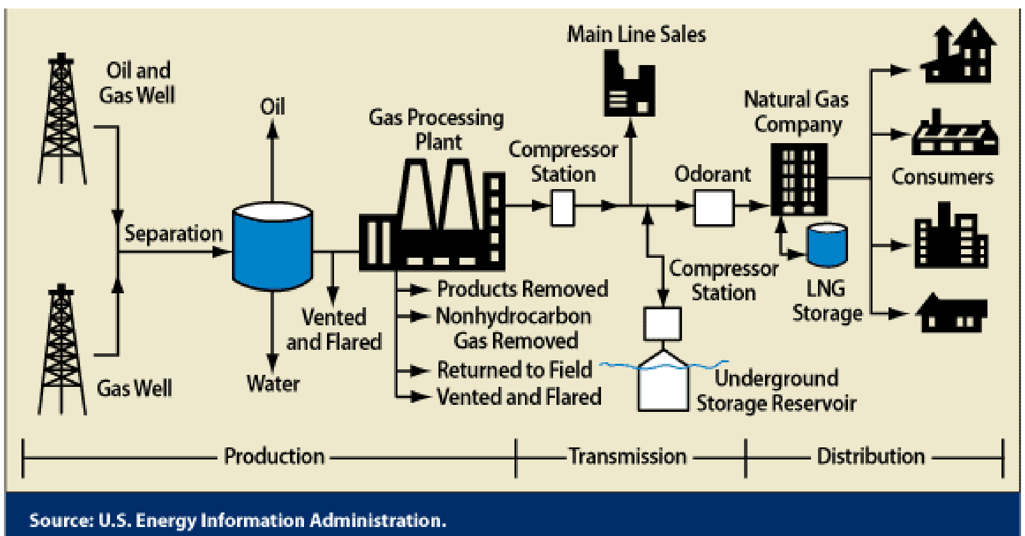
Potential Emissions = Σ (Emission Factor x N_{count})

Mean Emission Factor for each source category

N_{count}	N_{spuds}	$N_{completions}$	$N_{gas\ wells}$	$N_{oil\ wells}$	$N_{separators}$	N_{tanks}	$N_{compressors}$

Source: NREL and NOAA

Life Cycle Assessment



Longitudinal:

Sequence of processes, each modeled independently, summed across space and time, and scaled to a unit of final product

$\propto$

Unit of end product (e.g., kWh)

LCA: Quantifying Attributable Impacts (e.g., Energy Choices)

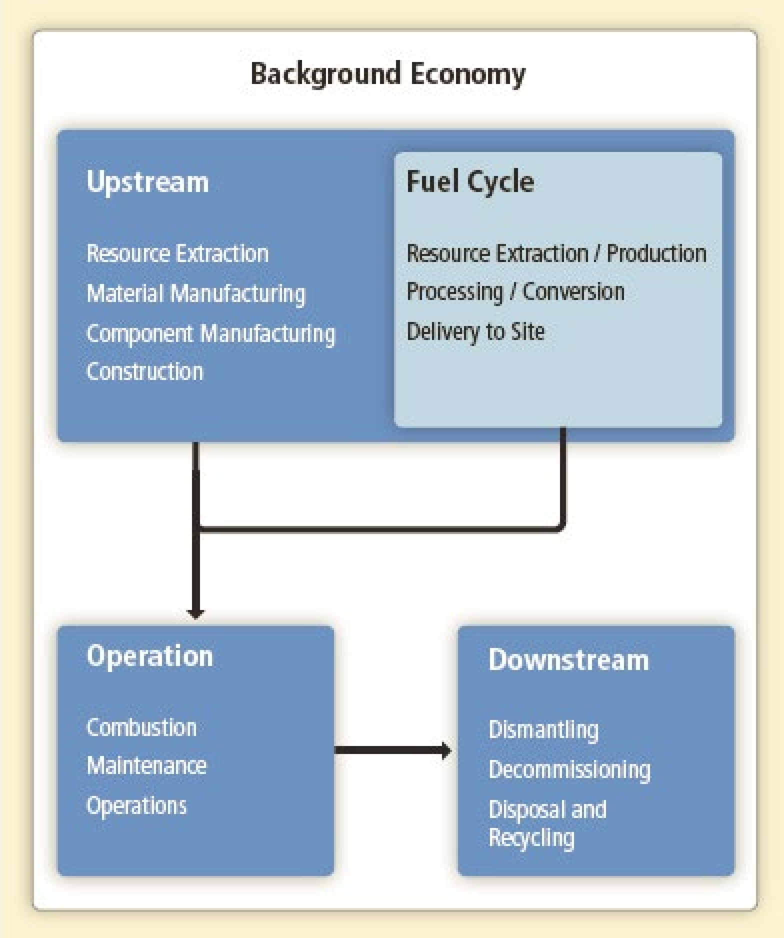
LCA quantifies resource consumption, energy use, and emissions, from cradle-to-grave

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

Forms a basis for consistent comparison of renewable and conventional energy technologies, internationally recognized and used in, for example, Intergovernmental Panel on Climate Change (IPCC) reports.

Metrics

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



Life cycle for energy supply technologies

Source: IPCC SRREN 2012

Example: LCA Used in IPCC 5th Assessment Report (AR5)

Potential emission reduction from mitigation measures (7.8.1):
"***When assessing the potential of different mitigation opportunities, it is important to evaluate the options from a lifecycle perspective*** to take into account the emissions in the fuel chain and the manufacturing of the energy conversion technology (Annex II.6.3)."

Material flow analysis, input-output analysis, and lifecycle assessment (Annex.II.6):
"In the WGIII AR5, findings from material flow analysis, input-output analysis, and lifecycle assessment are used in Chapters 1, 4, 5, 7, 8, 9, 11, and 12."

Lifecycle assessment (A.II.6.3):
"Lifecycle assessment plays an increasingly important role in climate mitigation research (SRREN Annex II, Moomaw et al. 2011). ***In Working Group III (Mitigation) AR5, lifecycle assessment has been used to quantify the GHG emissions associated with mitigation technologies***, e. g., wind power, heat recovery ventilation systems, or carbon dioxide capture and storage. ***Lifecycle assessment is thus used to compare different ways to deliver the same functional unit, such as one kWh of electricity.***

Lifecycle assessment has also been used to **quantify co-benefits and detrimental side-effects of mitigation technologies and measures**, including other environmental problems and the use of resources such as water, land, and metals."

Depth and Breadth of LCA at NREL

Chapter 3

Total Fuel Cycle Emissions Analysis of Biomass-Ethanol Transportation Fuel

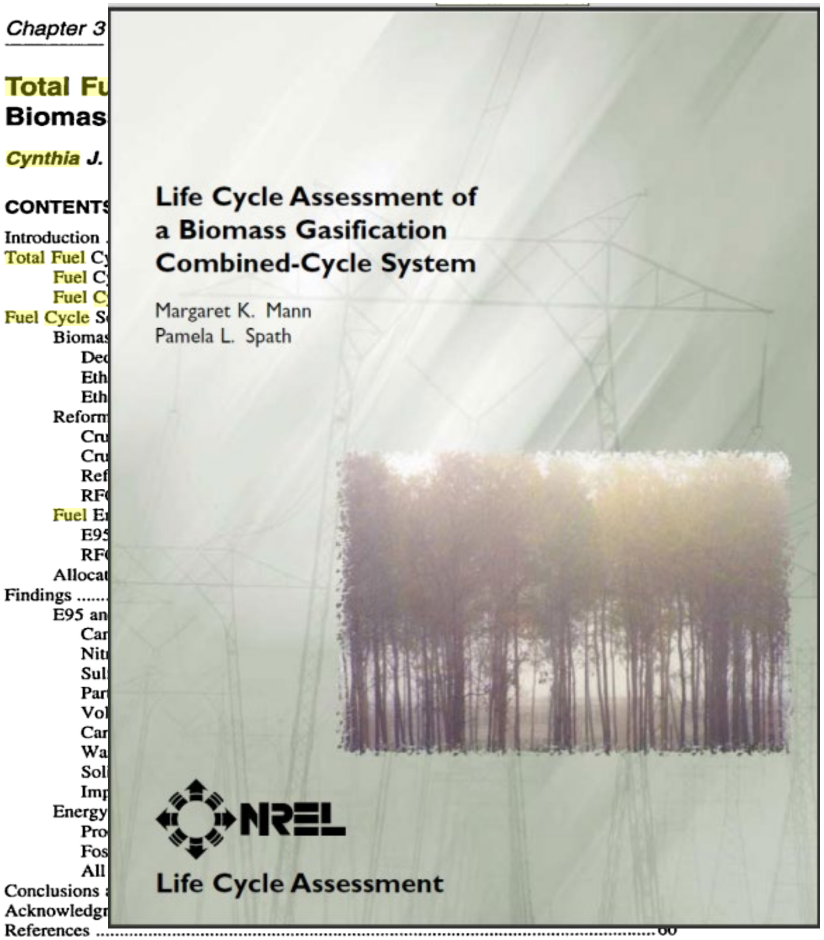
Cynthia J. Riley and K. Shaine Tyson

CONTENTS

1992 → **2015**

Current projects: Life cycle air emission inventories for biofuels, comparative PV manufacture LCA, importance of natural gas methane leakage.

Depth and Breadth of LCA at NREL



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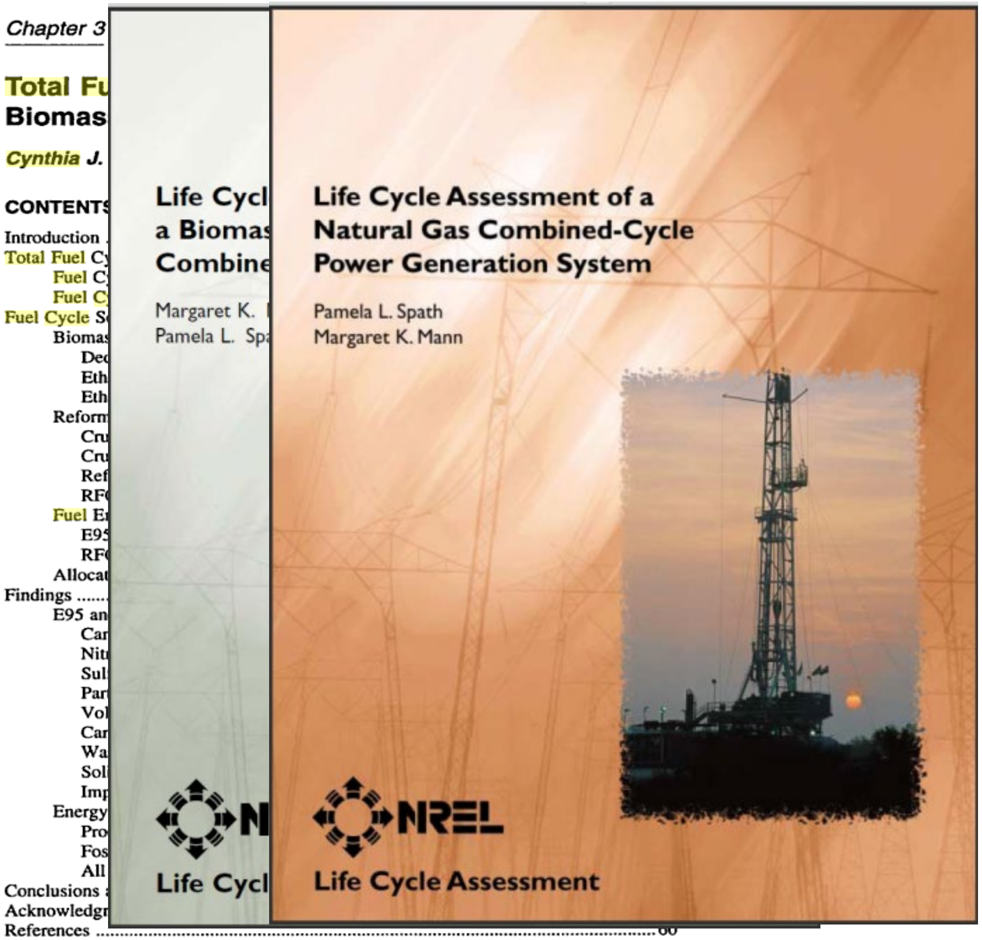

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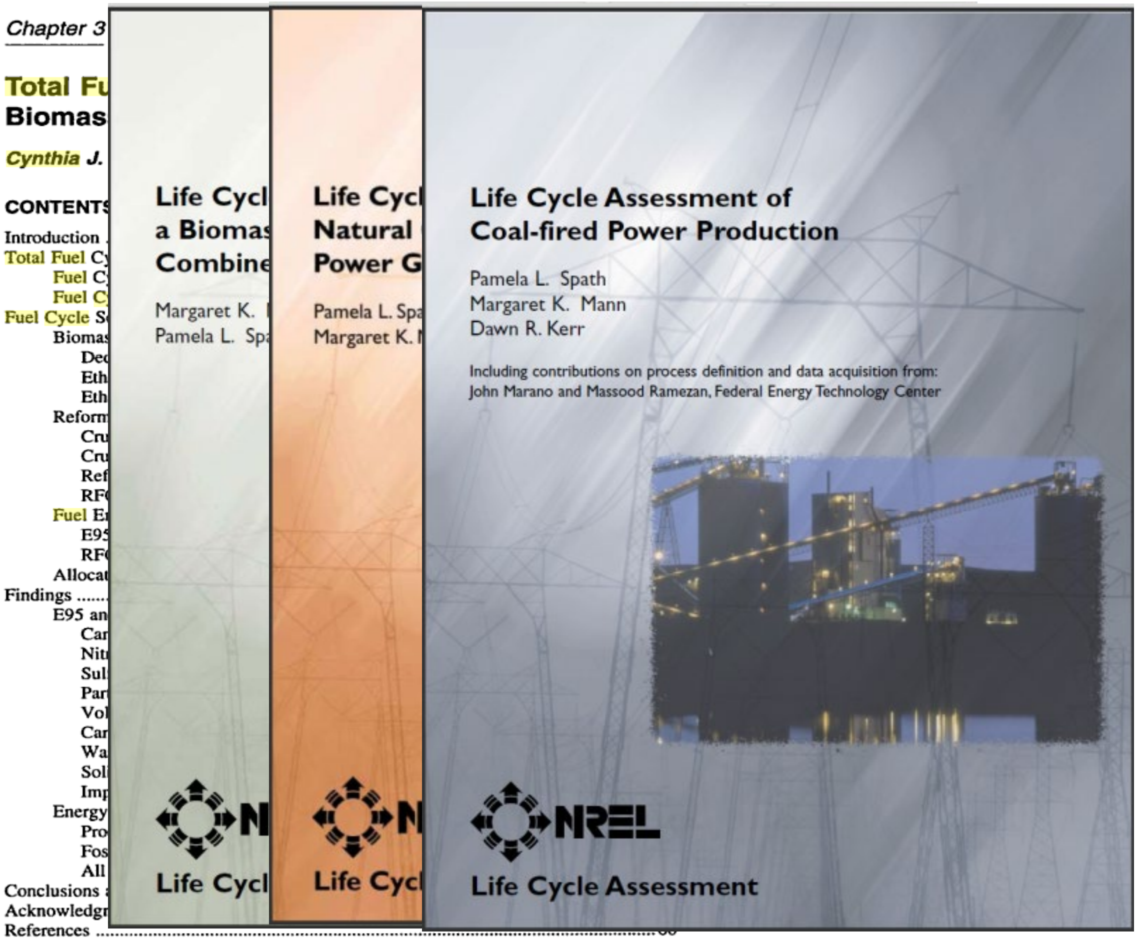

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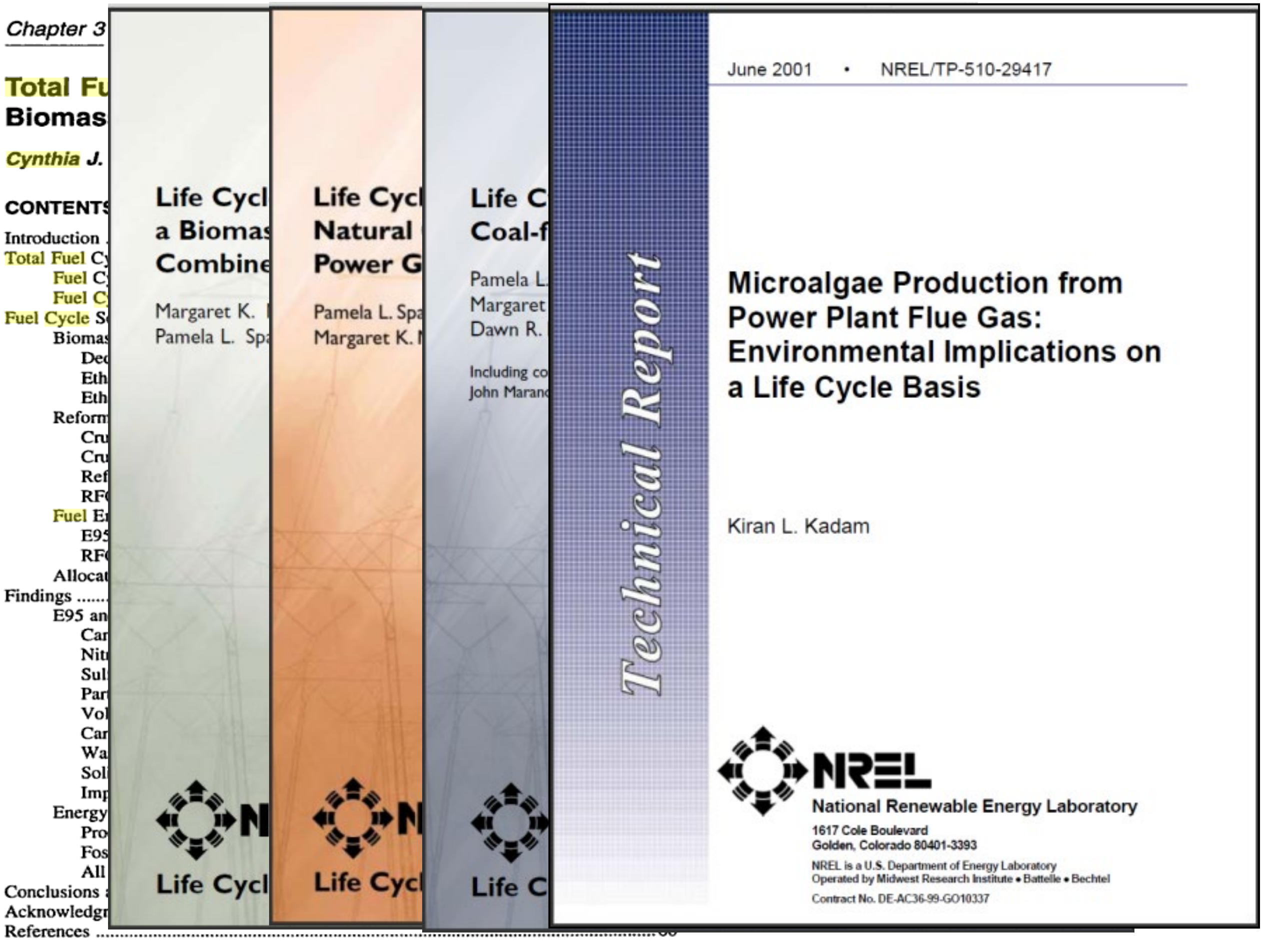

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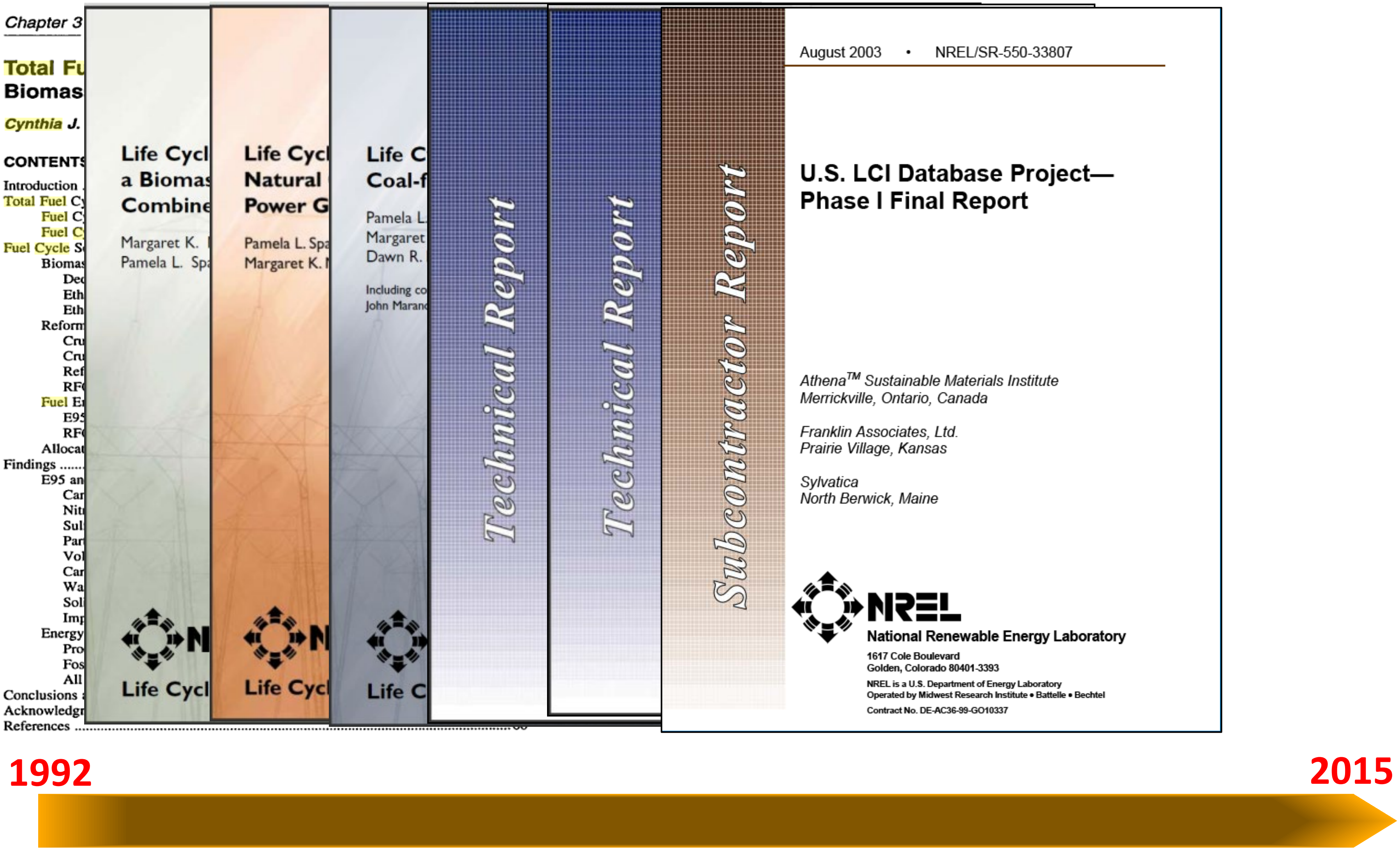

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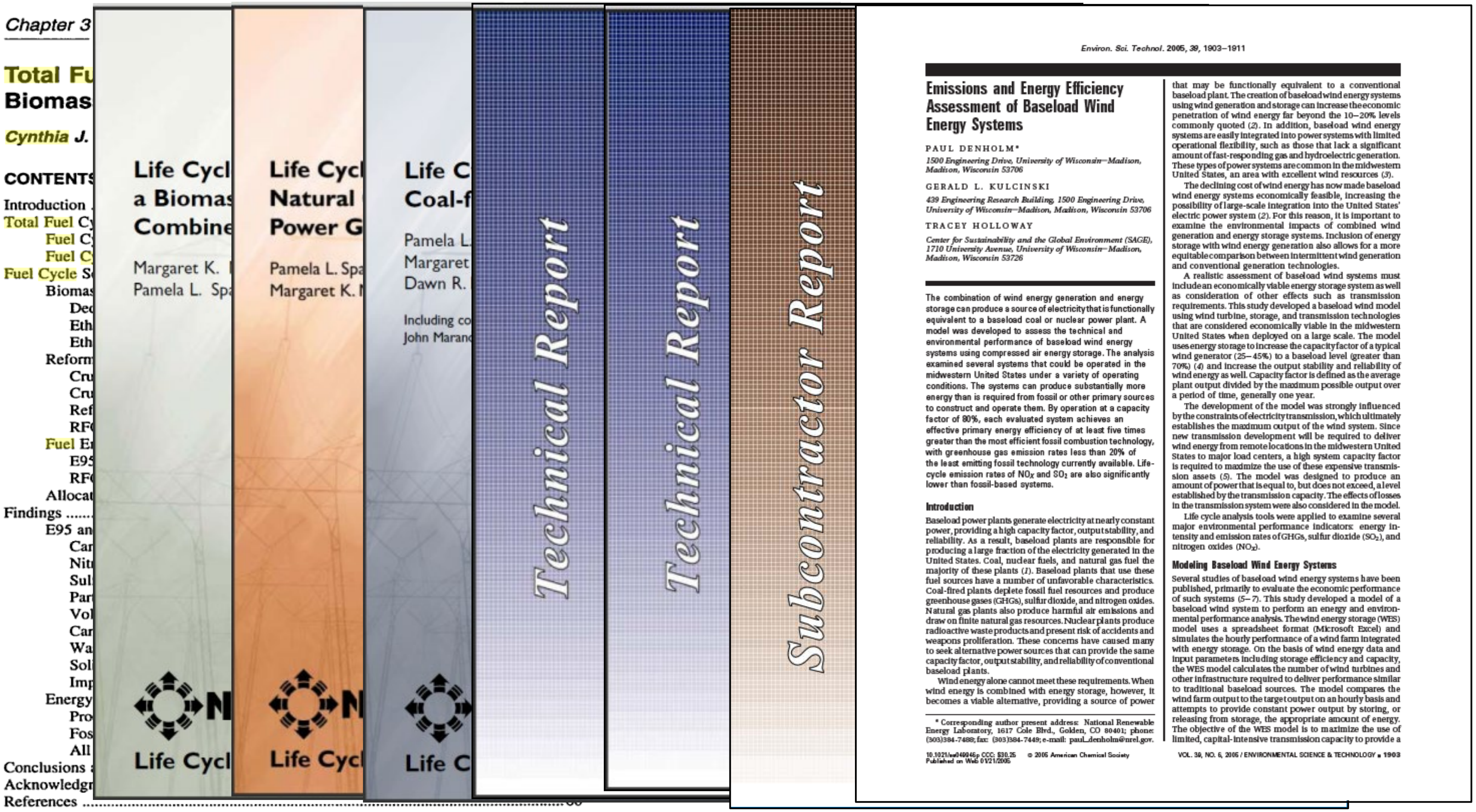

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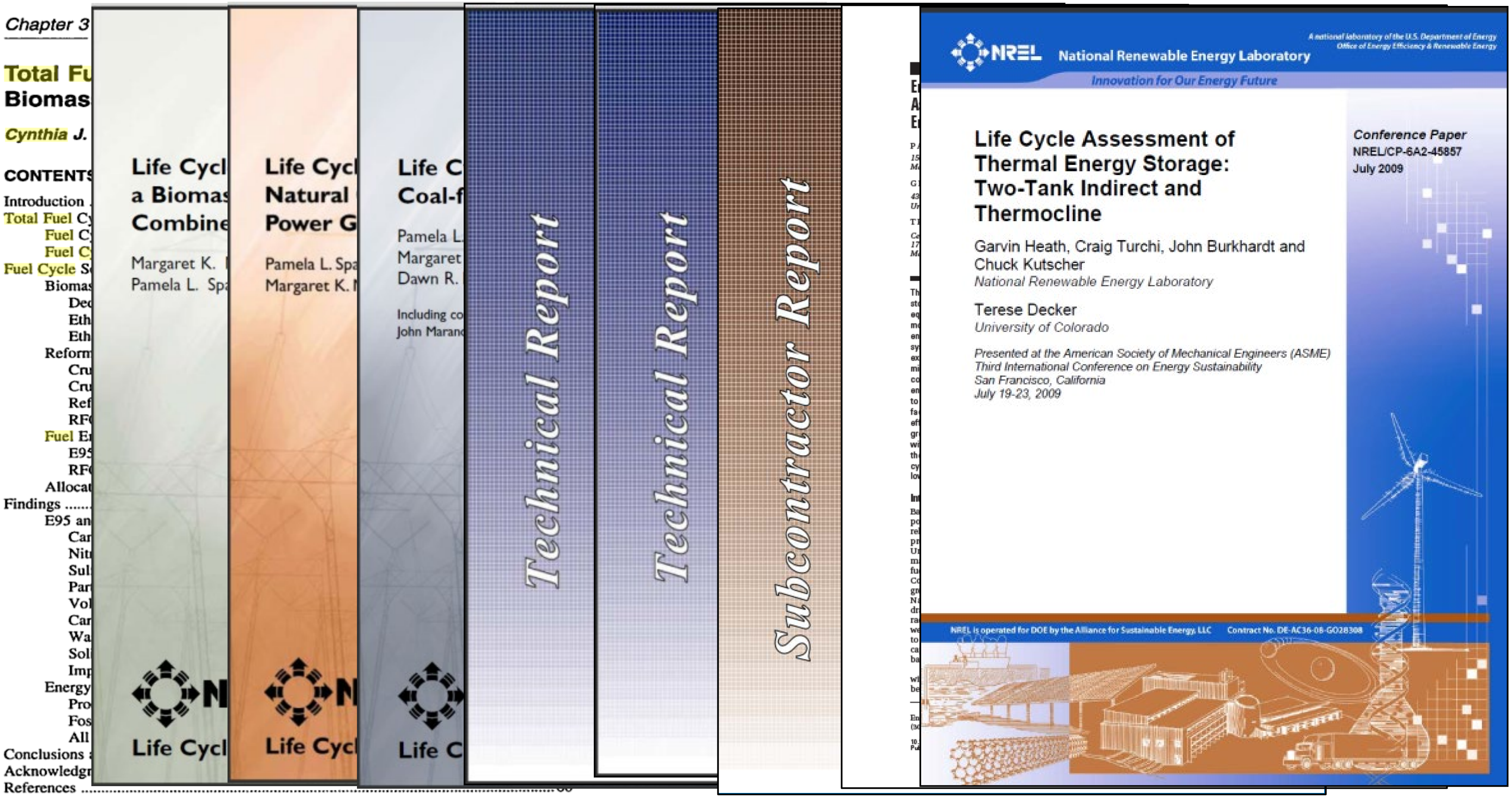

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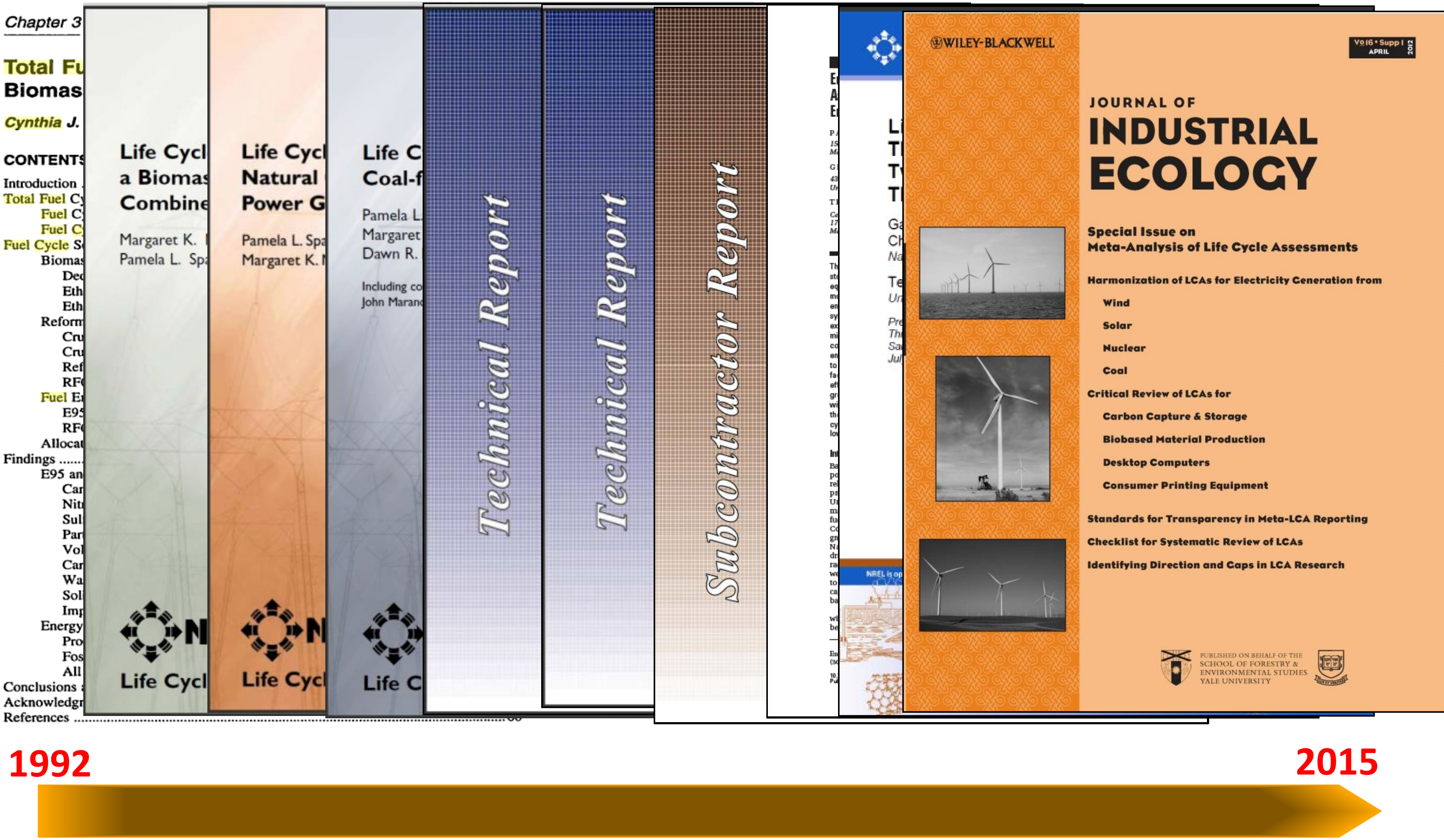

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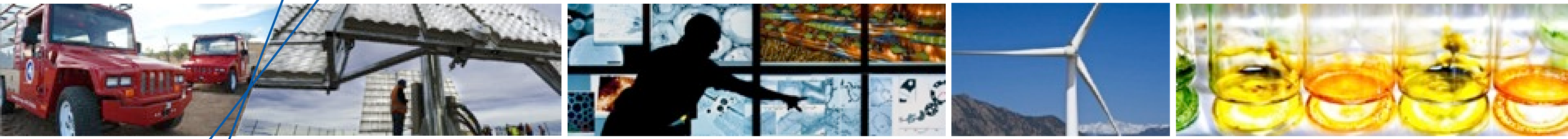
Review of Environmental Impacts of Electricity Generation Technologies:



- Greenhouse Gas (GHG) Emissions
- Water Use
- Land Use

Greenhouse Gas Emissions from Electricity Generation Technologies:

1. Systematic Review and Harmonization of LCAs
2. Natural Gas Methane Emissions

Special Issue of *Journal of Industrial Ecology* on Meta-Analysis of LCA
Issue publication date: May 2012

Conventional Natural Gas (*JIE* 2014)
Unconventional Natural Gas (*PNAS* 2014)

Methane emissions from natural gas systems (*Science* 2014).

Need for Systematic Review and Meta-Analysis

Context

- Considerable previous work in assessing life cycle environmental impacts of electricity generation technologies
  - Scrutinized **> 2,000** references to date
- Lack of holistic evaluation of this work in a consistent manner, especially across technologies
- Methodological inconsistency has hampered cross-study comparisons
- Result is impression amongst decision makers that state of the science is inconclusive

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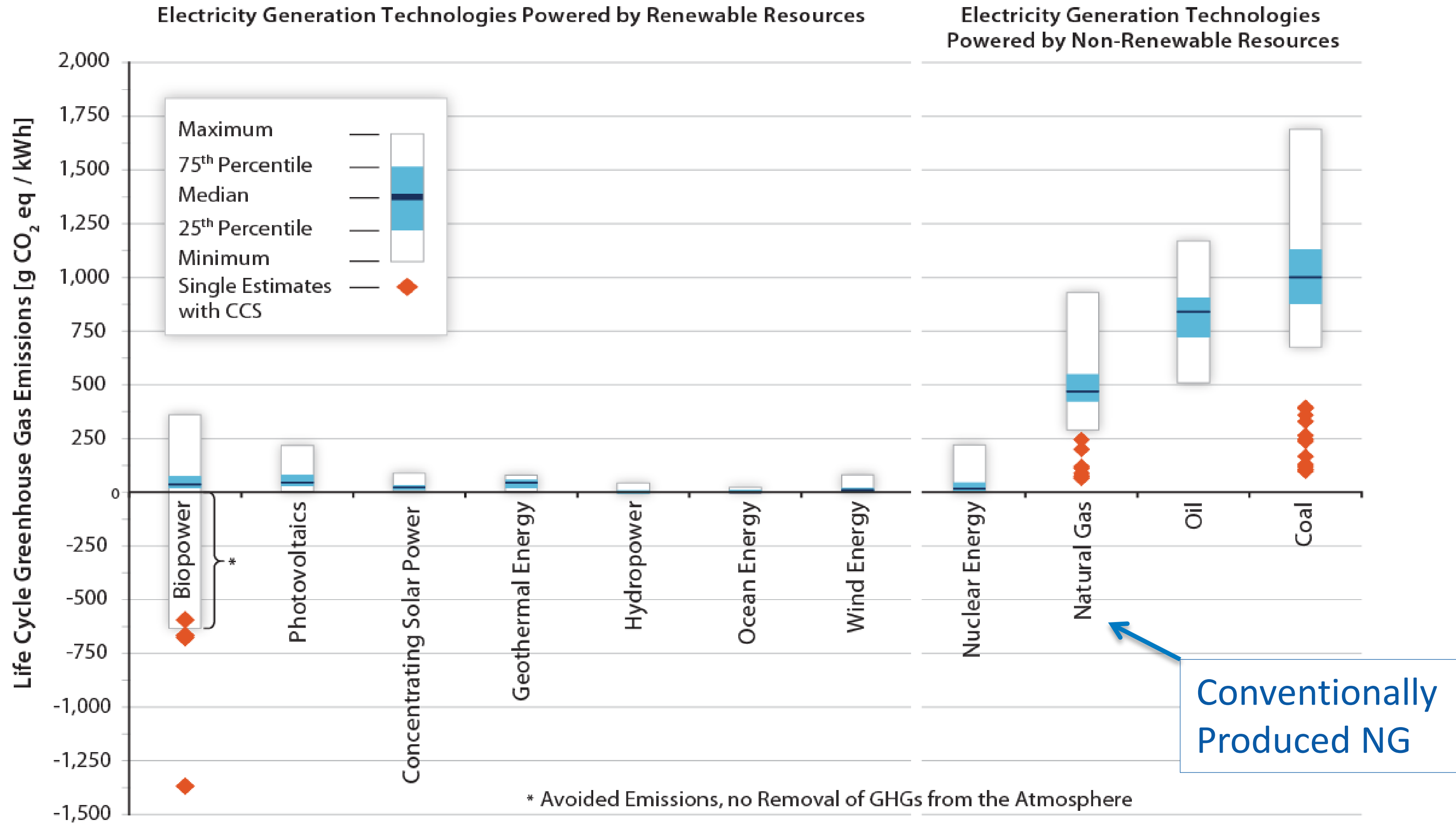
LCA Harmonization Study Goals

- Understand range of published results
- Reduce uncertainty and inconsistency around estimates of environmental impacts of electricity generation technologies
- Make the information useful to decision makers in the near term.

Large Variability for Some Technologies; Renewables Considerably Lower than Fossil

IPCC SRREN
SPM Fig. 8



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)

NREL's LCA Harmonization Project

Lifecycle greenhouse gas emissions (IPCC AR5 WGIII A.II.9.3):
"The assessment of GHG emissions and other climate effects associated with electricity production technologies presented here is based on two distinct research enterprises.

The first effort started with review of lifecycle GHG emission for the IPCC SRREN (Sathaye et al. 2011). This work was extended to a harmonization of LCA studies and resulted in a set of papers published in a special issue of the *Journal of Industrial Ecology* (2012)." (PNAS, too)

Types of Harmonization

System Harmonization
- System boundaries
- Global warming potential (GWP)

Technological Harmonization
- Plant performance characteristics (e.g., efficiency, capacity factor)
- Lifetime

Geographic Harmonization
- Solar resource.

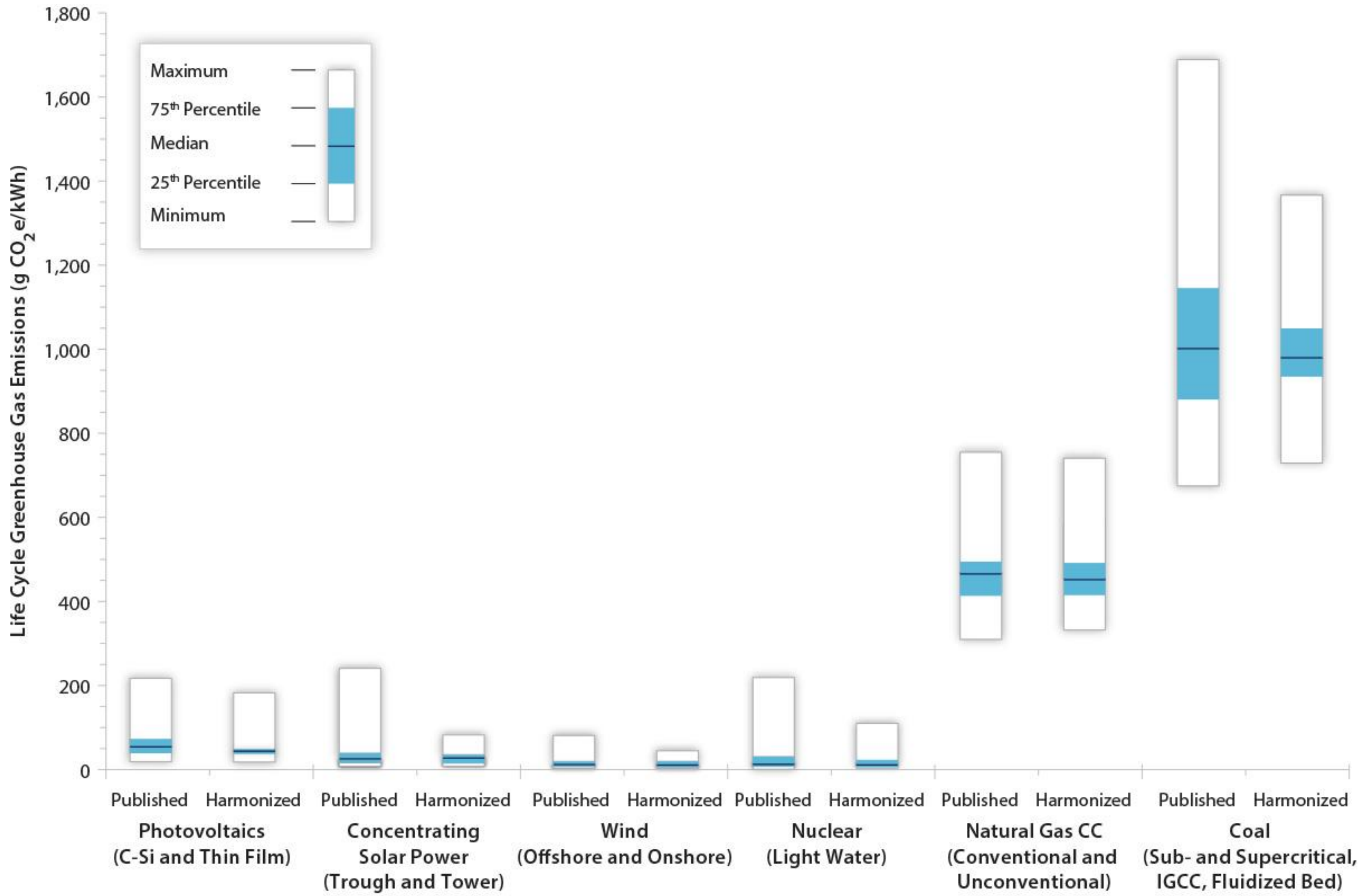
Method

1. Proportional adjustment of denominator of:

$$GHG = \frac{GHG_{lifetime}^{GWP\_weighted}}{lifetime\_generation}$$

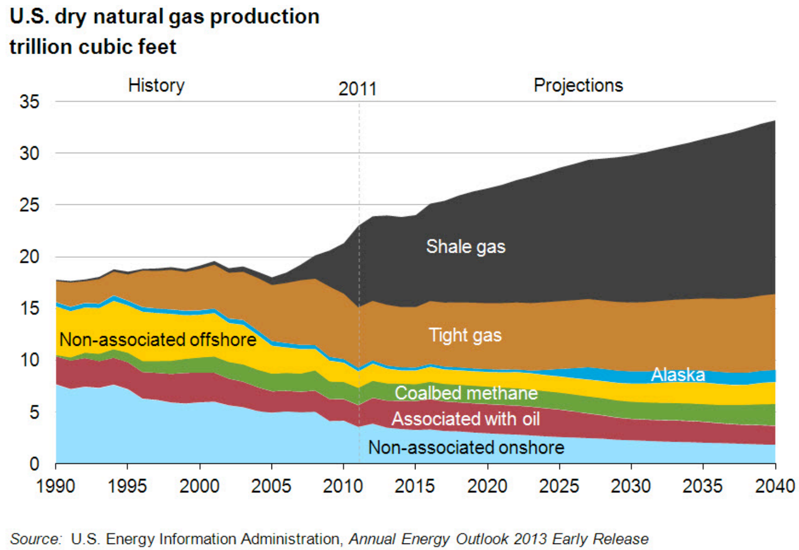
2. Addition or subtraction for system boundary

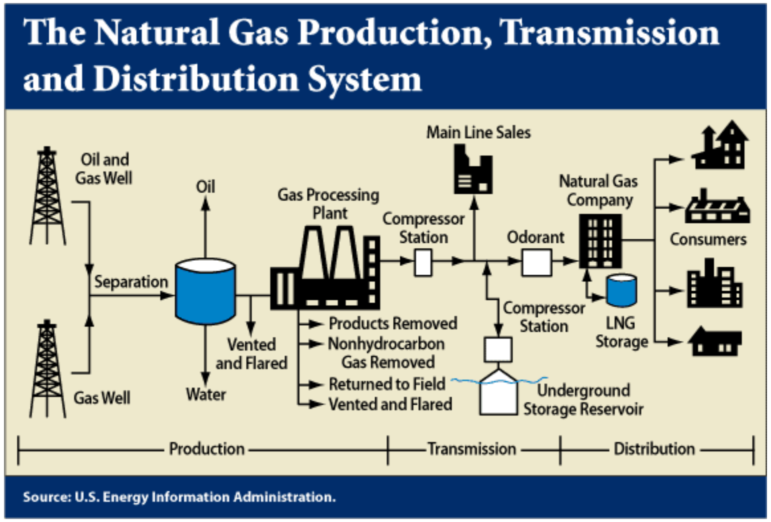
Methodological Harmonization Reduces Variability and Clarifies Central Tendency



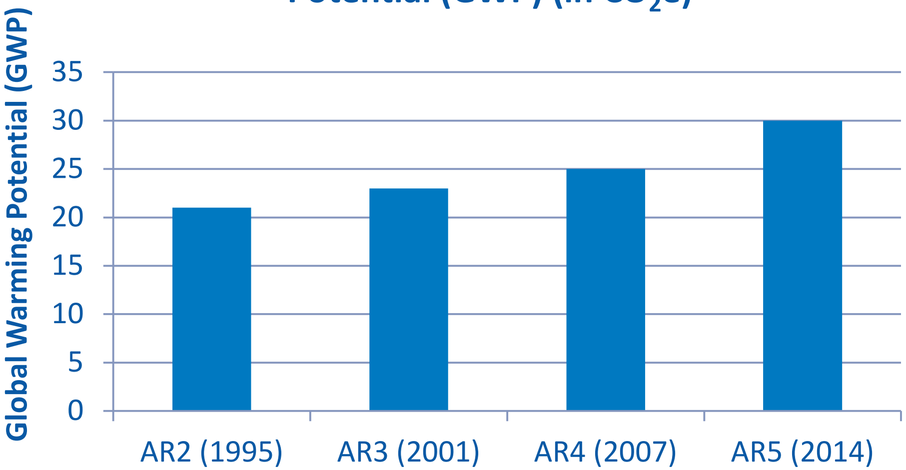
	Photovoltaics	Concentrating Solar Power	Wind	Nuclear	Natural Gas CC	Coal
Estimates	46	36	126	99	61	164
References	17	10	49	27	45	53

Example: Natural Gas and Methane



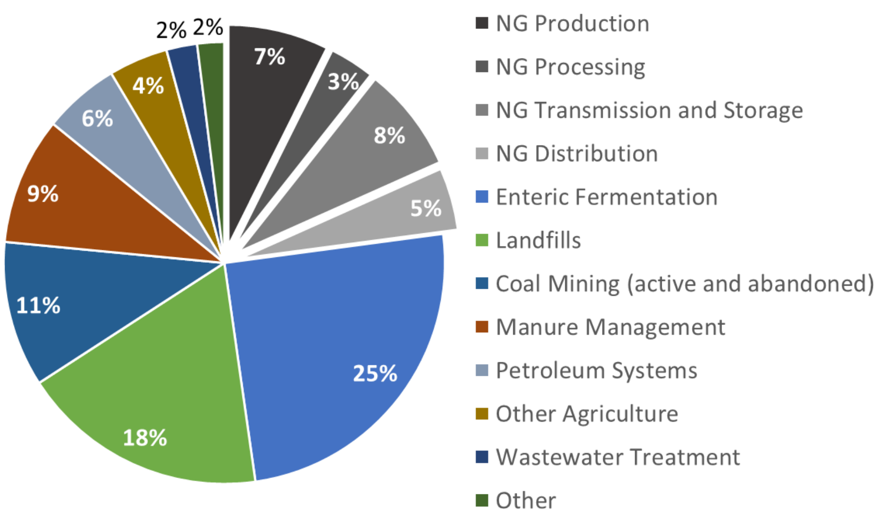


IPCC Methane 100-year Global Warming Potential (GWP) (in CO_2e)

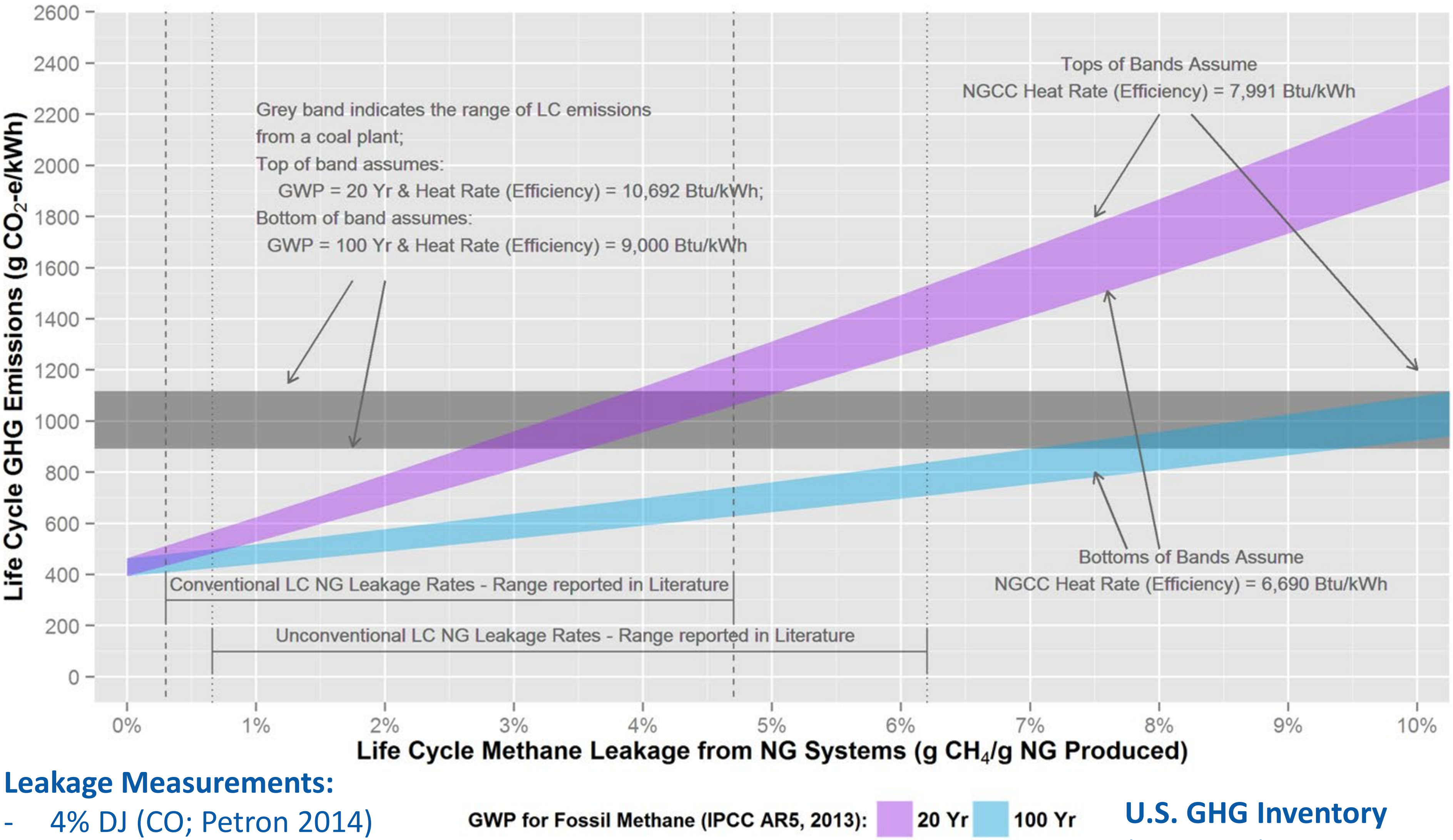


CO_2e = carbon dioxide equivalents; AR = Assessment Report

2014 U.S. GHG Inventory (using CH_4 100-yr GWP = 25)



Coal vs. Gas: Climate Benefit Depends on Leakage Rate and Global Warming Potential (GWP) Time Horizon



Leakage Measurements:

- 4% DJ (CO; Petron 2014)
- 9% Uintah (UT; Karion 2013)
- 17% LA basin (CA; Peischl 2013).

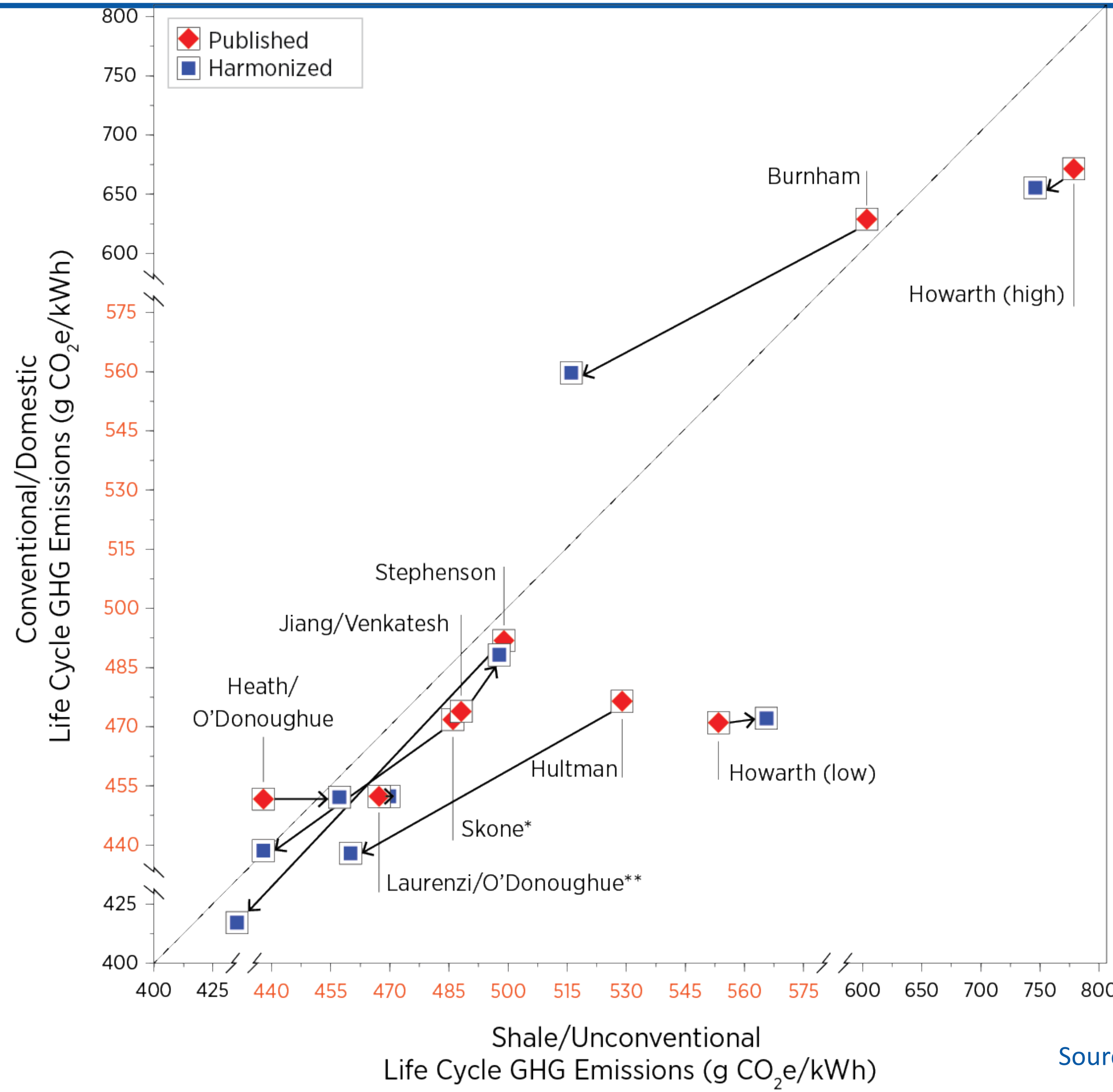
U.S. GHG Inventory
(EPA 2014): ~1.4%

Note: LC = life cycle, NGCC = natural gas combined cycle

Shale (Unconventional) Gas LCAs

Study	*Headline GHG result*
1. Howarth et al. 2011	1. NG > Coal
2. Jiang et al. 2011 (CMU)	2. Marcellus Gas < Domestic gas (conv. + unconv.) < Coal
3. Skone et al. 2011 (NETL) (added Marcellus in 2012)	3. Conv. (except onshore) < Barnett < Coal
4. Hultman et al. 2011	4. Unconv. < Conv. < Coal
5. Stephenson et al. 2011 (Shell)	5. Conventional < Shale < Coal
6. Burnham et al. 2012 (ANL)	6. Shale < Conventional < Coal
7. Logan et al. 2012 (JISEA)	7. Barnett/Unconv. ≈ Conv. < Coal
8. Laurenzi and Jersey 2013 (ExxonMobil)	8. Marcellus Gas < Coal

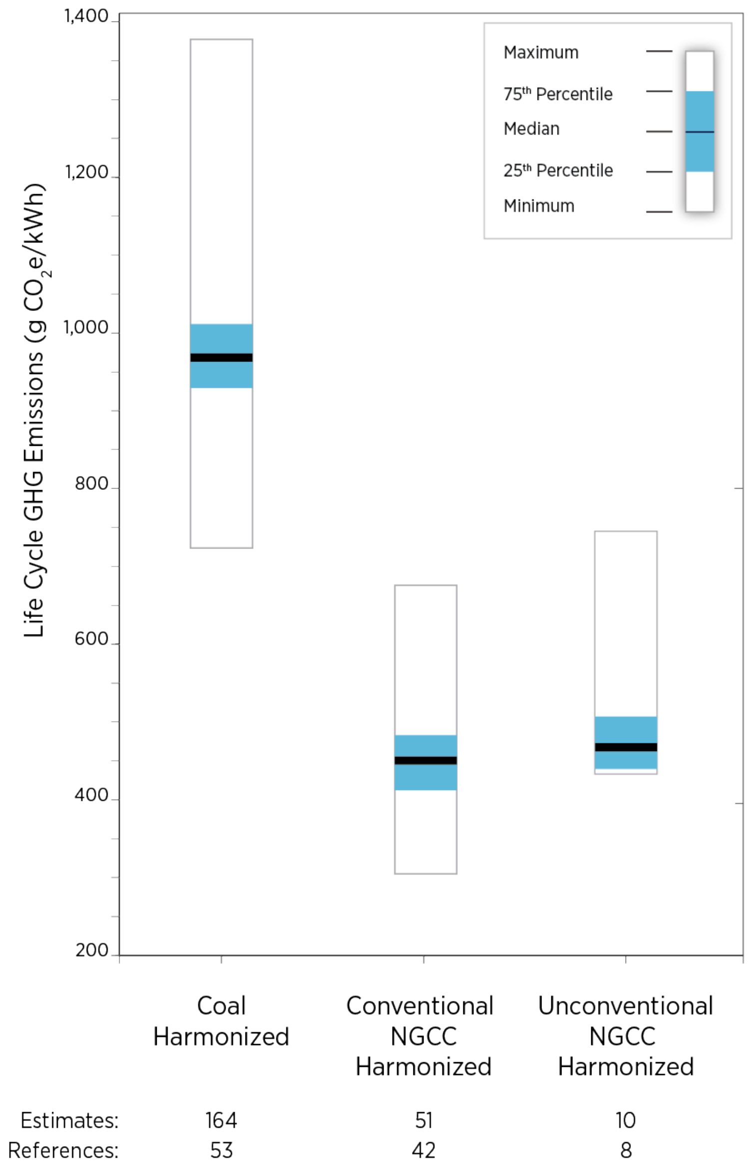
Harmonization of Shale Gas LCAs



Source: Heath et al. 2014

Life Cycle GHG Emissions (After Harmonization):

Comparing Unconventional to Conventional Gas and to Coal



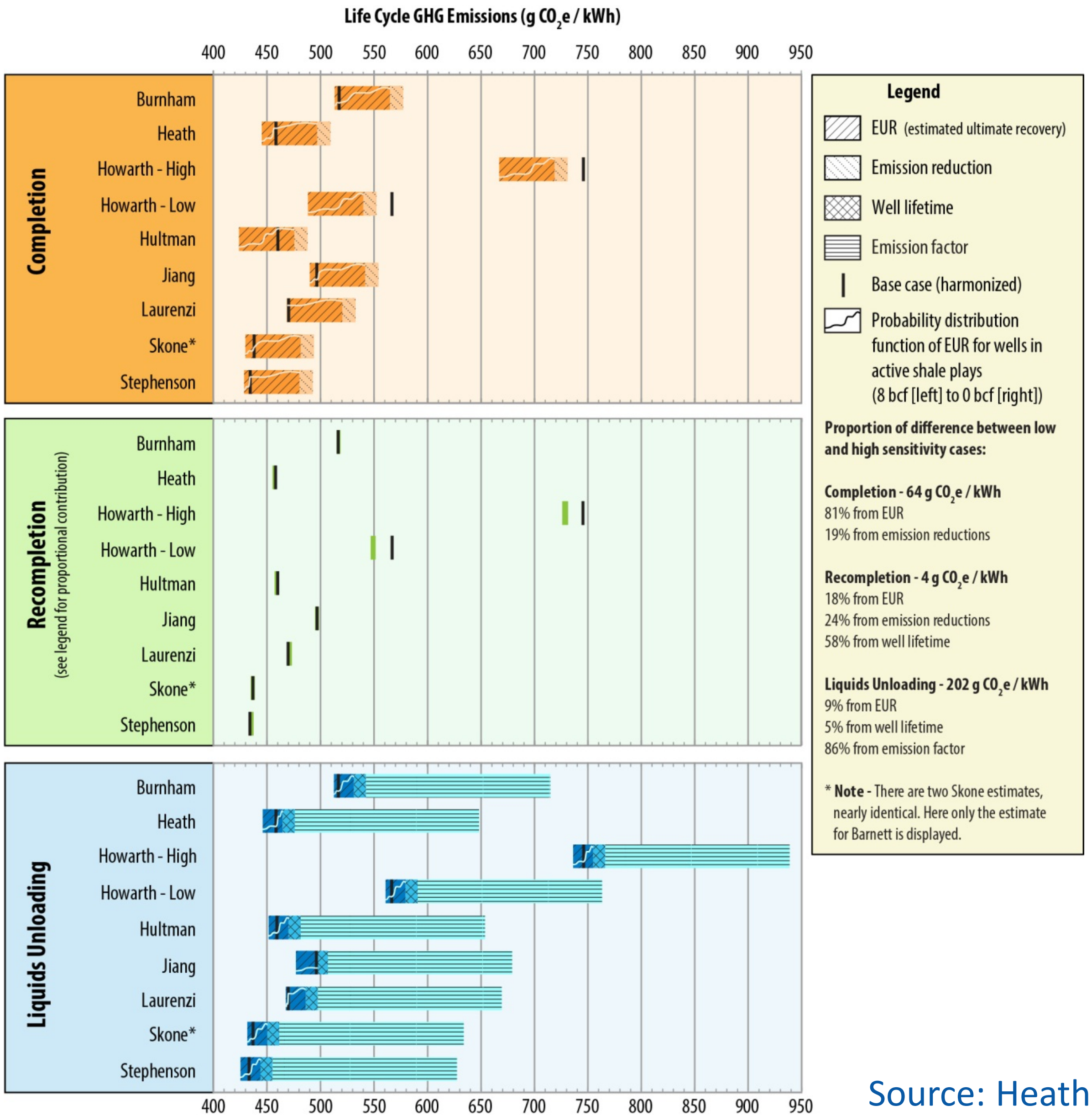
(Methane GWP = 30 for all categories)

Source: Heath et al. 2014

Central Conclusions

- After methodological harmonization, unconventional gas when used to generate electricity is roughly equal to conventional gas in life cycle GHG emissions
- Comparing median estimates, both types of natural gas have half the emissions of coal.

Life Cycle GHG Emissions Sensitive to Assumptions About Liquids Unloading and Estimated Ultimate Recovery (EUR)



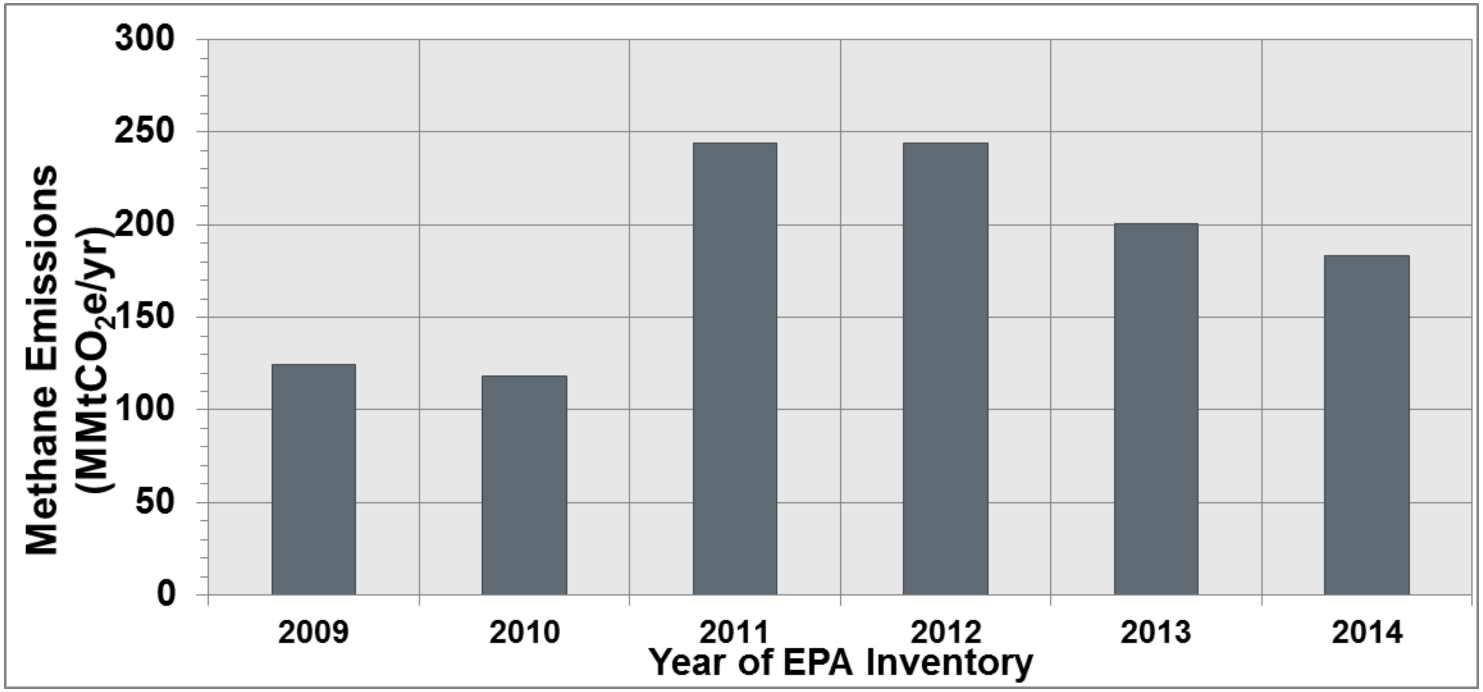
Central Conclusions

- In certain circumstances, gas used to generate electricity can lead to life cycle GHG emissions that can approach those from best-performing coal:
  - Best coal ~750 g CO_2e/kWh (Whitaker et al. 2013)
- Need more empirical research to verify and clarify emission sources, their prevalence, and variability.

Source: Heath et al. 2014

LCAs Rely on Data from Inventories, Which Are Evolving

NG methane inventory for the year 2007 across six U.S. EPA GHG Inventories (2009-2014)



Sources: Larsen 2013 and U.S. EPA 2014

U.S. GHG Inventory, 2011 vs. 2010

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

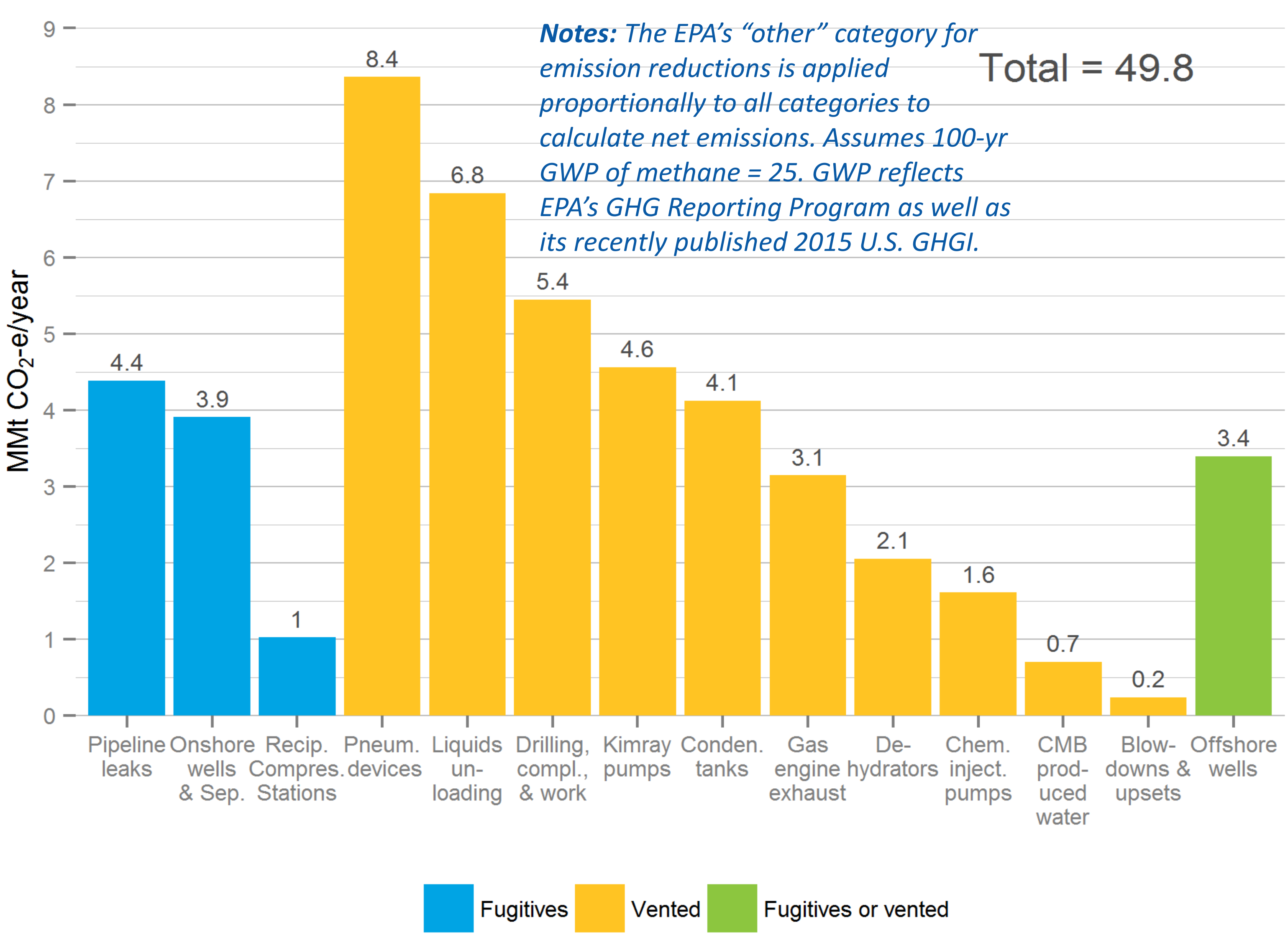
2013 vs. 2012

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

2014 vs. 2013

1. **EFs for:**
   – Condensate tanks
   – Transmission and storage centrifugal compressors
2. **Further modifications to liquids unloading emissions.**

Inventories Support Policy Development and Prioritization: Natural Gas Production Segment Methane Emissions

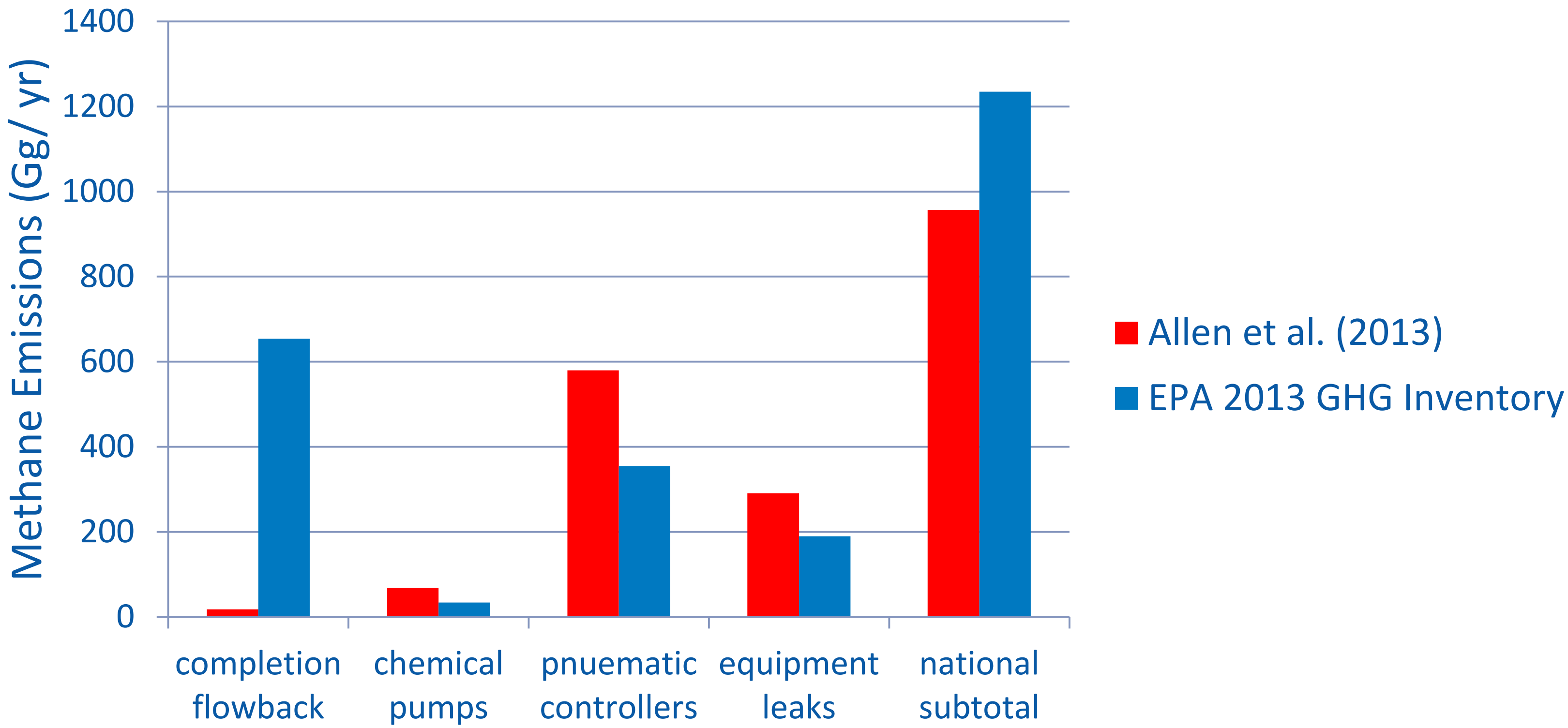


Notes: *The EPA's "other" category for emission reductions is applied proportionally to all categories to calculate net emissions. Assumes 100-yr GWP of methane = 25. GWP reflects EPA's GHG Reporting Program as well as its recently published 2015 U.S. GHGI.*

Source: U.S. EPA 2014 GHG Inventory

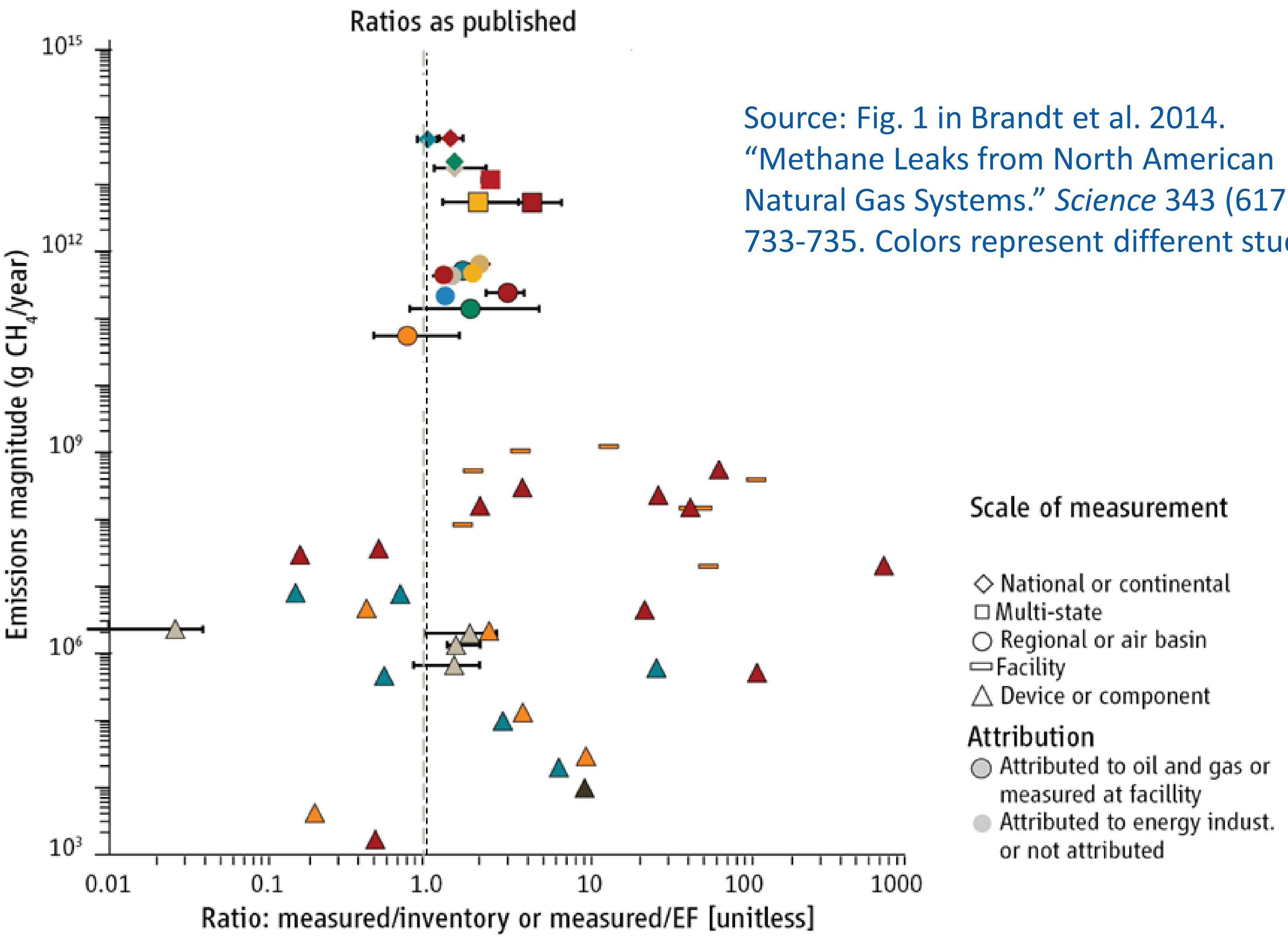
Challenge: Measurements ≠ Inventory

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



Allen et al.'s conclusion: Some sources overestimated by inventory, some underestimated, with errors compensating to result in similar national estimate.

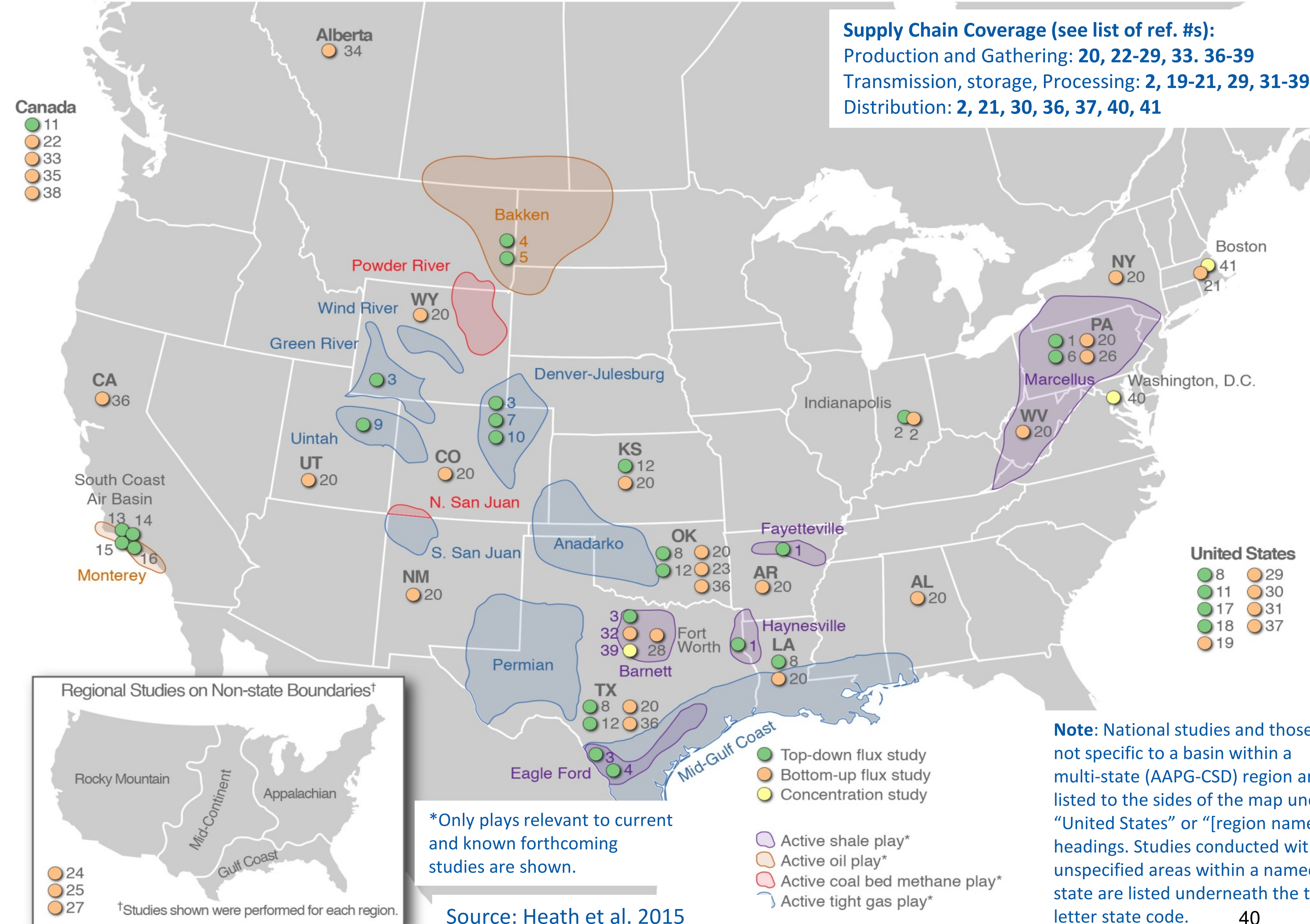
Inventories Typically Underestimate Emissions



Source: Fig. 1 in Brandt et al. 2014. "Methane Leaks from North American Natural Gas Systems." *Science* 343 (6172): 733-735. Colors represent different studies.

CH_4 Measurement Studies Published Through Feb. 2015

Supply Chain Coverage (see list of ref. #s):
Production and Gathering: **20, 22-29, 33. 36-39**
Transmission, storage, Processing: **2, 19-21, 29, 31-39**
Distribution: **2, 21, 30, 36, 37, 40, 41**



*Only plays relevant to current and known forthcoming studies are shown.

Source: Heath et al. 2015

Note: National studies and those not specific to a basin within a multi-state (AAPG-CSD) region are listed to the sides of the map under "United States" or "[region name]" headings. Studies conducted within unspecified areas within a named state are listed underneath the two-letter state code.

Opportunities to Reduce Methane Emissions

Despite scientific uncertainty:

- Leakage detection and repair programs have been shown to be profitable
  - Though revenue retention of recovered gas differs by industry segment
- If we can find them cheaply and quickly, super-emitting sources are profitable to fix
- EPA GHG Inventory is a critical resource that should be improved to provide better policy guidance
  - Reconciliation of measurements to inventory is needed to increase confidence in both inventories and measurements.

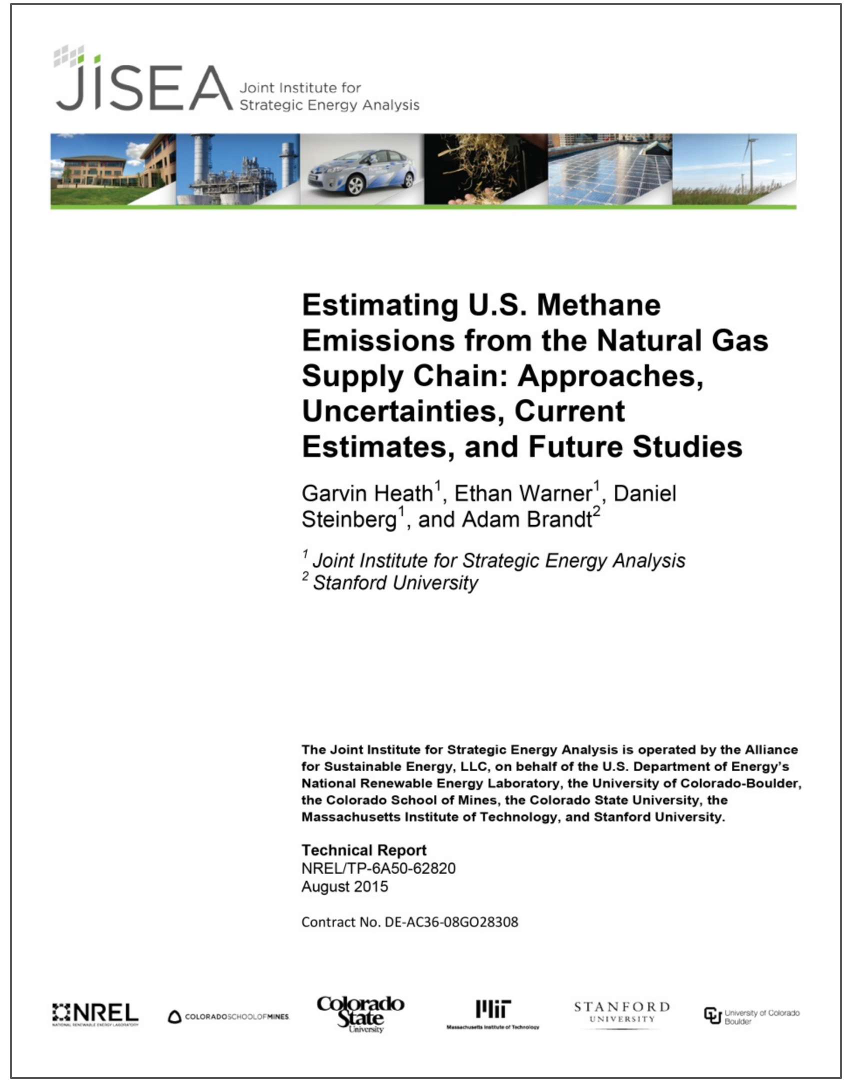
Recent Report: Inventory Improvement Opportunities (8/2015)

Goals:

- Summarize methods and results of the U.S. GHGI
- Identify potential gaps and barriers to improvement
- Identify opportunities to improve accuracy

Foci:

- Methane emissions from the natural gas sector
- National GHG inventory
  - Implications for other inventories (e.g., state) and other pollutants.



JISEA Joint Institute for Strategic Energy Analysis

Estimating U.S. Methane Emissions from the Natural Gas Supply Chain: Approaches, Uncertainties, Current Estimates, and Future Studies

Garvin Heath[1], Ethan Warner[1], Daniel Steinberg[1], and Adam Brandt[2]

[1] Joint Institute for Strategic Energy Analysis
[2] Stanford University

The Joint Institute for Strategic Energy Analysis is operated by the Alliance for Sustainable Energy, LLC, on behalf of the U.S. Department of Energy's National Renewable Energy Laboratory, the University of Colorado-Boulder, the Colorado School of Mines, the Colorado State University, the Massachusetts Institute of Technology, and Stanford University.

Technical Report
NREL/TP-6A50-62820
August 2015

Contract No. DE-AC36-08GO28308

NREL COLORADO SCHOOL OF MINES Colorado State University MIT STANFORD UNIVERSITY University of Colorado Boulder

http://www.nrel.gov/docs/fy16osti/62820.pdf

Water Use In Energy Technologies: A Life Cycle Perspective

Life cycle water consumption of electricity generation technologies: Review and harmonization. (*ERL* 2013)

Operational water consumption and withdrawal factors for electricity generating technologies: A review of existing literature. (*ERL* 2012)

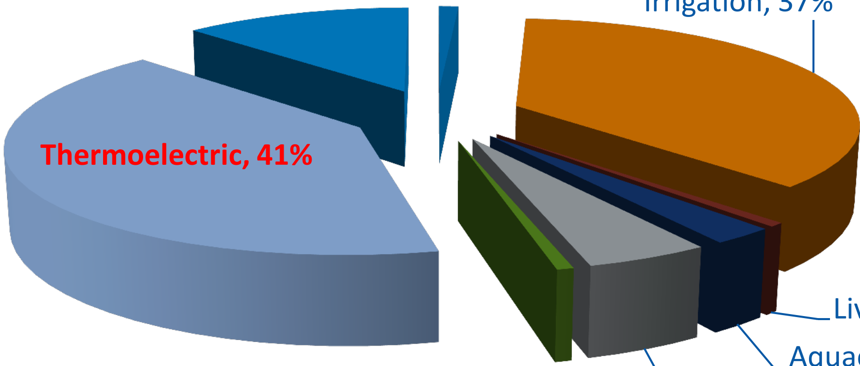
James Meldrum

Jordan Macknick

Garvin Heath

In the U.S., the Electric Sector is a Major End-user of Water

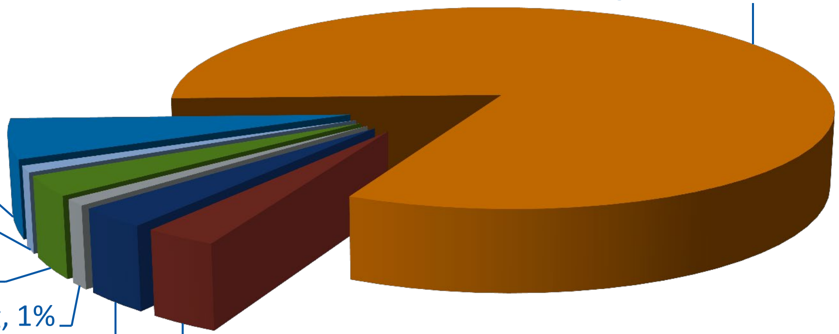
U.S. Freshwater Withdrawals (2005)[1]



Water withdrawals: water removed from the source (e.g., aquifer, river, lake, or ocean) for use.

Water consumption: water that is evaporated (or swallowed, incorporated into a product, or otherwise used) such that it is not available for reuse at the same location.

U.S. Freshwater Consumption (1995)[2*]

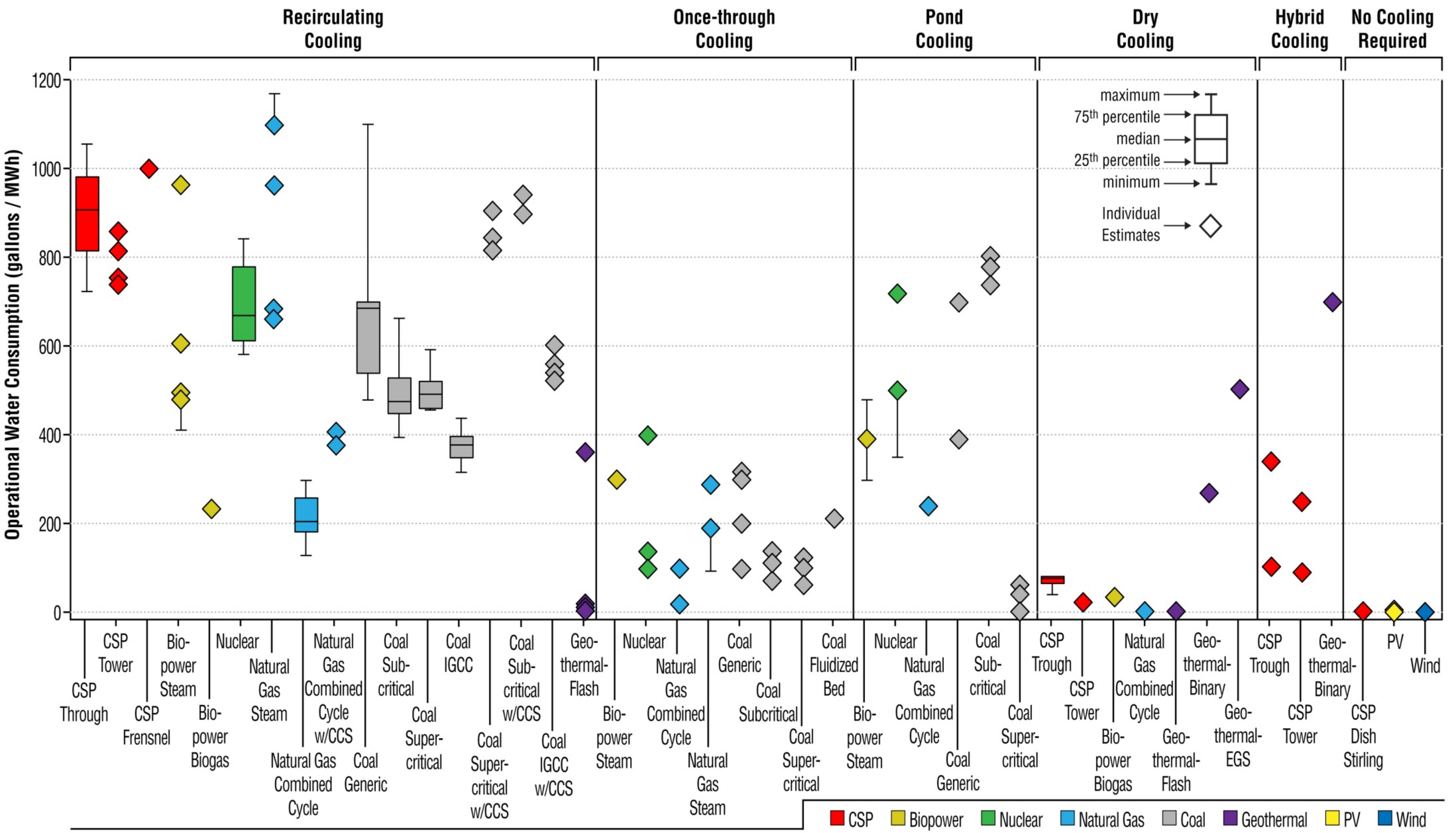


Thermoelectric water requirements (USGS):

- **Withdrawal: ~ 540 Mm^3 /day (41%)**
- **Consumption: ~ 15 Mm^3 /day (3%)**

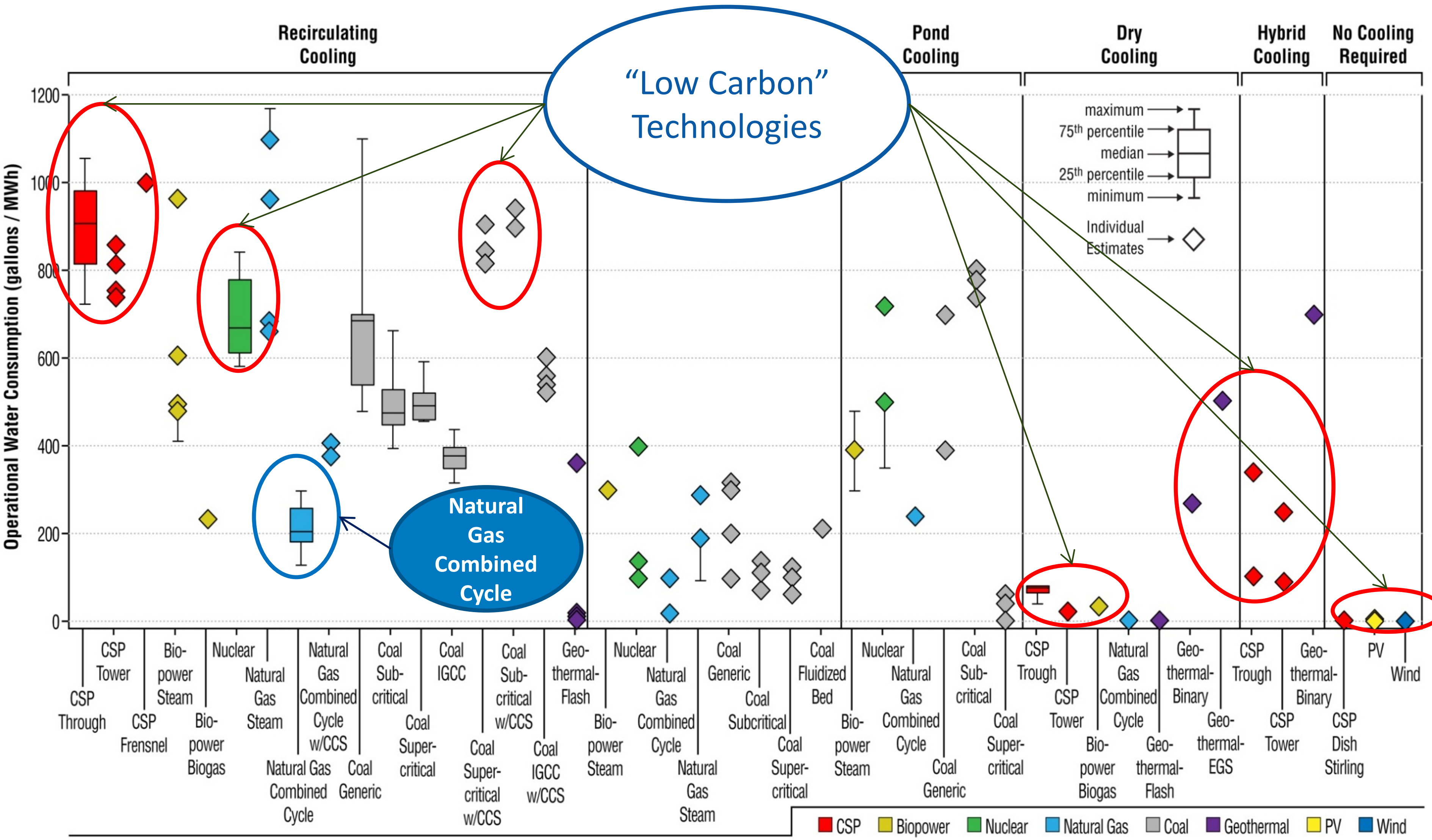
Sources: [1]USGS. 2009. "Estimated Use of Water in the United States in 2005." USGS Circular 1344. Reston, VA: USGS.
[2]USGS. 1998. "Estimated Use of Water in the United States in 1995." USGS Circular 1200. Reston, VA: USGS.
*1995 is the most recent consumption data collected by the USGS

Operational Water *Consumption* Rates (gal/MWh)



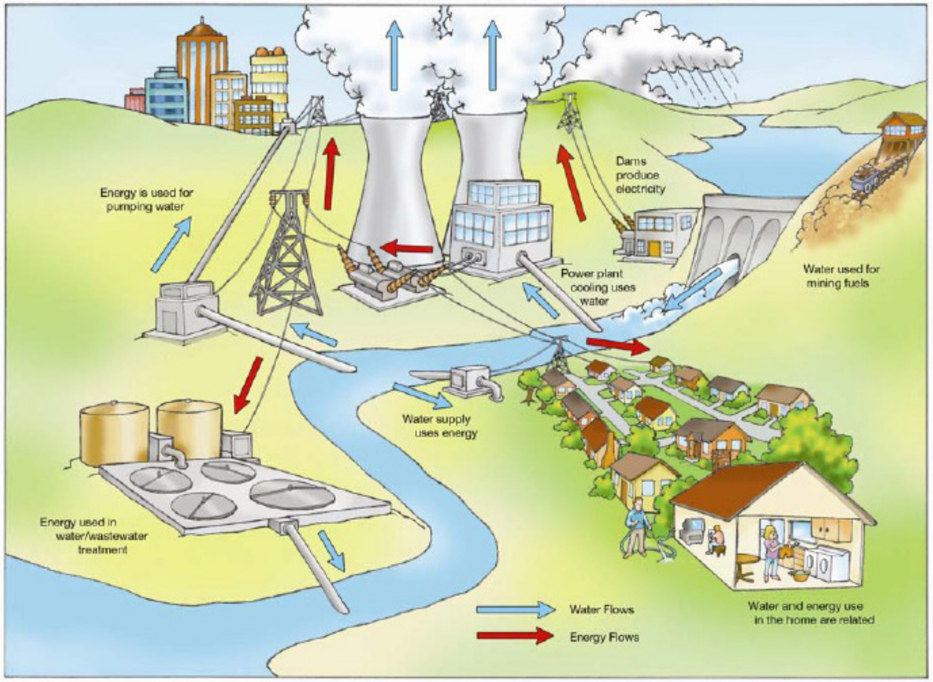
Source: Macknick, J., R. Newmark, G. Heath, and K.C. Hallett. 2012. "Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature." *Environmental Research Letters* 7 (045802).

Operational Water *Consumption* Rates (gal/MWh)



Source: Macknick, J., R. Newmark, G. Heath, and K.C. Hallett. 2012. "Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature." *Environmental Research Letters* 7 (045802).

Uses of Water in Life Cycle



Source: DOE, 2006

Manufacturing and Construction
- Embedded water in materials
- Component manufacturing
- Power plant construction (dust suppression)
- Power plant decommissioning

Power Plant Operation
- Steam cycle
- Environmental controls (e.g., scrubbers)
- Hotel/washing
- ***Cooling system***

Fuel Cycle (NG, coal, nuclear)
- Extraction (drilling, fracking, mining)
- Processing
- Transport
- End of life storage/handling

Harmonization of Water Use Estimates

Goal: Common metrics and assumptions across a variety of energy types

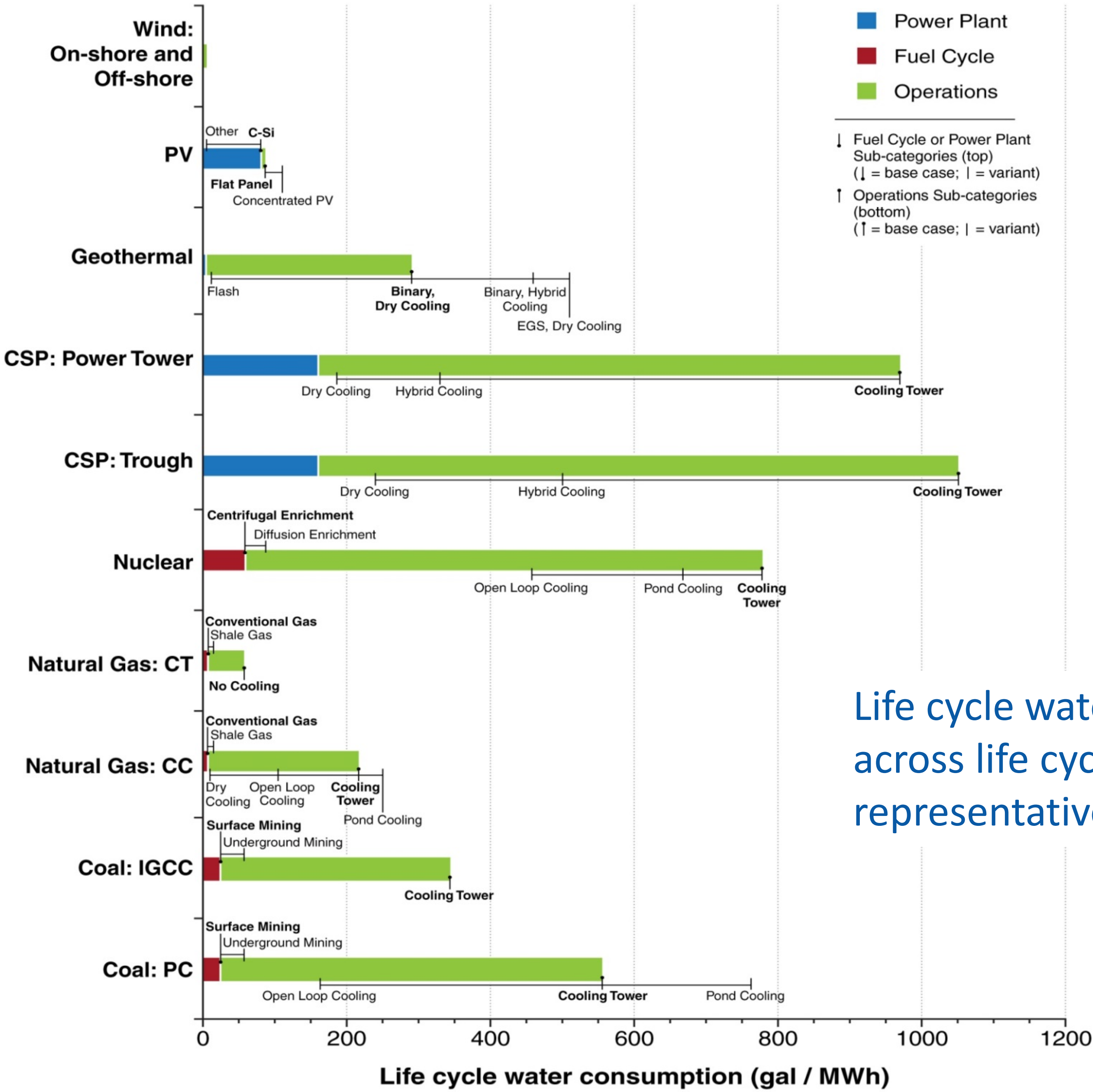
Common metric: gallons/MWh of electricity generated. This is important because more than LCAs were utilized.

Harmonization: When possible, certain parameters were modified to a consistent value to provide greater consistency and comparability across studies.

Parameters

- Thermal efficiency
- Fuel heat content
- Solar-to-electric efficiency
- Solar resource
- Capacity factor
- Plant lifetime

Sensitivity estimated through low and high ranges of harmonized parameters.



Life cycle water consumption across life cycle stages for representative facilities.

Source: Meldrum et al. 2013

Summary of Water Use Results

- Water is used in every life cycle stage
  - This use occurs in different places and times
- Withdrawal and consumption for thermoelectric facility operations is typically much higher than for other stages
  - Varies drastically by cooling type
- PV and wind technologies have lower life cycle use
  - Most of their use comes from manufacturing
- Estimates vary by details of technologies investigated, scenarios, etc.

Implications

Water use creates vulnerabilities at every step along fuel and supply chains

- Extreme weather events are one source of risk
  - 2011 Texas drought limited development of shale gas
  - 2007 Southeast drought led to power plant curtailment
- Operations are particularly vulnerable
  - Potential EPA regulation (Section 316(b) under CWA)
  - Cooling technologies face cost/performance trade-offs

Choices (e.g., specific technology, supply chains) can have impacts on risk and vulnerability for owners and purchasers.

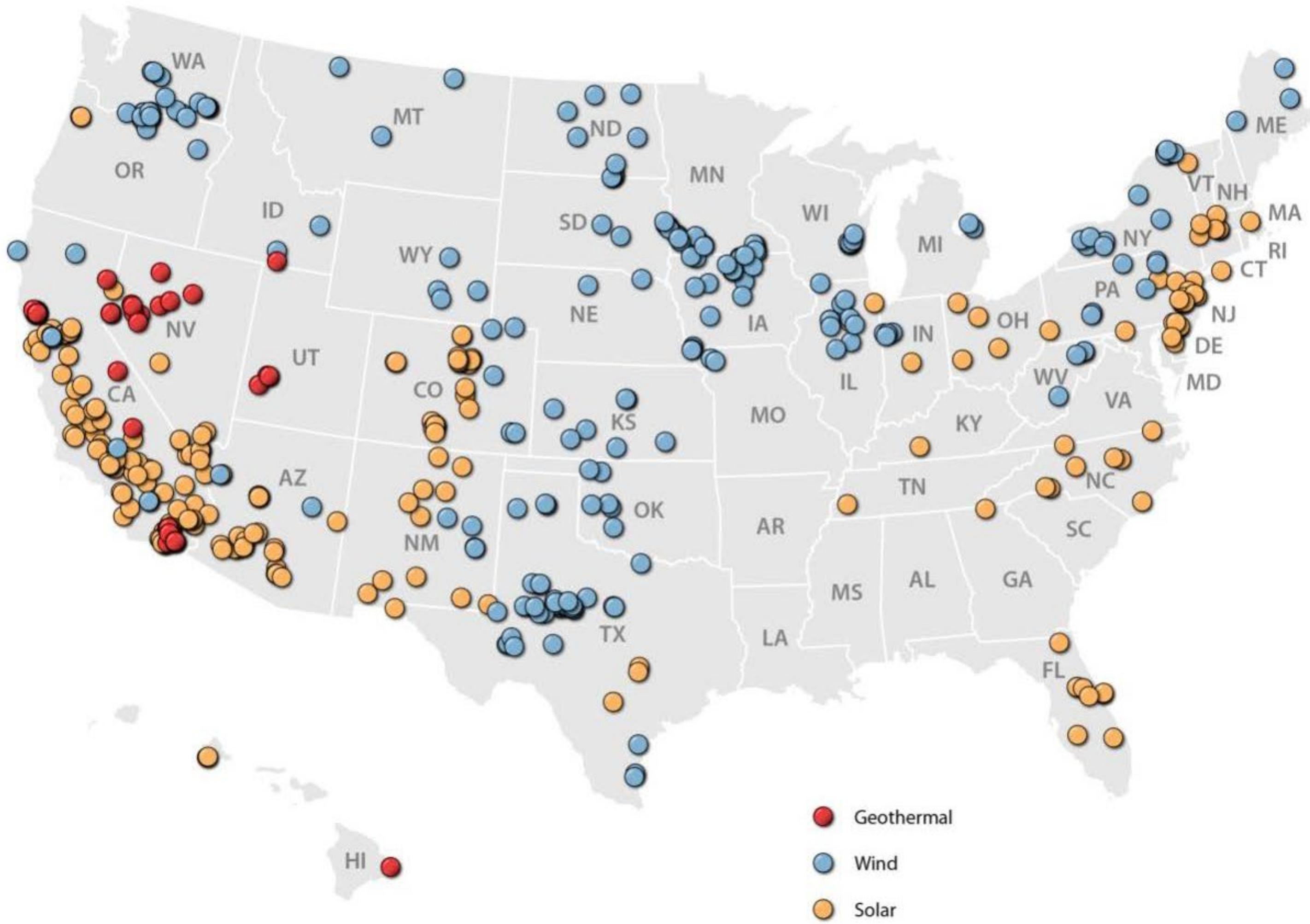
Operational Land Use by Selected Electricity Generation Technologies

Land-Use Requirements of Modern Wind Power Plants in the United States. 2009. NREL/TP-6A2-45834.

Land-Use Requirements for Solar Power Plants in the United States. 2013. NREL/TP-6A20-56290.

Land Use for Wind, Solar, and Geothermal Electricity Generation Facilities in the United States.
(EPRI report: Ong et al. 2013)

Sites Assessed



As of 2012:

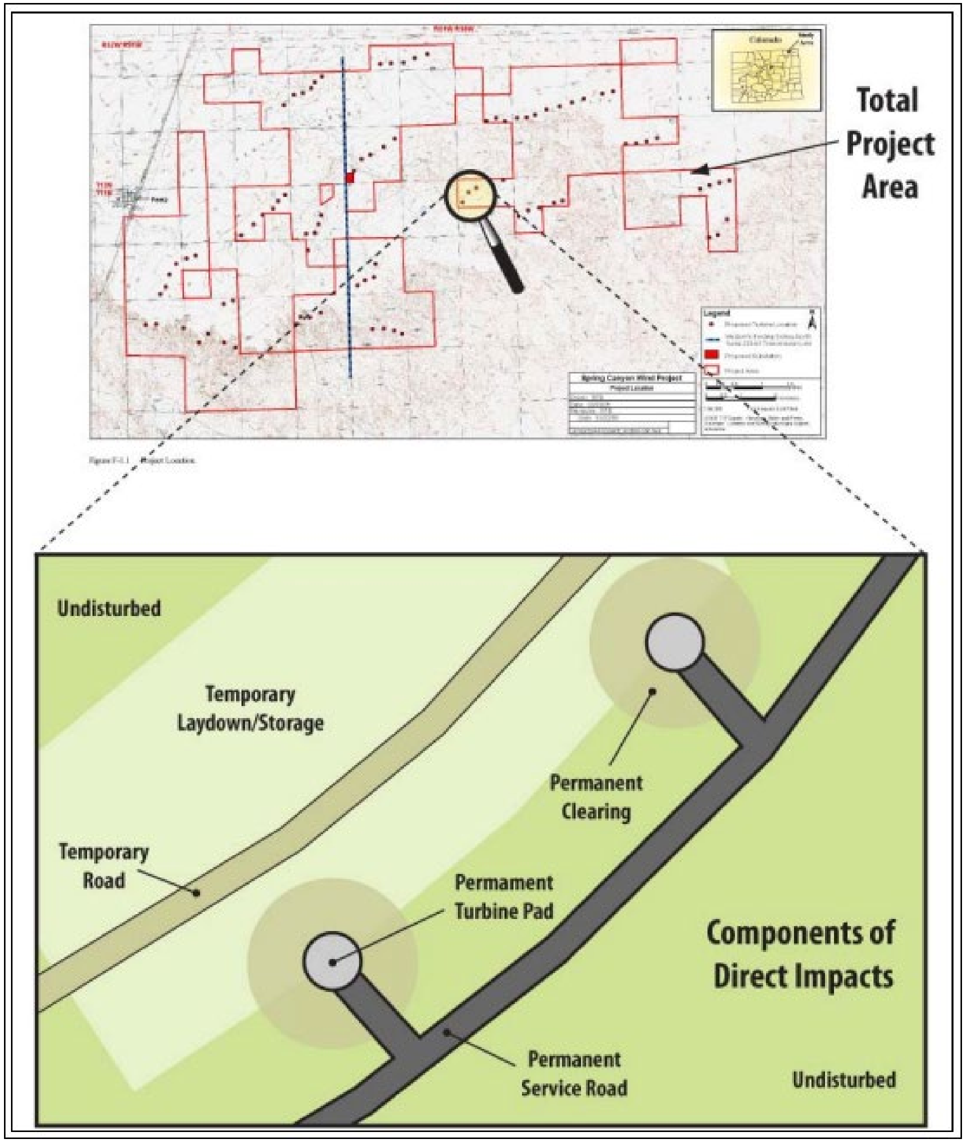
- 51% of installed wind capacity
- 80% of installed solar (PV + CSP)
- All known geothermal.

Ong et al. 2013.

Methods: Direct vs. Total Area

Methods:

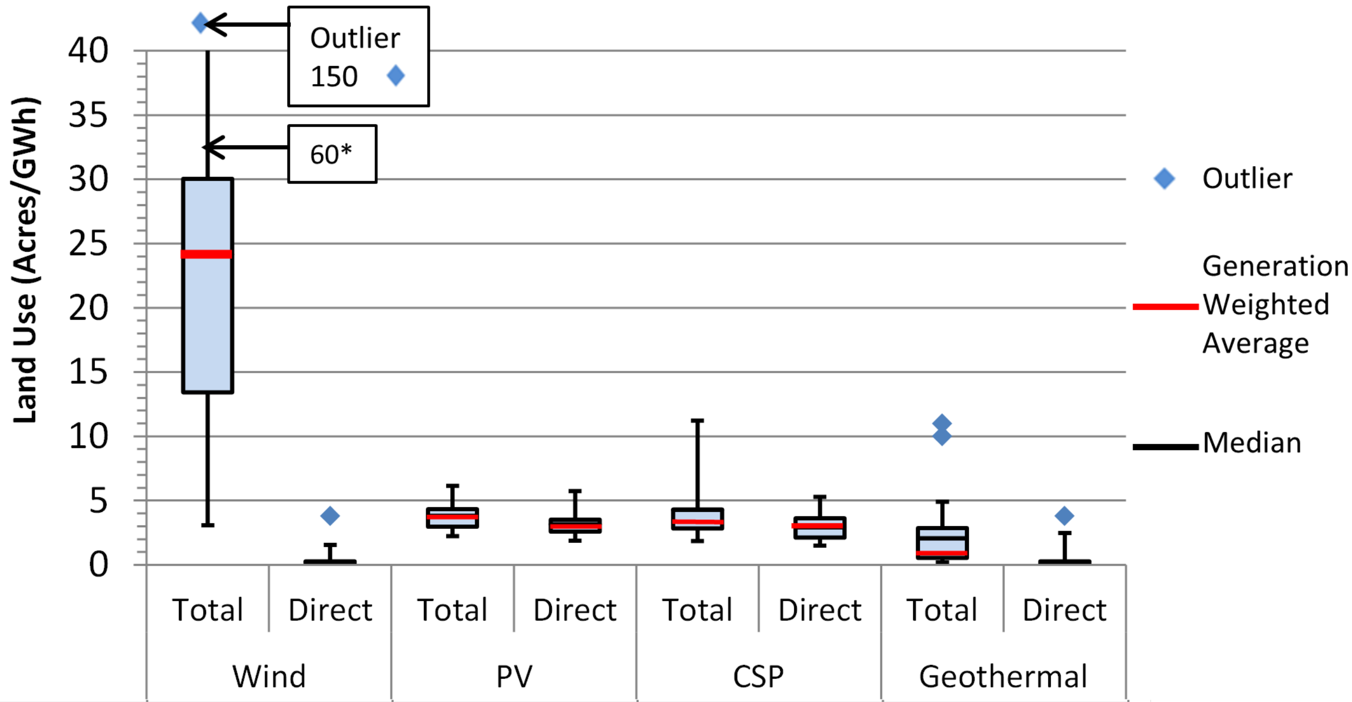
- Documents
  - Official documents (e.g., EIS)
  - Developer documents
  - Third-party sources
- Satellite imagery analysis.



Source: Denholm et al. 2009

Land Use per Unit Generation

Generation-basis accounts for differences in capacity factor between technologies (e.g., CSP and geothermal vs. PV and wind).

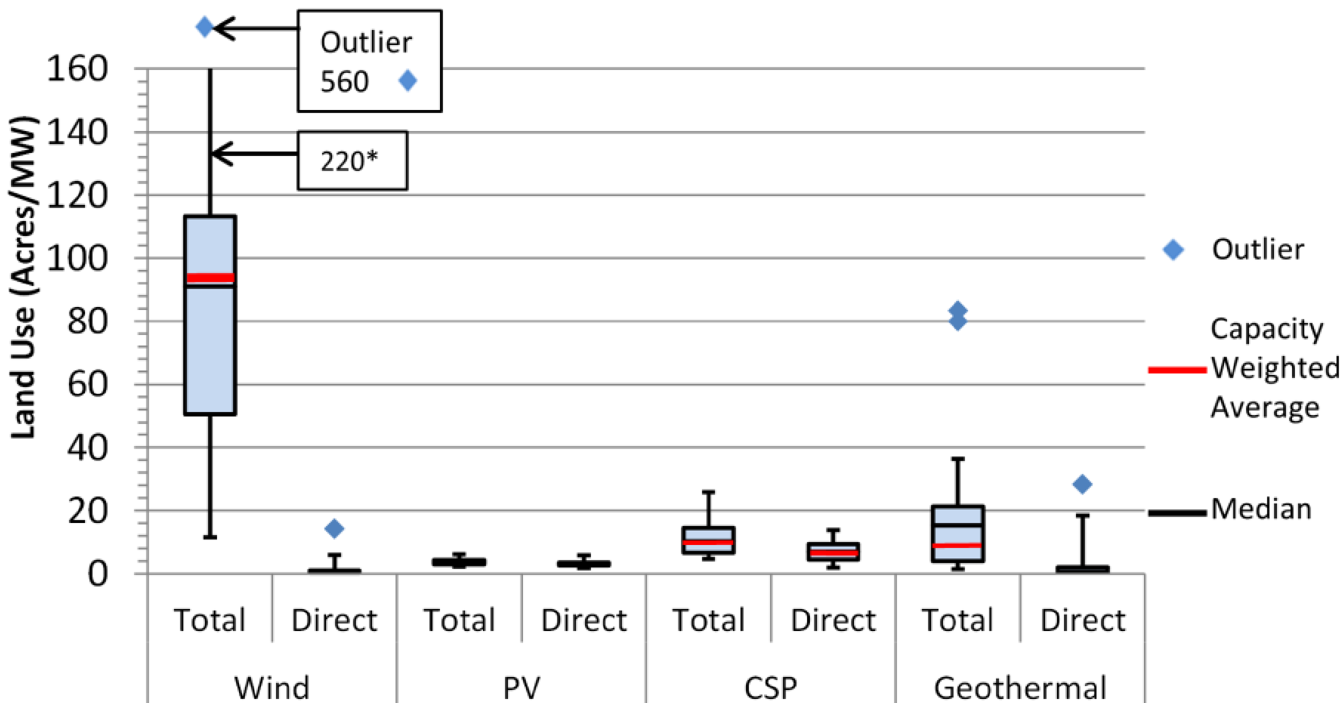


	Wind Total	Wind Direct	PV Total	PV Direct	CSP Total	CSP Direct	Geothermal Total	Geothermal Direct
Sample Size	161	93	147	106	25	18	70	70
Gen. Weighted Avg.	24	0.19	3.5	3.1	3.2	2.7	0.34	0.039
Median	24	0.25	3.8	3.2	4.3	2.9	2.1	0.26

Ong et al. 2013.

Land Use per Unit Capacity

Capacity-basis is useful for estimating land area and costs for new projects since power plants are often rated in terms of capacity.



	Wind Total	Wind Direct	PV Total	PV Direct	CSP Total	CSP Direct	Geothermal Total	Geothermal Direct
Sample Size	161	93	147	106	25	18	70	70
Cap. Weighted Avg.	89	0.70	8.0	7.0	9.7	7.8	9.7	1.0
Median	91	0.94	8.5	7.0	10.4	6.9	15	1.9

Ong et al. 2013.

Summary

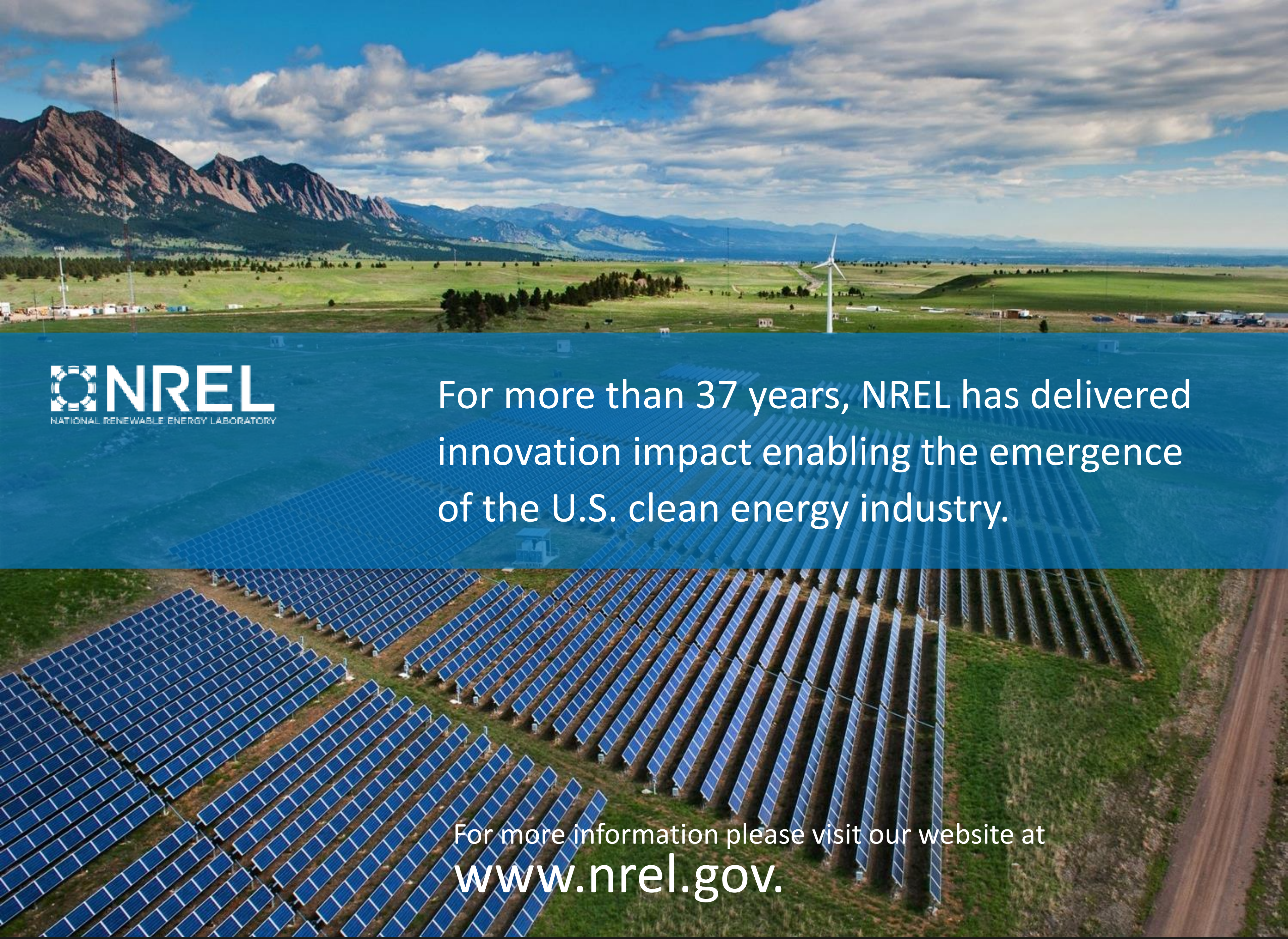
- **GHG emissions**: RE generally much lower than combustion technologies, similar to nuclear, but with variability and uncertainty that in some cases is important, for instance natural gas methane emissions.
- **Water use**: RE vs. conventional isn't the right classification for water. Because operational use dominates, thermal vs. non-thermal, and by cooling technology, are more salient. But water uses in other life cycle phases presents vulnerabilities and needs to be understood better.
- **Land use**: Footprint could be seen as significant for wind/solar/geothermal, but need a nuanced understanding to see real impacts. Not all land "used" → integrative vegetation could lead to many benefits. Analysis of life cycle land use for conventionals (e.g., natural gas, biopower) is necessary for fair comparisons, and this information is lacking.

Final Thoughts

- LCA is *one tool* for sustainability analysis; others are complimentary (e.g., techno-economic analysis, social)
- LCA-type systems thinking has strengthened the current climate change and energy independence discussions by providing fair and quantitative comparisons on challenging topics
  - Can help to anticipate problems before large-scale implementation
  - Focus R&D to reduce those impacts
- LCA is growing in recognition (*Science*, *Nature*, *PNAS* publications, etc.)
- Many research horizons still within LCA
  - Regional specificity
  - Timing of impacts
  - Impact assessment
  - Uncertainty and sensitivity analyses
  - Communication of results
- Career avenues range from research (academia, national labs) to practice (consulting, industry) to informed consumer of LCA results (government, climate/energy modeling).

Leading the Way to a Clean Energy Future

Garvin.Heath@nrel.gov



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BNL: Vasilis Fthenakis, Hyung Chul Kim

Others: Michael Whitaker (ICF), Adam Brandt (Stanford), and other *Science* article co-authors

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Supplementary Slides

Other Environmental Effects from Electricity Generation Technologies through Life Cycle Assessment

Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies
(*PNAS* 2014)

GREEN ENERGY CHOICES: The Benefits, Risks, and Trade-Offs of Low-Carbon Technologies for Electricity Production
(UNEP IRP report, forthcoming)

Environmental Trade-offs with Low Carbon Energy Sources

IPCC AR5 WGIII: Lifecycle greenhouse gas emissions (A.II.9.3):
"The assessment of GHG emissions [for electricity] is based on two research enterprises.

The second effort is a broader study of lifecycle environmental impacts and resource requirements (Hertwich et al. 2014). The study aims at a consistent technology comparison where lifecycle data collected under uniform instructions in a common format are evaluated in a single model based on a common set of background processes."

Impacts assessed: particulate matter exposure, freshwater ecotoxicity, freshwater eutrophication, and climate change

- Most RE have impacts ≤10% of those resulting from a modern NGCC.
- CCS can increase non-CO_2 pollutant emissions by 20-100% vs. same tech. without CCS.

Material requirements:

- Per kWh, low-carbon technologies can be higher than for conventional fossil (e.g., 11-40 times more copper for PV and 6-14 times more iron for wind).
- While high material requirements do not present a fundamental obstacle at least for bulk materials (e.g., 2 years of current global copper and 1 year of iron production will suffice to build a low-carbon energy system capable of supplying the world's electricity needs in 2050), critical metals may constrain technology choices for PV and wind systems.

Environmental Trade-offs with Low Carbon Energy Sources