

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



Leading the Way to a Clean Energy Future

Presenter: Garvin Heath, Ph.D.
Date: January 13, 2016
Venue: 96th AMS Annual Meeting
18th Conference on Atmospheric Chemistry

NREL/PR-6A20-65645

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

Vehicle Technologies
Hydrogen
Biofuels

Energy Productivity

Residential Buildings
Commercial Buildings

Renewable Electricity

Solar
Wind
Water: Marine Hydrokinetics
Geothermal

Systems Integration

Grid Integration of Clean Energy
Distributed Energy Systems
Batteries and Thermal Storage

Partners

Private Industry
Federal Agencies
State/Local Government
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

SOLAR

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



WIND

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



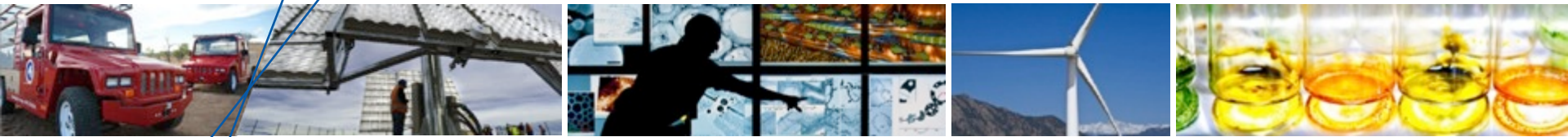
TRANSPORTATION



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.

Analysis



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.

$$\text{Controlled Emissions} = \sum (\text{Potential Emission} - \text{Emission Reduction})$$

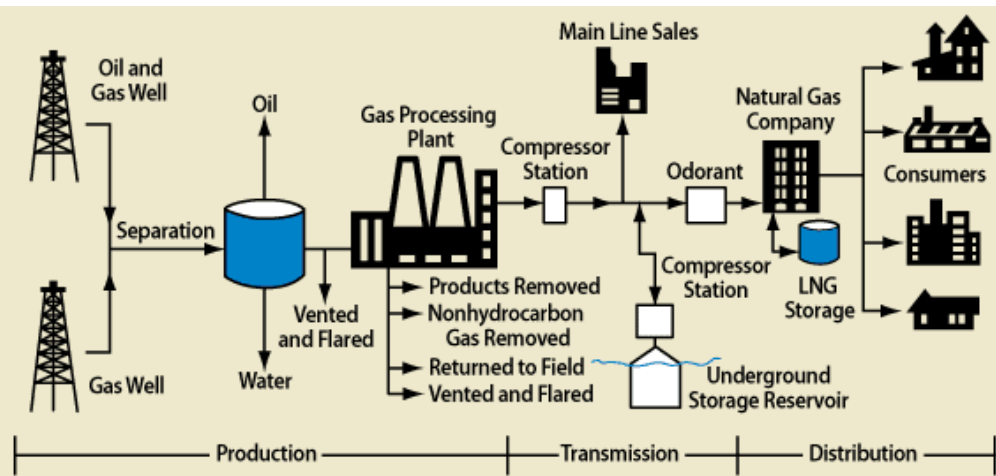
$$\text{Potential Emissions} = \sum (\text{Emission Factor} \times N_{\text{count}})$$

Mean Emission Factor for each source category

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

Source: NREL and NOAA

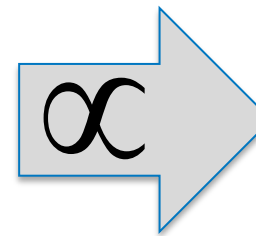
Life Cycle Assessment



Source: U.S. Energy Information Administration.

Longitudinal:

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



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

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

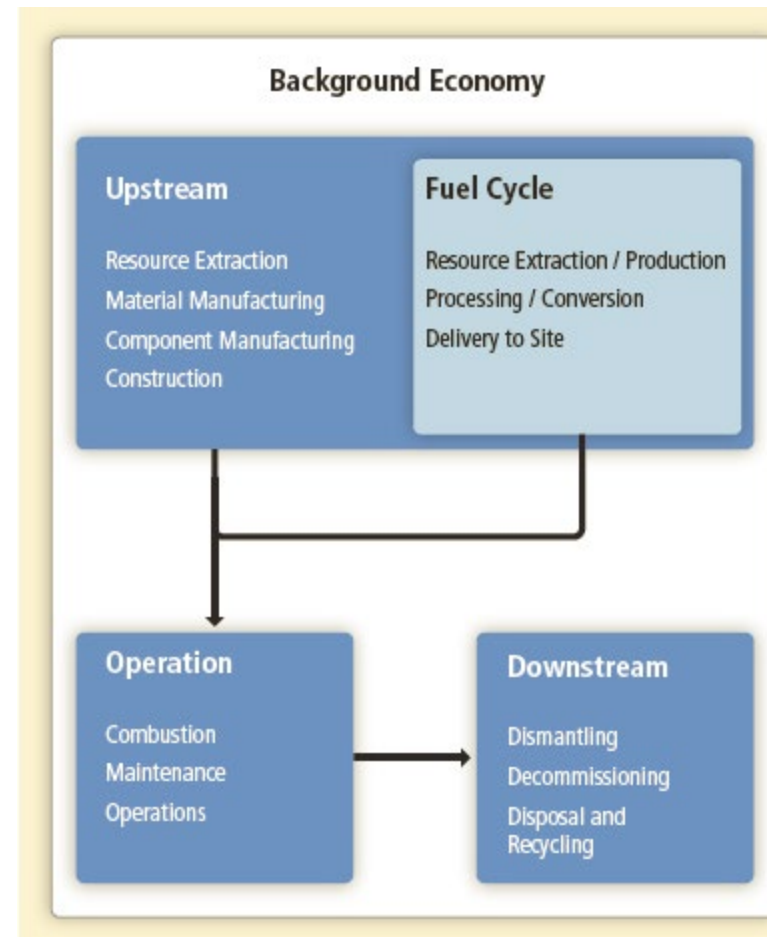
LCA quantifies resource consumption, energy use, and emissions, from cradle-to-grave

- 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

Introduction	30
Total Fuel Cycle Analysis Methodology	31
Fuel Cycles	32
Fuel Cycle Boundaries	33
Fuel Cycle Scenarios	38
Biomass-Ethanol Fuel Cycles	38
Dedicated Energy Crop Supply	38
Ethanol Production	39
Ethanol Fuel Distribution	40
Reformulated Gasoline Fuel Cycle	41
Crude Oil Production	41
Crude Oil Transportation	42
Refining	42
RFG Distribution	44
Fuel End Use Characteristics	44
E95	45
RFG	45
Allocation Methodology	45
Findings	46
E95 and RFG Fuel Cycles	46
Carbon Monoxide Emissions (CO)	46
Nitrogen Oxides Emissions (NO _x)	47
Sulfur Dioxide Emissions (SO ₂)	49
Particulate Matter Emissions (PM)	50
Volatile Organic Compound Emissions (VOC)	51
Carbon Dioxide Emissions (CO ₂)	52
Wastewater Emissions	53
Solid Waste Emissions	53
Impact of Adding the Secondary Emissions Associated with Electricity	54
Energy Ratios	55
Process Energy Requirements	56
Fossil Fuel Energy	57
All Energy Sources	57
Conclusions and Discussion	58
Acknowledgments	60
References	60

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

Chapter 3

**Total Fuel
Biomass**

Cynthia J.

CONTENTS

Introduction

Total Fuel C

Fuel C

Fuel C

Fuel Cycle S

Biomass

Dec

Eth

Eth

Reform

Cru

Cru

Ref

RF

Fuel E

E95

RF

Allocat

Findings

E95 an

Car

Nit

Sul

Par

Vol

Car

Wa

Sol

Imp

Energy

Pro

Fos

All

Conclusions

Acknowledg

References

Life Cycle Assessment of a Biomass Gasification Combined-Cycle System

Margaret K. Mann
Pamela L. Spath



Life Cycle Assessment

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

Chapter 3

**Total Fuel
Biomass**

Cynthia J.

CONTENTS

Introduction

Total Fuel C

Fuel C

Fuel C

Fuel Cycle S

Biomass

Dec

Eth

Eth

Reform

Crud

Crud

Ref

RF

Fuel E

E95

RF

Allocat

Findings

E95 an

Car

Nit

Sul

Par

Vol

Car

Wa

Sol

Imp

Energy

Pro

Fos

All

Conclusions

Acknowledg

References

**Life Cycle
a Biomass
Combine**

Margaret K. ...
Pamela L. Sp


Life Cycle

**Life Cycle Assessment of a
Natural Gas Combined-Cycle
Power Generation System**

Pamela L. Spath
Margaret K. Mann


Life Cycle Assessment



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

Chapter 3

**Total Fuel
Biomass**

Cynthia J.

CONTENTS

Introduction

Total Fuel C

Fuel C

Fuel C

Fuel Cycle S

Biomass

Dec

Eth

Eth

Reform

Crud

Crud

Ref

RF

Fuel E

E95

RF

Allocat

Findings

E95 and

Car

Nit

Sul

Par

Vol

Car

Wa

Sol

Imp

Energy

Pro

Fos

All

Conclusions

Acknowledg

References

**Life Cycle
a Biomass
Combine**

Margaret K. Spath
Pamela L. Spath

**Life Cycle
Natural
Power G**

Pamela L. Spath
Margaret K. Spath

**Life Cycle Assessment of
Coal-fired Power Production**

Pamela L. Spath
Margaret K. Spath
Dawn R. Kerr

Including contributions on process definition and data acquisition from:
John Marano and Massood Ramezan, Federal Energy Technology Center



Life Cycle



Life Cycle



Life Cycle Assessment

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

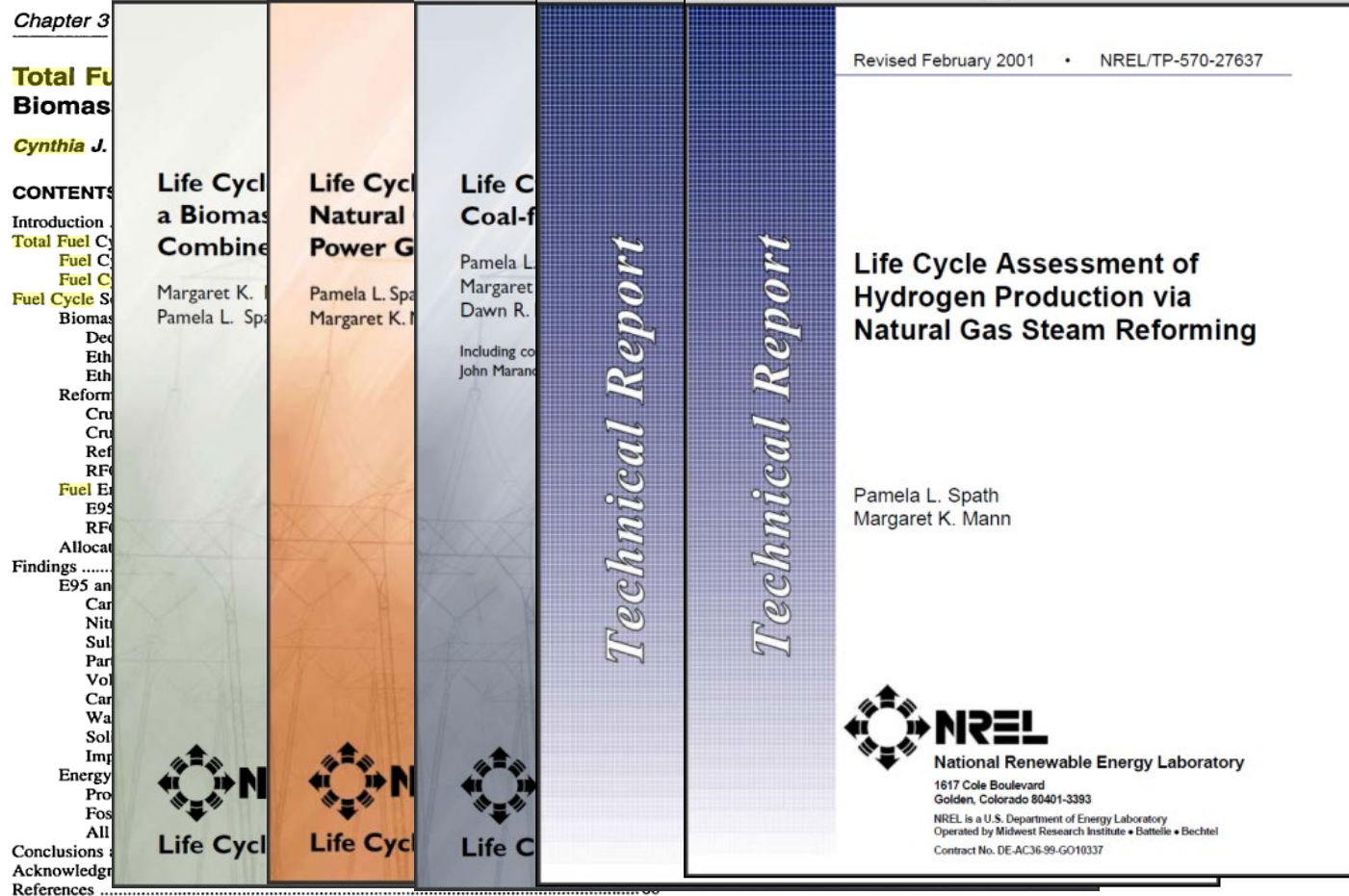


1992

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

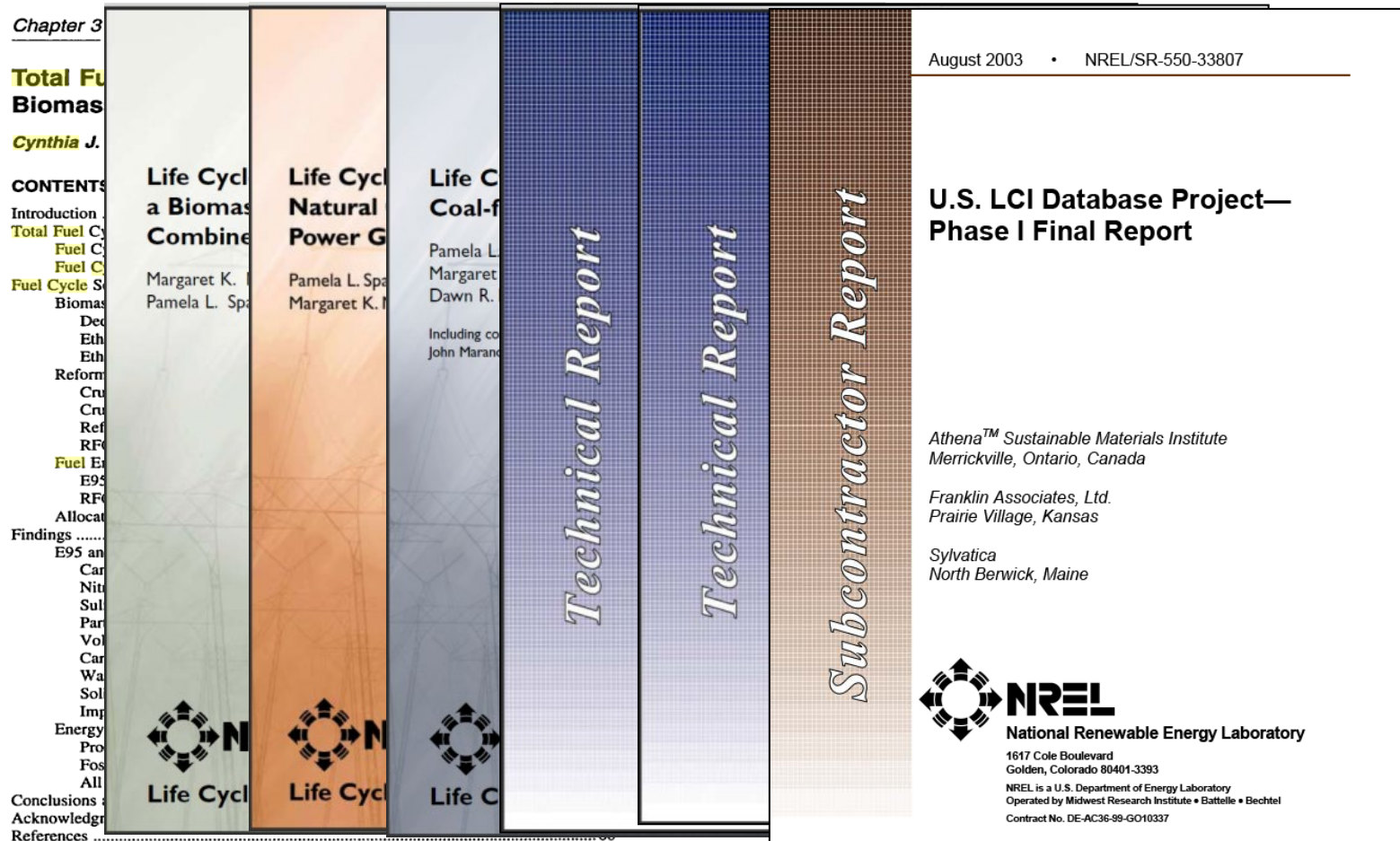


1992

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



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

Chapter 3

Total Fuel Biomass

Cynthia J.

CONTENTS

Introduction

Total Fuel C

Fuel C

Fuel Cycle S

Biomass

Dec

Eth

Eth

Reform

Cr

Cr

Ref

RF

Fuel E

E95

RF

Allocat

Findings

E95 an

Car

Nit

Sul

Par

Vol

Car

Wa

Sol

Imp

Energy

Pro

Fos

All

Conclusions

Acknowledg

References

Life Cycle
a Biomass
Combine

Margaret K. J.
Pamela L. Sp



Life Cycle

Life Cycle
Natural
Power G

Pamela L. Sp
Margaret K. J.



Life Cycle

Life C
Coal-f

Pamela L.
Margaret
Dawn R.



Life C

Technical Report

Technical Report

Subcontractor Report

Emissions and Energy Efficiency Assessment of Baseload Wind Energy Systems

PAUL DENHOLM*

1500 Engineering Drive, University of Wisconsin-Madison,
Madison, Wisconsin 53706

GERALD L. KULCINSKI

439 Engineering Research Building, 1500 Engineering Drive,
University of Wisconsin-Madison, Madison, Wisconsin 53706

TRACEY HOLLOWAY

Center for Sustainability and the Global Environment (SAGE),
1770 University Avenue, University of Wisconsin-Madison,
Madison, Wisconsin 53726

The combination of wind energy generation and energy storage can produce a source of electricity that is functionally equivalent to a baseload coal or nuclear power plant. A model was developed to assess the technical and environmental performance of baseload wind energy systems using compressed air energy storage. The analysis examined several systems that could be operated in the midwestern United States under a variety of operating conditions. The systems can produce substantially more energy than is required from fossil or other primary sources to construct and operate them. By operation at a capacity factor of 80%, each evaluated system achieves an effective primary energy efficiency of at least five times greater than the most efficient fossil combustion technology, with greenhouse gas emission rates less than 20% of the least emitting fossil technology currently available. Life-cycle emission rates of NO_x and SO_x are also significantly lower than fossil-based systems.

Introduction

Baseload power plants generate electricity at nearly constant power, providing a high capacity factor, output stability, and reliability. As a result, baseload plants are responsible for producing a large fraction of the electricity generated in the United States. Coal, nuclear fuels, and natural gas fuel the majority of these plants (1). Baseload plants that use these fuel sources have a number of unfavorable characteristics. Coal-fired plants deplete fossil fuel resources and produce greenhouse gases (GHGs), sulfur dioxide, and nitrogen oxides. Natural gas plants also produce harmful air emissions and draw on finite natural gas resources. Nuclear plants produce radioactive waste products and present risk of accidents and weapons proliferation. These concerns have caused many to seek alternative power sources that can provide the same capacity factor, output stability, and reliability of conventional baseload plants.

Wind energy alone cannot meet these requirements. When wind energy is combined with energy storage, however, it becomes a viable alternative, providing a source of power

* Corresponding author present address: National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO 80401; phone: (303)384-7488; fax: (303)384-7449; e-mail: paul.denholt@nrel.gov.

that may be functionally equivalent to a conventional baseload plant. The creation of baseload wind energy systems using wind generation and storage can increase the economic penetration of wind energy far beyond the 10-20% levels commonly quoted (2). In addition, baseload wind energy systems are easily integrated into power systems with limited operational flexibility, such as those that lack a significant amount of fast-responding gas and hydroelectric generation. These types of power systems are common in the midwestern United States, an area with excellent wind resources (3).

The declining cost of wind energy has now made baseload wind energy systems economically feasible, increasing the possibility of large-scale integration into the United States' electric power system (2). For this reason, it is important to examine the environmental impacts of combined wind generation and energy storage systems. Inclusion of energy storage with wind energy generation also allows for a more equitable comparison between intermittent wind generation and conventional generation technologies.

A realistic assessment of baseload wind systems must include an economically viable energy storage system as well as consideration of other effects such as transmission requirements. This study developed a baseload wind model using wind turbine, storage, and transmission technologies that are considered economically viable in the midwestern United States when deployed on a large scale. The model uses energy storage to increase the capacity factor of a typical wind generator (25-45%) to a baseload level greater than 70% (4) and increase the output stability and reliability of wind energy as well. Capacity factor is defined as the average plant output divided by the maximum possible output over a period of time, generally one year.

The development of the model was strongly influenced by the constraints of electricity transmission, which ultimately establishes the maximum output of the wind system. Since new transmission development will be required to deliver wind energy from remote locations in the midwestern United States to major load centers, a high system capacity factor is required to maximize the use of these expensive transmission assets (5). The model was designed to produce an amount of power that is equal to, but does not exceed, a level established by the transmission capacity. The effects of losses in the transmission system were also considered in the model.

Life cycle analysis tools were applied to examine several major environmental performance indicators: energy intensity and emission rates of GHGs, sulfur dioxide (SO₂), and nitrogen oxides (NO_x).

Modeling Baseload Wind Energy Systems

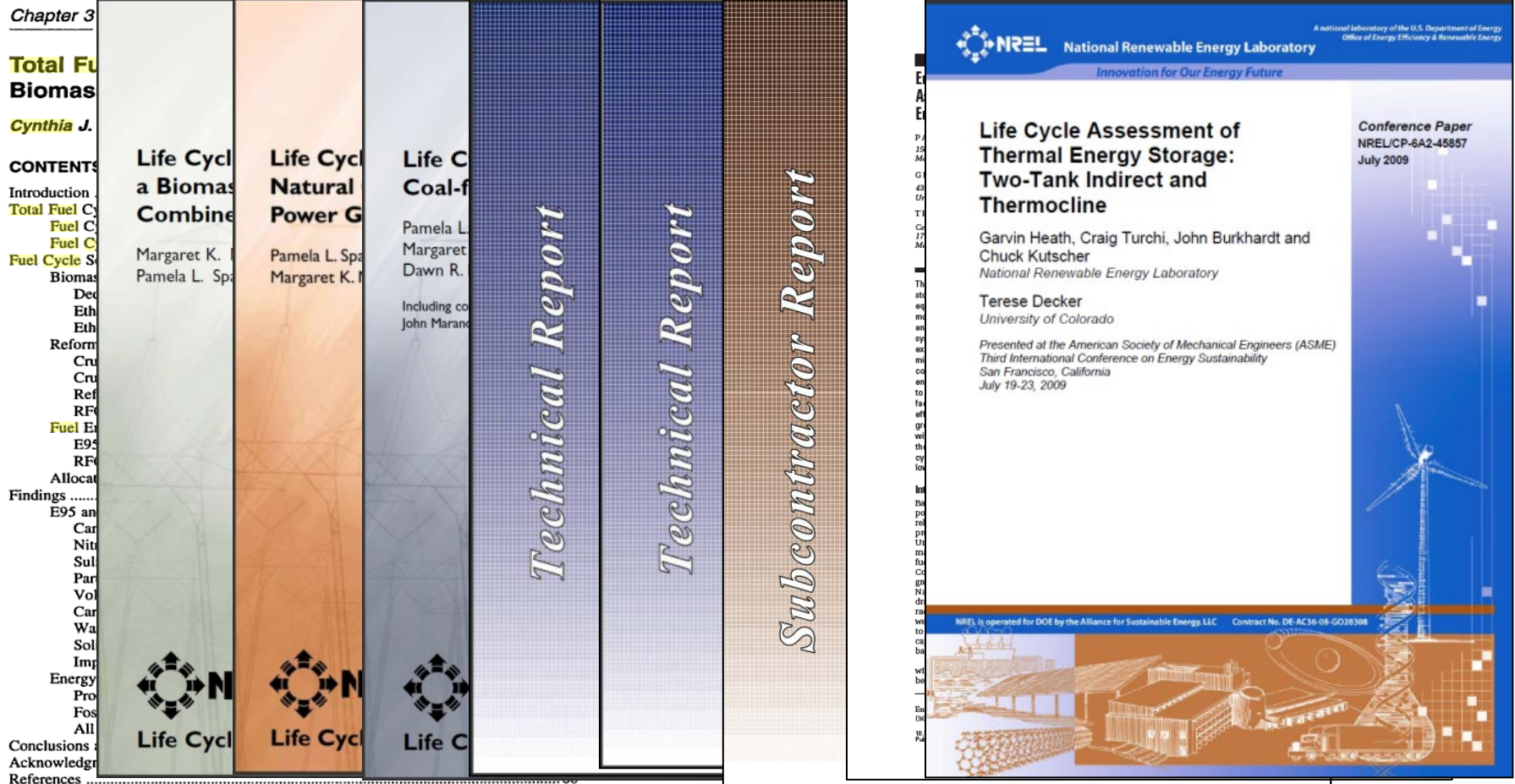
Several studies of baseload wind energy systems have been published, primarily to evaluate the economic performance of such systems (5-7). This study developed a model of a baseload wind system to perform an energy and environmental performance analysis. The wind energy storage (WES) model uses a spreadsheet format (Microsoft Excel) and simulates the hourly performance of a wind farm integrated with energy storage. On the basis of wind energy data and input parameters including storage efficiency and capacity, the WES model calculates the number of wind turbines and other infrastructure required to deliver performance similar to traditional baseload sources. The model compares the wind farm output to the target output on an hourly basis and attempts to provide constant power output by storing, or releasing from storage, the appropriate amount of energy. The objective of the WES model is to maximize the use of limited, capital-intensive transmission capacity to provide a

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



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

Chapter 3

Total Fuel Biomass

Cynthia J.

CONTENTS

Introduction

Total Fuel Cycle

Fuel Cycle

Fuel Cycle

Fuel Cycle

Biomass

Decomposition

Ethical

Ethical

Reform

Crude

Crude

Refined

RF

Fuel Efficiency

E95

RF

Allocation

Findings

E95 and

Carbon

Nitrogen

Sulfur

Particulate

Volatility

Carbon

Water

Solar

Impacts

Energy

Production

Fossil

All

Conclusions

Acknowledgments

References

**Life Cycle
a Biomass
Combine**

Margaret K. L.
Pamela L. Sp



Life Cycle

**Life Cycle
Natural
Power G**

Pamela L. Sp
Margaret K. L.



Life Cycle

**Life C
Coal-f**

Pamela L.
Margaret
Dawn R.
Including co
John Marand

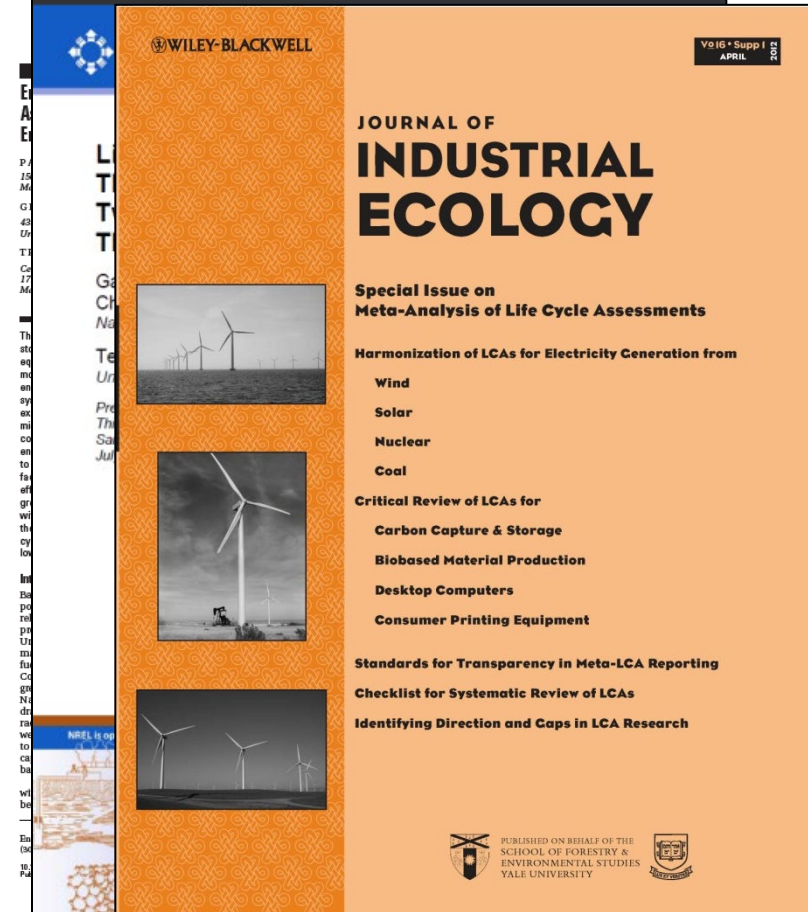


Life C

Technical Report

Technical Report

Subcontractor Report



1992

2015

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

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



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

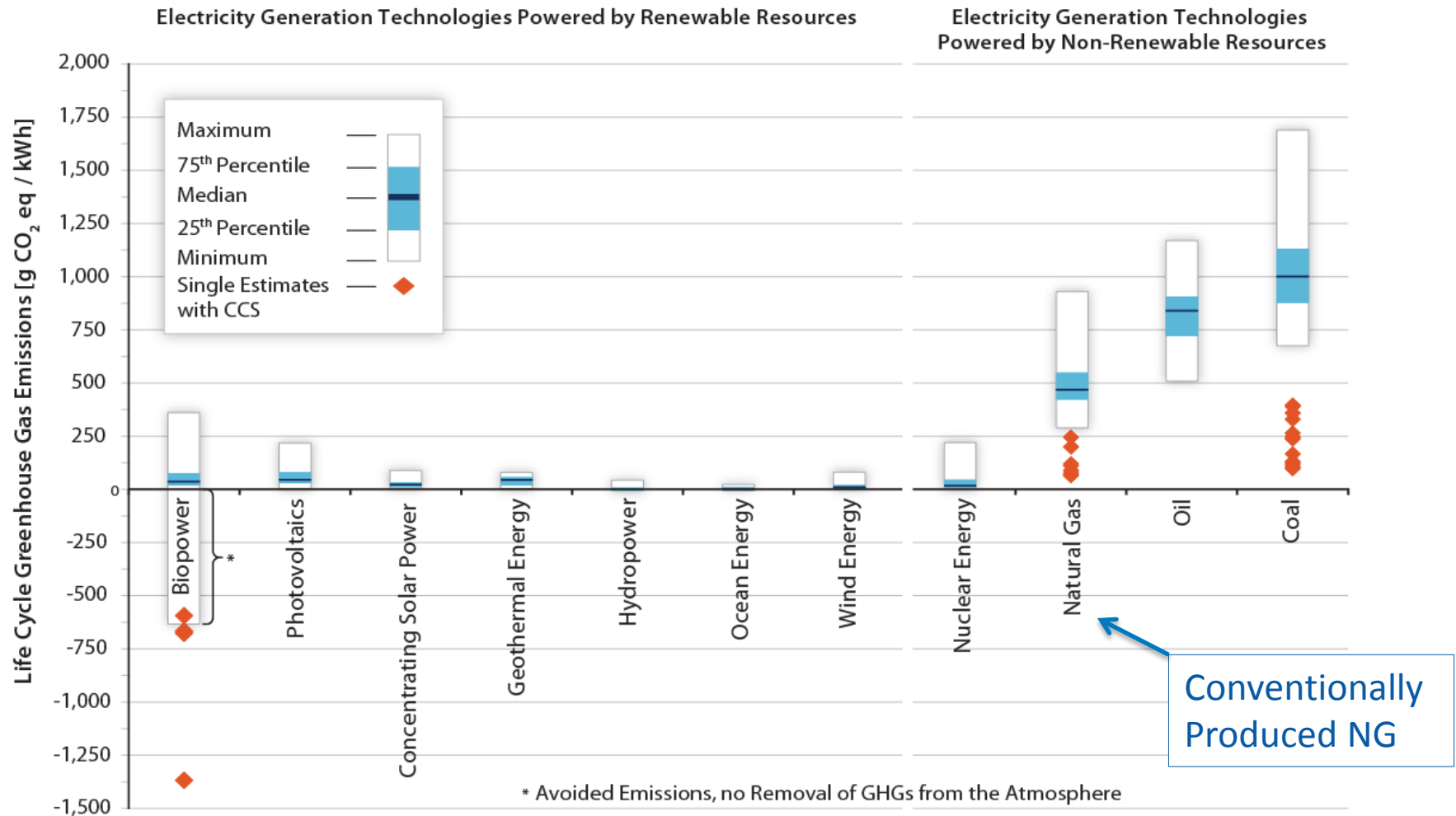
LCA Harmonization Study Goals

- 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.

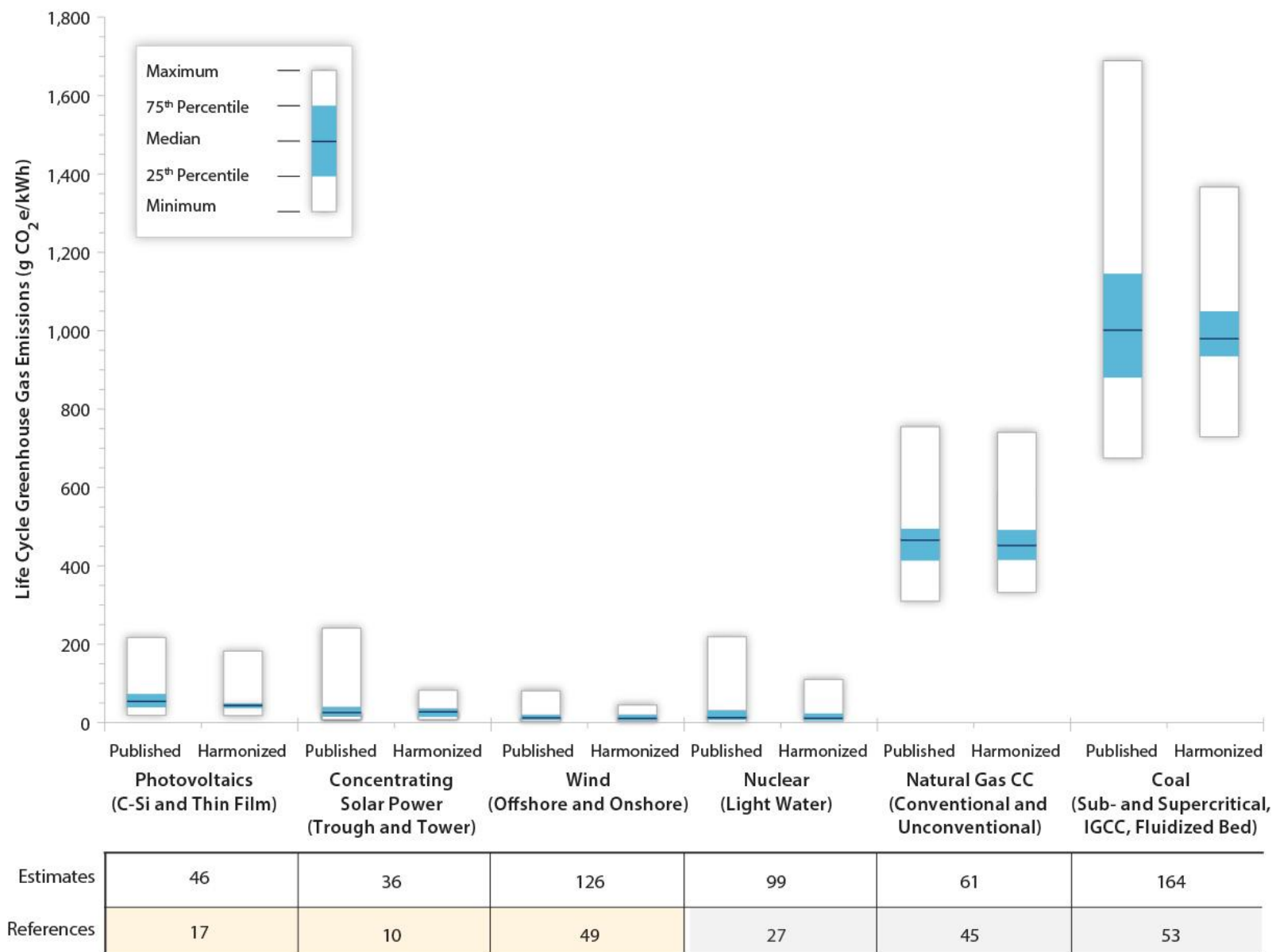
Method

1. Proportional adjustment of denominator of:

$$GHG = \frac{GHG_{lifetime}^{GWP_weighted}}{lifetime_generation}$$

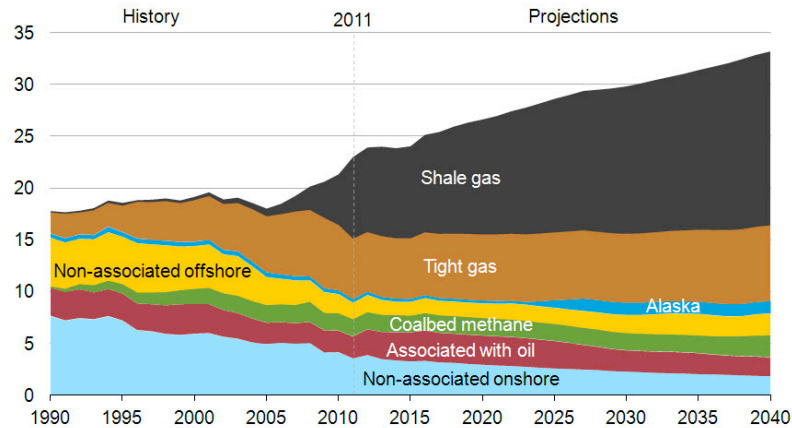
2. Addition or subtraction for system boundary

Methodological Harmonization Reduces Variability and Clarifies Central Tendency



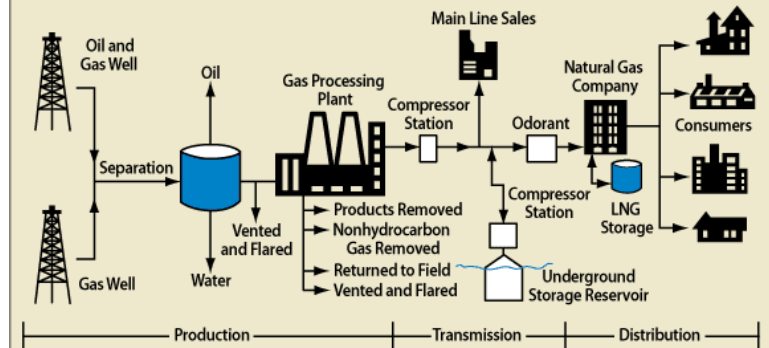
Example: Natural Gas and Methane

U.S. dry natural gas production
trillion cubic feet



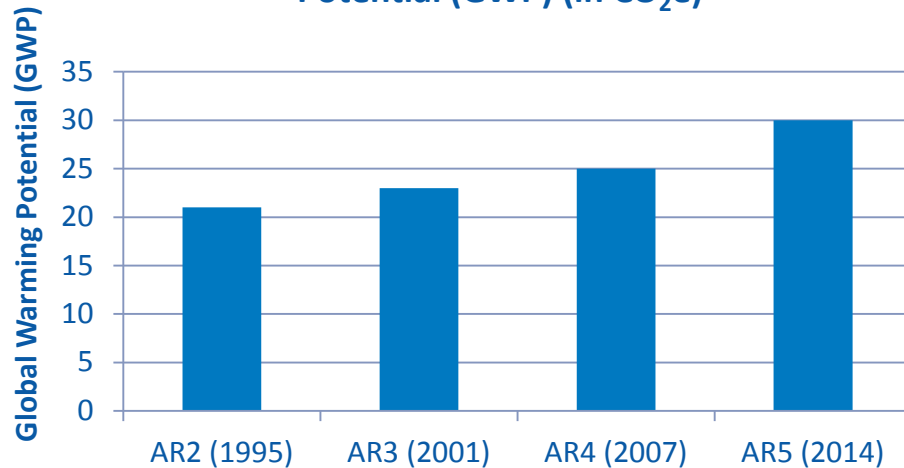
Source: U.S. Energy Information Administration, *Annual Energy Outlook 2013 Early Release*

The Natural Gas Production, Transmission and Distribution System



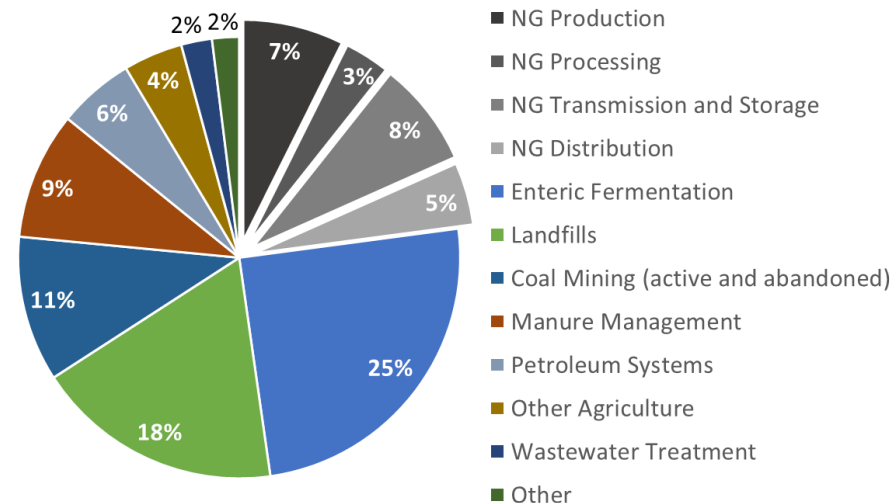
Source: U.S. Energy Information Administration.

IPCC Methane 100-year Global Warming Potential (GWP) (in CO₂e)

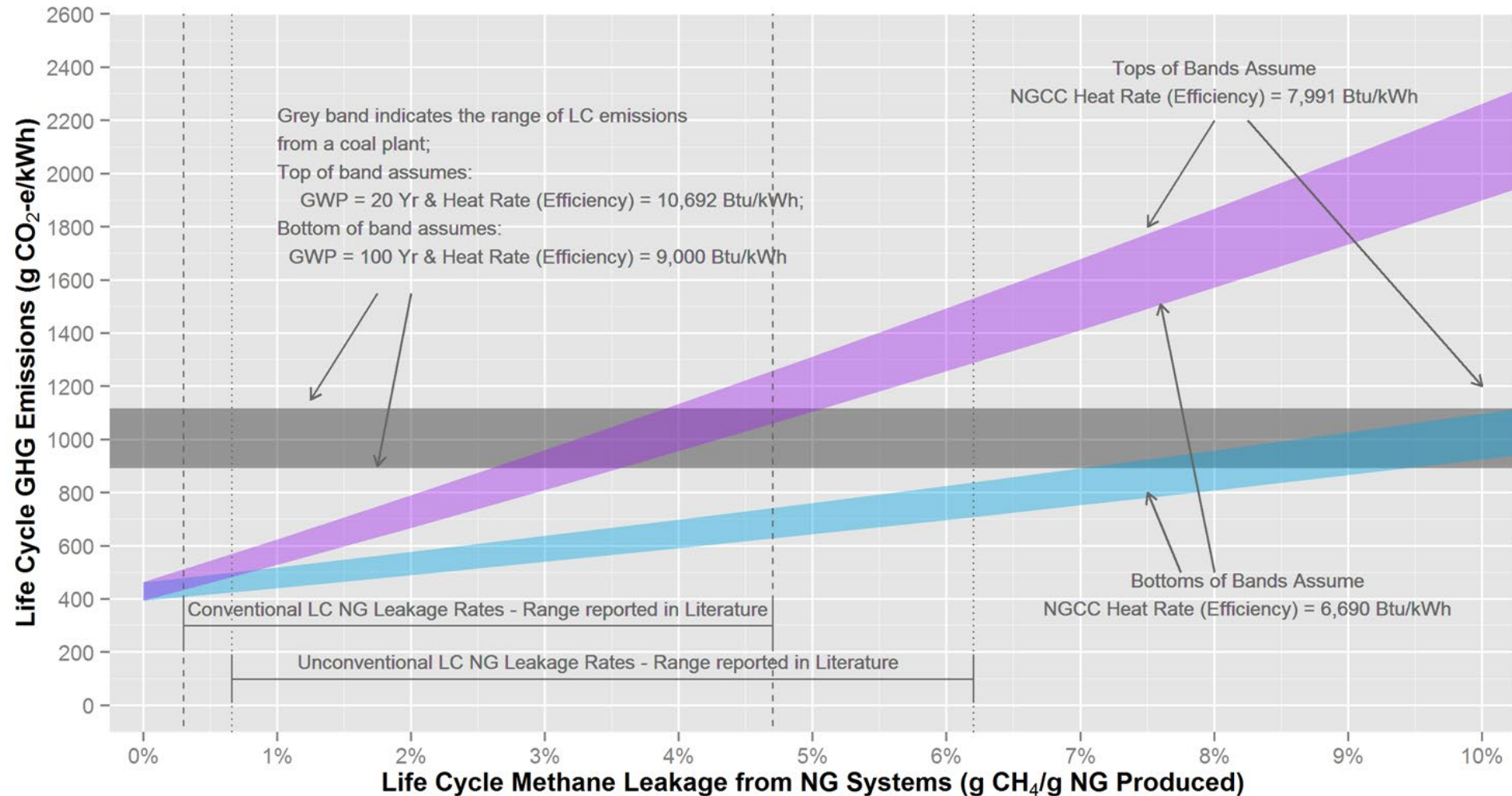


CO₂e = carbon dioxide equivalents; AR = Assessment Report

2014 U.S. GHG Inventory (using CH₄ 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).

GWP for Fossil Methane (IPCC AR5, 2013): 20 Yr 100 Yr

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

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

Shale (Unconventional) Gas LCAs

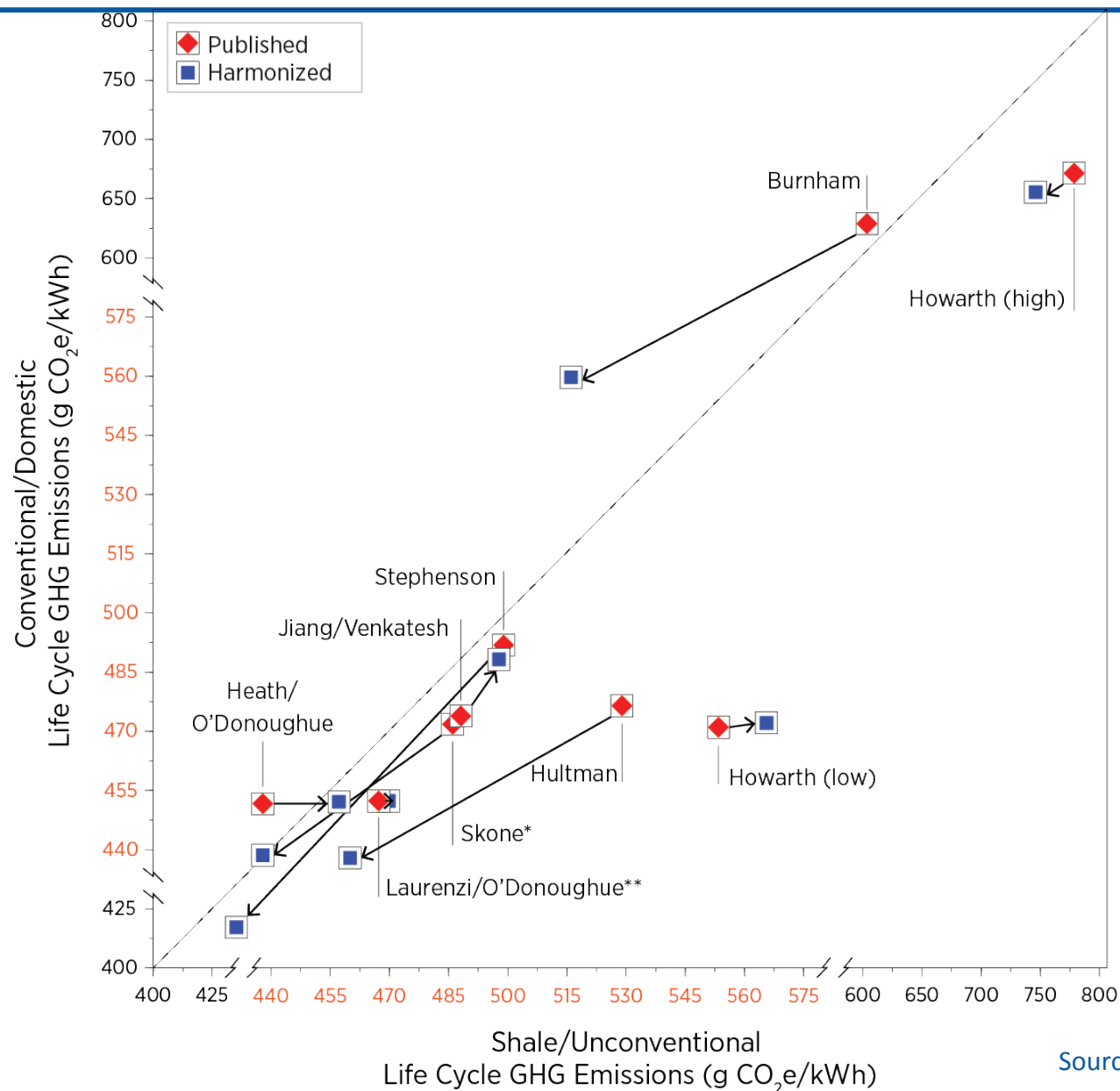
Study

1. Howarth et al. 2011
2. Jiang et al. 2011 (CMU)
3. Skone et al. 2011 (NETL)
(added Marcellus in 2012)
4. Hultman et al. 2011
5. Stephenson et al. 2011
(Shell)
6. Burnham et al. 2012 (ANL)
7. Logan et al. 2012 (JISEA)
8. Laurenzi and Jersey 2013
(ExxonMobil)

Headline GHG result

1. NG > Coal
2. Marcellus Gas < Domestic gas
(conv. + unconv.) < Coal
3. Conv. (except onshore) <
Barnett < Coal
4. Unconv. < Conv. < Coal
5. Conventional < Shale < Coal
6. Shale < Conventional < Coal
7. Barnett/Unconv. \approx Conv. < Coal
8. Marcellus Gas < Coal

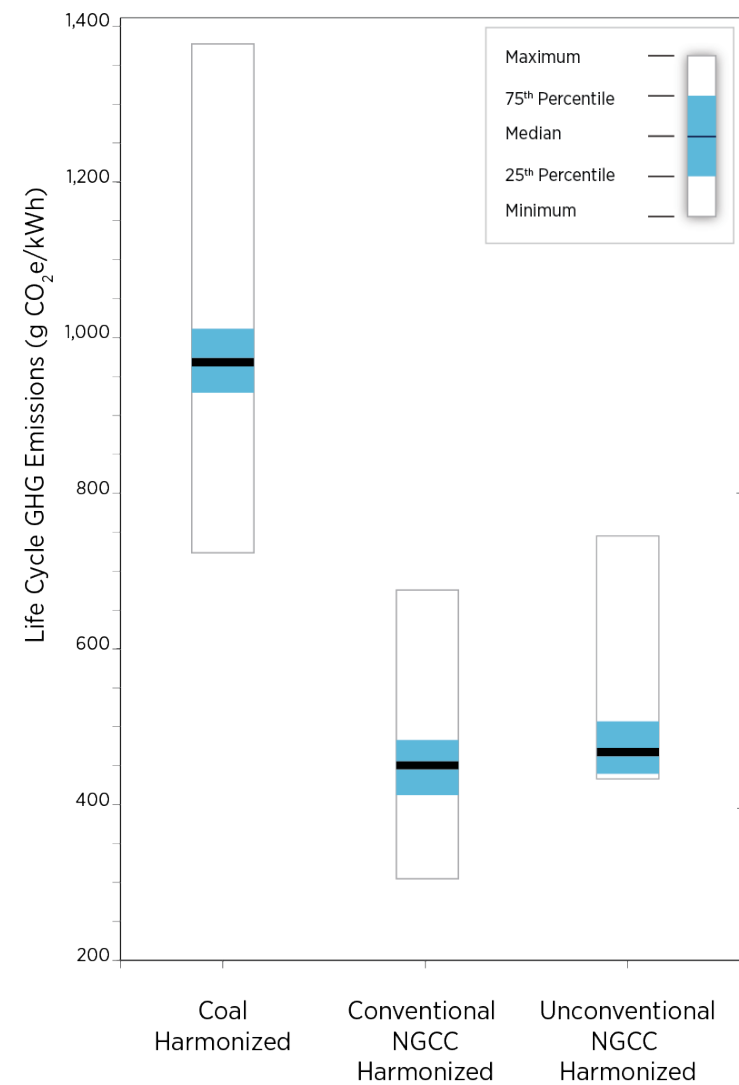
Harmonization of Shale Gas LCAs



Source: Heath et al. 2014

Life Cycle GHG Emissions (After Harmonization):

Comparing Unconventional to Conventional Gas and to Coal



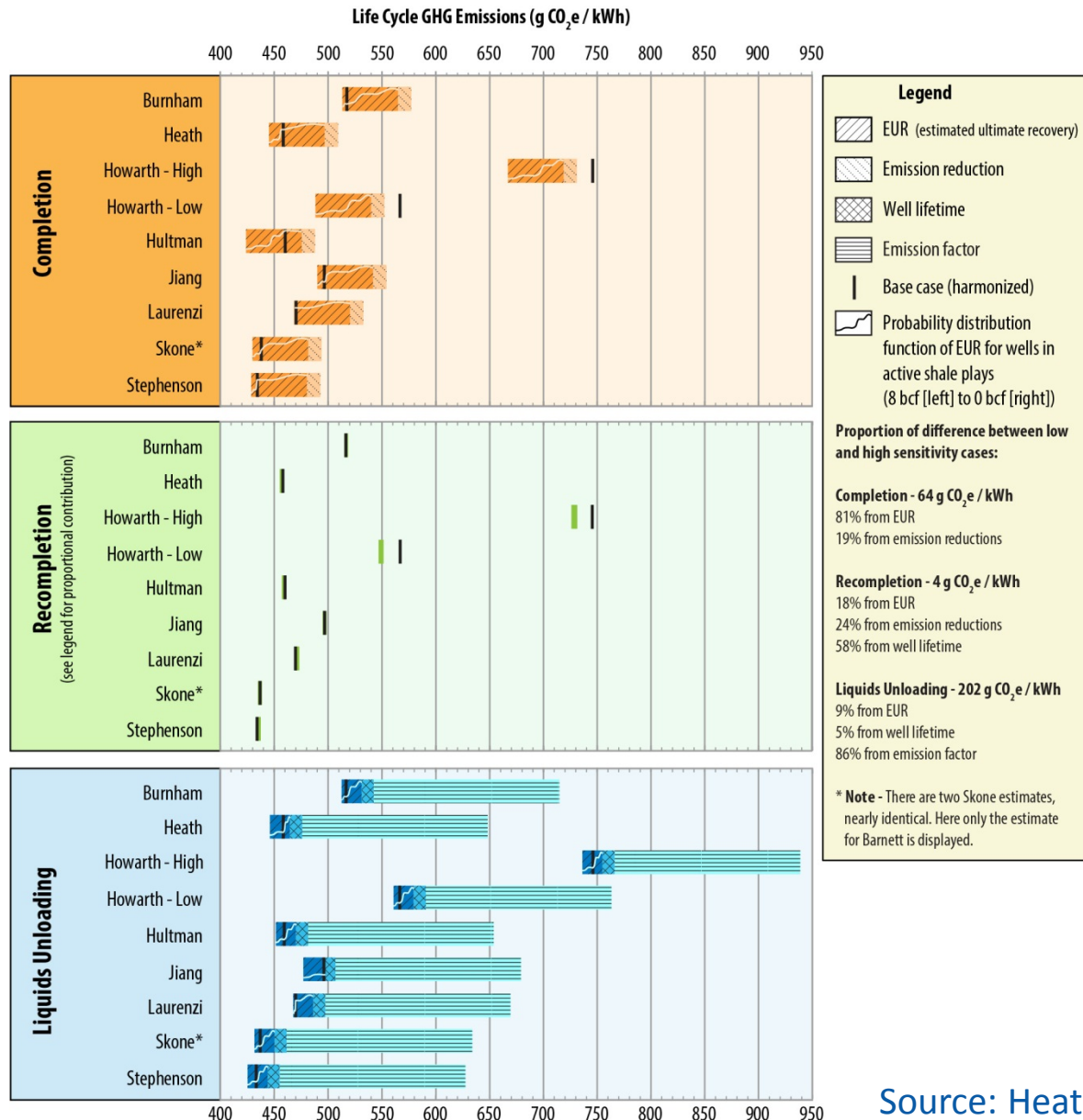
Source: Heath et al. 2014

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.

(Methane GWP = 30 for all categories)

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



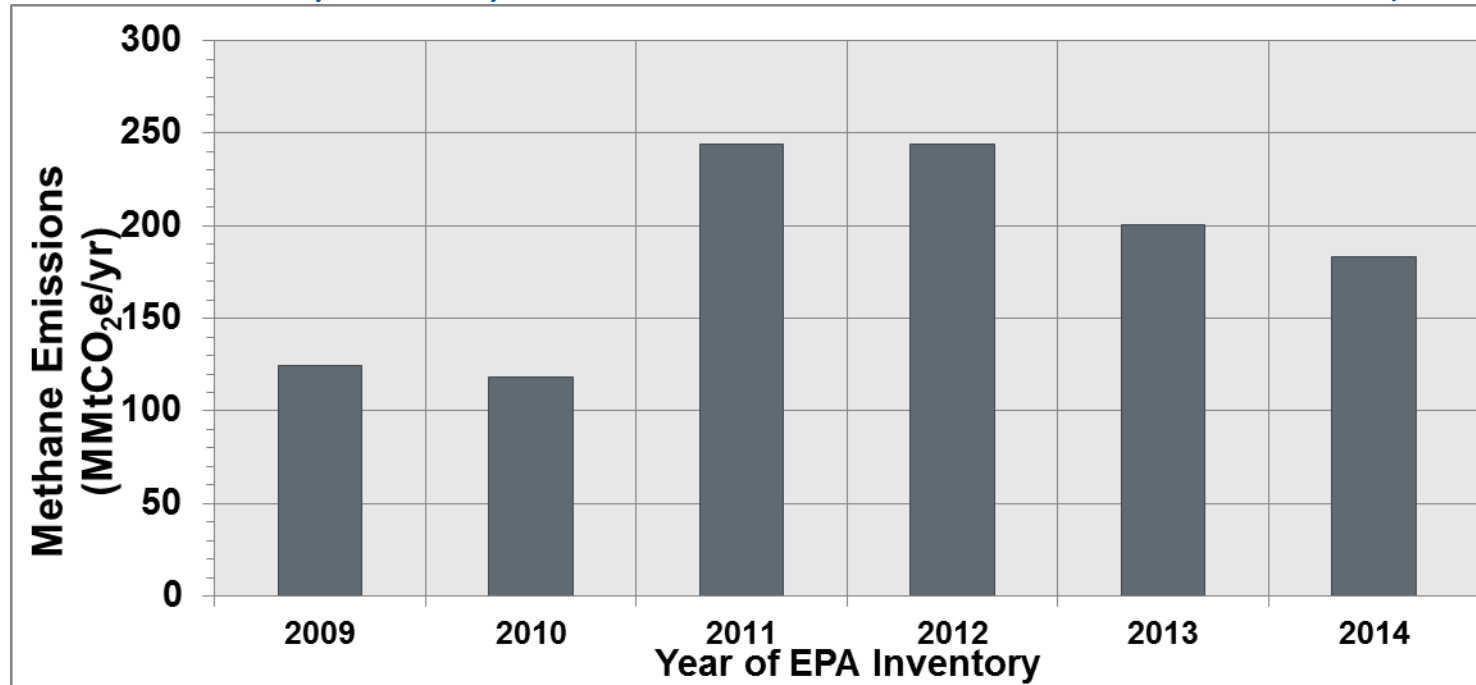
Central Conclusions

- 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 CO₂e/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.

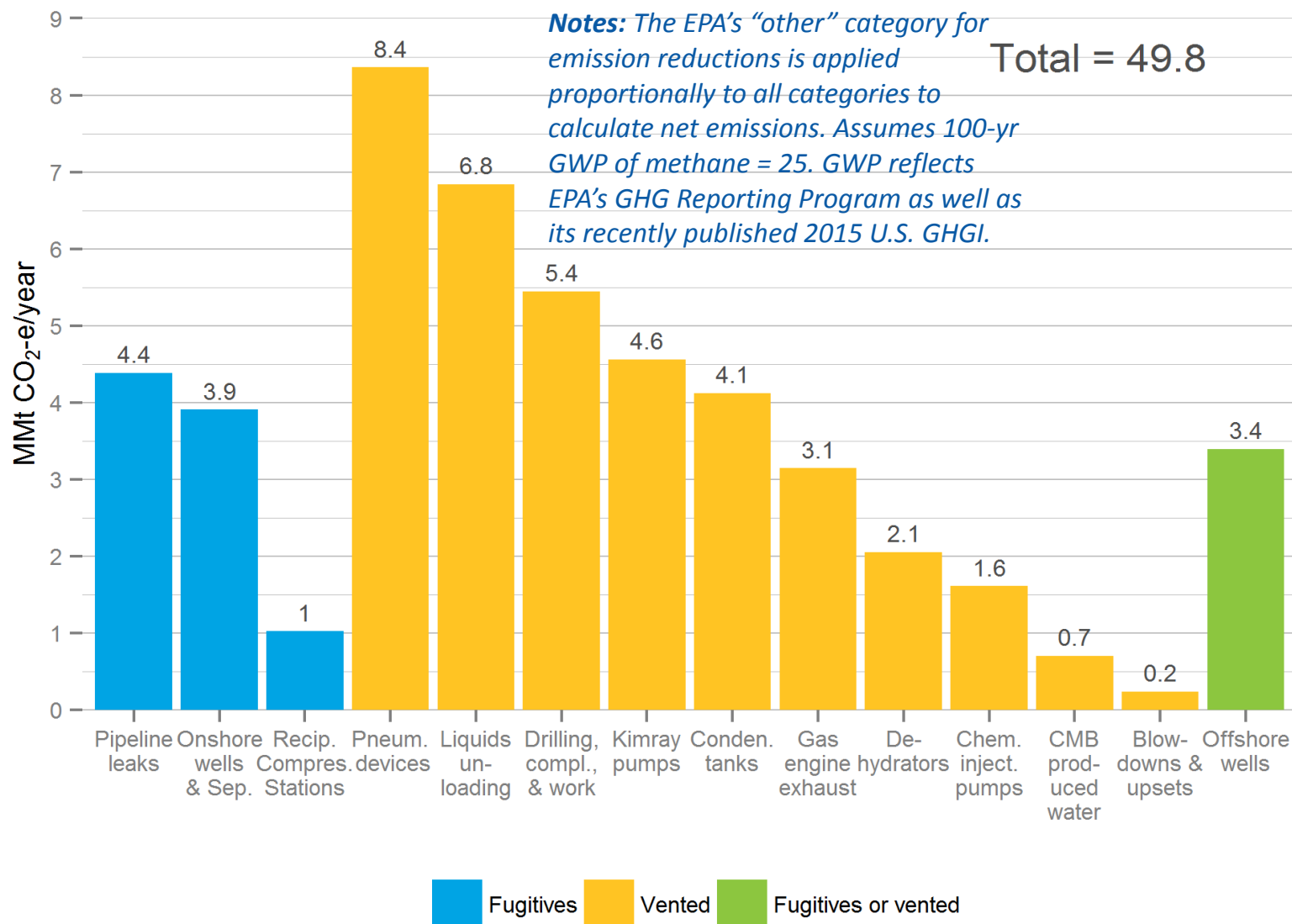
2013 vs. 2012

1. Liquids unloading: ~80%.

2014 vs. 2013

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

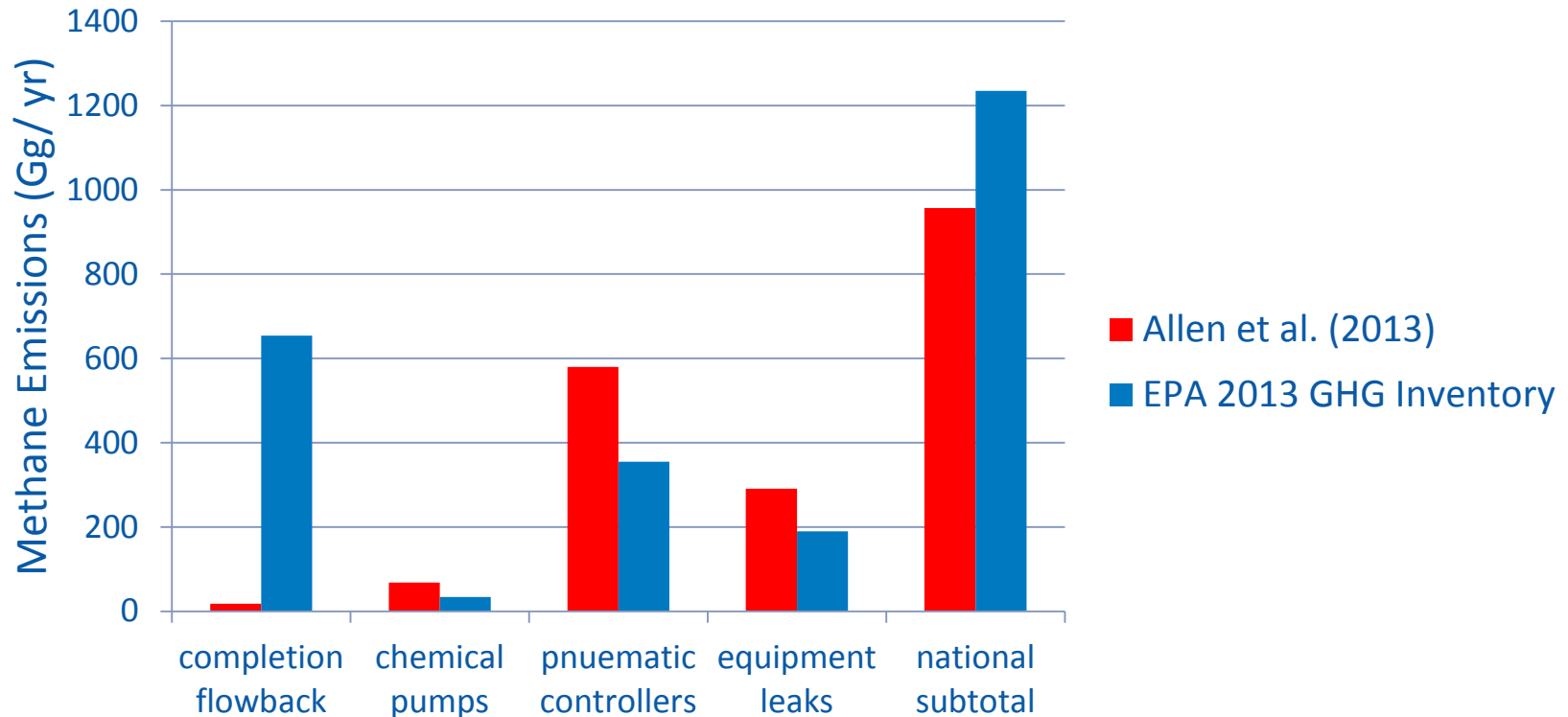
Inventories Support Policy Development and Prioritization: Natural Gas Production Segment Methane Emissions



Source: U.S. EPA 2014 GHG Inventory

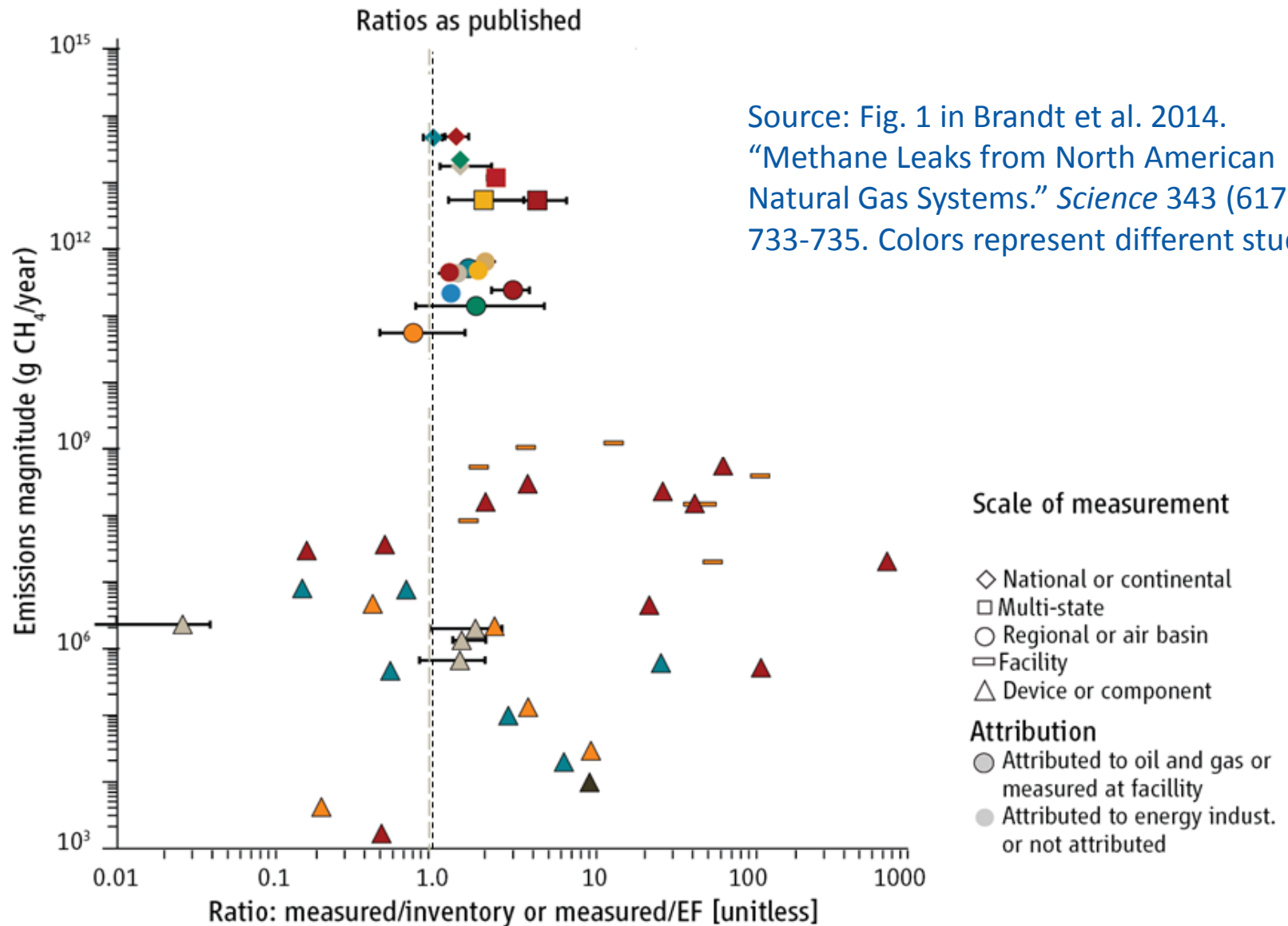
Challenge: Measurements ≠ Inventory

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

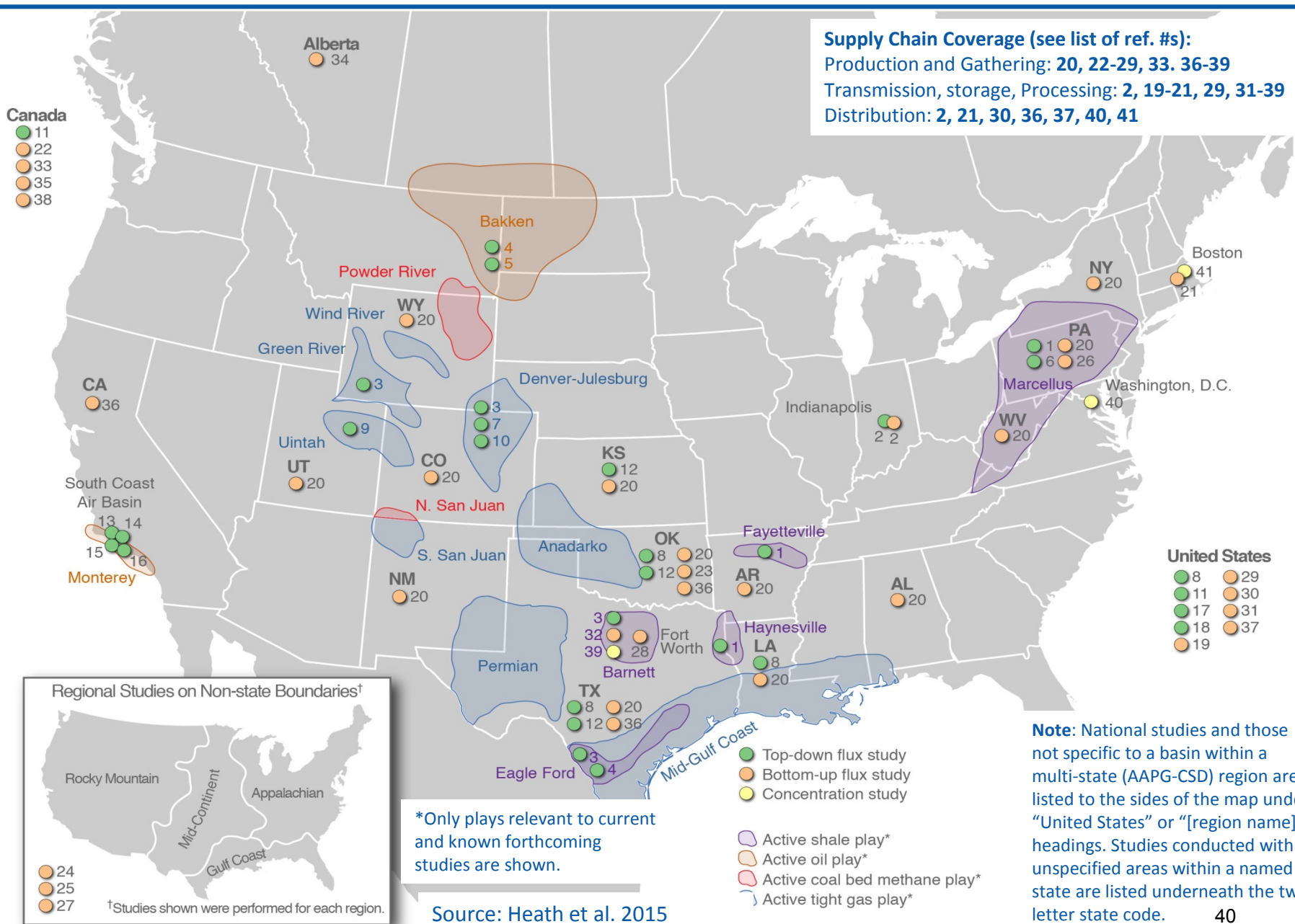


Allen et al.'s conclusion: Some sources overestimated by inventory, some underestimated, with errors compensating to result in similar national estimate.

Inventories Typically Underestimate Emissions



CH₄ Measurement Studies Published Through Feb. 2015



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.

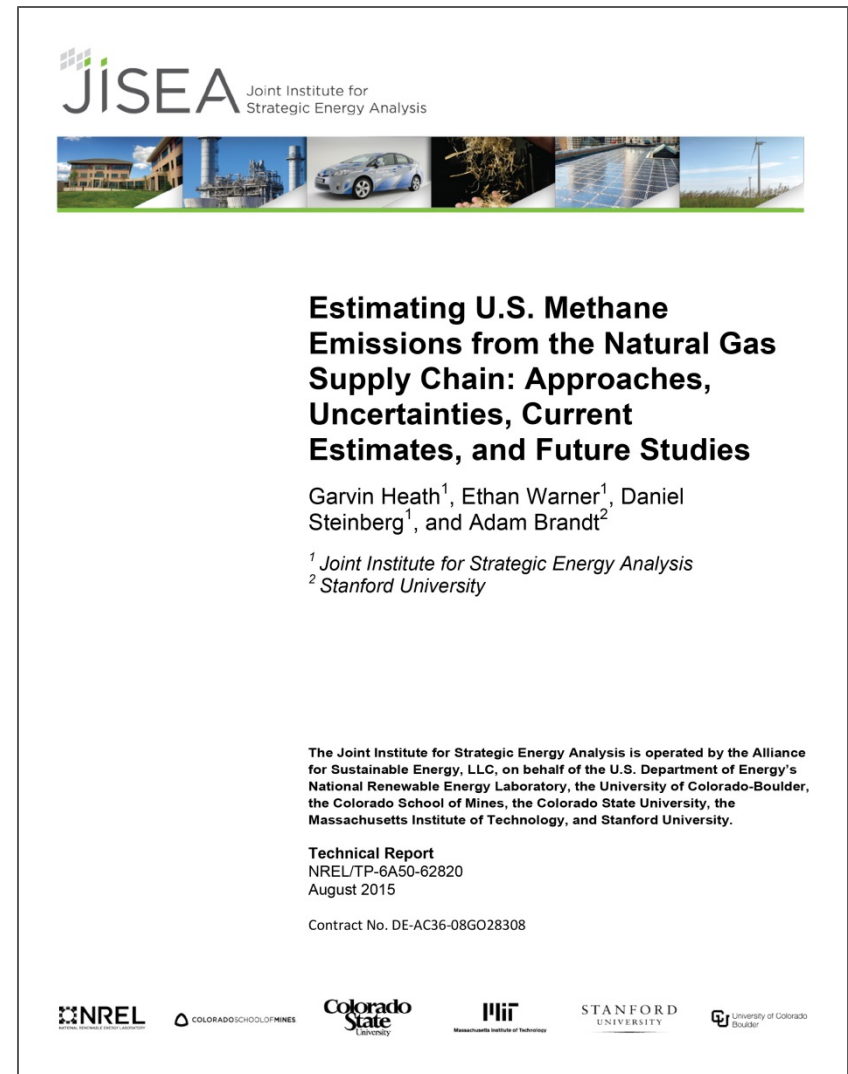
Recent Report: Inventory Improvement Opportunities (8/2015)

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.



<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)

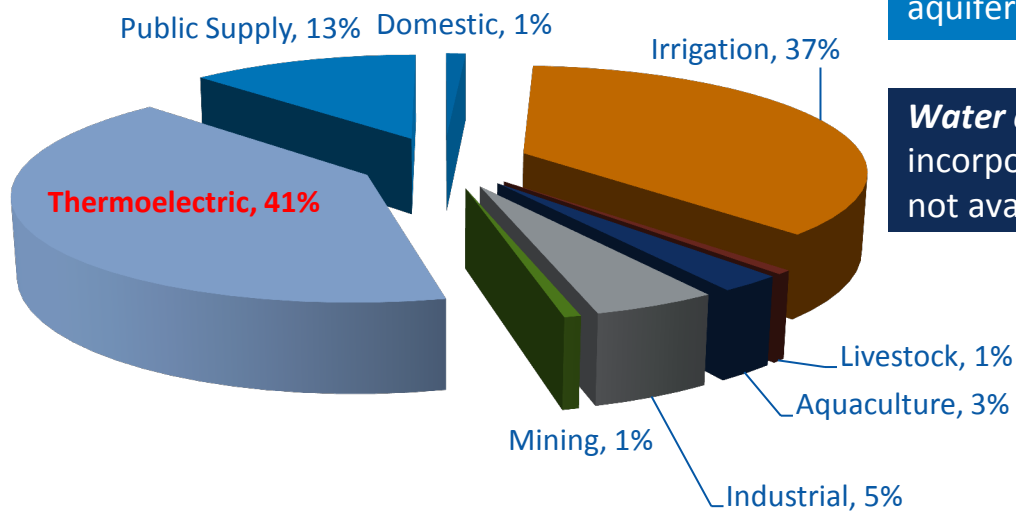
James Meldrum

Jordan Macknick

Garvin Heath

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

U.S. Freshwater Withdrawals (2005)¹



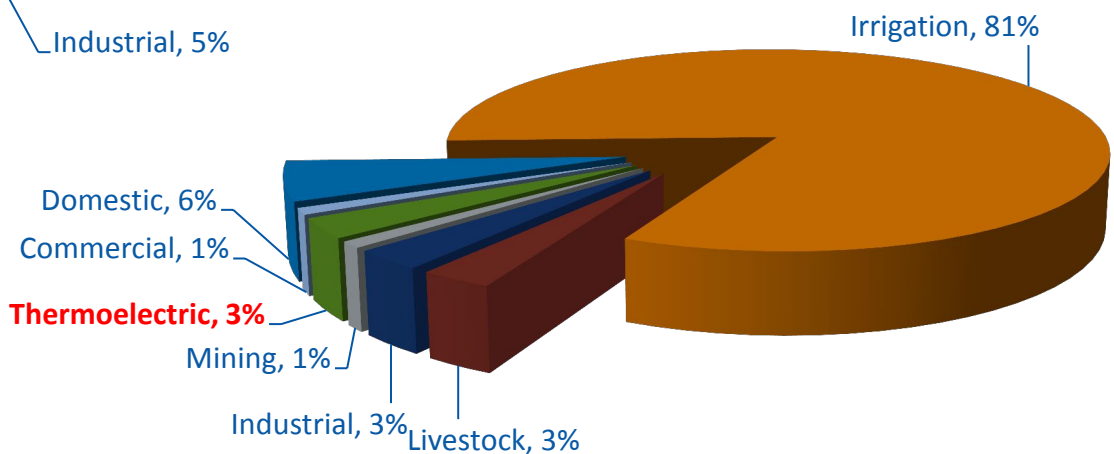
Water withdrawals: water removed from the source (e.g., aquifer, river, lake, or ocean) for use.

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.

Thermoelectric water requirements (USGS):

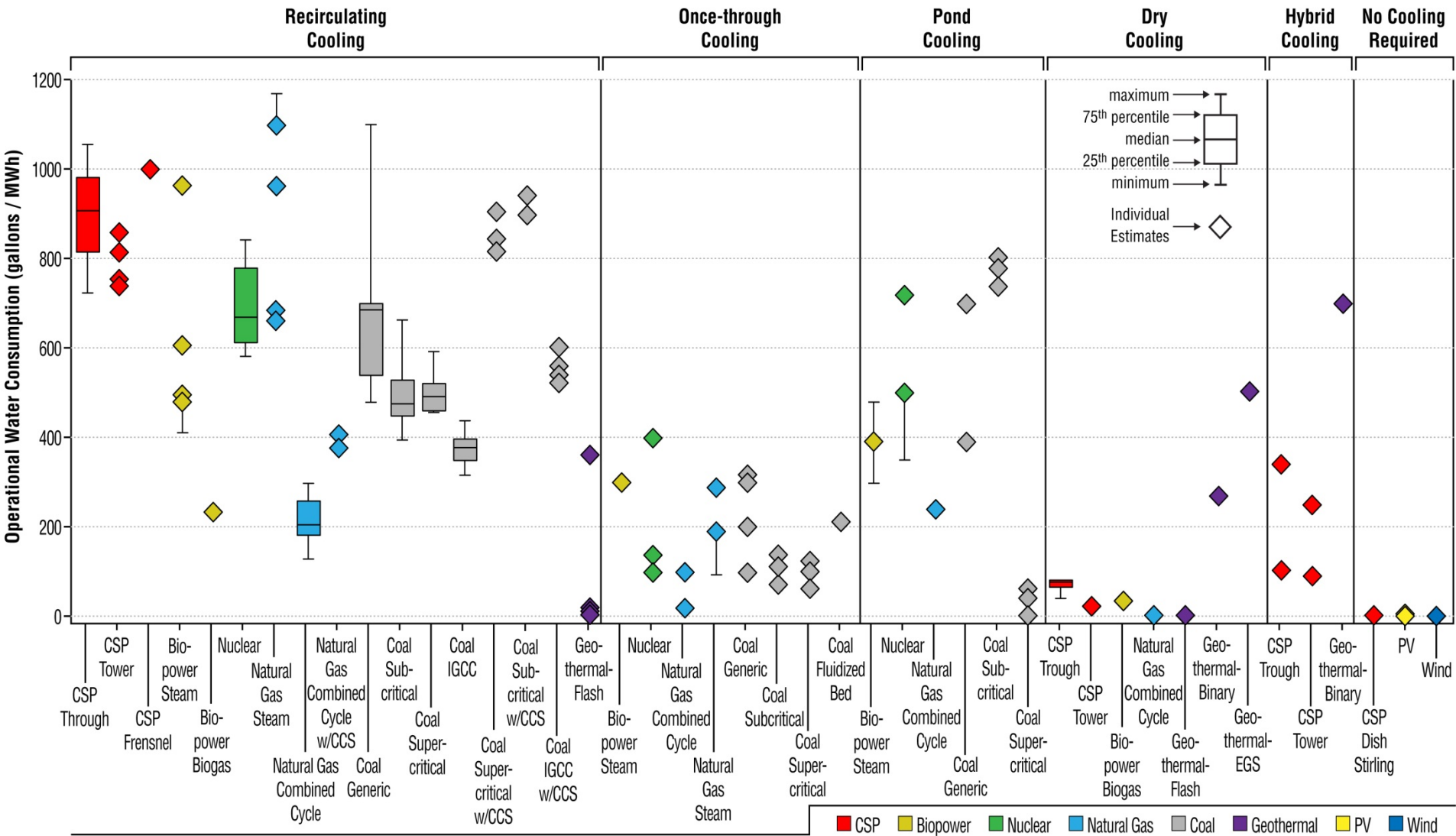
- Withdrawal: ~ 540 Mm³ /day (41%)
- Consumption: ~ 15 Mm³ /day (3%)

U.S. Freshwater Consumption (1995)^{2*}



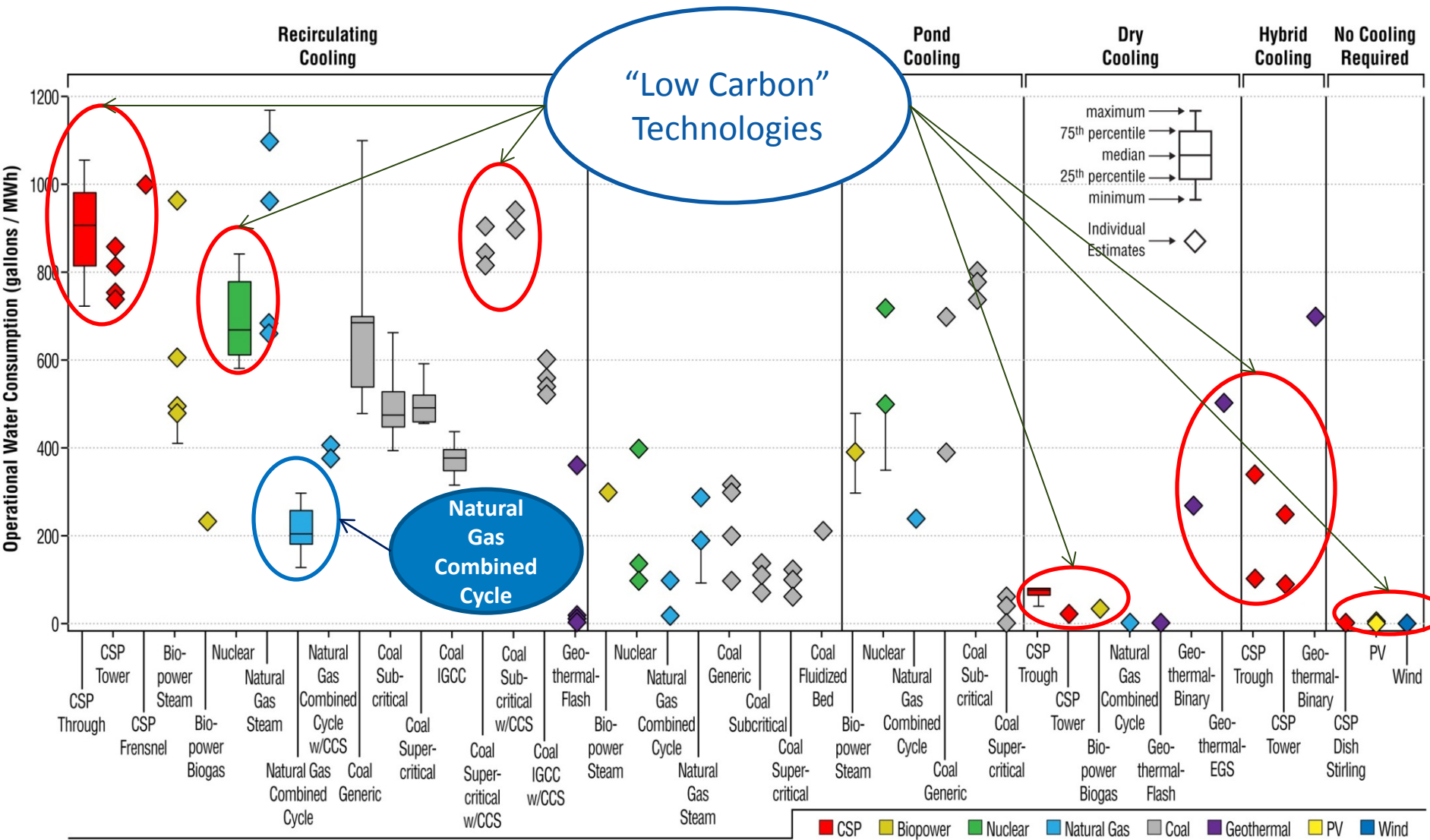
Sources: ¹USGS. 2009. "Estimated Use of Water in the United States in 2005." USGS Circular 1344. Reston, VA: USGS.
²USGS. 1998. "Estimated Use of Water in the United States in 1995." USGS Circular 1200. Reston, VA: USGS.
*1995 is the most recent consumption data collected by the USGS

Operational Water *Consumption* Rates (gal/MWh)



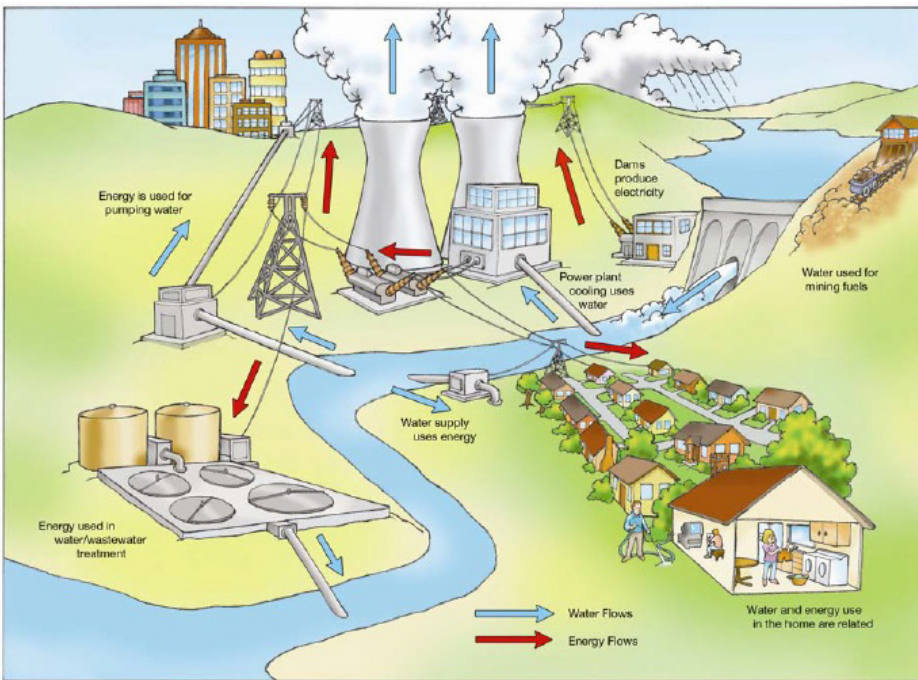
Source: Macknick, J., R. Newmark, G. Heath, and K.C. Hallett. 2012. "Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature." *Environmental Research Letters* 7 (045802).

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



Fuel Cycle (NG, coal, nuclear)

- Extraction (drilling, fracking, mining)
- Processing
- Transport
- End of life storage/handling



Power Plant Operation

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

Harmonization of Water Use Estimates

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

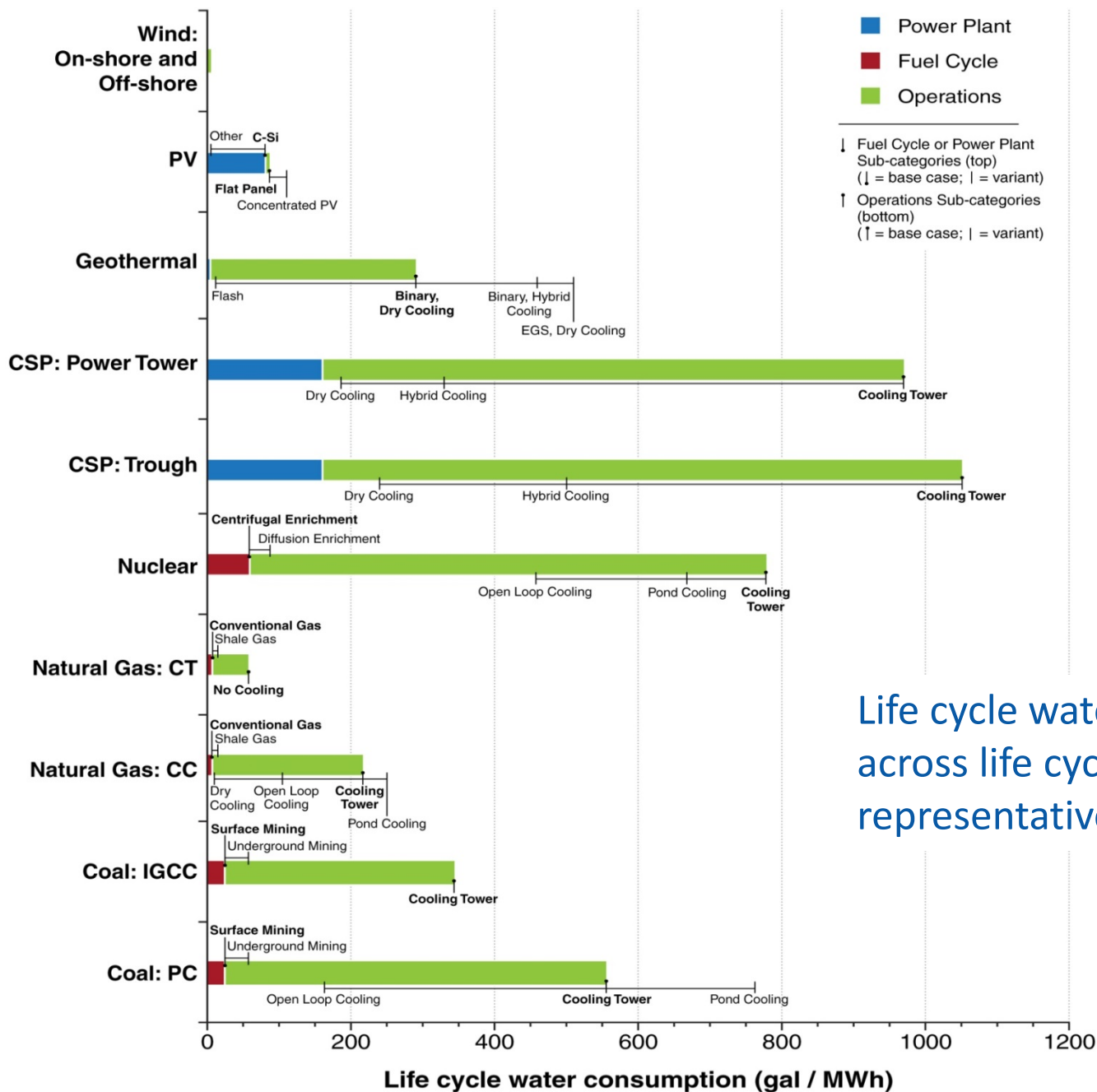
Common metric: gallons/MWh of electricity generated. This is important because more than LCAs were utilized.

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.

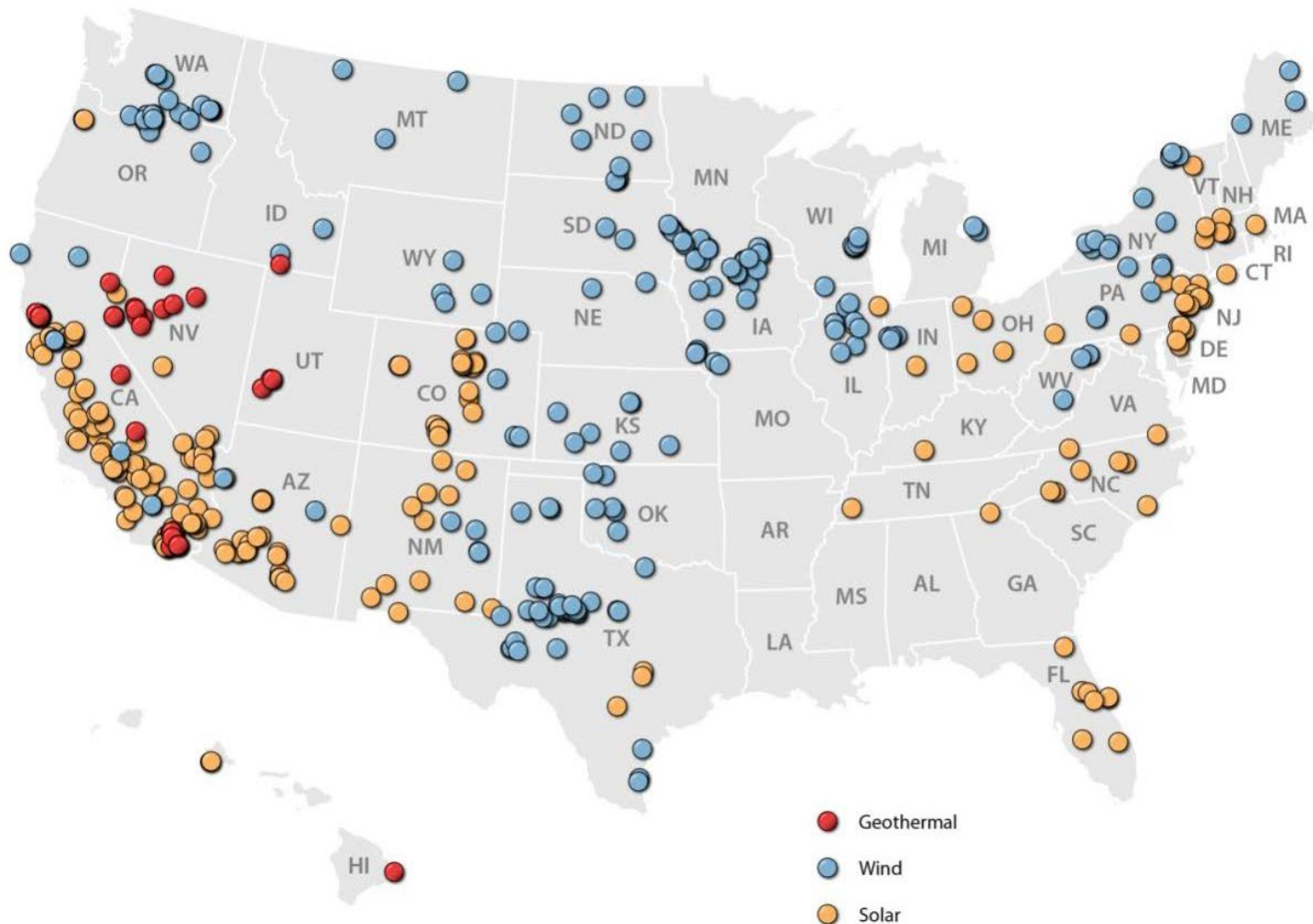
Operational Land Use by Selected Electricity Generation Technologies

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:

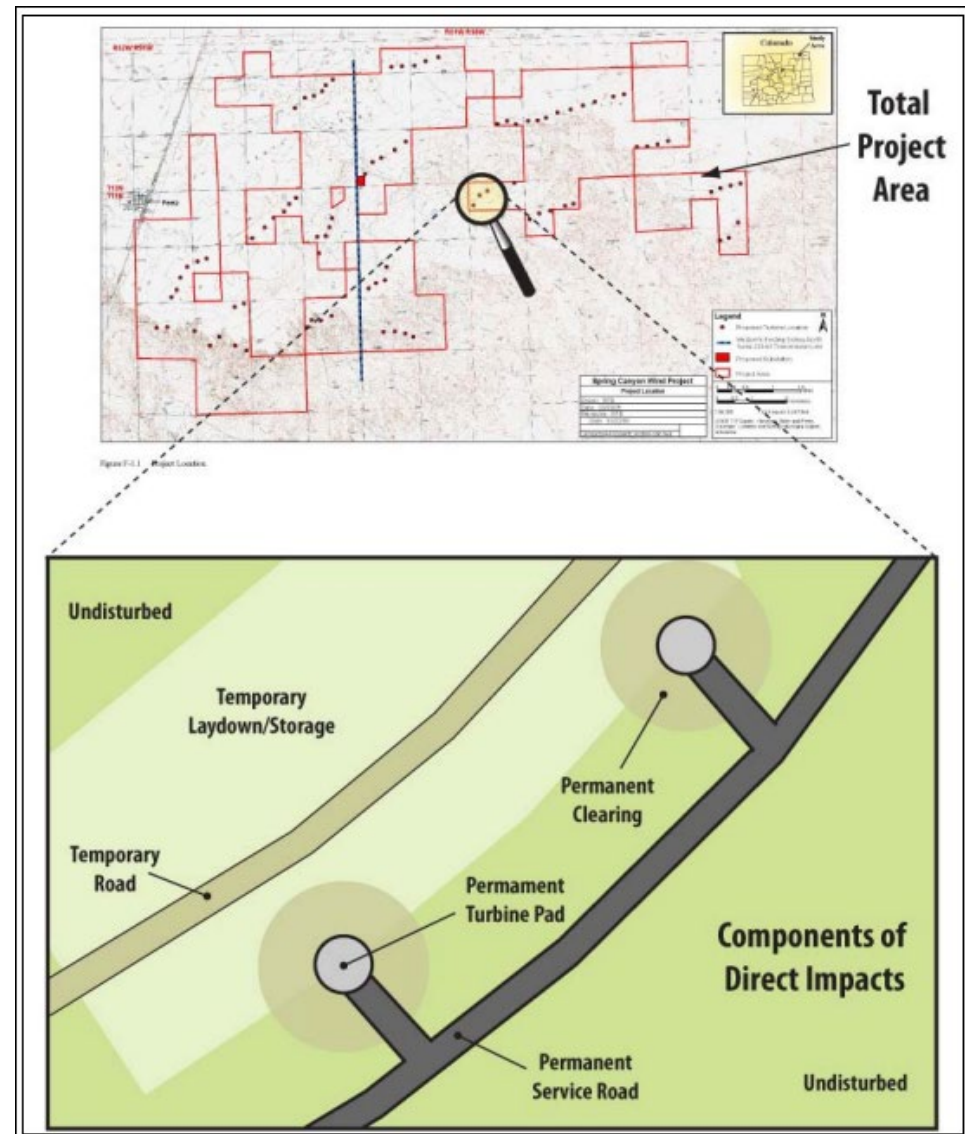
- 51% of installed wind capacity
- 80% of installed solar (PV + CSP)
- All known geothermal.

Ong et al. 2013.

Methods: Direct vs. Total Area

Methods:

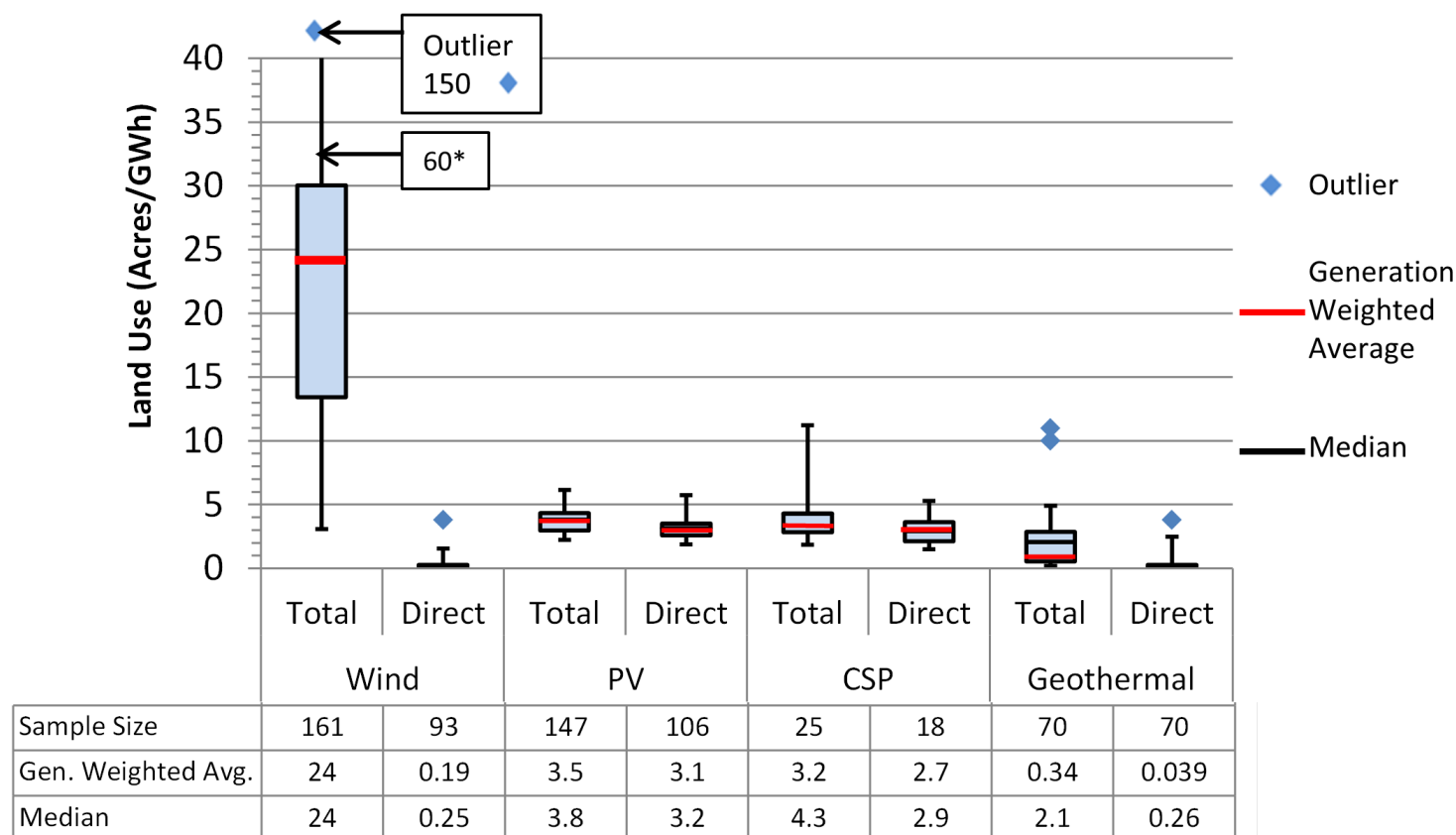
- Documents
 - Official documents (e.g., EIS)
 - Developer documents
 - Third-party sources
- Satellite imagery analysis.



Source: Denholm et al. 2009

Land Use per Unit Generation

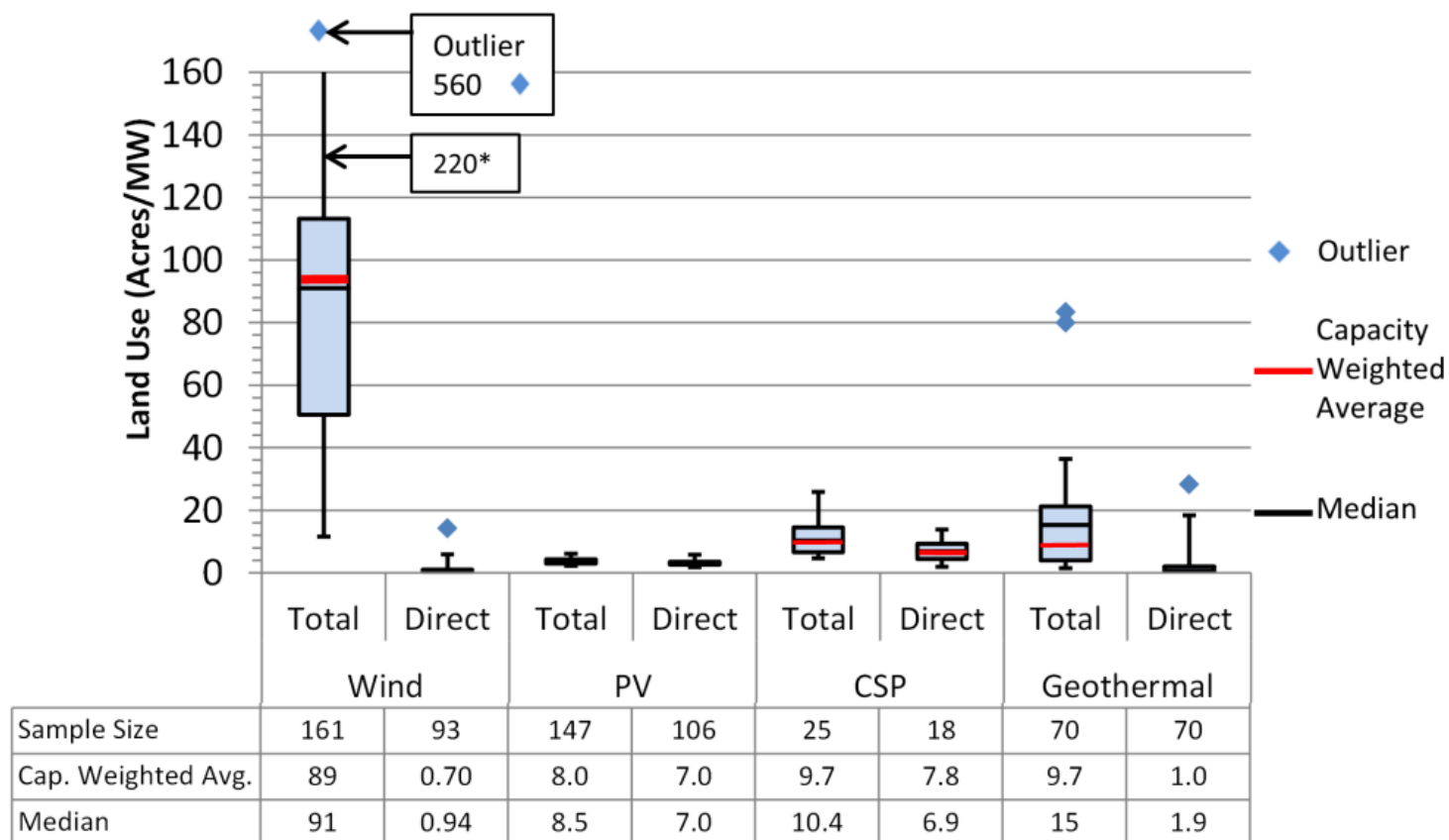
Generation-basis accounts for differences in capacity factor between technologies (e.g., CSP and geothermal vs. PV and wind).



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.



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





For more than 37 years, NREL has delivered innovation impact enabling the emergence of the U.S. clean energy industry.

For more information please visit our website at www.nrel.gov.

Acknowledgments

Funding from U.S. DOE (EERE and EPSA), EPRI and Novim

Contributors:

NREL: Ethan Warner, Patrick O'Donoughue, Stacey Dolan, David Hsu, John Burkhardt, Pamala Sawyer, Martin Vorum, Elliot Cohen, Jordan Macknick, James Meldrum, Craig Turchi, Douglas Arent, Morgan Bazilian

BNL: Vasilis Fthenakis, Hyung Chul Kim

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

References

- Heath G, Warner E, Steinberg D, Brandt A. 2015. Estimating U.S. Methane Emissions from the Natural Gas Supply Chain: Approaches, Uncertainties, Current Estimates, and Future Studies. Joint Institute for Strategic Energy Analysis, Golden CO. NREL/TP-6A50-62820. <http://www.nrel.gov/docs/fy16osti/62820.pdf>.
- E.G. Hertwich, Thomas Gibon, Evert A. Bouman, Anders Arvesen, Sangwon Suh, Garvin Heath, Joseph D. Bergesen, Andrea Ramirez, Mabel Vega, Lei Shi. 2014. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *Proceedings of the National Academy of Sciences* 112(20): 6277–6282 <http://www.pnas.org/content/112/20/6277.abstract>.
- Heath G, O'Donoughue P, Arent D, Bazilian M. (2014) Harmonization of initial estimates of Shale Gas Life Cycle Greenhouse Gas Emissions for Electric Power Generation. *Proceedings of the National Academy of Sciences*. 111(31): E3167–E3176. <http://www.pnas.org/content/111/31/E3167.abstract>.
- Brandt A.R., G.A. Heath, E.A. Kort, F. O'Sullivan, G. Petron, S.M. Jordaan, P. Tans, J. Wilcox, A.M. Gopstein, D. Arent, N.J. Brown, R. Bradley, G.D. Stucky, D. Eardley, R. Harriss (2014). Methane Leaks from North American Natural Gas Systems. *Science* (343) 733-735. <https://www.sciencemag.org/content/343/6172/733.summary>
- Sean Ong, Clinton Campbell, Paul Denholm, Robert Margolis, and Garvin Heath. 2013. Land-Use Requirements for Solar Power Plants in the United States. NREL Report No. TP-6A20-56290. <http://www.nrel.gov/docs/fy13osti/56290.pdf>.
- Meldrum J, Nettles-Anderson S, Heath G, Macknick J. 2013. Life cycle water consumption of electricity generation technologies: Review and Harmonization. *Environmental Research Letters*. 8 015031. <http://iopscience.iop.org/1748-9326/8/1/015031/article>
- J Macknick, 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 [doi:10.1088/1748-9326/7/4/045802](https://doi.org/10.1088/1748-9326/7/4/045802)
- Ong, S.; Campbell, C.; Heath, G. 2012. Land Use for Wind, Solar, and Geothermal Electricity Generation Facilities in the United States. Final Report # 1023819 for Electric Power Research Institute. Palo Alto, CA.
- Sathaye, J., O. Lucon, A. Rahman, J. Christensen, F. Denton, J. Fujino, G. Heath, S. Kadner, M. Mirza, H. Rudnick, A. Schlaepfer, A. Shmakin, 2011: Renewable Energy in the Context of Sustainable Development. In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

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 $\leq 10\%$ of those resulting from a modern NGCC.
- CCS can increase non-CO₂ 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

The key to sound future energy decisions lies in being able to determine the right mix of technologies for local or regional situations, as well as the best policy objectives.

This infographic compares electricity generation technologies and highlights the environmental benefits, and trade-offs of each technology. The assessment is based on a comparison of clean technologies with conventional fossil fuel power plants. The graphic presents an overview over the life cycle impacts of different technology groups compared to the global electricity generation mix in the year 2010.

COMPARISON OF TECHNOLOGIES
AND IMPACTS

