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
- 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
• 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
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
• 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.

**Life Cycle Assessment**

**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 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.

*Source: IPCC SRREN 2012*
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.”
Current projects: Life cycle air emission inventories for biofuels, comparative PV manufacture LCA, importance of natural gas methane leakage.
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Depth and Breadth of LCA at NREL

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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
  o 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

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- Considerable previous work in assessing life cycle environmental impacts of electricity generation technologies
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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

**Electricity Generation Technologies Powered by Renewable Resources**

- **Maximum**
- **75th Percentile**
- **Median**
- **25th Percentile**
- **Minimum**
- **Single Estimates with CCS**

**Electricity Generation Technologies Powered by Non-Renewable Resources**

- **Nuclear Energy**
- **Natural Gas**
- **Oil**
- **Coal**

* Avoided Emissions, no Removal of GHGs from the Atmosphere

**Count of Estimates**

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<thead>
<tr>
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<tr>
<td>Coal</td>
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Conventionally Produced NG
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:

\[ GHG = \frac{GHG_{GWP\_weighted}}{\text{lifetime \_ generation}} \]

2. Addition or subtraction for system boundary
Methodological Harmonization Reduces Variability and Clarifies Central Tendency

![Graph showing life cycle greenhouse gas emissions (g CO₂-e/kWh) for different energy sources.](image)

<table>
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<tr>
<th>Energy Source</th>
<th>Published Estimates</th>
<th>Harmonized Estimates</th>
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<tr>
<td>Photovoltaics (C-Si and Thin Film)</td>
<td>46</td>
<td>36</td>
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<td>Concentrating Solar Power (Trough and Tower)</td>
<td>126</td>
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<tr>
<td>Wind (Offshore and Onshore)</td>
<td>61</td>
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<tr>
<td>Nuclear (Light Water)</td>
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<tr>
<td>Natural Gas CC (Conventional and Unconventional)</td>
<td>17</td>
<td>10</td>
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<tr>
<td>Coal (Sub- and Supercritical, IGCC, Fluidized Bed)</td>
<td>49</td>
<td>49</td>
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| References | 27 | 45 | 53 |
Example: Natural Gas and Methane

U.S. dry natural gas production
trillion cubic feet

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<th>Year</th>
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<th>Projections</th>
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<td>2030</td>
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<td>2040</td>
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</table>

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

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

<table>
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<tr>
<th>Year</th>
<th>GWP (CO₂e)</th>
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<td>AR2 (1995)</td>
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<td>AR3 (2001)</td>
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<td>AR4 (2007)</td>
<td>25</td>
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<tr>
<td>AR5 (2014)</td>
<td>30</td>
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</tbody>
</table>

2014 U.S. GHG Inventory (using CH₄ 100-yr GWP = 25)

- NG Production: 25%
- NG Processing: 18%
- NG Transmission and Storage: 11%
- NG Distribution: 9%
- Enteric Fermentation: 7%
- Landfills: 6%
- Coal Mining (active and abandoned): 5%
- Manure Management: 4%
- Petroleum Systems: 3%
- Other Agriculture: 2%
- Wastewater Treatment: 2%
- Other: 2%

CO₂e = carbon dioxide equivalents; AR = Assessment Report

The Natural Gas Production, Transmission and Distribution System

Source: U.S. Energy Information Administration.
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
1. Howarth et al. 2011
2. Jiang et al. 2011 (CMU)
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

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.

Source: Heath et al. 2014

(Methane GWP = 30 for all categories)
Life Cycle GHG Emissions Sensitive to Assumptions About Liquids Unloading and Estimated Ultimate Recovery (EUR)

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)

**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

**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.

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 facility
- Attributed to energy industry or not attributed
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

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.

Source: Heath et al. 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)$^{1}$

- Public Supply, 13%
- Domestic, 1%
- Thermoelectric, 41%
- Irrigation, 37%
- Livestock, 1%
- Aquaculture, 3%
- Mining, 1%
- Industrial, 5%

Thermoelectric water requirements (USGS):
- Withdrawal: ~ 540 Mm$^3$/day (41%)
- Consumption: ~ 15 Mm$^3$/day (3%)

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)$^{2*}$

- Irrigation, 81%
- Domestic, 6%
- Commercial, 1%
- Thermoelectric, 3%
- Mining, 1%
- Industrial, 3%
- Livestock, 3%

Sources:
$^{2*}$1995 is the most recent consumption data collected by the USGS

NATIONAL RENEWABLE ENERGY LABORATORY
Operational Water Consumption Rates (gal/MWh)

Operational Water Consumption Rates (gal/MWh)

Uses of Water in Life Cycle

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

**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*

Source: DOE, 2006
**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


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
  o Official documents (e.g., EIS)
  o Developer documents
  o 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).

<table>
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<tr>
<th></th>
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<th>Total</th>
<th>PV</th>
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<td>0.26</td>
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</table>

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

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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


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)
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-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.

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.”
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.

The environmental impacts of producing the materials required by different energy technologies are included in the below life cycle results. Material requirements are identified here as an indication of resource use. The higher material requirements represent a reasonable share of global production.

To meet the world’s electricity needs in 2050— as per the International Energy Agency’s “Blue Map Scenario”— annual requirements are one year of current global iron production and two years of copper production.