Input–output life cycle environmental assessment of greenhouse gas emissions from utility scale wind energy in the United States

Presented by Indraneel Kumar

Based on Kumar, I., W. Tyner, and K. Sinha (2016), Energy Policy Volume 89

Outline:

- Background
- Wind Energy Development and Issues in Indiana
- Paper presentation
    - Literature Review
    - Scope: LCA Boundary
    - Data Preparation
    - Results and Discussions

Background:

- The paper is based, in part, on a PhD Dissertation.

- One of the three research questions:

    - How much land is suitable for wind farms siting in Indiana given the constraints of environmental, ecological, cultural, settlement, physical infrastructure and wind resource parameters?

    - What are the life cycle costs and economic and financial feasibility?

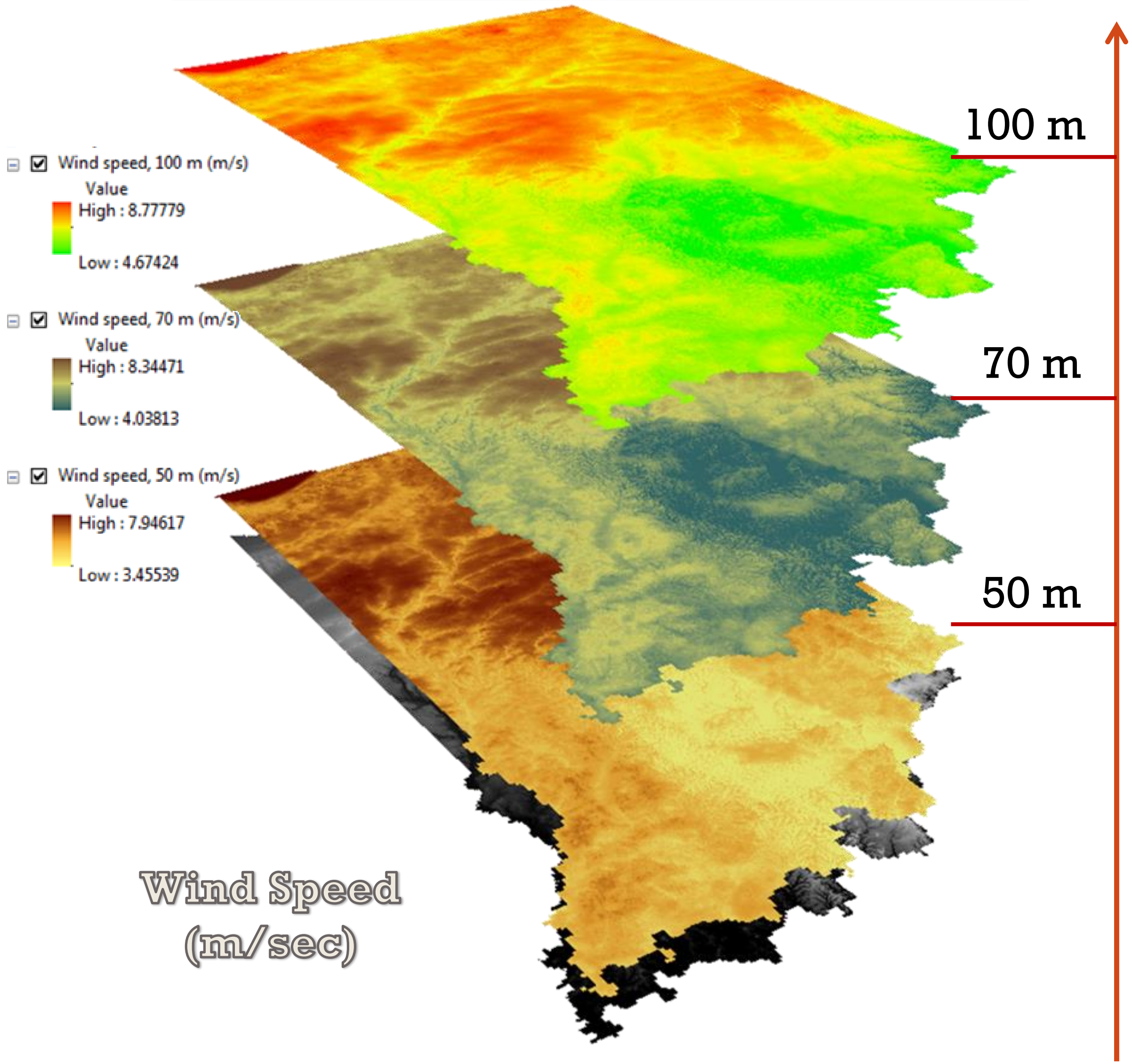
    - Is wind energy production and development in a state an emission less undertaking?

Background: Wind Energy Share in Other U.S. States

- Iowa and South Dakota, more than 25% of electricity from wind power
- 9 States, wind power provides more than 12% of electricity
- Midwestern states' share of wind energy in 2013: Iowa (27.4%); Wisconsin (2.4%); Minnesota (15.7%); Michigan (2.4%); Illinois (4.7%); Indiana (3.2%); Ohio (0.8%)
- Texas is 1st ranked for installed capacity (12.4 GW), more than 7,700 turbines, 9.9% of 2013 electricity generation is from wind

Source: American Wind Energy Association (AWEA) and Energy Information Administration (EIA) websites

Background: Wind Energy in Indiana



- Indiana had 1,758.6 MW installed capacity by Aug, 2015.
- 1,035 wind turbines
- 5 large scale projects installed (100+ turbines)
- Different estimates for remaining capacity in Indiana
- 30,000 MW remaining (WIndiana Conf., 2010)
- 148,277 MW capacity, 32% land area available (NREL, 2011)
- Detailed land suitability analysis?

Source: Map developed by the author using IGS, NREL, TrueWind Solutions
http://www.in.gov/oed/2413.htm

Background: Wind Farm Issues in Indiana

http://www.fws.gov/midwest/endangered/permits/hcp/FowlerRidge/

- Blanket setback standards adopted by Indiana counties
- 305 meters set back from dwelling units, schools, any structure
- Inadequate setback from roads, railroads, utilities ROW
- Wisconsin has 381 meters, Canada has 600 meters
- Site suitability studies from UK recommend 1,000 meters

- Fowler Ridge wind farm (355 turbines), Benton County, Habitat Conservation Plan (2 years), for incidental take permit for Indiana Bats (approved in January, 2014)
- Monitoring study, 800+ common bats and 60 birds carcasses (April-Oct, 2010)
- Indiana has migratory birds stopover sites, Important Bird Areas (Audubon Soc.)

Research question:

- Is wind energy really emission free and green?
- The specific research question is:
  - How much green house gas (GHG) emissions are expected from wind power development in a state?
- Rotation of wind turbine blades and conversion of wind into electrical energy is an emission free activity.
- However, life cycle activities of extraction, mining, manufacturing, transportation, construction, commissioning, and de-commissioning are not emission-free activities.

Literature Review:

- EIO-LCA (economic input output life cycle assessment) uses economic input output tables to estimate environmental emissions.

- The first such effort to estimate environmental impacts through IO table was by Leontief (1970).

- Green Design Institute (Carnegie Mellon Univ.) has developed EIO-LCA data and analysis for several products in response to intensive data requirements and resources needed for the traditional, bottom-up LCA (life cycle assessment) methods (Hendrickson et al. 2006; Lave et al. 1995).

- Traditional LCA could not include all life stages due to lack of data, lack of information on supply chains, and $ and time needed for surveys.

Literature Review: IO Table

- Inter-industry transactions, final demand, exports and total demand (IO table) form a system of linear equations

$$X_{11} + X_{12} + X_{13} + X_{14} + X_{15} + X_{16} + Y_1 = Z_1$$

$$X_{21} + X_{22} + X_{23} + X_{24} + X_{25} + X_{26} + Y_2 = Z_2$$

$$X_{n1} + X_{n2} + X_{n3} + X_{n4} + X_{n5} + X_{n6} + Y_n = Z_n$$

$$\sum_j X_{ij} + Y_i = Z_i$$

Reduced form

$$\sum_i X_{ij} + V_j + M_j = Q_j$$

Transposed

$$\sum_j a_{ij} * q_j + Y_i = q_i$$

Substitution

$$A * q + Y = q$$

Reduced form

$$q = (I - A)^{-1} * Y$$

$(I\text{-}A)^{-1}$, Leontief Inverse or Total requirements table

$$a_{ij} = X_{ij}/q_j$$

Direct requirements

- Assumption for EIO-LCA includes that the input output (IO) table, backward linkages or purchasing or embedded supply chains can account for life cycle events, such as mining, processing, manufacturing, etc.

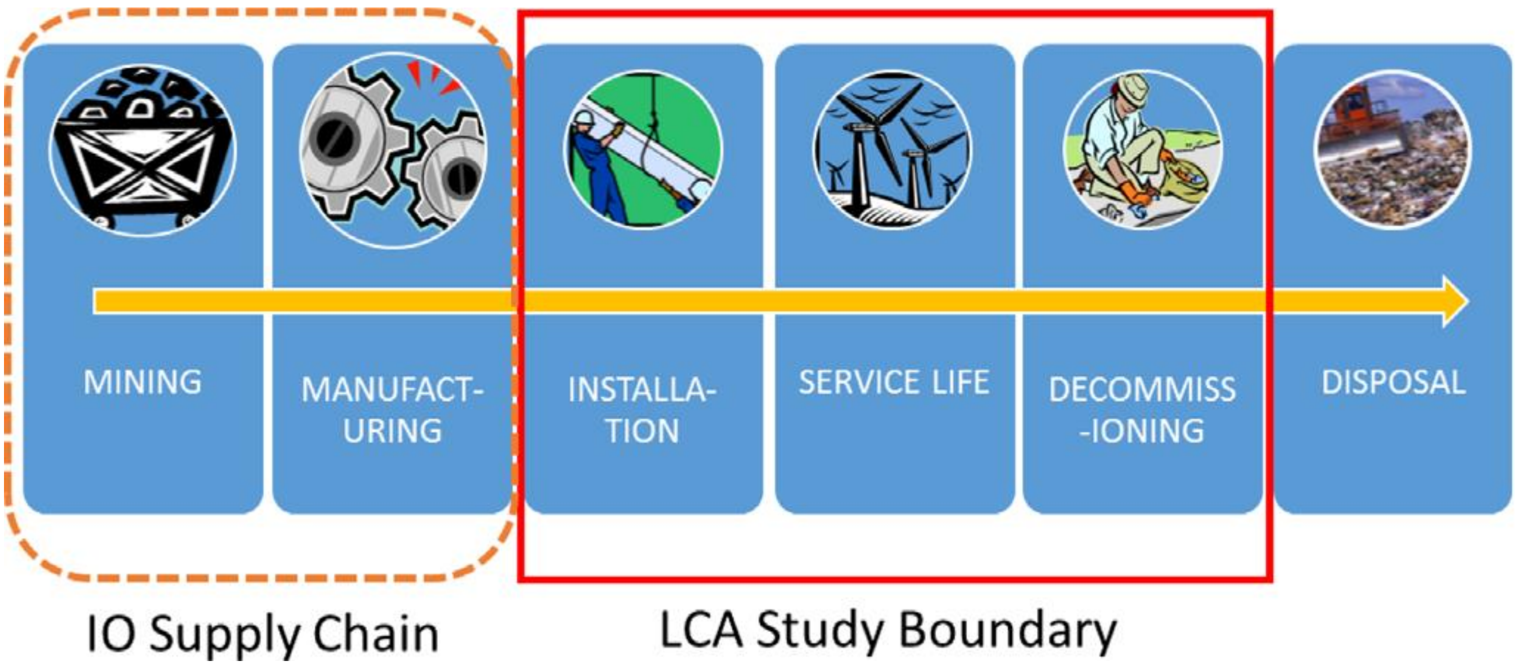
Literature Review:

- EIO-LCA does have limitations that are inherent to the IO table.
  - Insufficient disaggregation of industry sectors
  - Assumed linearity of the IO linkages
  - Lack of input substitution and economies of scale
  - Inability to capture product and process diversity within an industry sector
  - Insufficient data on emissions by industry sectors
- The strength of EIO-LCA is tractability of the life cycle assessment, which can be complex if all stages from "cradle to grave" are included.
- EIO-LCA is emerging as a prominent tool for product, industrial design, and policy analysis and carbon footprint assessments (Deng et al. 2011, Trappey et al. 2013, Williams et al. 2009)

Scope and LCA Boundary:

- Previous studies focused on manufacturing and production stages as they produced maximum emissions.

- However, wind turbines have a longer life cycle of 20-25 years and O& M is significant including decommissioning and the removal of the wind turbine.



Case Study Data Preparation:

$$B_i = R_i[I - A]^{-1}Y_i$$

Environmental Burden — B_i

Emissions Matrix — R_i

$$\begin{bmatrix} b1 \\ b2 \\ b3 \end{bmatrix} = \begin{bmatrix} R1 & 0 & 0 \\ 0 & R2 & 0 \\ 0 & 0 & R3 \end{bmatrix} \begin{bmatrix} a11 & a12 & a13 \\ a21 & a22 & a23 \\ a31 & a32 & a33 \end{bmatrix} \begin{bmatrix} Y1 \\ Y2 \\ Y3 \end{bmatrix}$$

- R_i is a diagonal matrix of environmental emissions per $ output by industry sector
- $[I\text{-}A]^{-1}$ is the Leontief Inverse or the Total Requirement Matrix
- Y_i is a vector of total demand
- B_i is emission by sector I and $\sum_{i=1}^{n} B_i$ is the total emissions
- $Y_i = Y_c + Y_{om} + Y_d$ where total demand is aggregation of capital, O&M, and the decommissioning costs

Case Study Data Preparation:

- The 2010 total requirements matrix in producers' price for 71 industry sectors in NAICS 3-digit is obtained from BEA. It forms the Leontief Inverse.
- Gross output by sector is obtained from the BEA.
- These are not import adjusted values!
- GHGRP and GHGIP from EPA is used to develop GHG emission estimates by industry sectors at NAICS 3-digit level. This is used with gross industry output from BEA to develop the diagonal matrix *Ri*.
- Capital, O&M, and decommissioning costs of wind turbines and break-up by sectors are obtained from various published sources. Present values are obtained from life cycle costs. It is used to develop the three demand vectors (Y_i).

Case Study Data and Results:

Net Present Value (NPV) for Life Cycle Costs of 1.5 MW Wind Turbine ($ 2010)

Installation cost	Fixed O & M	Variable O & M	Decommissioning cost
$3,000,000	$195,800	$ 237,700	$50,000

GHG Emissions in Metric Tons, Life Cycle Period of One Turbine

Category	Yc+Yom+Yd	Yc
Total GHG emissions	1,912.3	1,713.3

Energy Production by 1.5 MW Wind Turbine during Life Cycle

Energy Production	KWh/turbine/Year	Total KWh/turbine, 25 Years
Minimum KWh	2,681,313	67,032,825
Mean KWh	4,088,855	102,221,375
Maximum KWh	5,257,528	131,438,200

- There is uncertainty in energy production through the life cycle of a wind turbine as climate conditions have long-term variations (Wan, 2012). Actual climate data from Indiana is used to estimate Weibull curves and the total energy production. Parameters from NREL research is used to run the Monte Carlo simulations to assess the sensitivity or range of energy production.

Case Study Data and Results:

Range of Life Cycle Emissions in Metric Tons GHG CO_2e per GWh

GHG emissions (metric tons per GWh)	Yc+Yom+Yd	Yc
Minimum energy	28.5	25.6
Mean energy	18.7	16.8
Maximum energy	14.5	13.0

Life Cycle GHG Emissions of Wind and Fossil Fuel Sources (Grams GHG CO2e per KWh)

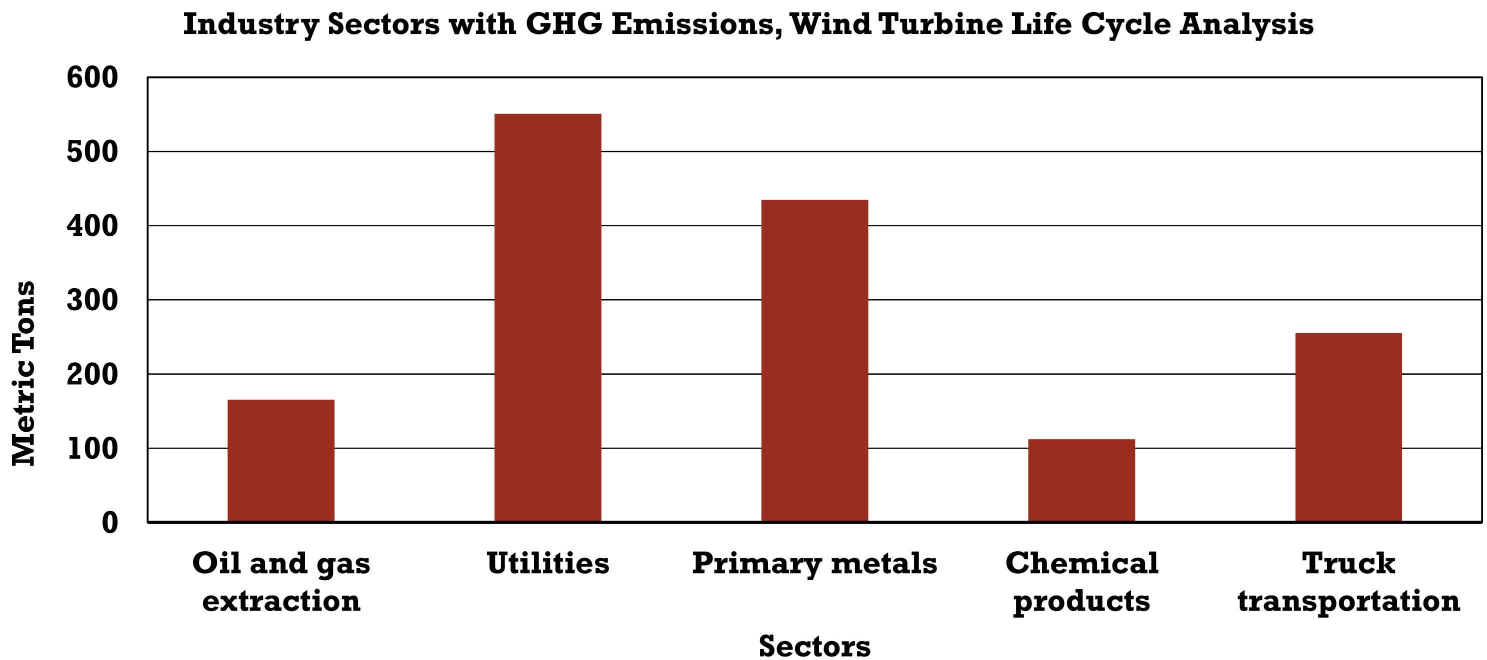
Energy Source	Minimum	Maximum
Wind Turbine (Indiana)	14.5	28.5
Coal-fired Power Plant	950	1,250
Natural gas-fired Power Plant	360	575
Oil-fired Power Plant	700	800

Source: Coal-fired, natural gas-fired, and oil-fired from Weisser, 2007

- Meta-analysis by Nugent and Sovacool (2014) and harmonized study by Dolan and Heath (2012).
- Wind energy remains a low emission source when compared to fossil fuel based energy sources.

Case Study Data and Results:

Industry Sectors with 100 Metric Tons or More GHG Emissions in Wind Turbine LCA



- oil and gas used for mining, utilities, manufacturing, and transportation
- utilities due to energy used during manufacturing
- primary metal because of manufacturing of tower and turbine parts
- chemicals because of manufacturing of turbine blades and parts
- truck transportation used for material movement during processing, manufacturing, and construction cause GHG emissions as all the life cycle events are considered.

Results and Policy Implications:

- The present study finds that around 90% of emissions through the life cycle of wind turbine occur in the upstream activities of mining, processing, manufacturing and production, transportation, and installation phases.

- However, operation and maintenance and disposal added around 10% or 200 metric tons of GHG through the life cycle.

- GHG emission intensities could be unique to the region and depend on regional traits, such as supply chains in the manufacturing and procurement of wind turbines, existing transportation infrastructure, capacity for local operation and maintenance, and turbine disposal policies.

- The GHG emission intensities (grams CO2e per KWh) are dependent on energy generation, which are affected by wind speed, capacity factor, and regional climate characteristics.

- EIO-LCA can be a useful tool as states develop strategies for replacing fossil fuel based power sources under the EPA's Clean Power Plan.

- EIO-LCA uses publicly available data and can be a useful initial tool for policy analysts, planners, and engineers to estimate emissions from wind and other renewable energy sources.

Thank You!

Questions?
Discussions!
Comments!

Presented by: Indraneel Kumar, PhD, AICP
Regional Planner: GIS and Spatial Analysis
Purdue Center for Regional Development
Purdue University