Gone with the Wind: Renewable Energy Infrastructure, Welfare, and Redistribution

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Background

Rise of Renewable Energy

- **wind and solar energy**: sharply fallen cost (Levelized Cost of Electricity, LCOE)
- 50 to 70 percent of global electricity production by 2040 (Arkolakis and Walsh, 2023)

Wind Energy in Germany

- **heavily subsized** turbine through feed-in-tariffs, "onshore" (87%) vs. "offshore"
- **High density**: 97% turbines located within 2km of residential population

Impact of turbines on amenities

- **visual**: up to 200m high with rotor blades up to 75m long, -6.5% within 1km (Gibbons, 2015)
- **sound**: rotation of blades produces noise and infrasound (very localized) (Zou, 2020)

Development Plan until 2030

- ambitious goals for further development of wind energy, from 58GW to 115GW in 2030
- **2021 Climate Act Germany**: 2045 climate neutrality
- efficiency, capacity, enormous speed-up in the **number** (add about 2200 per year)
- **slowdown** in turbine construction: not enough area (minimum distance rules, 500-1500m)

Large expansion of decentralized infrastructure ⇔ Resistance of local residents

This Paper

Research Questions

- What are the **local costs** of renewable energy infrastructure?
- How can **future allocations** achieve climate targets while keeping adverse impacts on welfare and inequality low?

Literature & Contributions

- Welfare costs of **environmental disamenities**
  - house prices as a revealed preference measure
    - Chay and Greenstone (2005), Greenstone and Gallagher (2008), Gibbons (2015), Currie et al. (2015)
  - novel IV strategy, location choice model, alternative allocations of turbines...
- **Quantitative Spatial GE Model** in geographic implications of climate change
  - **Adaptation**: higher temperatures, rising sea levels, natural disasters risks ...
    - individuals (migration), firms (production network), countries (specialized sectors)
    - Bilal and Rossi-Hansberg (2023), Balboni et al. (2023), Conte et al. (2021)
  - **Mitigation**: policy-relevant, inform efforts to reduce emissions and welfare costs
    - quantitatively important local costs, optimal allocation of infrastructure
    - Arkolakis and Walsh (2023), Balboni (2021), Hsiao (2023)

Data

Geographic unit of analysis

- finer + consistent shape and size: 1-by-1 km grid cell level
- local effects, within-municipality **sorting**

Sample

- 133,339 grid cells with positive residential/workplace population
- 92% positive population, 49% positive employment

Wind Turbine

- coordinates and construction year (2000-2015)
- complement 2016-2017 from *The Wind Power*

House Prices

- **quality-adjusted** house price index (residualization)
- platform: *ImmobilienScout24*, 35 million houses and flats, from 2007
- asking price, date of the ad, object's location and characteristics

Residents, workers, and wages

- ≈ 40 million individuals every year, residential/job address
- wages = average wage among all **full-time workers** in a neighborhood

Data

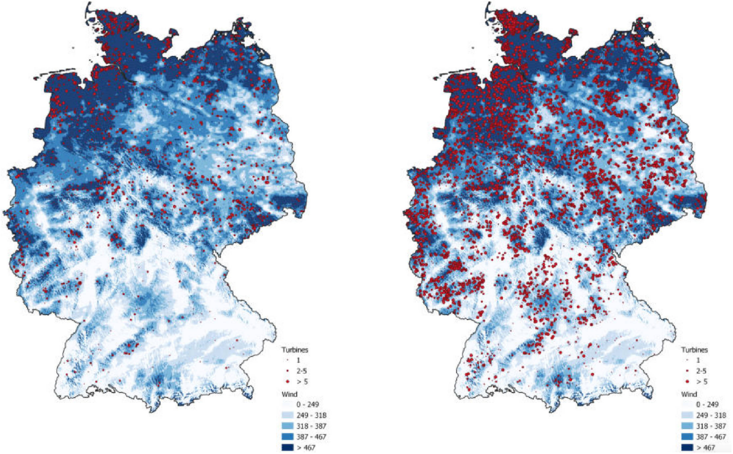

Figure: Wind Turbines (**Left**: 2000; **Right**: 2017)

Step 1: Reduced-Form Estimate

$$\Delta y_n = \beta \cdot \Delta T_n + \varepsilon_n$$

Endogeneity

- **Demand**: politicians allow turbine in regions where expected electricity demand to grow
- **Supply**: developers may avoid regions with expected strong resistance from residents

$$\Delta y_n = \beta \cdot \Delta \hat{T}_n + \gamma X_n + \delta_{d(n)} + \varepsilon_n$$

Long Difference

- Δy_n: change in the outcome variable (house prices, share high-skilled residents)
- $\Delta \hat{T}_n$: predicted number of wind turbines constructed between 2000-2017
- **IV: technology-induced changes**
  - ΔW_n: change of **wind power density** due to height increase (reap 59% higher)
  - $\Delta W_n S_n$: interaction with the share of **land available** for wind turbine development

Step 1: Reduced-Form Estimate

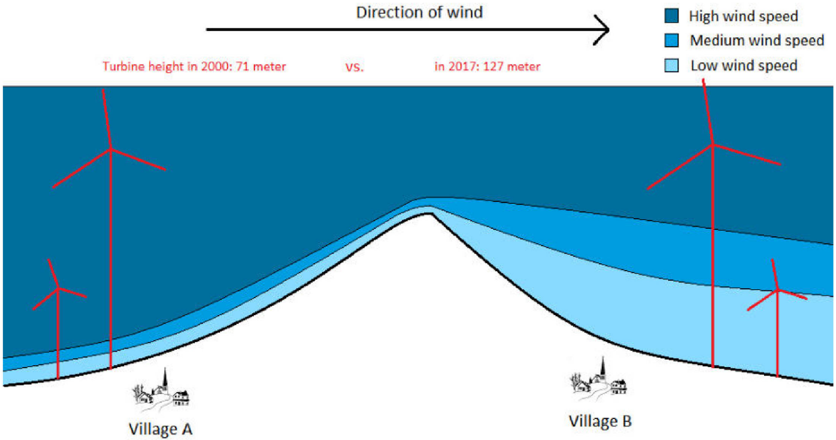

Figure: Schematic Illustration of IV Strategy

Step 2: First-Order Impact

Setup

- L workers (ω, high-skilled or low-skilled, $\theta \in \{h, l\}$)
- N neighborhoods (n)

Utility

$$\max_{h,c} \quad u_n^\theta(\omega) = A_n^\theta \cdot (h^\theta)^{\alpha^\theta} \cdot (c^\theta)^{1-\alpha^\theta} \cdot \varepsilon_n(\omega) \quad \text{s.t.} \;\; Q_n \cdot h^\theta + c^\theta = w_n^\theta \Rightarrow v_n^\theta(\omega) = \frac{A_n^\theta w_n^\theta}{Q_n^{\alpha^\theta}} \varepsilon_n^\theta(\omega)$$

$$\varepsilon_n^\theta(\omega) \sim F^\theta(\varepsilon) = \exp(-\varepsilon^{-\kappa^\theta}) \Rightarrow \lambda_n^\theta = \frac{\left(\frac{A_n^\theta w_n^\theta}{Q_n^{\alpha^\theta}}\right)^{\kappa^\theta}}{\sum_{r=1}^N \left(\frac{A_r^\theta w_r^\theta}{Q_r^{\alpha^\theta}}\right)^{\kappa^\theta}}$$

$$\ln(A_n^\theta) = \frac{1}{\kappa^\theta} \cdot \ln(R_n^\theta) + \alpha^\theta \cdot \ln(Q_n) - \ln(w_n^\theta) + c^\theta$$

- $R_n^\theta = L^\theta \cdot \lambda_n^\theta$: the number of residents in a neighborhood
- c^θ: short for the denominator sum and total population

Step 2: First-Order Impact

Interpretation

- Ahlfeldt et al. (2015): amenities (unobserved) rationalize the distribution of population
- **revealed preference summary statistic**: various channels, clear economic magnitude

Generalization

$$\ln(A_n^\theta) = \frac{1}{\kappa^\theta} \cdot \ln(R_n^\theta) + \alpha^\theta \cdot \ln(Q_n) - \ln(W_n^\theta) + c^\theta$$

- model-consistent income in the residential neighborhood W_n^θ
  - depends on wages in surrounding workplaces i
- $W_n^\theta \equiv \left(\sum_{i=1}^{N} (w_i^\theta / d_{ni}^\theta)^{\kappa^\theta}\right)^{1/\kappa}$

Estimation

$$\Delta \ln(A_n^\theta) = \frac{1}{\kappa^\theta} \cdot \Delta \ln(R_n^\theta) + \alpha^\theta \cdot \Delta \ln(Q_n) - \Delta \ln(w_n^\theta) + \Delta c^\theta$$

- additional turbine amenities decreases by **1.4%** (high-skilled) and by **0.9%** (low-skilled)
- Highway: 18% amenities loss (Brinkman and Lin, 2024)

Step 3: General Equilibrium Impact

Residence and Workplace Choice (Ahlfeldt et al., 2015)

$$v_{ni}^{\theta}(\omega) = \frac{A_n'^{\theta} w_i'^{\theta}}{d_{ni}^{\theta} Q_n^{\alpha^{\theta}}} \varepsilon_{ni}^{\theta}(\omega) \quad \text{where} \quad A'^{\theta} = a_n'^{\theta} \cdot \exp(\beta^{\theta} \cdot T_n) \quad d_{ni}^{\theta} = \exp(-\mu^{\theta} \tau_{ni})$$

$$\varepsilon_{ni}^{\theta}(\omega) \sim F(\varepsilon) = \exp\left(-D_n^{\theta} E_i^{\theta} \varepsilon^{-\kappa^{\theta}}\right)$$

- **share** of individuals live in n and work in i

$$\lambda_{ni}^{\theta} = \frac{D_n^{\theta} E_i^{\theta} \left(\frac{A_n' w_i' \theta}{d_{ni}^{\theta} Q_n^{\alpha^{\theta}}}\right)^{\kappa^{\theta}}}{\sum_{r=1}^{N} \sum_{s=1}^{N} D_r^{\theta} E_s^{\theta} \left(\frac{A_r' w_s'^{\theta}}{d_{rs}^{\theta} Q_r^{\alpha^{\theta}}}\right)^{\kappa^{\theta}}} = \frac{\left(\frac{A_n^{\theta} w_i^{\theta}}{d_{ni}^{\theta} Q_n^{\alpha^{\theta}}}\right)^{\kappa^{\theta}}}{\sum_{r=1}^{N} \sum_{s=1}^{N} \left(\frac{A_r^{\theta} w_s^{\theta}}{d_{rs}^{\theta} Q_r^{\alpha^{\theta}}}\right)^{\kappa^{\theta}}}$$

- **Adjusted Amenities**: $A_n^{\theta} \equiv (D_n^{\theta})^{1/\kappa} A_n'^{\theta}$; **Adjusted Wages**: $w_i^{\theta} \equiv (E_i^{\theta})^{1/\kappa} w_i'^{\theta}$

$$R_n^{\theta} = L^{\theta} \sum_{i \in N} \lambda_{ni}^{\theta}, \quad L_i^{\theta} = L^{\theta} \sum_{n \in N} \lambda_{ni}^{\theta}$$

Step 3: General Equilibrium Impact

Labor Market (Diamond, 2016)

$$\ln\left(w_i^h\right) = \gamma^{hh}\ln\left(L_i^h\right) + \gamma^{lh}\ln\left(L_i^l\right) + z_i^h$$
$$\ln\left(w_i^l\right) = \gamma^{hl}\ln\left(L_i^h\right) + \gamma^{ll}\ln\left(L_i^l\right) + z_i^l$$

- labor demand parameters γ: capture substitution patterns across skill types and spillovers

$$L^\theta = \sum_{n\in N} R_n^\theta = \sum_{n\in N} L_n^\theta \quad \textit{(Market Clear)}$$

Housing Market

$$HD_n = \frac{R_n^h\bar{v}_n^h\alpha^h + R_n^l\bar{v}_n^l\alpha^l}{Q_n} \quad \text{where} \quad \bar{v}_n^\theta = \sum_{i\in N}\lambda_{ni|n}^\theta w_i^\theta = \sum_{i\in N}\frac{\left(w_i^\theta/d_{ni}^\theta\right)^{\kappa^\theta}}{\sum_{s\in N}\left(w_s^\theta/d_{ns}^\theta\right)^{\kappa^\theta}} w_i^\theta$$

$$HS_n = \bar{H}_n Q_n^{\eta_n} \Rightarrow \bar{H}_n Q_n^{1+\eta_n} = R_n^h\bar{v}_n^h\alpha^h + R_n^l\bar{v}_n^l\alpha^l$$

Step 3: General Equilibrium Impact

Welfare

$$\bar{U}^{\theta} = E\left[v_{ni}^{\theta}(\omega)\right] = \Gamma\left(\frac{\kappa^{\theta}-1}{\kappa^{\theta}}\right)\left[\sum_{r\in N}\sum_{s\in N}\left(A_r^{\theta} w_s^{\theta}\right)^{\kappa^{\theta}}\left(d_{rs}^{\theta} Q_r^{\alpha^{\theta}}\right)^{-\kappa^{\theta}}\right]^{\frac{1}{\kappa^{\theta}}}$$

- Residents are **free to move** $\rightarrow$ expected utility **equalizes** across locations

Equilibrium

- $\{R_n^{\theta}, L_n^{\theta}, \bar{v}_n^{\theta}, w_n^{\theta}, Q_n\}_{n,\theta} + \bar{U}^{\theta}$
- 2N+2 unknowns

Step 4: Counterfactual Analysis

Alternative Turbine Placement

$$\ln([v_{ni}^{\theta}(\omega)_{\Upsilon_0}]) - \ln([v_{ni}^{\theta}(\omega)_{\Upsilon_1}])$$

$$\min_{\{T_n\}_n} \quad \sum_{n=1}^{N} \mu^h \left[R_n^h\right]_{\Upsilon_0} \ln\left(\left[A_n'^h\right]_{\Upsilon_0} / \left[A_n'^h\right]_{\Upsilon_1}\right) + (1-\mu^h)\left[R_n^l\right]_{\Upsilon_0} \ln\left(\left[A_n'^l\right]_{\Upsilon_0} / \left[A_n'^l\right]_{\Upsilon_1}\right)$$

$$\min_{\{T_n\}_n} \quad \sum_{n=1}^{N} \left(\beta^h \cdot \left[R_n^h\right]_{\Upsilon_0} + \beta^l \cdot \left[R_n^l\right]_{\Upsilon_0}\right) \cdot \left([T_n]_{\Upsilon_1} - [T_n]_{\Upsilon_0}\right)$$

- areas **available** for wind development
- achieving same **electricity** capacity
- **maximum** wind turbine density

Welfare and Inequality

- 84% lower, 0.83% to 0.13%
- more burden on **rural** (13%), **low-income** (6%) and **low-educated** (5%) municipalities
- **Why inefficient?** distribute turbines equally, appears fairer, politically feasible

Step 4: Counterfactual Analysis

(a) Data, 2017 (b) Cost-Minimizing Alternative

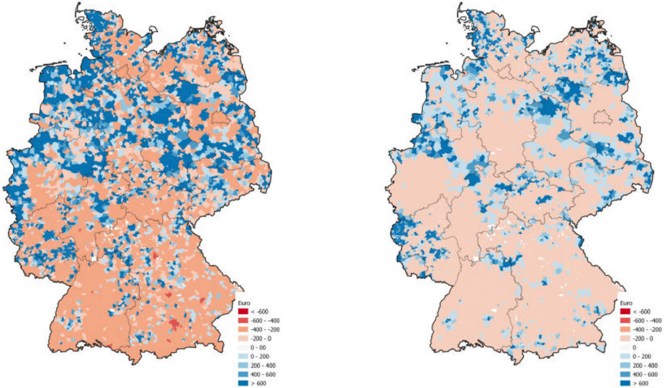

Figure: Compensatory Transfers, 2017 (**Red**: pay, **Blue**: receive)

Potential Application

The Dynamics of wastewater treatment plants (WWTP) in China

- What is the **evolution of spatial distribution** patterns of WWTPs in Chinese cities?
- What is the magnitude of the **welfare impact** of these dynamics on local residents?

Existing Infrastructure (WWTPs) ⇔ the Entry of New Ones (wind turbines)

Figure: A motivation example: Liede WWTP in Guangzhou, Guangdong (Operate since Nov. 1999)

Source: Google Earth Pro

About the Researcher

- "In my research, I combine **quasi-experimental** and **structural methods** to study climate change, the transition to a low-carbon economy, and other applied topics."
- "A question that motivates me: How can economists help to **smooth the aggregate and redistributive costs** of the climate transition?"
- **Fields:** Economic Geography and Environmental Economics

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Source: The Homepage of Milan Quentel.

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