House of Energy Markets & Finance

The future spatial distribution of onshore wind energy capacity based on a probabilistic investment calculus

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OR 2024 Munich, 9/30/2024

UNIVERSITÄT DUISBURG ESSEN

Offen im Denken

Introduction

- Ambitious goals regarding climate neutrality require massive investments in renewables
- Planning and approval processes are intended to be accelerated & necessary areas must be provided
- The regional distribution of RES impacts **grid expansion requirements** and network development scenarios
  - For onshore wind: technical and socioeconomic challenges, e.g. land availability

- Various stakeholders (private investors, grid operators) use pragmatic methods to forecast RES investments, lacking a **robust economic foundation**

➢ New method: accounts for investor decision primarily driven by **expected profitability**, incorporating observable and unobservable factors

- ➢ How does **economic efficiency** and **spatial restrictions** influence the future allocation of wind power capacities?
- ➢ Discrete decision-making process → Application of a binomial **nested logit model**: calculate investment probabilities, considering historical expansion dynamics

General modeling approach for future wind site development

- Capacity targets established at higher levels (national/state) and broke into smaller areas for detailed planning
  - Regionalization models: assess regional potentials and constraints → strategic development of energy infrastructure
- Existing studies can be divided into two main phases
  1. Analysis of existing power plants and identification of suitable land areas, influenced by political considerations and social acceptance
  2. Wind farm siting process to determine installed capacity and geolocation of turbines

  → Lack of consistent economic analyses

Bons et al., 2023
Pape & Geiger, 2023
Schmid et al., 2021
Matthes et al., 2018
Moser et al., 2020

- Incorporating **NPV** for a comprehensive financial picture
- Use of **discrete choice models** for more realistic decisions (including unobservable component)

Modeling wind energy investments using discrete choice models

- **Discrete choice models** use observable data to calculate the probability that a decision maker chooses a particular alternative out of a limited quantity of alternatives, including the possibility of choosing none
- **Nested logit** is a generalization of logit that allows for a particular pattern of correlation in the unobserved utility. They provide a valuable framework for understanding decision-making processes by accounting for the hierarchical structure of decisions and capturing the interdependencies between choices

- $U_{nj} = W_{nk} + Y_{nj} + \varepsilon_{nj}$
- $P_{ni} = P_{ni|B_k} \cdot P_{nB_k} = \frac{e^{\frac{Y_{ni}}{\lambda_k}}}{\sum_{j \in B_k} e^{\frac{Y_{nj}}{\lambda_k}}} \cdot \frac{e^{W_{nk} + \lambda_k I_{nk}}}{\sum_{l=1}^{K} e^{W_{nl} + \lambda_l I_{nl}}}$

Lower level: probability of choosing alternative *i* (turbine type) given the nest

Upper level: probability of choosing nest *k* (decision invest or not in region)

n user group/region
i, j specific/arbitrary alternative
k, l index of specific/arbitrary nest
U_{nj} total utility
W_{nk} nest specific utility
ε_{nj} unobservable utility
Y_{nj} utility of alternative in specific nest
B_k subset of all alternatives within nest k

$$I_{nk} = \log\left(\sum_{j \in B_k} e^{\frac{Y_{nj}}{\lambda_k}}\right)$$

Inclusive value: links the levels by bringing information from the lower into the upper model

Investment profitability assessment

- Derivation of **wind speed data** for center coordinates of each region and adjustment to hub heights
- Computation of corresponding **wind energy production** WP_{ni} from power curves considering losses
- Derivation of **compensation factor** $corr_{ni}^{comp}$ for under/overperforming sites according to a reference yield (§26 EEG 2023)

- The infeed profit sums up to

$$Z_{ni} = comp \cdot corr_{ni}^{comp} \cdot WP_{ni} \quad \forall\, n, i$$

- Considering the investment costs, the NPV per region and turbine type yields to

$$NPV_{ni} = -C_i^{inv} + Z_{ni} \cdot \frac{(1+r)^{LT} - 1}{(1+r)^{LT} \cdot r} \qquad \forall\, n, i$$

Data and parameter settings

Wind speed on 10 and 100m in 0.25°x0.25° grid	ERA 5 Reanalysis (Copernicus, ECMWF, Climate Change Service)
Turbine Data	Bundesnetzagentur, MaStR Marktstammdatenregister
Power curves	The WindPower – Wind Energy Market Intelligence
Expansion targets	Die Bundesregierung
8-type aggregation of wind turbines	(Pöstges & Weber, 2023) House of Energy Markets & Finance
Data on exclusion areas	Copernicus, Land Monitoring Service, Bundesamt für Kartographie und Geodäsie, European Environment Agency

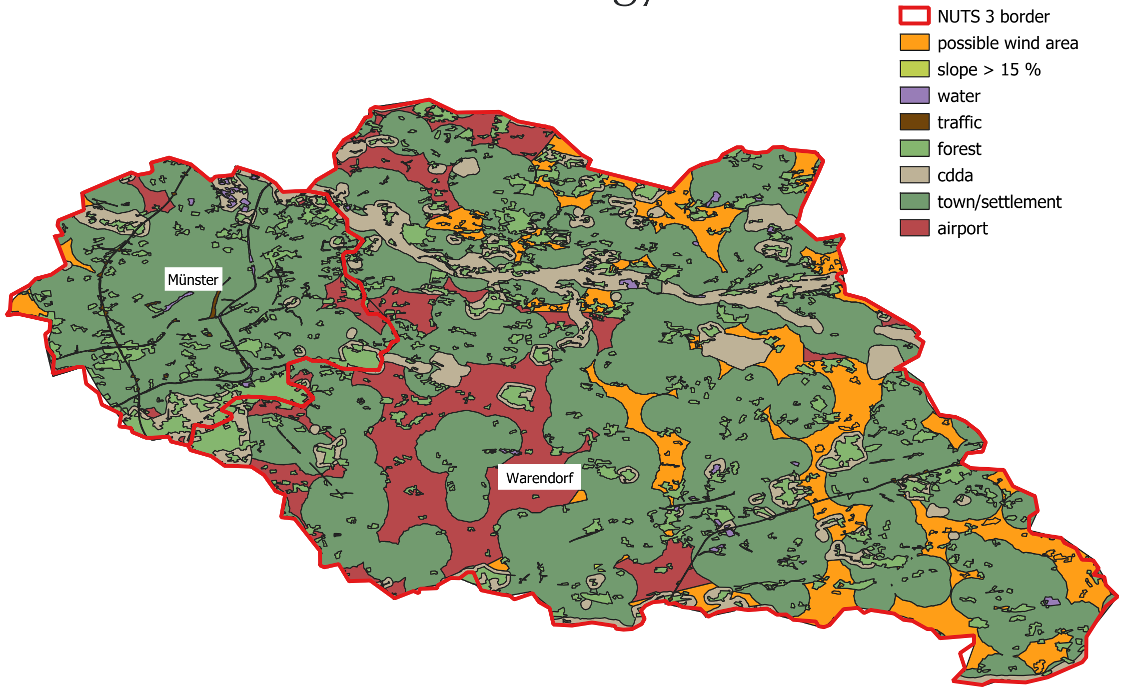
- Representative weather year: 2012
- Base year: 2022
- Target year: 2030 with target capacity of 115 GW*
- Time horizon DC model: 10 years

- Turbine lifetime: 22 years
- Compensation: 0.08 EUR/kWh
- Interest rate: 3.5 %
- Power potential: 22.5 MW/km2

*§4 EEG 2023

Determination of used and available area

- Area restriction analysis: identify max. of possible installed capacity per region
- Areas that are not suitable for the installation of wind energy are excluded



- A purely potential-based distribution would lead to large differences in the area targets of the states → target distribution that is **uniform as possible** across the states is implemented
- The relative available area of the regions a_n^{avail} within each federal state are **scaled** according to contribution values
- The available wind area for the discrete choice model is

$$A_{ni}^{avail,DC} = \underbrace{A_{ni}^{avail}}_{\text{Available total wind area}} - \underbrace{\frac{Cap_{ni}^{base}}{PP} + \underbrace{\frac{Cap_{ni}^{DC}}{PP}}_{A_{ni}^{used,DC}}}_{\text{Area already used before the start of the analysis period of the discrete choice model}} \quad \forall\, n, i$$

Parameter estimation

- Set up a ‚modified' discrete choice model with the
  - Explanatory variable $x = NPV_{ni}$
  - Explained variable $y = a_{ni}^{used,DC} = A_{ni}^{used,DC} / A_{ni}^{avail,DC} = a_{ni}$ (renamed for simplicity)
  - Relative area per region not used for wind energy $a_{n0} = 1 - \sum_i a_{ni}$
- Extend the log-likelihood function since we consider a nested logit model with binomial decision at the upper level

$$LL(\beta, \gamma, \lambda) = \sum_{k \in \{0,1\}} \sum_i a_{ni} \ln\left(P_{ni|B_k} \cdot P_k\right)$$

- Since we are not mapping a binary decision, but the **share of used area**, we add the 0-alternative

$$LL(\beta, \gamma_k, \lambda_k) = \sum_n \sum_i a_{ni} \cdot \left(\ln\left(\frac{e^{Y_{ni} = \frac{\alpha_i + \beta \cdot x_{ni}}{\lambda_k}}}{\sum_{j \in B_k} e^{\frac{\alpha_j + \beta \cdot x_{nj}}{\lambda_k}}} \right) + \ln\left(\frac{e^{\gamma_k + \lambda_k I_{nk}}}{1 + e^{\gamma_k + \lambda_k I_{nk}}} \right) \right) + a_{n0} \cdot \ln\left(\frac{1}{1 + e^{\gamma_k + \lambda_k I_{nk}}} \right)$$

- Maximizing delivers parameter values

<u>Estimation parameters</u>:
$\boldsymbol{\alpha_i}$ utility of turbine *i* describing a natural preference not covered by economic viability
$\boldsymbol{\beta}$ utility increase on explanatory variable at lower level
$\boldsymbol{\gamma}$ utility increase of an explanatory variable for nest at upper level
$\boldsymbol{\lambda_k}$ independence measure of unobservable utility

$\boldsymbol{Y_{ni}}$ observable utility of alternative in specific nest

Simulation of future investment decisions

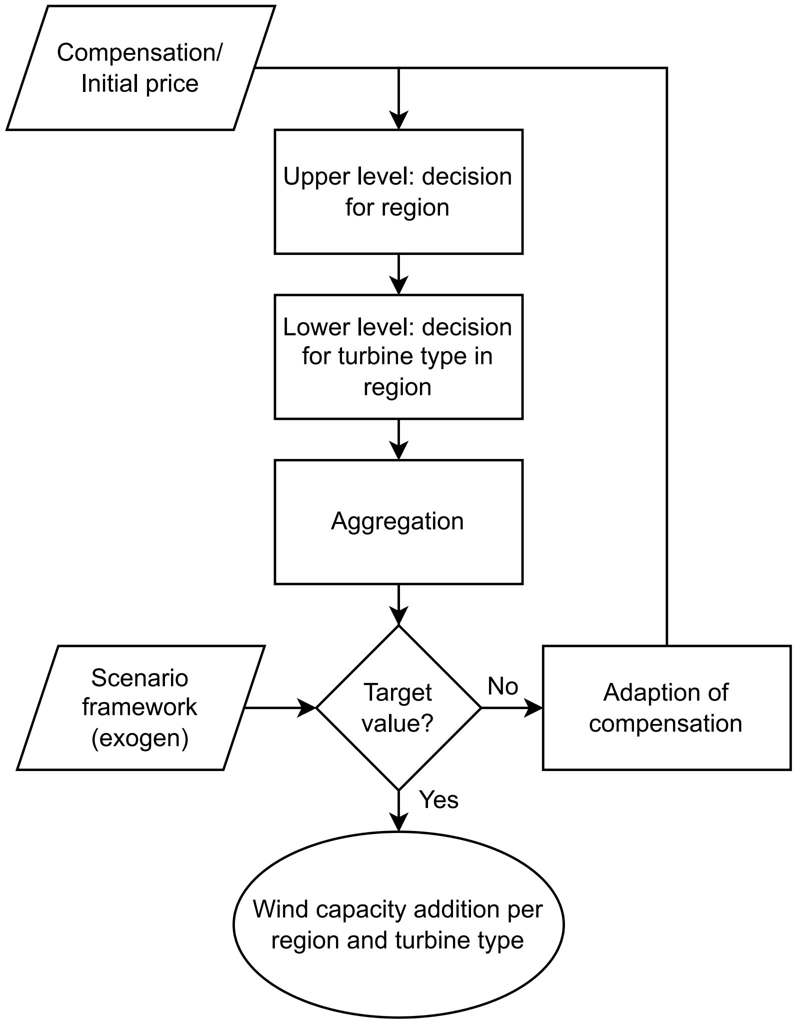
- Calculation of investment decision on regional level given the estimated parameters
- Starting from predetermined compensation, NPV is calculated for each turbine type and region
- Calculation of the predicted market share

$$P_{ni} = \frac{e^{\frac{\alpha_i + \beta \cdot x_{ni}}{\lambda}}}{\sum_{j \in B_k} e^{\frac{\alpha_j + \beta \cdot x_{nj}}{\lambda}}} \cdot \frac{e^{\gamma + \lambda \cdot I_{nk}}}{1 + e^{\gamma + \lambda \cdot I_{nk}}}$$

- The total installed capacity IC is then calculated according to

$$IC = \sum_{i} \sum_{n} InvF \cdot A_{ni}^{avail,sim} \cdot PP \cdot P_{ni} + Cap_{ni}^{sim}$$

- If the installed capacity is lower than the target capacity, the compensation (initial price) will increase and vice versa until the target is fulfilled



Idiosyncratic parameters and investment decision

Parameter	Estimate	Standard error	t-Stat
β	3.2353	0.4935	6.5559***
γ	-51.5071	7.8616	-6.5517***
λ	1.0828	0.242	4.4742***
α_1	4.9968	0.887	5.6336***
α_2	-0.1652	0.2779	-0.5944
α_3	1.4592	0.3084	4.7313***
α_5	-0.4559	0.3192	-1.4283
α_6	-1.9102	0.4226	-4.5206***
α_7	-2.0419	0.5992	-3.4076***
α_8	-3.3863	0.917	-3.693***
R^2		0.1733	

*** p<0.05, ** p<0.01, *** p<0.001**

- Turbine 4 as reference
- e.g. a negative α_8 indicates that the large, high-capacity type 8 was often not constructed despite a high NPV, which is frequently associated with building restrictions and expected disamenity costs

- the total installed wind power capacity for every region and every turbine type in the area under consideration can be calculated

	2030	2035	2040
Estimated total installed capacity	115.736 GW	158.554 GW	161.506 GW
Total target installed capacity	115 GW	157 GW	160 GW
Needed compensation for wind energy plants	8.10 ct/kWh	8.27 ct/kWh	7.58 ct/kWh

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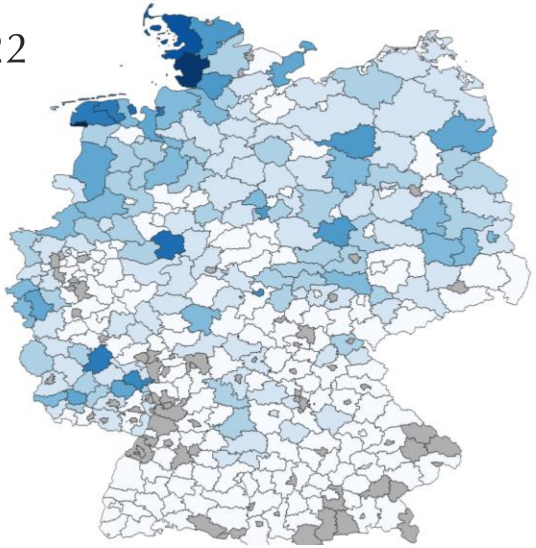
Future spatial distribution of capacities

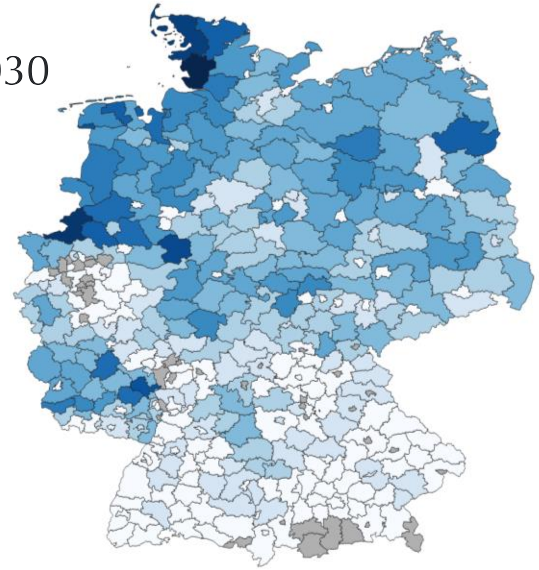
2022



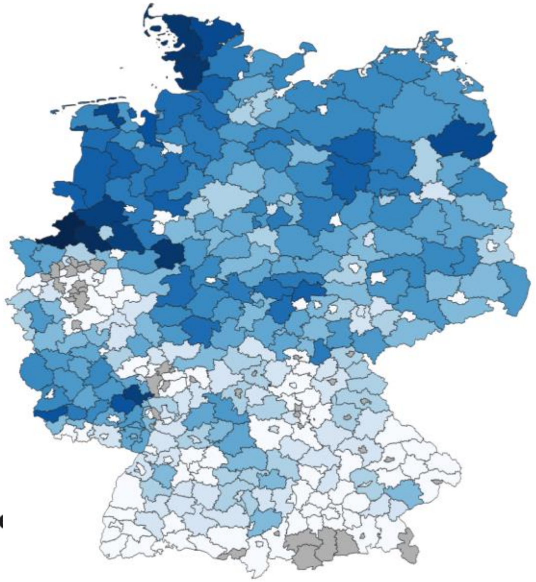
kW/km²

- = 0
- > 0
- > 100
- > 200
- > 300
- > 400
- > 500
- > 600
- > 700
- > 800
- > 900
- > 1000
- > 1100
- > 1200
- > 1300
- > 1400
- > 1500

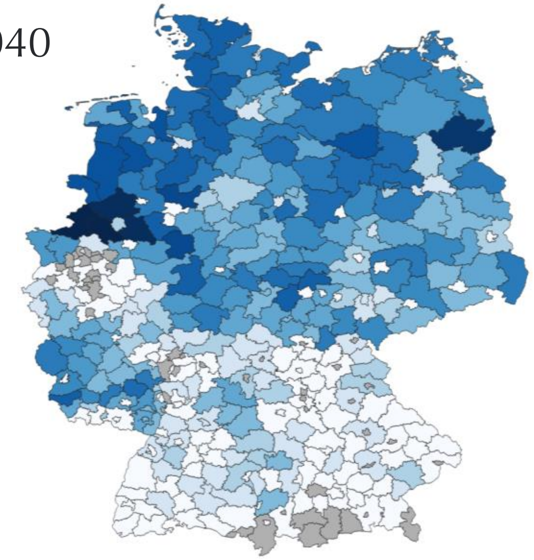
2030



2035



2040



Final remarks

- Incomplete and inconsistent spatial planning data affects model accuracy
- Current designated areas fall short of meeting future wind energy targets – unified method needed
- Allocation of future wind power capacities is influenced by economic factors (i.e. NPV) and spatial restrictions
- Nested logit model captures hierarchical decision-making allowing for more accurate predictions
- Study insights are essential for policymakers, investors and grid operators to align with Germany's renewable energy targets

➢ The future **spatial distribution of onshore wind energy** in Germany will be shaped by a combination of **economic, spatial, and political** factors. The use of advanced modeling techniques, such as the **nested logit model**, provides a powerful tool for understanding and guiding these developments.

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Thank you for your attention!

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Probability of exhaustion per NUTS 3 region

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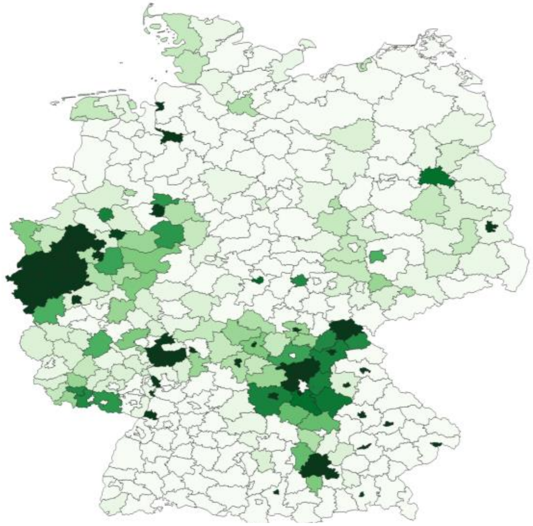
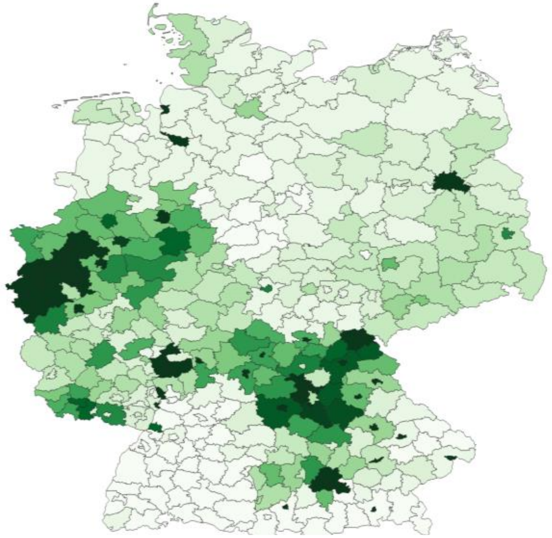
Motivation – Material & Methods – Calculation – **Results (III)** – Outlook

2022



2030



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- 0,1 - 0,15
- 0,15 - 0,2
- 0,2 - 0,25
- 0,25 - 0,3
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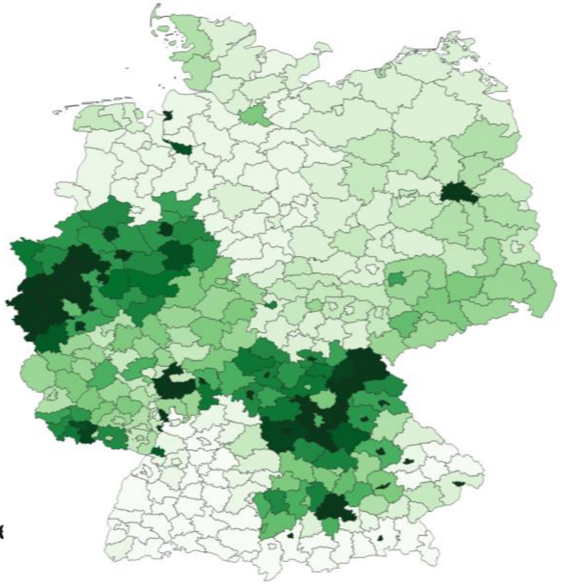
- 0,35 - 0,4
- 0,4 - 0,45
- 0,45 - 0,5
- 0,5 - 0,55
- 0,55 - 0,6
- 0,6 - 0,65
- 0,65 - 0,7
- 0,7 - 0,75
- 0,75 - 0,8
- 0,8 - 0,85
- 0,85 - 0,9
- 0,9 - 0,95
- 0,95 - 1

2035



2040