

Locational (In)Efficiency of Renewable Energy Feed-in into the Electricity Grid: A Spatial Regression Analysis

IAEE Webinar

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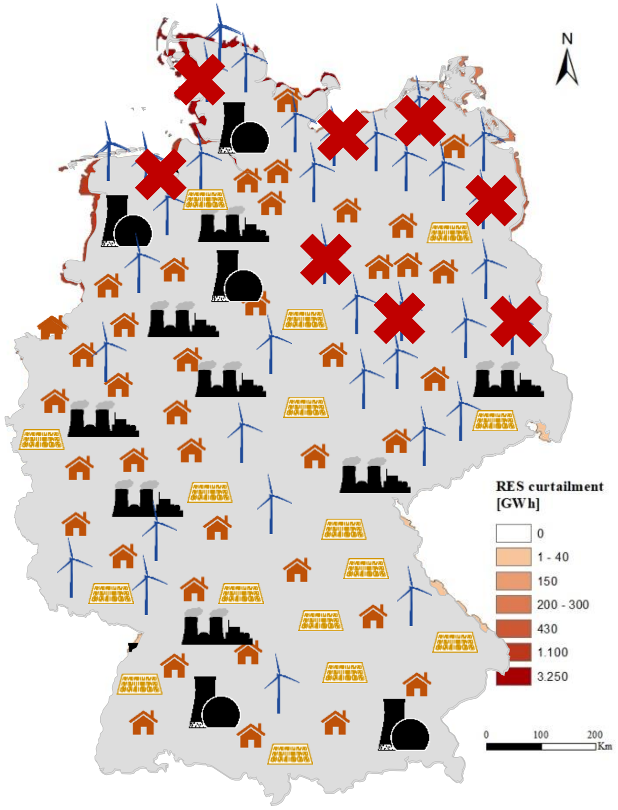
Background and motivation



Challenges

- Regional imbalance between electricity generation and consumption
- Variable electricity generation by renewables
- Electricity infeed into the distribution grid
- Reinforcement of the electricity grid is lagging behind

Overstress of the electricity infrastructure

Curtailment of power plants

Compensation for the restrained electricity

Passing on the costs to customers in the region concerned

Q1 Which drivers induce the occurrence of RES curtailment?

Q2 What are the regional curtailment costs of different renewables?

Literature review

Integration costs of renewables (Hirth et al., 2015)

Grid-related costs	Balancing costs	Profile costs
Opportunity costs of transporting electricity	Costs for forecasting errors of weather conditions	Costs for matching electricity supply and demand

Related literature:

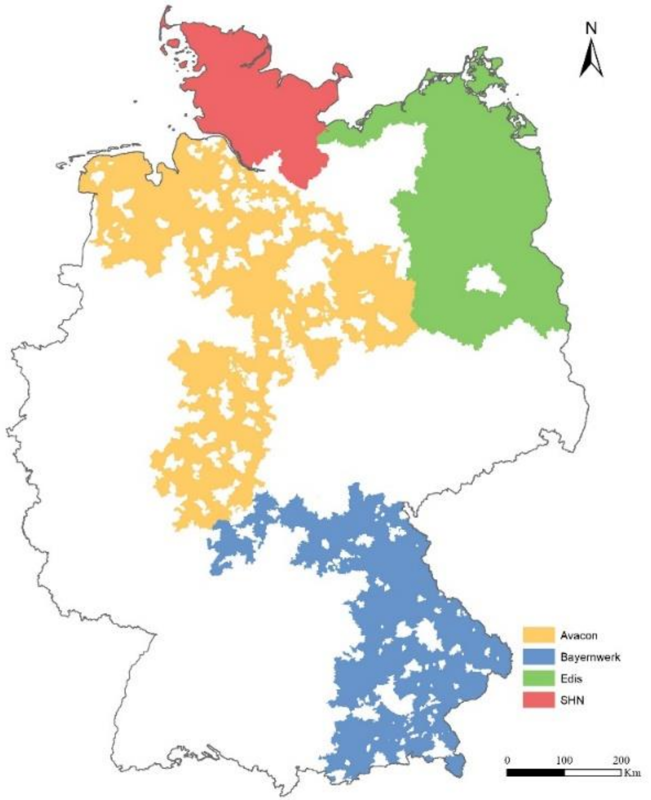
- Quantifies the integration costs of renewables
- Qualitatively investigated the reasons for the occurrence of RES curtailment

Merits of the paper:

- Quantification of RES curtailment costs in a high spatial resolution
- Explanation of the correlation between renewables and RES curtailment
- Explanation of the impact of different renewables on RES curtailment costs

Hirth, L., F. Ueckerdt, and O. Edenhofer (2015). Integration Costs Revisited – An Economic Framework for Wind and Solar Variability. Renewable Energy 74, 925–939

Description of the study region



Wind dominated
- Wind energy capacity: High
- PV system capacity: Low
- Electricity demand: Low
- RES curtailment: High

→ SHN

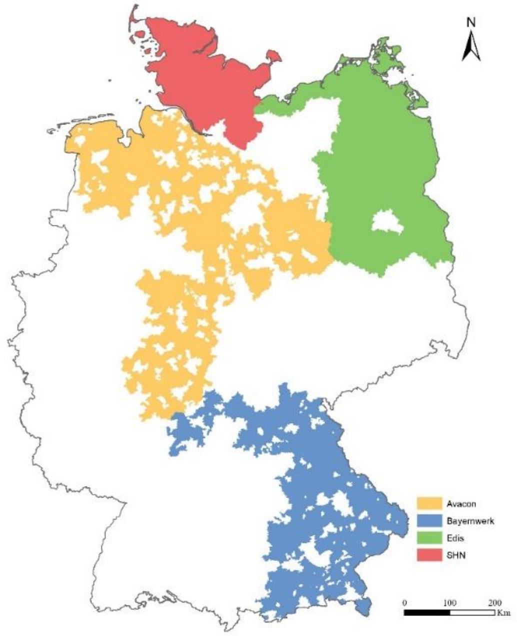
Low load
- Wind energy capacity: High
- PV system capacity: High
- Electricity demand: Medium
- RES curtailment: Medium

→ Avacon, Edis

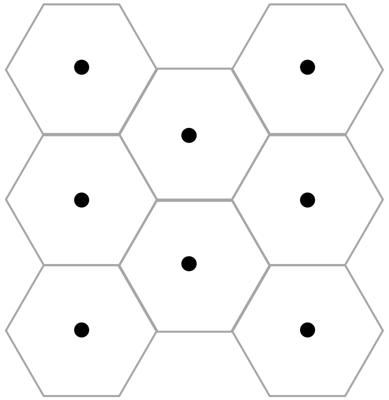
PV dominated
- Wind energy capacity: Low
- PV system capacity: High
- Electricity demand: High
- RES curtailment: Low

→ Bayernwerk

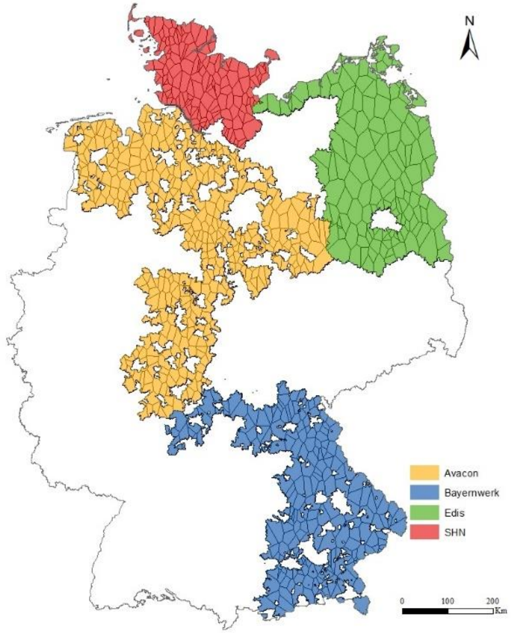
Scope of the analysis



- 4 DSO regions
- 3 years (2015 – 2017)



- ➢ Voronoi tessellation
- ➢ High-to-medium voltage transformer stations



- 1,111 DSO subregions
- 3 years (2015 – 2017)
- ➢ 3,333 observations

DSO = Distribution System Operator

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Methodology

Two-step Heckit sample selection model

Step 1: Selection equation

- Probit model
- Corrects bias from non-randomly selected samples
- All subregion considered

$$y_{1t}^* = \alpha_0 + \alpha_1 x_{1t} + \epsilon_1$$

$$y_{1t} = \begin{cases} 1, & y_{1t}^* > 0 \\ 0, & y_{1t}^* \leq 0 \end{cases}$$

Impact of renewables on the probability of occurrence of RES curtailment

Step 2: Output equation

- Spatial econometric model
- Captures cross-sectional dependence
- Only subregion with RES curtailment costs between 2015 – 2017

$$y_{2it}^* = \beta_i + \beta x_{2it} + \theta^T \sum_{j=1}^{m} w_{ij} x_{2jt} + e_{it}$$

$$e_{it} = \lambda_{ij}^T f_t + \varepsilon_{it}$$

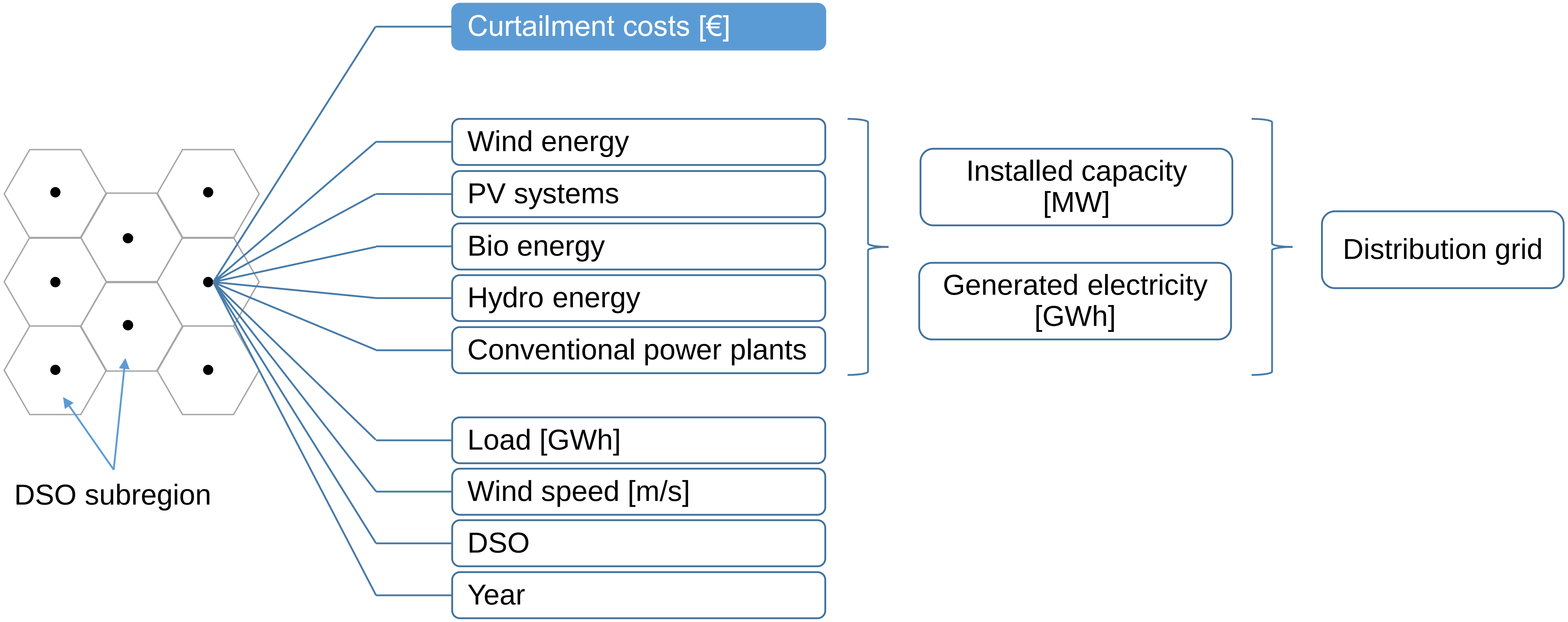
SLX

CCE

Impact of renewables on RES curtailment costs

SLX = Spatial lag of X, CCE = Correlated common effects

Regression variables



PV = Photovoltaic (including rooftop PV)

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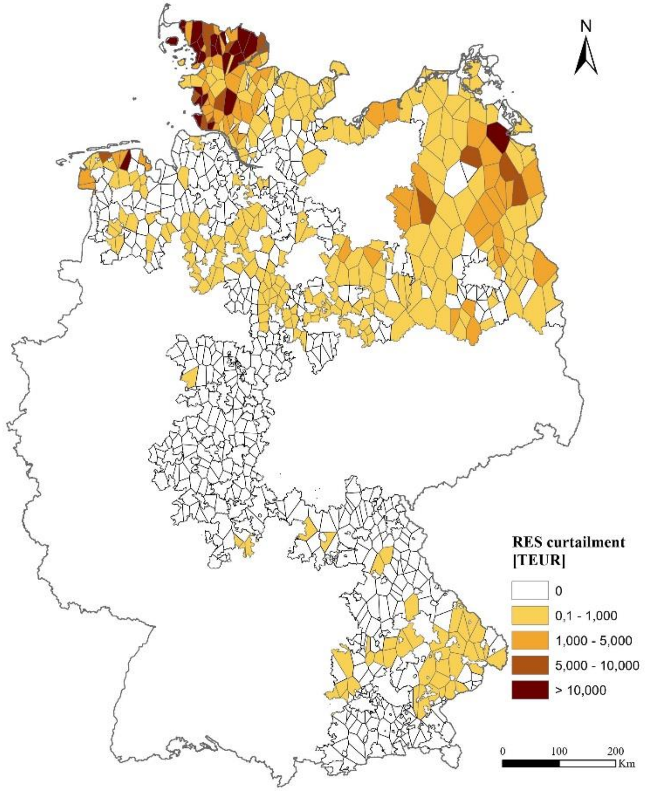
Calculating the dependent variable



1. Calculating the potential hourly electricity output of renewables during the curtailment measures
2. Computing the reduced power output of renewables stemming from curtailment measure
3. Determining the RES curtailment costs in the DSO subregion

RES = Renewable Energy Source, DSO = Distribution System Operator

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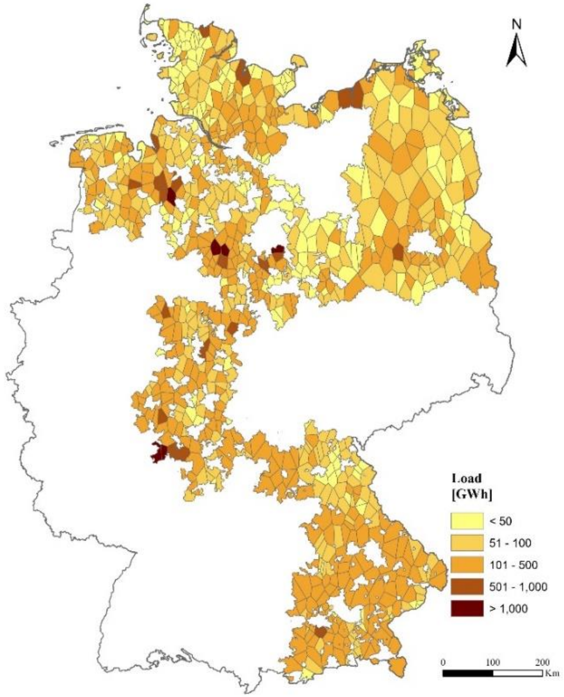
Calculation of the load in the DSO subregions



Population of municipalities (LAU)

GVA of administrative district (NUTS 3)

Yearly electricity demand in Germany (NUTS 0)

DSO subregions

GVA per municipalities

Load factor (GVA per municipality / GVA Germany)

Electricity demand of municipalities

Electricity demand of DSO subregions

GVA = Gross Value Added

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Regression results

	Installed capacity [MW]				Generated electricity [GWh]			
	Selection equation		Output equation		Selection equation		Output equation	
Wind	- 0.003***	(0.004)	0.007***	(0.002)	0.0007***	(0.0002)	0.002***	(0.001)
PV	- 0.003***	(0.002)	0.004	(0.005)	0.005***	(0.002)	0.002	(0.007)
Bio	- 0.003**	(0.005)	- 0.003	(0.009)	0.0007***	(0.0008)	- 0.001	(0.002)
Hydro	0.004	(0.032)	- 0.035	(1.340)	0.002	(0.008)	- 0.229	(0.367)
Conventional	0.0001	(0.0003)	- 0.001	(0.001)	0.00	(0.0002)	- 0.001	(0.001)
Spatial Lag Wind			- 0.0002	(0.002)			0.001	(0.001)
Spatial Lag PV			0.003	(0.008)			0.010	(0.010)
Spatial Lag Bio			0.007	(0.009)			0.002	(0.002)
Spatial Lag Hydro			- 1.351	(2.007)			- 0.386	(0.551)
Spatial Lag Conventional			- 0.001	(0.002)			- 0.001	(0.001)
Load [GWh]	- 0.0004***	(0.0003)			- 0.0004***	(0.0003)		
(Adjusted) R^2	0.309		0.469		0.273		0.476	
Sensitivity	0.897				0.877			
Specificity	0.605				0.596			

Impact on likelihood of occurrence of RES curtailment per MW

- Wind: + 0.3%
- PV: + 0.3%
- Bio: + 0.3%
- Load: - 0.04% [GWh]

Regression results

	Installed capacity [MW]				Generated electricity [GWh]			
	Selection equation		Output equation		Selection equation		Output equation	
Wind	0.003***	(0.004)	0.007***	(0.002)	0.0007***	(0.0002)	0.002***	(0.001)
PV	0.003***	(0.002)	0.004	(0.005)	0.005***	(0.002)	0.002	(0.007)
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Sensitivity	0.897				0.877			
Specificity	0.605				0.596			

Impact on likelihood of occurrence of RES curtailment per GWh

- Wind: + 0.07%
- PV: + 0.05%
- Bio: + 0.07%
- Load: - 0.04%

Regression results

	Installed capacity [MW]				Generated electricity [GWh]			
	Selection equation		Output equation		Selection equation		Output equation	
Wind	0.003***	(0.004)	- 0.007***	(0.002)	0.0007***	(0.0002)	0.002***	(0.001)
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Sensitivity	0.897				0.877			
Specificity	0.605				0.596			

Impact on RES curtailment costs per MW

- Wind: + 0.7%

Regression results

	Installed capacity [MW]				Generated electricity [GWh]			
	Selection equation		Output equation		Selection equation		Output equation	
Wind	0.003***	(0.004)	0.007***	(0.002)	0.0007***	(0.0002)	- 0.002***	(0.001)
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(Adjusted) R^2	0.309		0.469		0.273		0.476	
Sensitivity	0.897				0.877			
Specificity	0.605				0.596			

Impact on RES curtailment costs per GWh

- Wind: + 0.02%

Regression results

	Installed capacity [MW]				Generated electricity [GWh]			
	Selection equation		Output equation		Selection equation		Output equation	
Wind	0.003***	(0.004)	- 0.007***	(0.002)	0.0007***	(0.0002)	- 0.002***	(0.001)
PV	0.003***	(0.002)	0.004	(0.005)	0.005***	(0.002)	0.002	(0.007)
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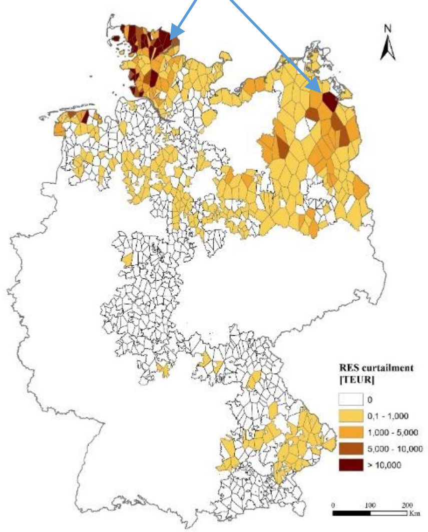
(Adjusted) R^2	0.309		0.469		0.273		0.476	
Sensitivity	0.897				0.877			
Specificity	0.605				0.596			

* Most affected subregions (4th quartile)



- Wind: 28,300 €/MW/a*
- Wind: 8.1 €/MWh*

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Conclusions and political implications

Procedure

- Investigating the impacts of implementing renewables into an inflexible energy system
- Analyzing the regionally varying costs of curtailing renewables to stabilize the electricity infrastructure

Results

- Most DSO subregions do not experience RES curtailment to a large extent
- Especially wind energy induces high RES curtailment costs in northern and eastern Germany

Recommendations

- Setting regionally varying price signals for renewables
- Setting incentives for flexibility options

RES = Renewable Energy Source, DSO = Distribution System Operator

Thank you for your attention

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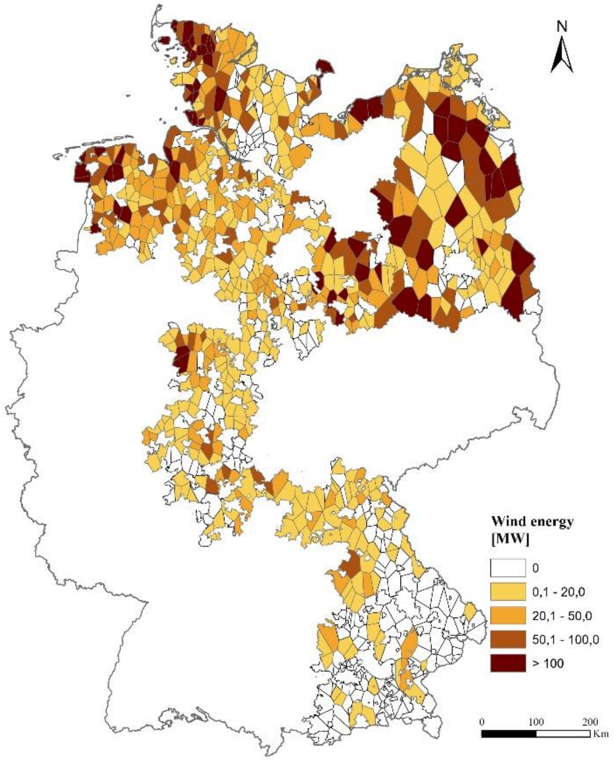
Aims and merits

Quantifying the effect of different renewable energy technologies on regional RES curtailment

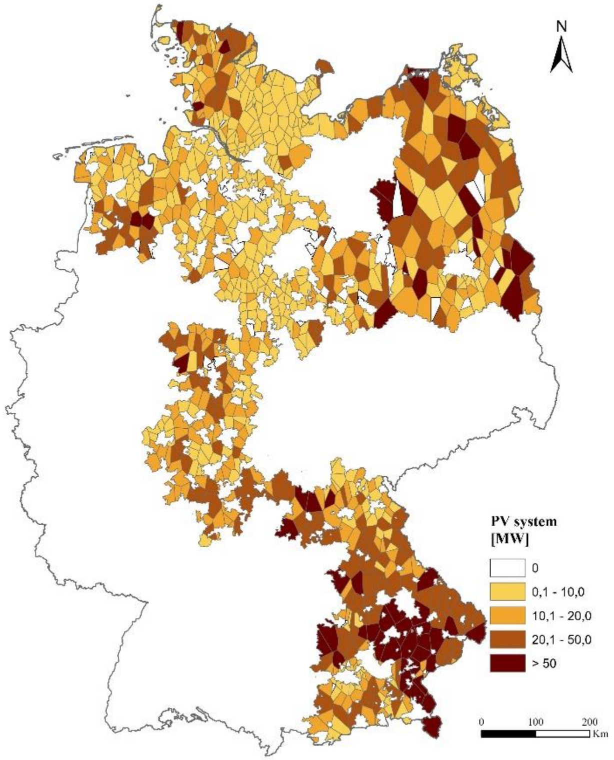
1	Elucidate why RES curtailment occurs only in some regions of Germany and not in others
2	Analyze the correlation of installed capacity and generated electricity of renewables and RES curtailment costs.
3	Calculate the regionally disaggregated amount and costs of RES curtailment in a higher spatial resolution than available in official publications.
4	Give policy recommendations based on the results

RES = Renewable Energy Source

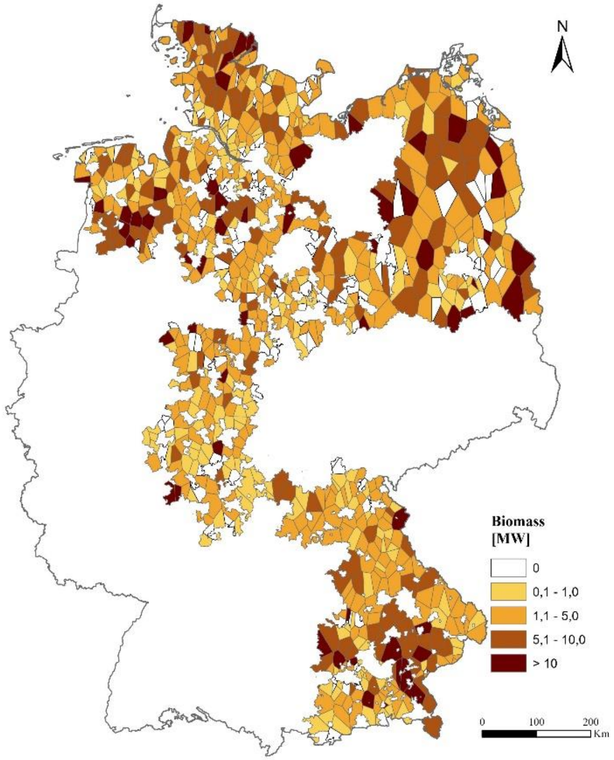
Explanatory variables



Wind energy capacity



PV system capacity



Biomass capacity

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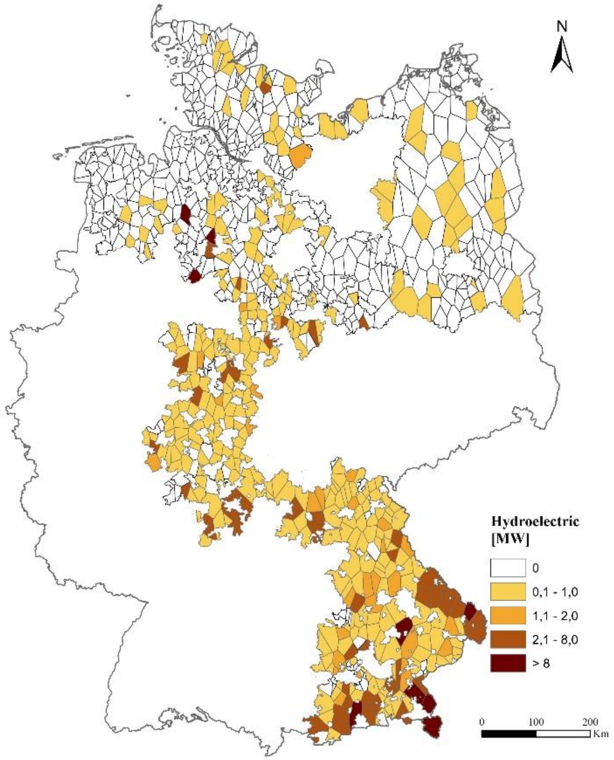
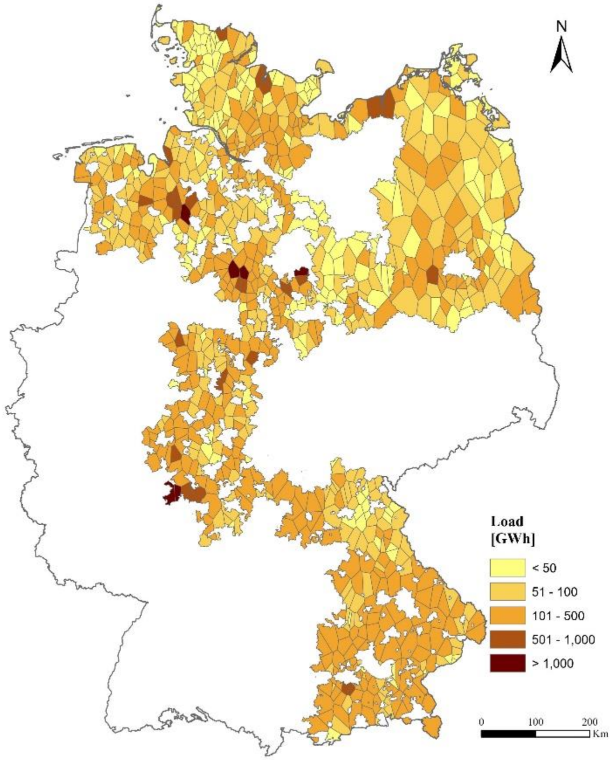
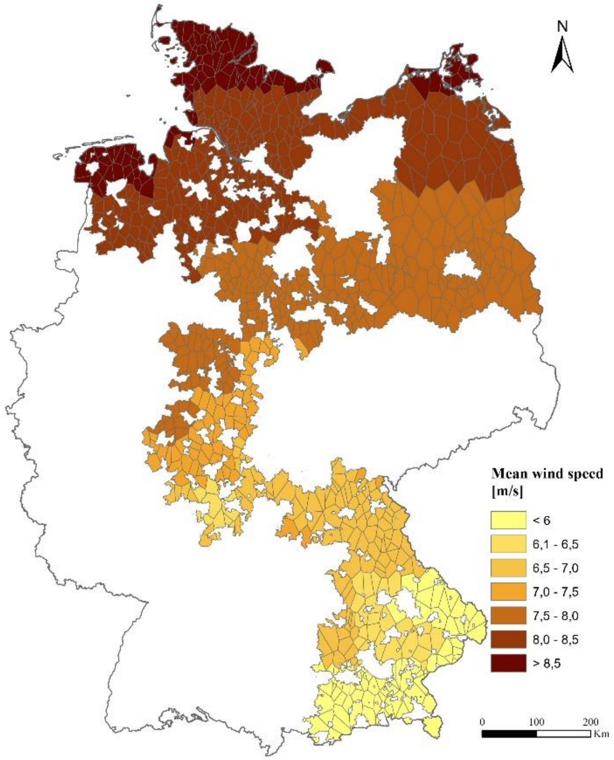
Explanatory variables



Hydroelectric capacity



Load



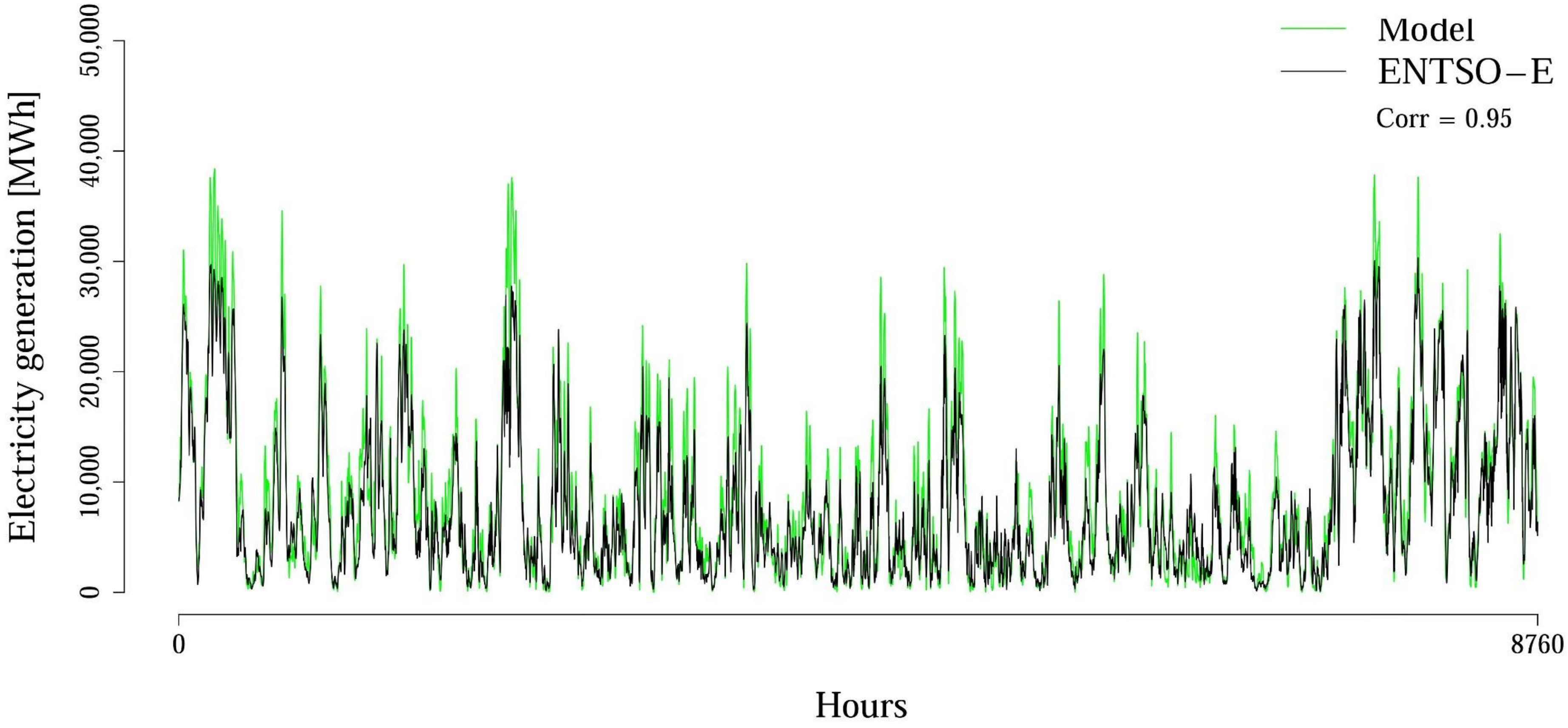
Mean wind speed

Descriptive statistics for the dependent variable and the explanatory variables

Variable	Unit	Year	Mean	Std.dev.	Min	Max	Total
RES curtailment cost	[€]	2015–2017	286,737	1,385,723	0	23,722,656	763,868,462
Wind energy	[MW]	2017	31.4	53.0	0	625	27,887
PV systems	[MW]	2017	17.0	20.4	0	216	15,105
Bio energy	[MW]	2017	3.5	6.4	0	140	3,118
Hydro energy	[MW]	2017	0.4	1.4	0	16	389
Conv. peak-load	[MW]	2017	17.0	99.5	0	1,770	15,101
Load	[GWh]	2017	146.9	327.3	5.8	7,441	130,480
Wind speed	[W/m^2]	2015–2017	7.7	0.9	3.4	9.6	
Wind energy	[GWh]	2017	67.2	159.8	0	1,619	59,715
PV systems	[GWh]	2017	14.0	17.0	0	191	12,379
Bio energy	[GWh]	2017	18.6	34.8	0	758	16,747
Hydro energy	[GWh]	2017	1.6	5.1	0	57	1,419
Conv. peak-load	[GWh]	2017	32.7	195.9	0	3,670	29,067

Comparison of ENTSO-E data and model outcome

Hourly wind electricity generation in Germany in 2015



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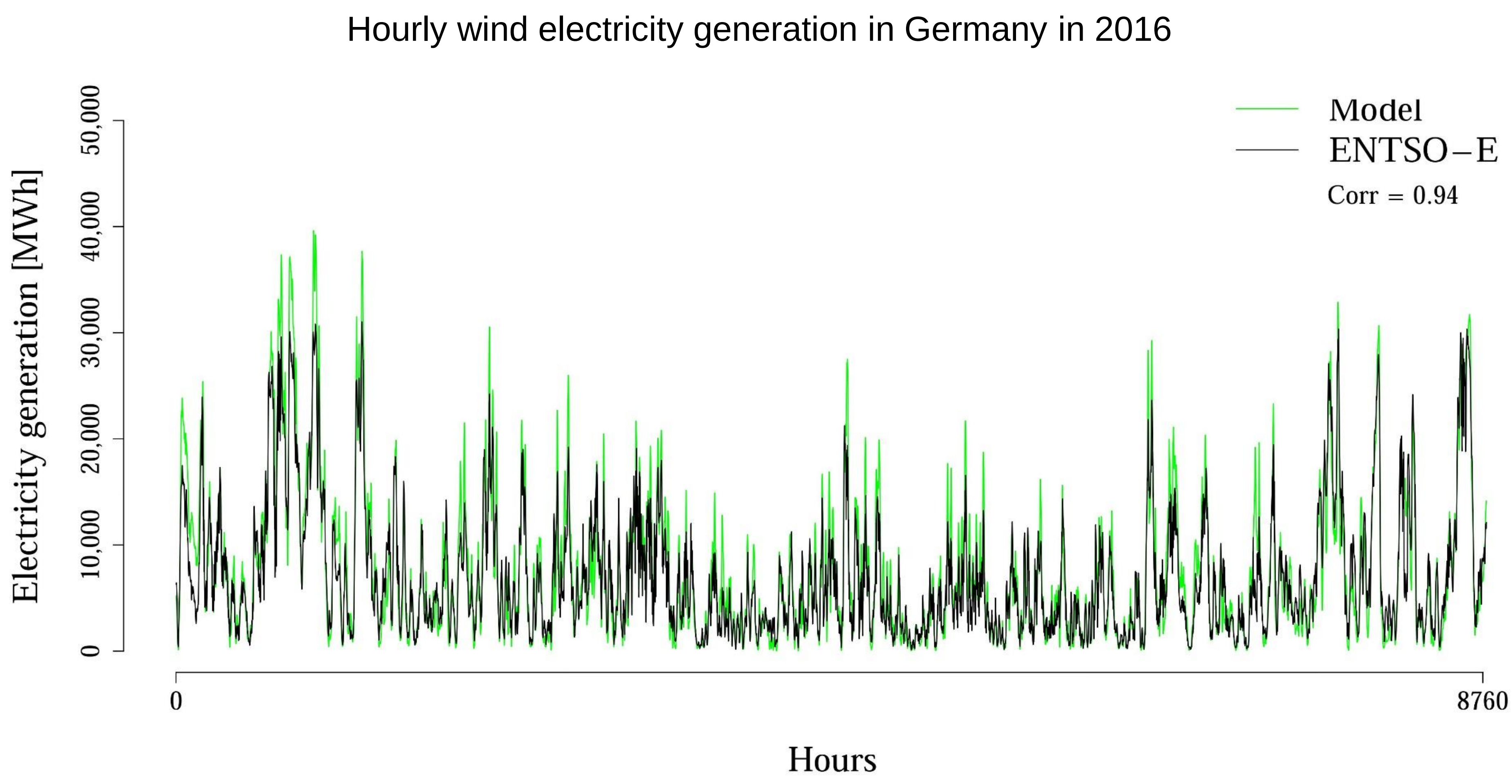
Comparison of ENTSO-E data and model outcome



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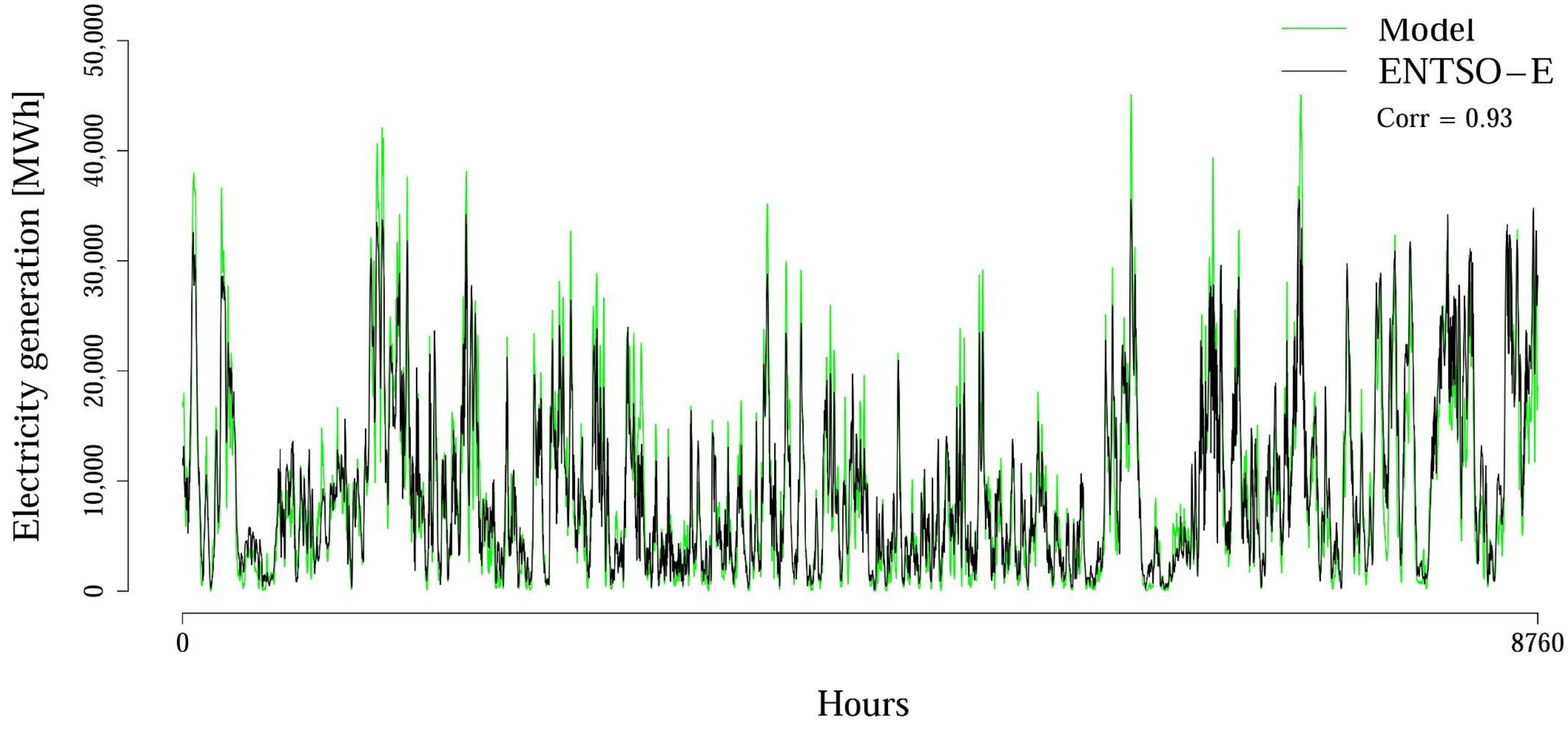
Comparison of ENTSO-E data and model outcome

Hourly wind electricity generation in Germany in 2017



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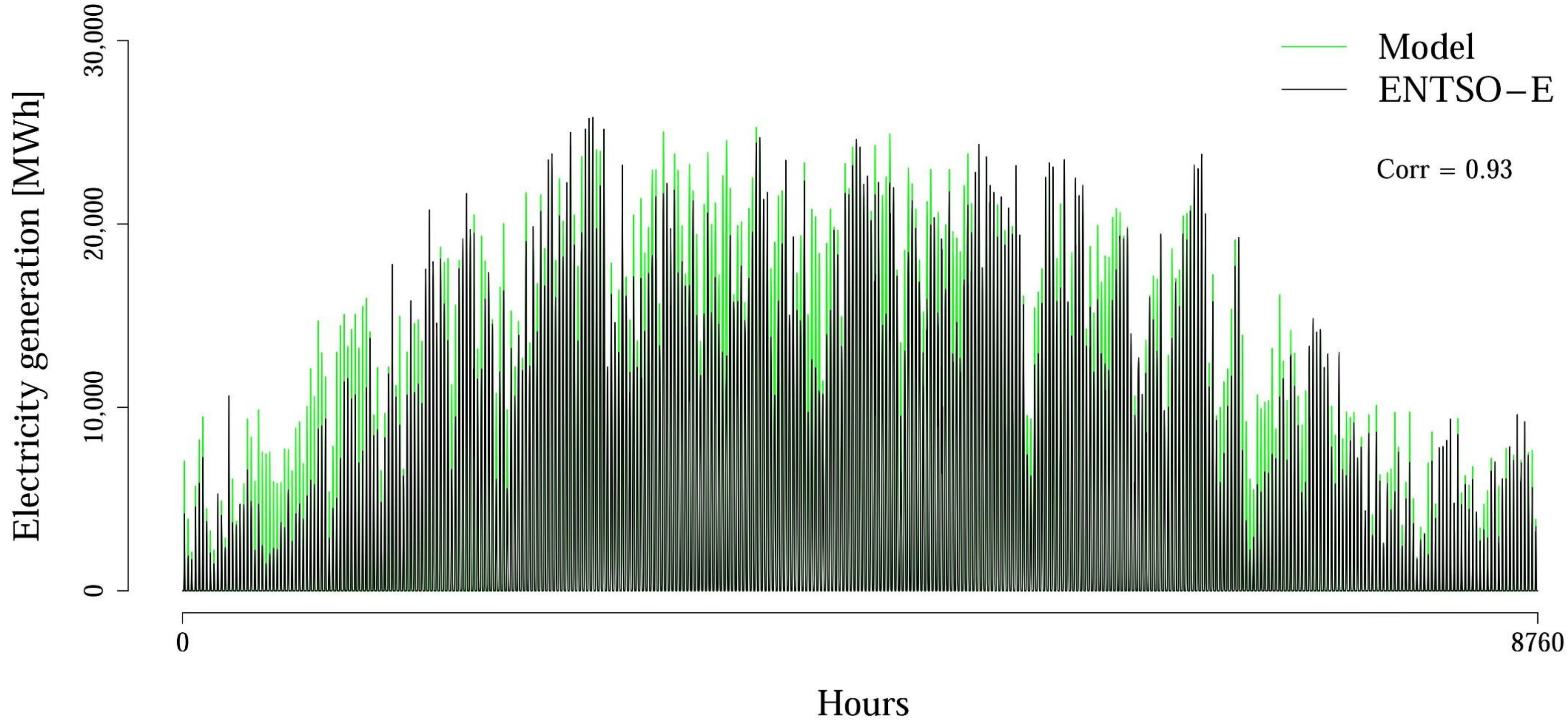
Comparison of ENTSO-E data and model outcome

Hourly PV electricity generation in Germany in 2015



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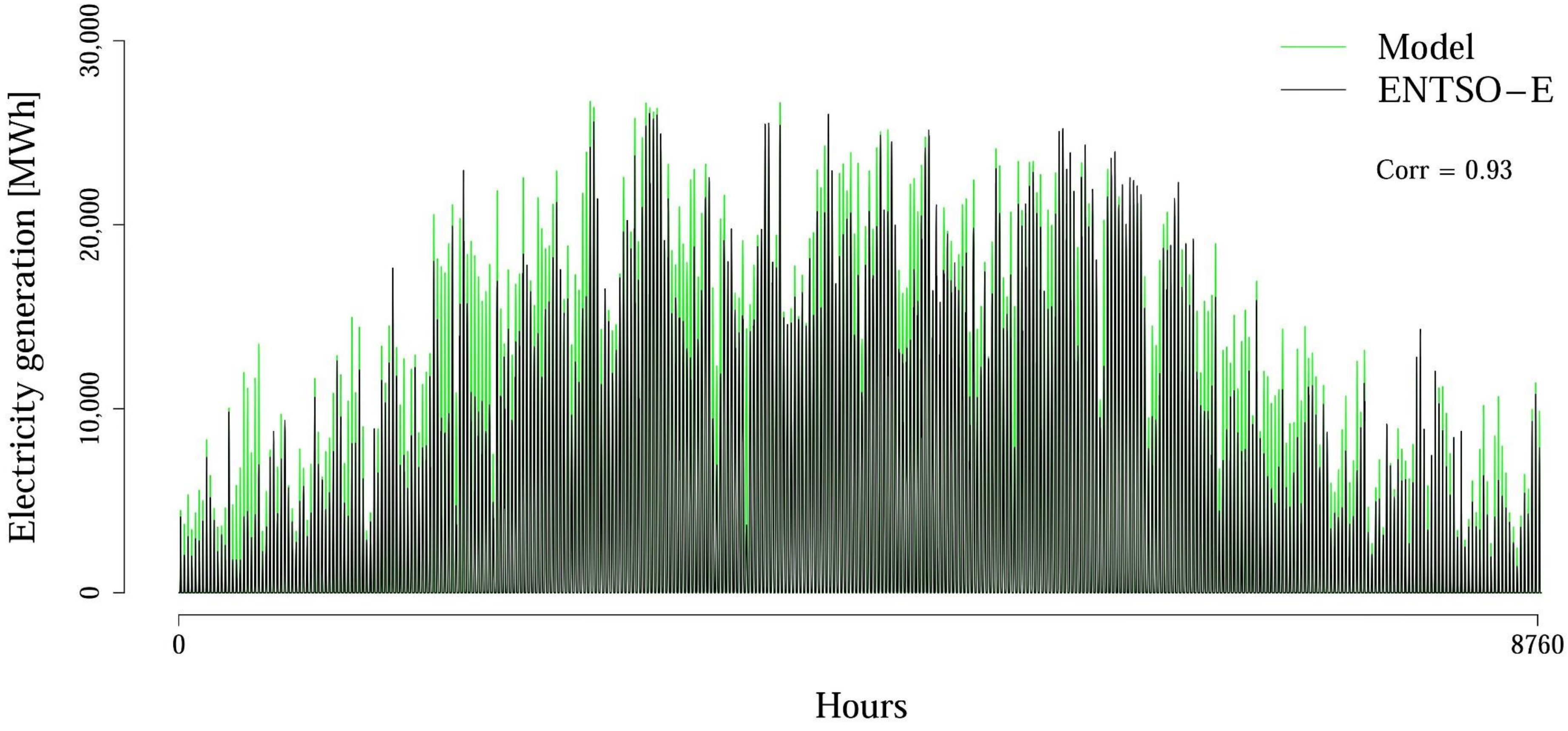
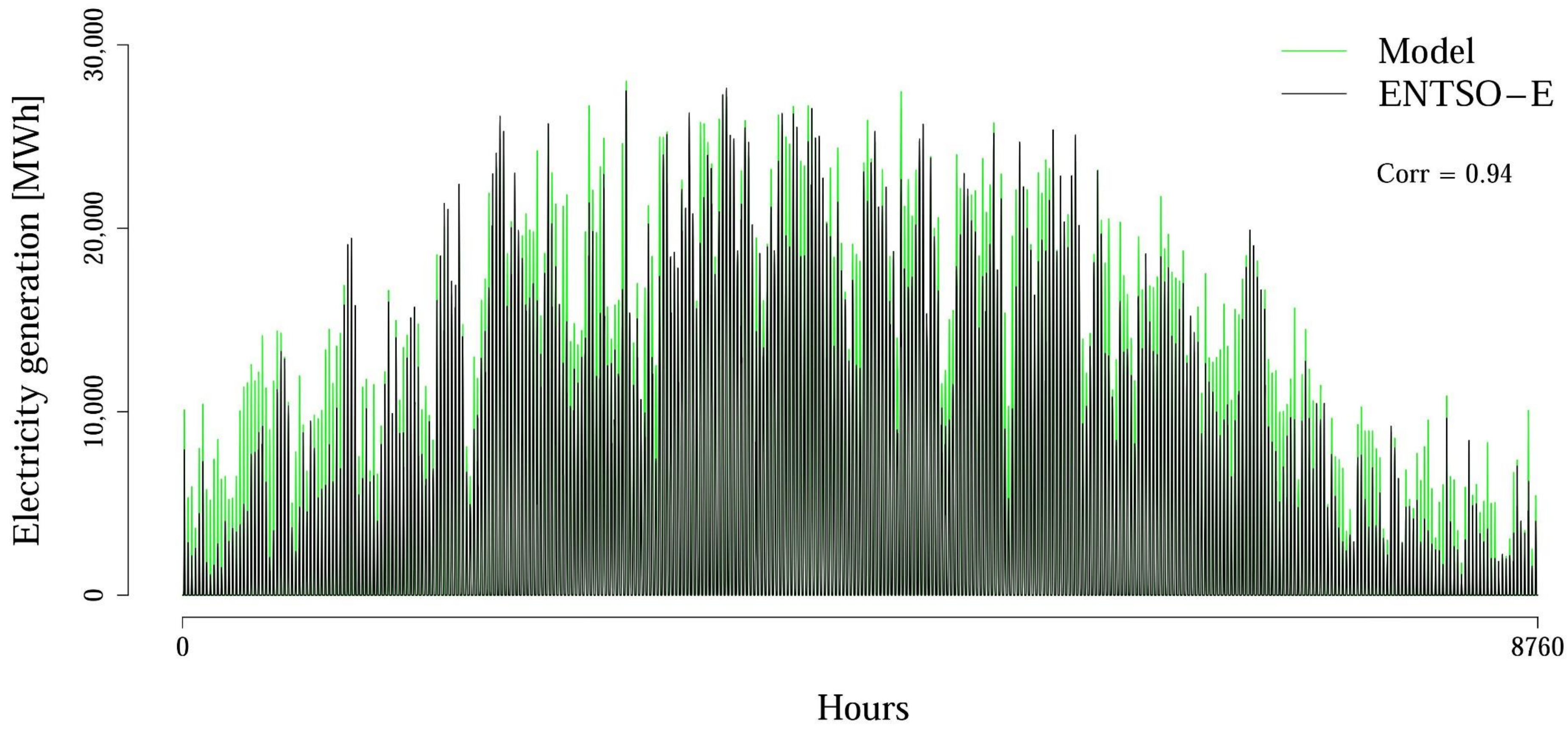
Comparison of ENTSO-E data and model outcome

Hourly PV electricity generation in Germany in 2016



Comparison of ENTSO-E data and model outcome

Hourly PV electricity generation in Germany in 2017



Comparison of calculated and published RES curtailment costs

DSO[1]	Federal States (FS)[2]	Area covered [%] [3]	Year	DSO costs [€][4]	FS costs [€][5]	Share [%][6]
Avacon	Lower Saxony, Saxony-Anhalt, Hesse	59.7[4]	2015	6,541,760	57,908,856	11.3
			2016	5,718,869	31,223,962	18.3
			2017	37,465,927	180,712,239	20.7
BW	Bavaria	57.8	2015	41,105	333,345	12.3
			2016	58,891	292,782	20.1
			2017	232,192	585,290	39.7
Edis	Brandenburg, Mecklenburg-Western Pomerania	71.7	2015	45,574,389	96,229,679	47.4
			2016	26,910,325	63,901,645	42.1
			2017	26,910,325	62,274,651	43.2
SHN	Schleswig-Holstein	99.4[6]	2015	265,360,723	312,942,279	84.8
			2016	126,665,577	273,012,271	46.4
			2017	200,474,705	351,246,341	57.1
Overall			2015	317,517,978	467,414,159	68.0
			2016	181,267,336	368,430,660	43.3
			2017	265,083,149	594,818,522	44.6

[1] *Avacon* = Avacon Netz AG, *BW* = Bayernwerk Netz GmbH, *Edis* = E.DIS Netz AG, *SHN* = Schleswig-Holstein Netz AG.
[2] Federal states in which the respective DSO operates. [3] Share of federal state area covered by respective DSO.
[4] RES curtailment costs in the respective DSO region as calculated in this study. [5] RES curtailment costs in the respective German federal states as published by the German Federal Network Agency (BNetzA, 2017d, 2018b). [6] Share of calculated to published RES curtailment costs.

Marginal costs of renewables per quartile

Variables	Unit	1st Q.	2nd Q.	3rd Q.	4th Q.
Wind energy	[€/MW]	18	302	2,939	28,277
Wind energy	[€/MWh]	0.005	0.10	0.80	8.10

The costs only apply for regions that experienced RES curtailment in the three consecutive years from 2015—2017.