(Mis)allocation of Renewable Energy Sources

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September 28, 2020

Introduction

- **R**enewable **E**nergy **S**ources (**RES**) in electricity markets come with large economic impacts:
  - High levelized costs (although close to grid parity in some regions)
  - Not perfectly correlated with demand
  - Intermittency (non-negligible unforecastable component)
  - High storage costs
  - Non-dispatchable

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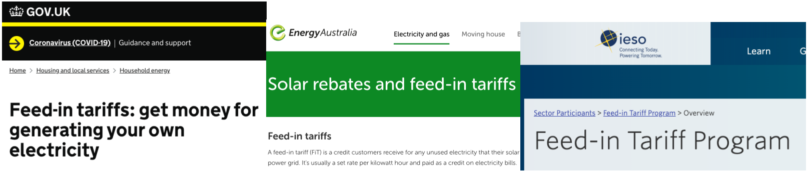
  - Not perfectly correlated with demand
  - Intermittency (non-negligible unforecastable component)
  - High storage costs
  - Non-dispatchable
- Do *uniform* policies to incentivize the deployment of RES, such as Feed-in-Tariffs (FiTs), properly account for the costs & benefits of these technologies?

Feed-in-Tariffs (FiTs)

- Guarantee a preferential rate paid to producers of electricity from RES
- Regulated by the government
- Specified as long-term contracts of about 15 - 20 years



Main research questions

- Are the uniform levels of FiTs comparable to the distribution of marginal benefits from RES (solar PV) across regions?
- Is the current allocation of solar PV plants optimal?

In this paper

1. Use of an extensive high-frequency dataset on electricity production and demand
   - We measure the benefits from an additional unit of electricity output from RES due to the displacement of production from conventional sources
2. Compute counterfactual scenarios in which RES capacity gets reallocated to maximize its benefits while keeping the total amount of RES capacity constant
3. We calculate the gains from an increase in transmission capacity between subregions
   - Compute shadow cost of transmission and use it to back out implied size of the transmission capacity

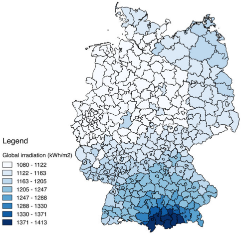
Contribution

- Provide a comprehensive framework to analyze uniform FiT policies
- Extend existing literature that focuses on emission displacement and ignores RES policies
- Quantifying the effects of RES expansions on ancillary services costs
- The use of actual RES output data as opposed to simulated data

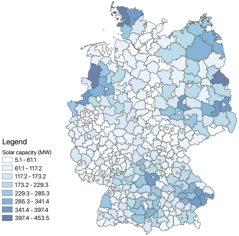
The Case of Germany

- Germany was the first country to implement large-scale FiTs (Renewable Energy Act, 2000)
- FiT are uniform for type of RES technology, not taking into account:
  - Regional differences in sunshine radiation
  - Regional differences in electricity demand
- Focus on solar as the main distributed RES with uniform FiT

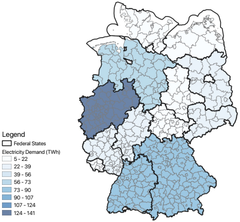
Sunshine and Solar Installations (2016)



(a) Global solar radiation.



(b) Installed solar capacity.



(c) Electricity Demand.

Notes: Global solar radiation (long-term averages) measured in kWh / m^2 in Panel 1a, cumulative solar capacity (Dec 2016) in Panel 1b, and electricity demand (2015) at state level in Panel 1c. Darker areas represent higher solar radiation, more installed capacity, and higher electricity demand, respectively. Data sources: German Weather Service, Official RES registry, and Statistical Offices of the German States, respectively.

Data and Marginal Benefits

Data

- **Electricity market data**: 4 **T**ransmission **S**ystem **O**perators (**TSO**s) in Germany, 2015 - 2016, **15-minute resolution**
  - Load and supply from renewable and non-renewable generators for each TSO (*ENTSO-E*)
  - Cost of ancillary services for each TSO (tender for the procurement of primary and secondary control reserve, *regelleistung.net*)
  - Daily electricity production costs by technology (coal, natural gas, fuel oil) (*Bloomberg*, fuel prices; *Energy Balance for Germany, AG Energiebilanzen*)
- **Micro data:**
  - Administrative data on RES (solar) installations and capacity
  - Solar production data at plant-level (*PV Output*) - approx. 300 stations.
  - Data on power plant locations, installed capacity, and unavailability

Transmission System Operators (TSOs)

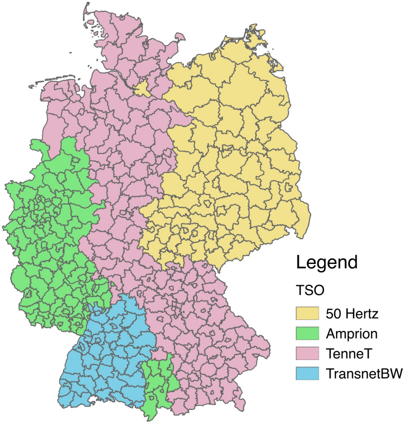


Figure: TSO service areas

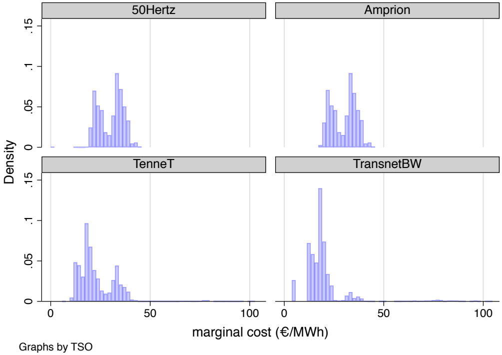
Marginal Sources

- At each 15-min interval, sort technologies by marginal cost to simulate dispatching
  - Assumption: load is dispatched by minimizing production costs
  - Retain identity of the marginal technology each period

Table: Simulated Frequencies of Marginal Technologies

Source	Freq.	Percent
Natural Gas	172,501	61.45
Hard Coal	100,765	35.90
Nuclear	3,522	1.25
Oil	3,187	1.14
Brown Coal / Lignite	655	0.23
Hydro: River	46	0.02
Hydro: Pumped storage	24	0.01
Biomass	4	0.00

Figure: Distribution of Marginal Operating Costs by TSO



Notes: Each panel shows the histogram of λ_{jt} for each TSO.

Marginal Benefits

- Following Callaway, Fowlie and McCormick (2018) and Tangeras and Wolak (2017)
- Separate marginal benefits (MB) from one unit of production of electricity from RES at region *j* and time *t* as:

$$\begin{aligned} MB_{jt} = \quad & \text{displaced emissions}_{jt} \\ & + \text{avoided operating costs}_{jt} \\ & \pm \text{ancillary service costs}_{jt} \end{aligned}$$

Marginal Benefits

- **displaced emissions** are the avoided emissions from the marginal fossil-fueled source displaced by renewables output
- **avoided operating costs** are the savings from the last MWh produced by the dispatchable unit
- **ancillary service costs** are the costs associated with maintaining system stability

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We compare the distribution of MB_{jt} against the uniform FiT incentive

Avoided Operating Costs and Displaced Emissions

$$OC_j = E[\text{avoided operating costs}_j] = \sum_{t=1}^{T} \omega_{jt}\lambda_{jt} = \overline{\lambda_j} + T \times Cov(\omega_j, \lambda_j)$$

- ω_{jt}, a weight, is the solar output (in MWh) in region j at time t divided by total amount of solar output throughout the entire interval [0, T]
- λ_{jt} is the marginal cost (in €/ MWh) of non-RES plants, $\overline{\lambda_j}$ is its mean

⇒ OC_j (in €/ MWh) is larger when the solar output is larger at times when λ_{jt} is also high

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- *Marginal emissions costs* based on the marginal technology displaced from solar production

$$E[\text{displaced emissions}_j] \quad = \quad \sum_{t=1}^{T} \omega_{jt} e_{jt} = \overline{e_j} + T \times Cov(\omega_j, e_j),$$

$\bar{e}_j$ is the expected value of e_{jt}.

Ancillary Service Costs

- Intermittency of solar imposes ancillary services costs associated with maintaining system stability
- We define the ancillary services AS_{jt} as:

$$\begin{aligned} AS_{jt}(R_{jt}, Q_{jt}) &= a_0 + a_1 R_{jt} + a_2 R_{jt}^2 + a_3 R_{jt}^3 + a_4 Q_{jt} + a_5 Q_{jt}^2 + a_6 Q_{jt}^3 + \\ &+ a_7 R_{jt} Q_{jt} + a_8 R_{jt} Q_{jt}^2 + a_9 R_{jt}^2 Q_{jt} + FE_. \end{aligned}$$

where a_i are the parameters to estimate, R_{jt} is the renewable output and Q_{jt} the total load at time t in TSO j.

$\Rightarrow$ marginal effect from an increase in RES output on ancillary services is $\partial AS_{jt}/\partial R_{jt}$

Clustering load profiles

k-means clustering

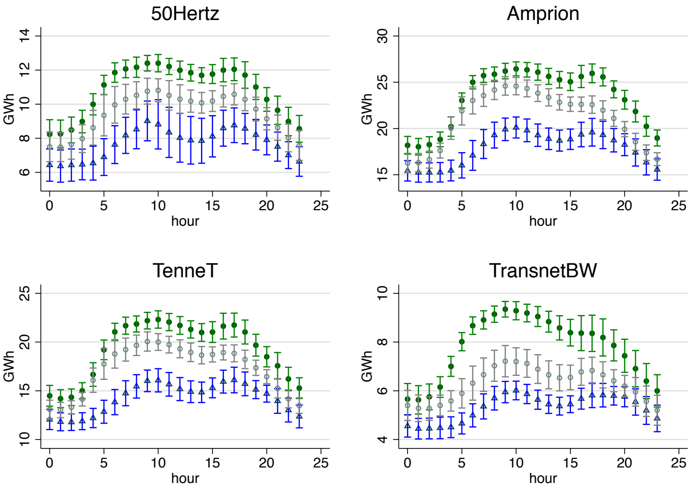

Figure: Clusters of Load Profiles by TSO

Total marginal benefits

TSO	Avoided ancillary service costs (€/MWh)	Avoided operating costs (€/MWh)	Avoided emissions (€/MWh)	Total (€/MWh)
Amprion	-1.05	29.39	12.48	40.82
	(3.15)	(6.35)	(2.09)	(6.85)
TenneT	0.09	21.97	22.34	44.4
	(1.37)	(10.14)	(7.28)	(8.41)
TransnetBW	-0.22	19.34	23.2	42.32
	(4.1)	(13.02)	(7.58)	(16.3)
50Hertz	-0.51	29.37	12.13	40.99
	(2.26)	(6.39)	(1)	(6.78)

Table: Expected Value and Standard Deviation of Marginal Benefits

Notes: The first three columns of results show each of the averages and standard deviations (in parentheses) of each of the components of marginal benefits. The last column contains the overall average and standard deviation (in parentheses) by TSO.

Misallocation

Misallocated RES?

- There is evidence of heterogeneous MBs from increasing RES capacity
- **Measuring misallocation:**
  - Productive inefficiencies occur through more capacity being allocated to areas with *lower solar productivity* and *lower marginal benefits*
  - Counterfactual: compare ‘actual’ output to ‘simulated’ (optimal) output
  - Reallocate solar capacity incrementally to areas where resulting benefits are highest subject to policy parameter
  - Take ratio of actual and benchmark total benefits
    1. Small scale residential installations
    2. All solar capacity, taking into account transmission

Measuring Misallocation

- Value of current allocation: each unit of observed solar output valued at the MB_{jt} (different every 15-min in each TSO)

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- Let $\mathcal{S}$ be the total amount of currently installed residential solar capacity in all the TSOs together. We divivde $\mathcal{S}$ in discrite blocks of size s (e.g. 1 MW). For a given value of γ we reallocate $\mathcal{S}$ as follows:
  1. Add a block of capacity of size s to the cumulative solar capacity in each TSO.

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  5. If $\mathcal{S}$ has not been completely reallocated, go back to step 1. Otherwise, the process ends since there is no more capacity to reallocate.

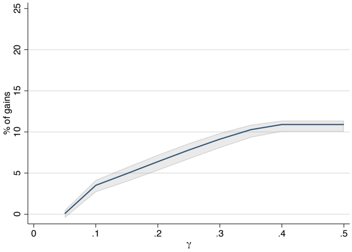
Measuring Misallocation

- The above algorithm exhausts all possibilities of allocation, conditional on *s* and will result in the optimal allocation
- As cumulative amount of solar increases in TSO, the value of the MB might change (different technology displaced)
- Use observed MB_{jt} in case less solar than in actual allocation, but allow for different values in case more solar gets allocated as in current allocation
- No transmission in this scenario: if total production from residential solar was large enough to cover total load, assign zero value for additional solar (never the case focusing on small scale solar)

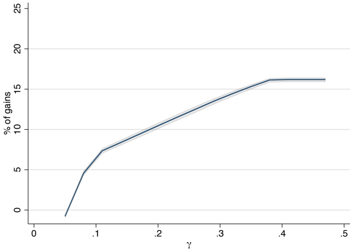
Quantifying the misallocation

$$\text{Reallocation value} = 100 \times \left(\frac{\text{value of reallocated solar cap.}}{\text{value of current distribution of solar cap.}} - 1 \right)$$

Figure: Value of Reallocation for Different Values of γ



(a) SCC = 31.71 €/tCO_2



(b) SCC = 50 €/tCO_2

Uncertainty in solar PV output and load

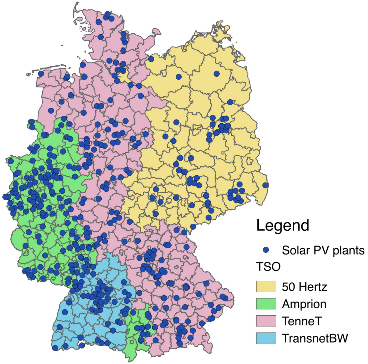
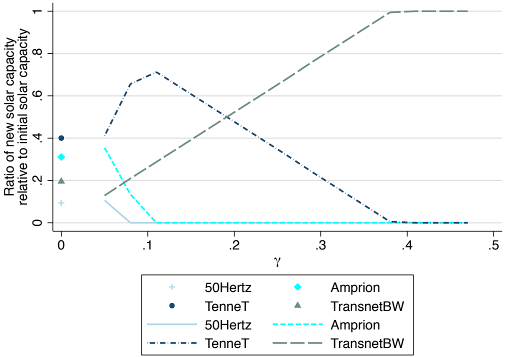


Figure: TSO service areas with PV plants (< 10 KW). PV Output

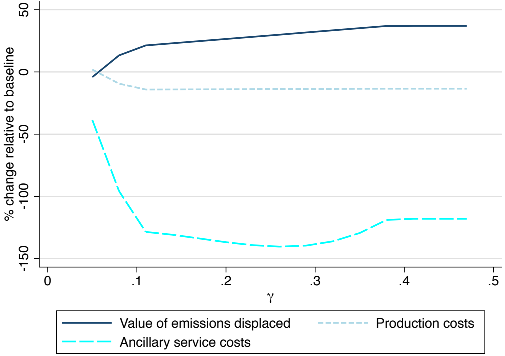
- Seemingly Unrelated Regression (SUR) for system of load and solar output.
- Predict joint distribution of residuals and increase / decrease load and solar in main reallocation by 2 SD measure.
- Take max and min value of possible combinations to construct uncertaintly for gains.

Ratio of Solar Capacity Relative to Total



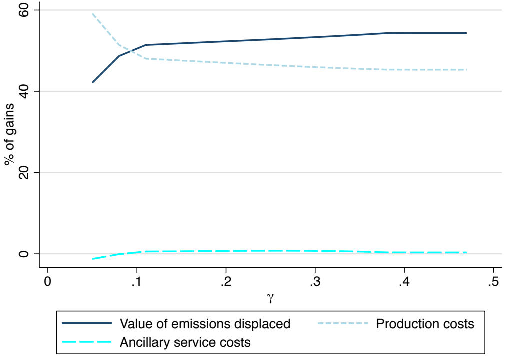
Notes: Increases in the solar rate γ allow for a higher reallocation of solar capacity in the best regions while lowering the reallocation amount to the worst regions. This occurs because total solar capacity remains constant. Markers at $\gamma = 0$ are the actual shares of residential solar installations ($\leq$ 10kW) before any reallocation.

Changes in each component relative to baseline



Notes: For each component we compute the difference of its value for a given value of γ and expressed as a percentage relative to the value of that component before any reallocation.

Decomposition of gains



Notes: At each value of γ, we compute the fraction of the value of each component relative to the total gains and express it as percentage.

The Value of Transmission

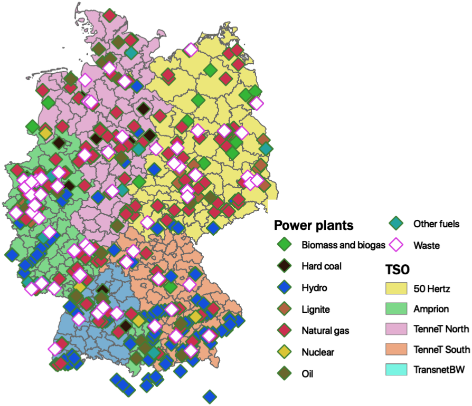
- Increasing penetration of distributed energy makes transmission lines more valuable
- Ongoing policy debate: German electricity grid development plan foresees high-voltage lines from North to South (*Net Development Plan*)
- To determine the *value of transmission* we repeat the misallocation counterfactual by splitting the largest TSO (TenneT) in two areas, **North** and **South**, and identify time periods with binding capacity constraint
- Focus on 'all' solar capacity. Redefine γ as share of solar in total capacity in each TSO

Counterfactual allocation: TenneT

Split TenneT in *North* and *South* region:

1. Map the location of each power plant in TenneT (conventional & RES)
2. Combine realized production data for RES with data on plant unavailability and average capacity factors of conventional power plants to construct hourly supply curves for both regions
3. Split demand in North and South region based on population figures
4. $\rightarrow$ Obtain the marginal costs λ_N and λ_S for both the North and South region within TenneT as the intersection of supply and demand

TSO areas and location of conventional power plants



Notes: Each symbol represents a conventional power plant. Data obtained from Open Power System Data `https://open-power-system-data.org`.

Estimate Capacity Constraint

Following Joskow and Tirole (2005) and LaRiviere and Lu (2017), we estimate the following supply functions:

$$E[\lambda_N] = a_N + b_N(R_N - Q_N) + b_N Q + FEs \quad (1)$$

$$E[\lambda_S] = a_S + b_S(R_S - Q_S) + b_S Q + FEs \quad (2)$$

- Q_S: load in the Southern region, Q: quantity traded
- Estimate equations for time intervals in which transmission constraint is binding ($\lambda_N \neq \lambda_S$)
- At these hours, any increases in load in N should not affect the scheduling of sources in S and vice versa
- With increasing capacity constraint, more expensive technologies need to be used in importing region

Estimating the supply functions

	(1)	(2)	(3)	(4)	(5)	(6)
	Gap = 2 €/ MWh		Gap = 5 €/ MWh		Gap = 8 €/ MWh	
	λ_N	λ_S	λ_N	λ_S	λ_N	λ_S
$R_N - Q_N$	-0.000932**		-0.000984**		-0.000480	
	(0.000301)		(0.000298)		(0.000418)	
Q_S	-0.00118		-0.00127		-0.00128	
	(0.000820)		(0.000814)		(0.00101)	
$R_S - Q_S$		-0.00634***		-0.00653***		-0.00730***
		(0.000586)		(0.000606)		(0.000675)
Q_N		0.00196*		0.00217*		0.00329**
		(0.000878)		(0.000889)		(0.00102)
N	4,461	4,461	4,398	4,398	3,787	3,787
R^2	0.820	0.708	0.823	0.711	0.834	0.708

Table: Estimates of Shadow Costs of Transmission

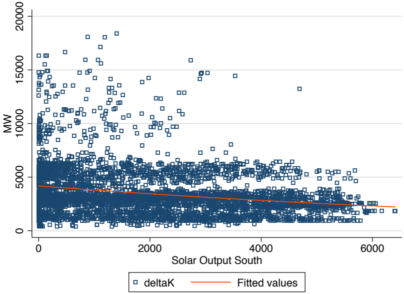
Notes: Dependent variable: as indicated on top of each column. Columns (1) and (2) correspond to a gap of 2 €/ MWh, columns (3) and (4) to a gap of 5 €/ MWh, last two columns to a gap of 8 €/ MWh. Standard errors clustered at the date level.

Capacity Imbalance

The change in price gap wrt capacity of the transmission line implies:

$$\text{capacity imbalance}_t = \Delta K_t = \frac{\Delta z_t}{b_N - b_S},$$

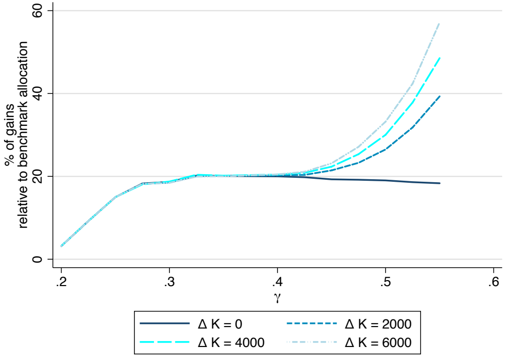
where $z_t \equiv \lambda_{N,t} - \lambda_{S,t}$ and $\Delta z_t = z_t - z_{t-1}$



Let $\overline{\Delta K}$ be the mean of the distribution of ΔK_t, then imputed marginal cost in region N is

$$\lambda_{N,t} = \lambda_{S,t} + z_{t-1} + (b_N - b_S)\overline{\Delta K}.$$

Reallocation with transmission capacity expansions



Notes: Each curve depicts the gains from reallocation if the transmission capacity between regions North and South is expanded by the amount indicated to the right of the graph.

Table: Benefit-Cost Analysis for Power Line Investment

Planned interconnection, ΔK [MW]		2,000			4,000	
Annualized investment costs [m€]						
Overhead lines		12.06			19.93	
Underground lines		150.77			249.14	
Capacity share, γ	.35	.4	.5	.35	.4	.5
Annual gains from reallocation [m€]	3.30	11.05	364.54	3.80	21.20	536.75
Benefit-cost ratio						
Overhead lines	0.27	0.92	30.22	0.20	1.11	28.00
Underground lines	0.02	0.07	2.42	0.02	0.09	2.24

Notes: Change in gains from reallocation for given γ comparing case of no interconnection ($\Delta K = 0$) with interconnection scenarios of 2,000 and 4,000 MW, respectively. Annualized investment costs for underground lines based on *SuedOstLink* project, with estimated total costs of 5 billion (bn) euros (Source: TenneT). For the 4,000 MW transmission, we assume a total cost of 7.94bn euros (*Suedlink* project). For overhead lines we assume that total investment cost represents approximately 8% of the underground cables. For both type of high-voltage lines we consider furthermore a 40 year lifespan and a 1% annual discount rate.

Conclusion

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- Results: Relatively low penetration rates of $\gamma = 20\%$ for reallocation represent approx. 6.4
- If a new transmission line is built between the North and the South regions would yield gains that range from 18 to 40% depending on the rate of solar penetration and the transmission capacity.
- A benefit-cost analysis shows that additional transmission can be beneficial if there is sufficient RES capacity reallocated across regions.

Thank you!

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