The Heterogeneous Value of Solar and Wind Energy: Empirical Evidence from the United States and Europe

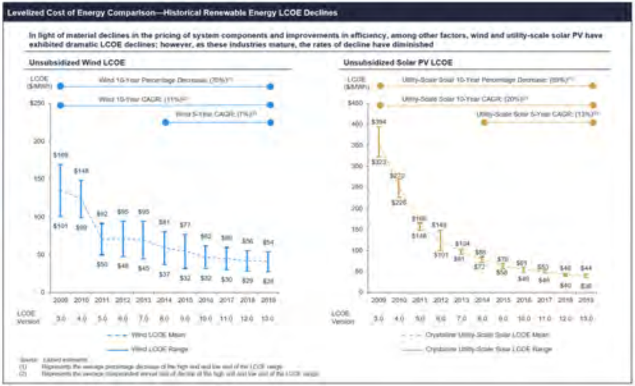
Kenneth Gillingham Marten Ovaere

Yale University

Harvard-Berkeley-Yale Virtual Seminar
May 13, 2020

Declining costs of renewables

- Cost declines for solar and wind have been dramatic
- Substantial policy support around the world
    - Some evidence policy led to declines (e.g., Gerarden 2019)
- But major heterogeneity in policy support
    - Spatially-differentiated regulation, with few linkages



Efficiency implications of differentiated policies

- Broad economics literature on the welfare benefits of spatially harmonized climate policies
  - Cost-effective: marginal abatement cost equalized across space
  - Prevents leakage
- Politically challenging
- Some externalities are spatially differentiated
- A social planner would maximize social welfare
  - So reduce emissions until marginal social cost (MSC) = marginal social benefit (MSB)
  - Each country/region would install renewables until MSC = MSB
  - Yet this appears to be far from the case around the world

Challenging to verify the deviation from efficiency

Major challenge: what is the MSB of installing renewables?

- Quantifying the MSB is crucial to quantify true subsidization
- Yet, it is more complicated than at first blush
  - Adding renewables to the grid can have spillover effects in multiple markets
  - We may not be able to just quantify the externalities and compare to the subsidy
- Don't forget innovation market failures
  - Popp (2019), Vogt-Schilb et al. (2018), Gerarden (2019), Bollinger & Gillingham (2018), Acemoglu et al. (2012), van Benthem et al. (2007), Jaffe et al. (2005)

This paper is about the MSB of renewables

- We quantify the value of utility-scale solar, onshore & offshore wind
  - With hourly data from all liberalized electricity markets in US and Europe
  - We cover all electricity markets, 2014-208
  - We include environmental externalities, but not innovation market failures
- We explore how the value of renewables declines with the share of renewables
- Several implications for policy
  - Where is it efficient to optimally increase investment on the margin?
  - Who is actually subsidizing renewables the most?
  - Relevant to debates over net metering and feed-in tariffs

Remuneration of rooftop solar fed into the grid

There is currently a major debate in many states about replacing **net metering** with a feed-in tariff based on the **value of the generation** to the electricity system.

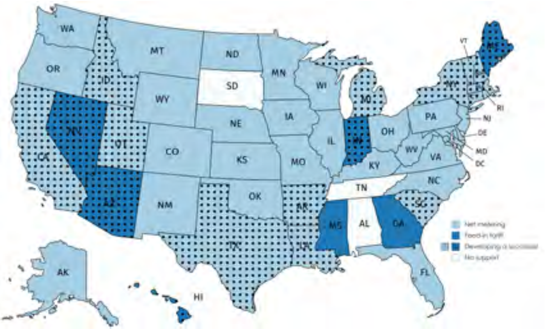


Figure: Map of U.S. states with net metering (light blue) or feed-in tariffs (dark blue) that are in the process of developing a value-based tariff (black dots).

Consider the stages of electricity supply

- We develop a data-driven methodology to quantify the marginal net benefits of renewable generation along the different stages of electricity supply.

Consider the stages of electricity supply

- We develop a data-driven methodology to quantify the marginal net benefits of renewable generation along the different stages of electricity supply.

What is the social value of installing renewables?

What is the social value of installing renewables?

1. **Energy**: Value of replaced generation in the energy market

What is the social value of installing renewables?

1. **Energy**: Value of replaced generation in the energy market
2. **Capacity**: Value of reduced need for installed generation capacity

What is the social value of installing renewables?

1. **Energy**: Value of replaced generation in the energy market
2. **Capacity**: Value of reduced need for installed generation capacity
3. **Ancillary services**: Changed cost of balancing the system and providing reserve capacity

What is the social value of installing renewables?

1. **Energy**: Value of replaced generation in the energy market
2. **Capacity**: Value of reduced need for installed generation capacity
3. **Ancillary services**: Changed cost of balancing the system and providing reserve capacity
4. **Emissions**: Value of avoided local (NO_X, SO_2, PM2.5) and global emissions (CO_2)

What is the social value of installing renewables?

1. **Energy**: Value of replaced generation in the energy market
2. **Capacity**: Value of reduced need for installed generation capacity
3. **Ancillary services**: Changed cost of balancing the system and providing reserve capacity
4. **Emissions**: Value of avoided local (NO_X, SO_2, PM2.5) and global emissions (CO_2)
5. **Transmission**: Changed cost of congestion and losses

What is the social value of installing renewables?

1. **Energy**: Value of replaced generation in the energy market
2. **Capacity**: Value of reduced need for installed generation capacity
3. **Ancillary services**: Changed cost of balancing the system and providing reserve capacity
4. **Emissions**: Value of avoided local (NO_X, SO_2, PM2.5) and global emissions (CO_2)
5. **Transmission**: Changed cost of congestion and losses
6. **Not quantified**: Reduced distribution line loading, innovation, etc.

Geographical scope: 1/3 of global wind & solar capacity

Figure 3: Map of independent system operators (ISOs) in the United States (left) and European countries included in the sample (right). ERCOT = Electric Reliability Council of Texas; ISONE = ISO New England; MISO = Midcontinent Independent System Operator; NYISO = New York ISO; PJM = Pennsylvania, New Jersey, Maryland; SPP = Southwest Power Pool; AT=Austria; BE=Belgium; CZ=Czechia; DE=Germany (includes Luxembourg); ES=Spain; FR=France; GB=Great Britain; NL=Netherlands; and PT=Portugal.

Literature: United States

	CAISO	ISONE	NYISO	ERCOT	MISO	PJM	SPP
Capacity	Callaway, Fowlie and McCormick, JAERE, 2018 (2010-2012, hourly) solar and wind generation based and irradiance and wind data						
Energy	Sexton, Kirkpatrick, Harris and Muller, WP, 2018 (2007-2015, hourly, eGrid regions) solar generation based on irradiance data						
Emissions				Fell and Kaffine, AEJ:EP, 2018 (2008-2013, daily)			
				Cullen, AEJ:EP, 2013 (2005-2007, hourly)			
				Novan, AEJ:EP, 2015 (2007-2011, hourly)			
				Fell, Kaffine and Novan, WP, 2019 (2011-2015, hourly)			
Congestion	Sexton et al., WP, 2018 (2017, hourly)						
Losses							
Ancillary							
Distribution							

Literature: United States

	CAISO	ISONE	NYISO	ERCOT	MISO	PJM	SPP
Capacity							
Energy							
Emissions							
Congestion							
Losses							
Ancillary							
Distribution							

Callaway, Fowlie and McCormick, JAERE, 2018
(2010-2012, hourly) solar and wind generation based and irradiance and wind data

Sexton, Kirkpatrick, Harris and Muller, WP, 2018
(2007-2015, hourly, eGrid regions)
solar generation based on irradiance data

Fell and Kaffine, AEJ:EP, 2018 (2008-2013, daily)

Cullen, AEJ:EP, 2013
(2005-2007, hourly)

Novan, AEJ:EP, 2015
(2007-2011, hourly)

Fell, Kaffine and Novan,
WP, 2019
(2011-2015, hourly)

Sexton et al.,
WP, 2018
(2017, hourly)

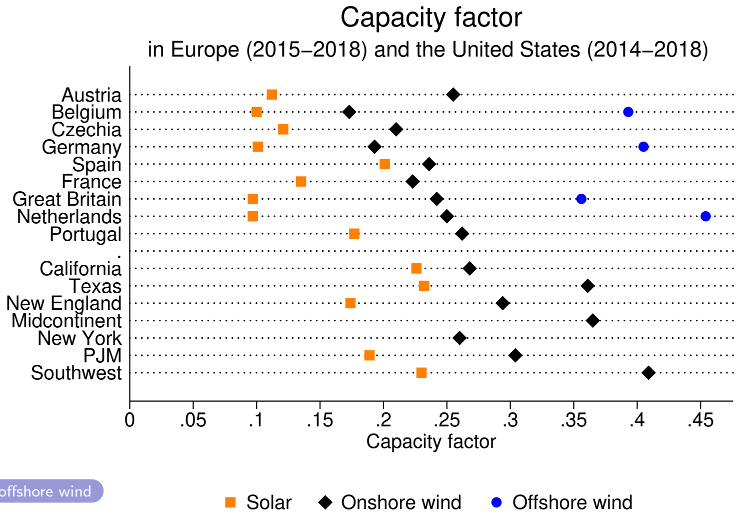
This paper
(2014-2018, hourly)
actual solar and wind generation data

Hourly data

For seven U.S. ISO regions (2014-2018) and nine European countries (2015-2018), hourly data on:

1. **Generation**
   - Fuel mix, load, day-ahead zonal or hub prices, forward capacity market prices, reserve prices & quantities, regulation/balancing prices & quantities
2. **Transmission**
   - Congestion, losses
3. **Emissions**
   - United States: monetize using AP3 (Clay et al., 2019)
   - Europe: monetize using European handbook on the external cost of transport (van Essen et al., 2019)

Heterogeneity in average capacity factors



Detailed data offshore wind

Estimating marginal avoided emissions

Estimating marginal avoided emissions

1. Estimate the marginal changes of all generation technologies in response to renewable generation (Cullen, 2013; Novan, 2015)

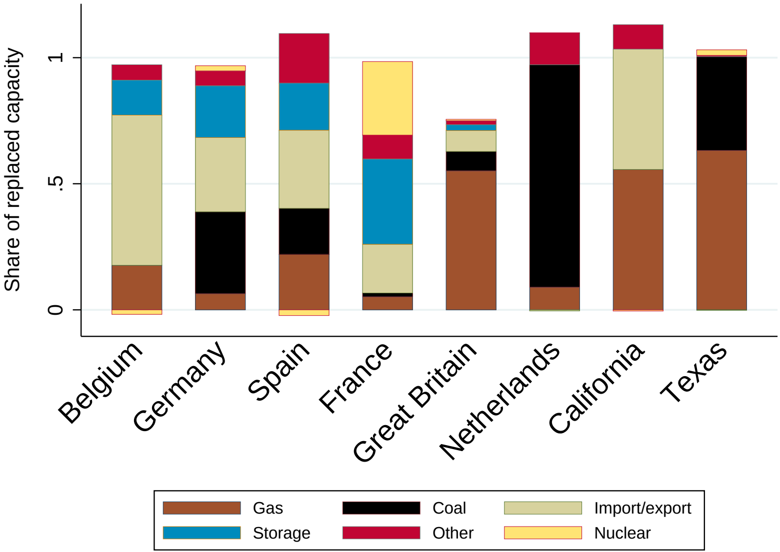
$$q_{\text{conv},it} = \sum_r \beta_{\text{r},i} q_{\text{r},it} + \sum_{n=1}^{3} \beta_{\text{load},i} load_{it}^n + p_{\text{commodity},it} + \delta_{hmy,i} + \epsilon_{it}$$

for $r = \{\text{solar,onshore,offshore}\}$ and

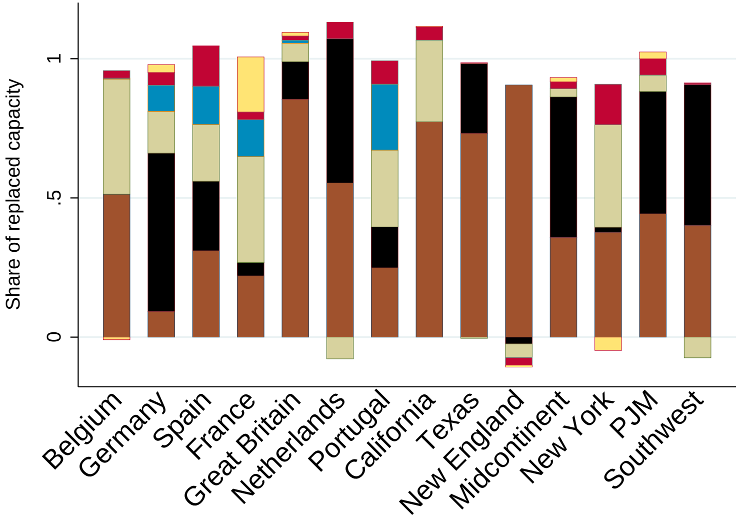
$\text{conv} = \{\text{lignite,hard coal,gas,nuclear,hydro,biomass,...}\}$

Dealing with exchanges

Generation replaced by solar



Generation replaced by onshore wind



Estimating marginal avoided emissions

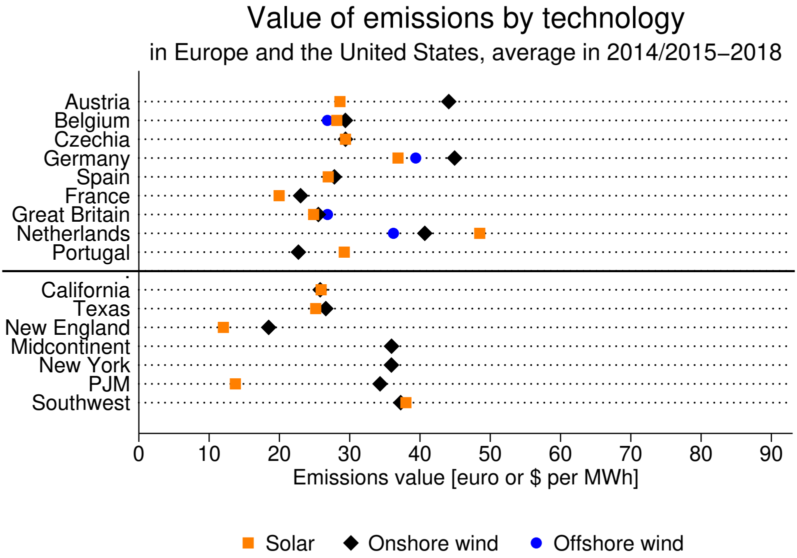
2. Multiply displaced generation by average emission intensities (NO_X, SO_2, PM2.5 and CO_2) to calculate marginal avoided emissions.
Graph

Estimating marginal avoided emissions

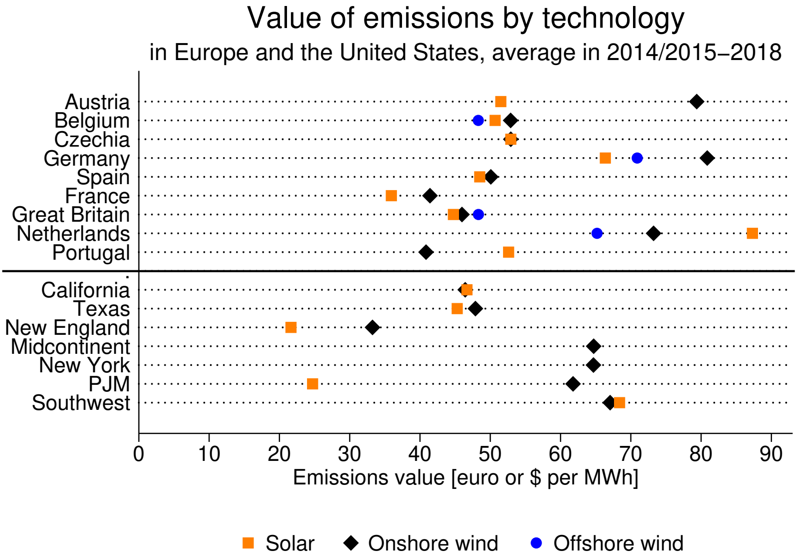
2. Multiply displaced generation by average emission intensities (NO_X, SO_2, PM2.5 and CO_2) to calculate marginal avoided emissions.
   Graph

3. Monetize the resulting emission changes using AP3 (Clay et al., 2019) for the United States and country-level estimates from the European handbook on the external cost of transport (van Essen et al., 2019).

Marginal avoided emissions (SCC = \$44/ton CO_2)



Marginal avoided emissions (SCC=\$111/ton CO_2)



Marginal effect on ancillary services

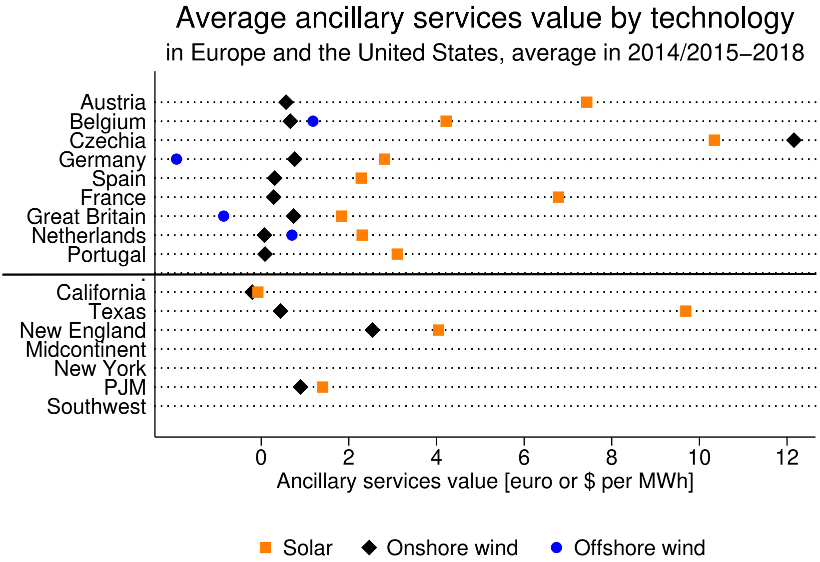
Marginal effect on ancillary services

3. Estimate how the cost of reserves and regulation change in response to renewable generation

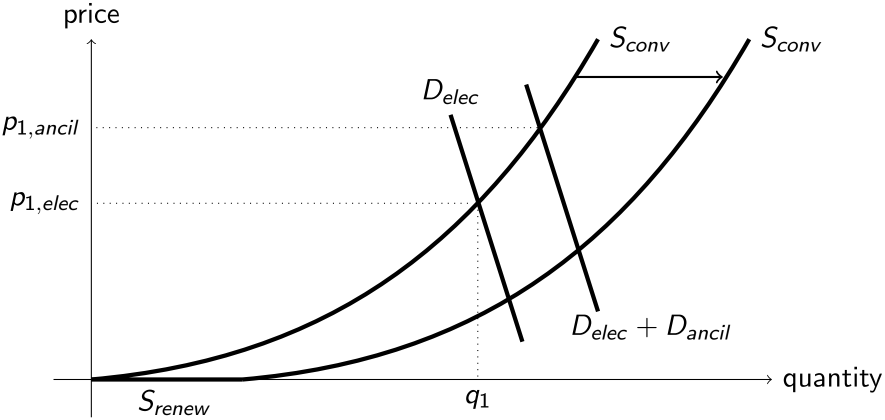
$$cost_{\text{ancillary},it} = \sum_{r} \beta_{\text{r},i} q_{\text{r},it} + \sum_{n=1}^{3} \beta_{\text{load},i} load_{it}^{n} + p_{\text{commodity},it} + \delta_{hmy,i} + \epsilon_{it} \qquad \text{for } r = \{\text{solar,onshore,offshore}\} \tag{1}$$

where $cost_{ancillary,it}$ is the cost of an ancillary service at time t and in region i. $\delta_{hmy,i}$ is an hour-by-month-by-year fixed effect in ISO zone or country i.

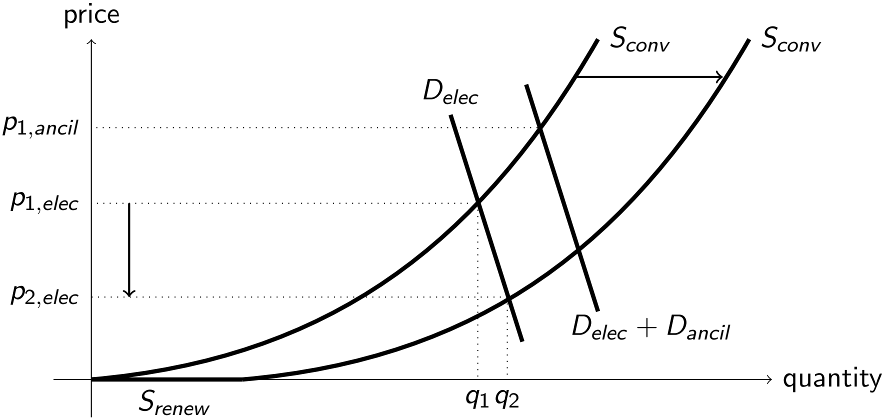
Effect on ancillary services values



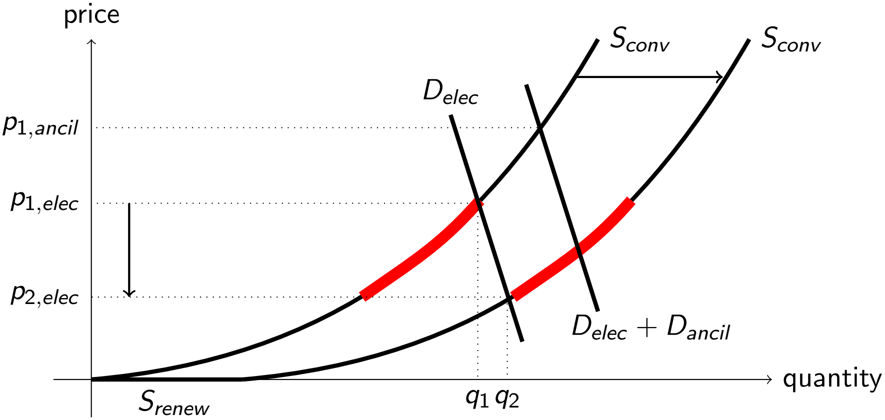
Ancillary services ("German Paradox")



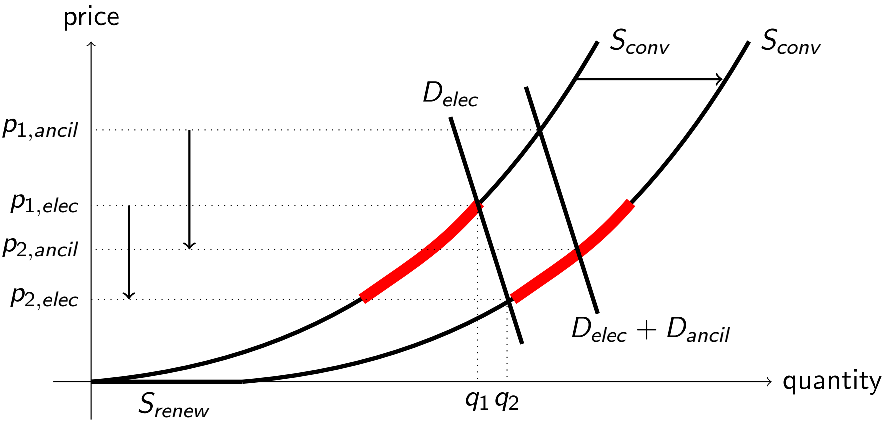
Ancillary services ("German Paradox")



Ancillary services ("German Paradox")



Ancillary services ("German Paradox")



Other markets: Energy value

1. **Energy**: Calculate market value of electricity generated

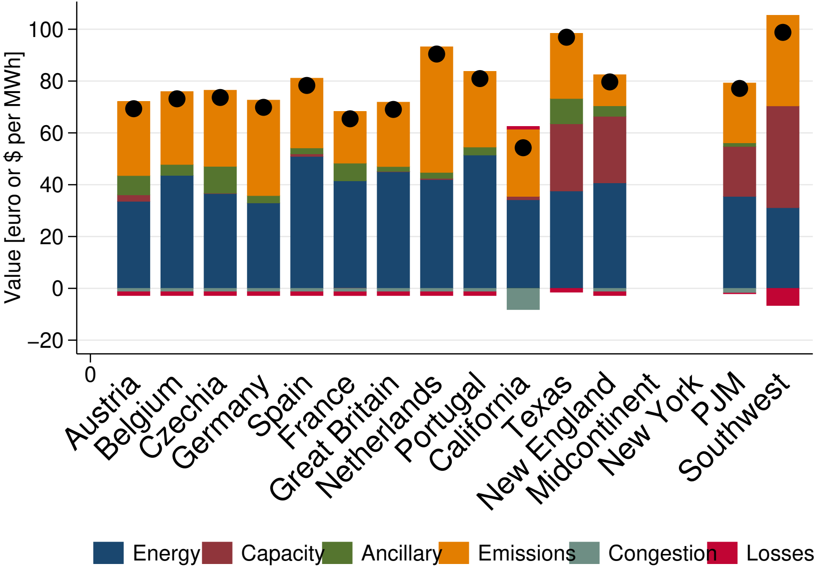
Other markets: Capacity

1. **Energy**: Calculate market value of electricity generated
2. **Capacity**: Calculate reduced need for installed generation capacity valued at cost of new entry

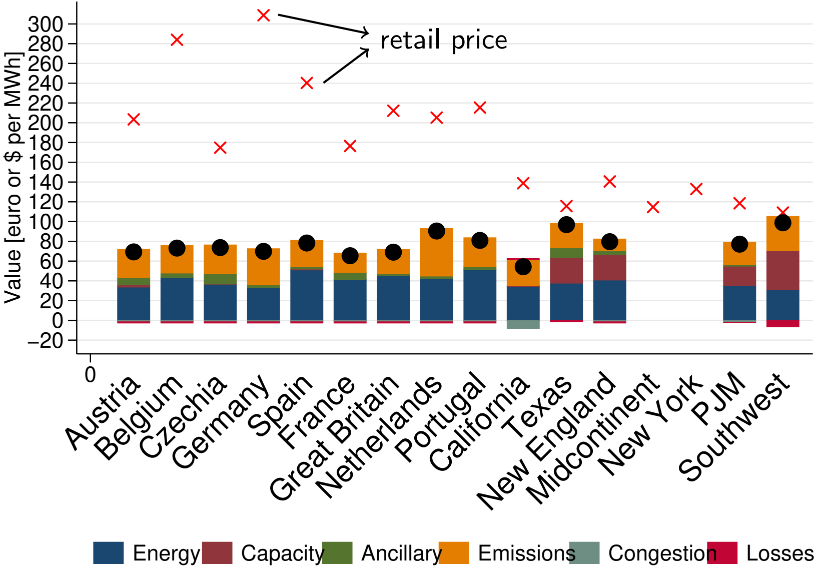
Other markets: Transmission

4. **Energy**: Calculate value of replaced generation in the energy market
5. **Capacity**: Calculate reduced need for installed generation capacity valued at cost of new entry
6. **Transmission**: Estimate how congestion costs/losses change in response to renewable generation (same specification as ancillary services)

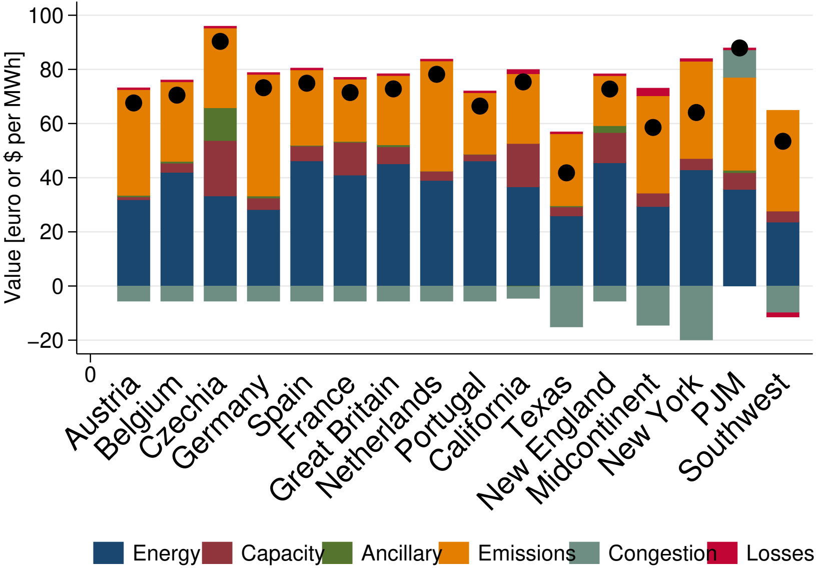
Value of solar (CO_2 \$44/ton)



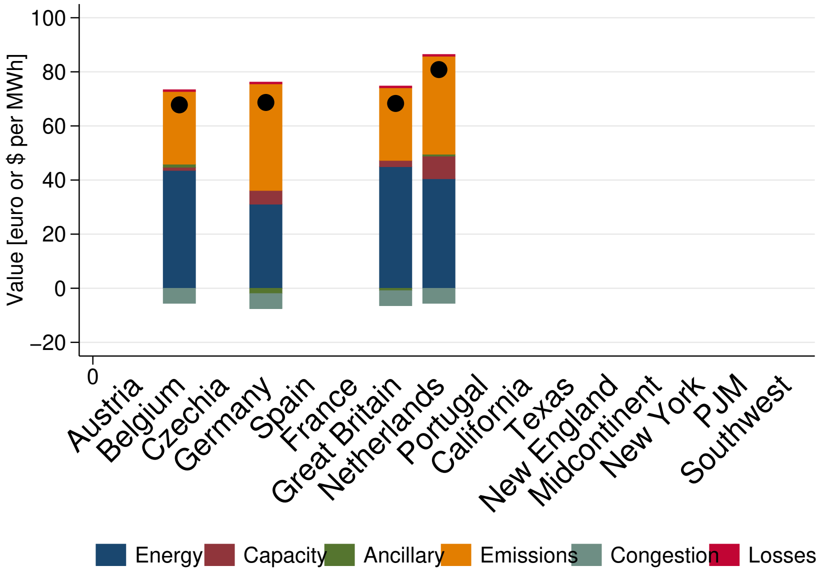
Value of solar versus retail price



Value of onshore wind



Value of offshore wind



Does the value of renewables decrease with a higher share?

Table: The value of a renewable technology decreases with its **generation share** (ratio of total renewable generation to total load).

	(1) log(value)	(2) log(value)	(3) log(value)
Renewable share	-0.011***	-0.012***	-0.010***
	[-0.017,-0.006]	[-0.017,-0.007]	[-0.014,-0.005]
Renewable share other			0.009***
			[0.004,0.015]
Observations	144	144	144
R^2	0.09	0.21	0.27
Year FE		Yes	Yes

Note: Unit of observation is region-year. Confidence intervals in brackets. p<0.001 (***).

Details

Region FEs

(1) Does the value of renewables decrease?

Table: The **total** value [$ per MWh] of solar decreases with its own **generation share** (ratio of total solar generation to total load) and increases with the generation share of wind (onshore + offshore).

	(1) log(value)	(2) log(value)	(3) log(value)
Share solar	-0.047***	-0.048***	-0.047***
	[-0.069,-0.025]	[-0.070,-0.027]	[-0.066,-0.028]
Share wind			0.013***
			[0.006,0.020]
Observations	59	59	59
R^2	0.21	0.31	0.43
Year FE		Yes	Yes

Note: Unit of observation is region-year. Confidence intervals in brackets. p<0.05 (*), p<0.01 (**), p<0.001 (***).

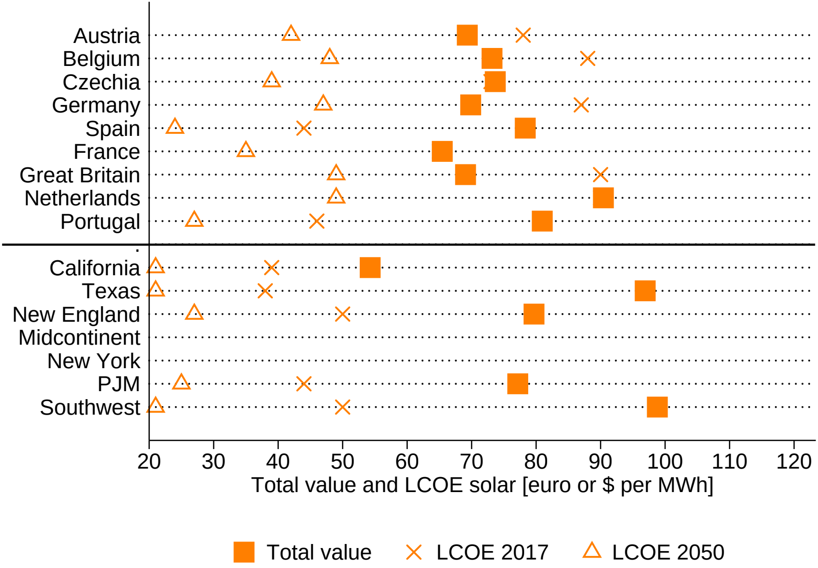
(1) Does the value of renewables decrease?

Table: The **total** value [$ per MWh] of wind (onshore + offshore) decreases with its **generation share** (ratio of total wind generation to total load) and increases with the generation share of solar.

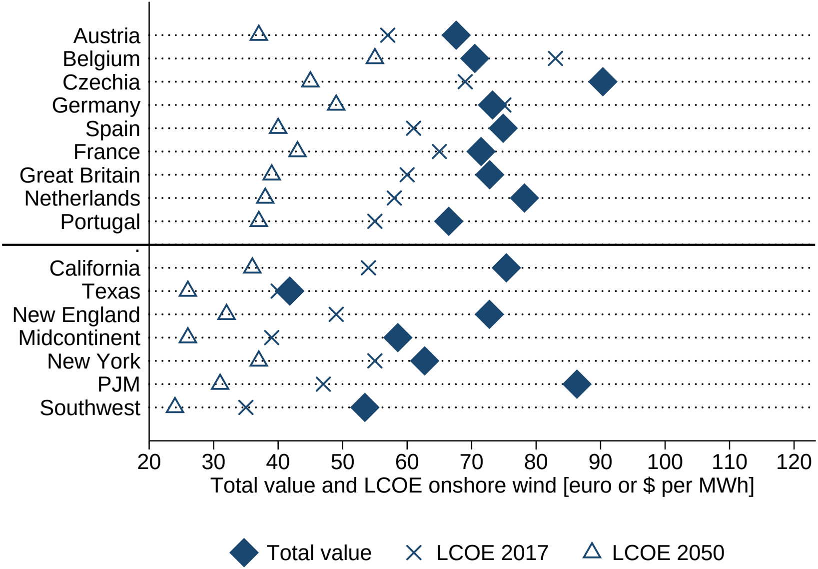
	(1)	(2)	(3)
	log(value)	log(value)	log(value)
Share wind	-0.007*	-0.008**	-0.008**
	[-0.012,-0.001]	[-0.013,-0.003]	[-0.013,-0.003]
Share solar			0.009
			[-0.003,0.021]
Observations	85	85	85
R^2	0.06	0.26	0.28
Year FE		Yes	Yes

Note: Unit of observation is region-year. Confidence intervals in brackets. p<0.05 (*), p<0.01 (**), p<0.001 (***).

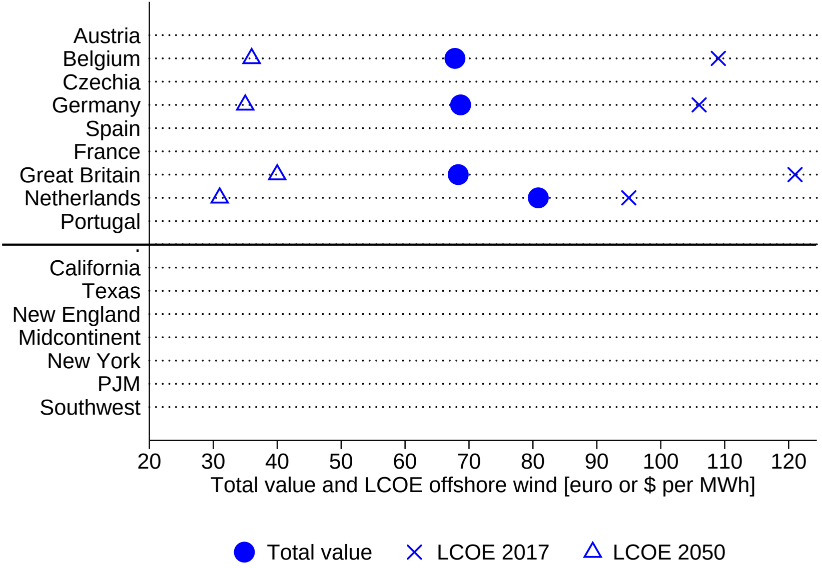
How does the value compare to costs for solar?



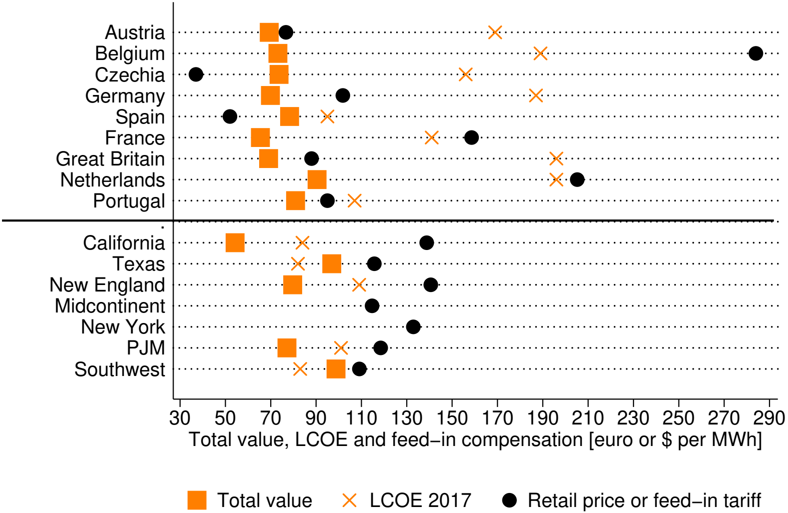
How does the value compare to costs for onshore wind?



How does the value compare to costs for offshore wind?



Remuneration of rooftop solar



Details

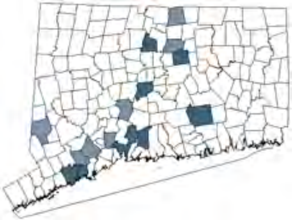
Conclusions

1. We are the first to quantify the marginal benefits of utility-scale renewables across many countries, technologies, and markets
   - The value of onshore wind and solar generation today is already above the technology cost in most places
   - The value of rooftop solar and offshore wind generation today tends to be below the cost, but we did not account for distribution costs
   - Values of all are below retail prices
2. We are the first to quantify how the value declines with increasing share.
   - Steeper for solar than wind
   - Large in magnitude: 1 pp $\Rightarrow$ 1% decline
   - This decline may compete with the decline in technology costs
3. Results can inform discussions of location of the next renewable investment.
   - Also clarify what the subsidies today actually are, telling us who (implicitly) is paying for the innovation.

Work-in-progress

Work-in-progress

- Field experiment in Connecticut. Circuit-level campaigns to encourage adoption of rooftop solar in specific circuits.
- Compare changes in (peak) line loading, voltage and interruptions between treated (dark blue) and control (light blue) circuits.

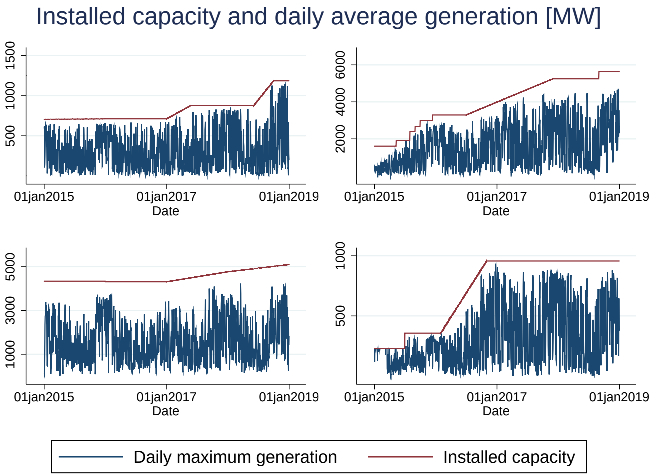


Thanks for your attention!

Questions? Comments?

kenneth.gillingham@yale.edu
marten.ovaere@yale.edu

Installed offshore wind capacity and generation



Back

Figure: Installed capacity and daily maximum generation [MW] in 2015-2018 for Belgium, Germany, Great Britain and Netherlands

(4) Emissions: dealing with exchanges

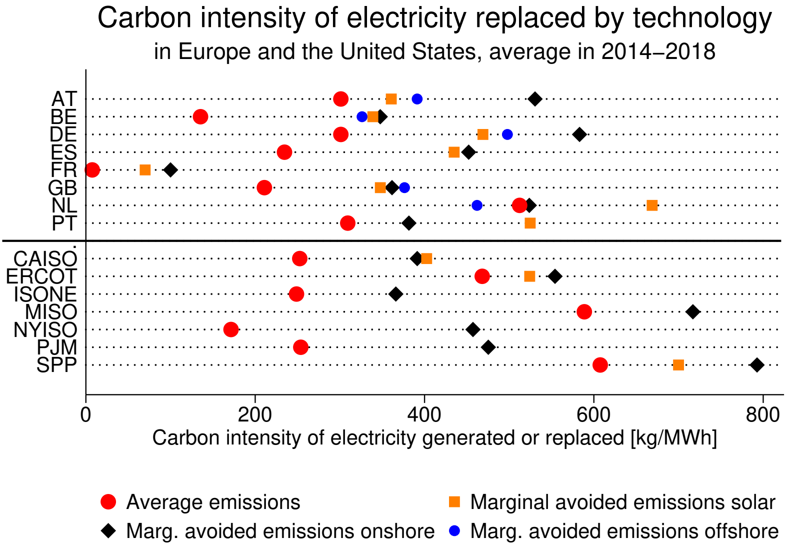
Estimate the effect of exchange over a specific border of ISO zone or country i on conventional generation:

$$q_{\text{conventional},it} = \beta_{\text{exchange},bi} q_{\text{exchange},bit} + \sum_{n=1}^{3} \beta_{\text{load},i} load_{it}^{n} \quad (2)$$

$$+ p_{\text{commodity},it} + \mathbf{x}_{it} + \delta_{hmy,i} + \epsilon_{it} \quad (3)$$

where $q_{\text{exchange},it}$ the import or export through border b. The vector $\mathbf{x}_{it}$ contains hourly generation of solar and wind generation in country i, as well as imports and exports on the other borders of country i. Back

(4) Emissions: results carbon intensity



Back

(1) Analysis: does the value of renewables decrease?

Estimate how the total value of a renewable technology changes if its share in total generation increases:

$$\text{totalvalue}_{r,it} = \beta_{\text{share},i}\text{share}_{r,it} + \delta_i + \delta_y + \epsilon_{it} \text{ for } r = \{\text{solar,onshore,offshore}\} \quad (4)$$

where $\text{Totalvalue}_{r,it}$ is the total value of renewable technology r, at year t, and in region or country i. δ_i and δ_t are a region and year fixed effects.

(1) Analysis: does the value of renewables decrease?

Table: The value [€/$ per MWh] of a renewable technology decreases with its **generation share** (ratio of total renewable generation to total load).

	(1) Across sample	(2) Within-region/country
Value of avoided energy	-0.29*	-0.40***
Value of decreased need for capacity	-0.52***	-0.66
Changed costs of ancillary services	-0.28**	-0.30*
Value of avoided emissions	-0.06	-0.30

Note: $p<0.1$ (*), $p<0.05$ (**), $p<0.01$ (***).

Back

(1) Does the value of renewables decrease?

Table: The **total** value [€/$ per MWh] of a renewable technology decreases with its **generation share** (ratio of total renewable generation to total load).

	(1) Total value	(2) Total value	(3) Total value
Renewable share	-1.012***	-1.064***	-1.580
	[-1.514,-0.510]	[-1.551,-0.577]	[-3.306,0.147]
Observations	144	144	144
R^2	0.09	0.18	0.38
Region FE			Yes
Year FE		Yes	Yes

Note: Unit of observation is region-year. Confidence intervals in brackets. For column (3) they are clustered by region and are based on the wild cluster bootstrap procedure from (Cameron et al., 2008; Roodman et al., 2019). p<0.05 (*), p<0.01 (**), p<0.001 (***).

Back

(3) Analysis: net metering

Table: Different ways of remunerating generation by distributed behind-the-meter solar, with examples from Europe on January 1^{th}, 2019.

Feed-in rate	Example
Feed-in tariff on excess	Austria: €76.7/MWh
	Germany: €101.8/MWh
	Portugal: €95/MWh
Wholesale price on total	Spain, Czechia
Feed-in tariff on excess and total	Great Britain: £38.2/MWh + £37.9/MWh
Feed-in tariff on excess or total	France: €100/MWh or €158.6/MWh
Net metering at retail rate	Belgium, Netherlands

Back

Cameron, A. C., Gelbach, J. B., and Miller, D. L. (2008). Bootstrap-Based Improvements for Inference with Clustered Errors. *Review of Economics and Statistics*, 90(3):414–427.

Clay, K., Jha, A., Muller, N., and Walsh, R. (2019). External Costs of Transporting Petroleum Products : Evidence from Shipments of Crude Oil from North Dakota by Pipelines and Rail. *The Energy Journal*, 40(1):55–72.

Roodman, D., MacKinnon, J. G., Nielsen, M. Ø., and Webb, M. D. (2019). Fast and wild: Bootstrap inference in Stata using boottest. *Stata Journal*, 19(1):4–60.

van Essen, H., van Wijngaarden, L., Schroten, A., Sutter, D., Bieler, C., Maffii, S., Brambilla, M., Fiorello, D., Fermi, F., Parolin, R., and El Beyrouty, K. (2019). *Handbook on the external costs of transport*.