The Value of Renewables: Observational and Experimental Evidence from the United States and Europe

Kenneth Gillingham Marten Ovaere

Yale University, School of Forestry & Environmental Studies

Heartland Workshop - September 29, 2019

Motivation

1. Worldwide solar and wind capacity has increased dramatically
   - Account for a sixth of global installed power capacity
   - (IEA, 2018) expects installed capacity to double by 2023

$\longrightarrow$ because their output is variable and not perfectly predictable, open question whether part of the fuel **savings are canceled by increased costs** like backup capacity, network congestion and system balancing.

Motivation

2. Major debate in many states about replacing **net metering** with a tariff that is closer to the **value of renewable generation** to the electricity system.

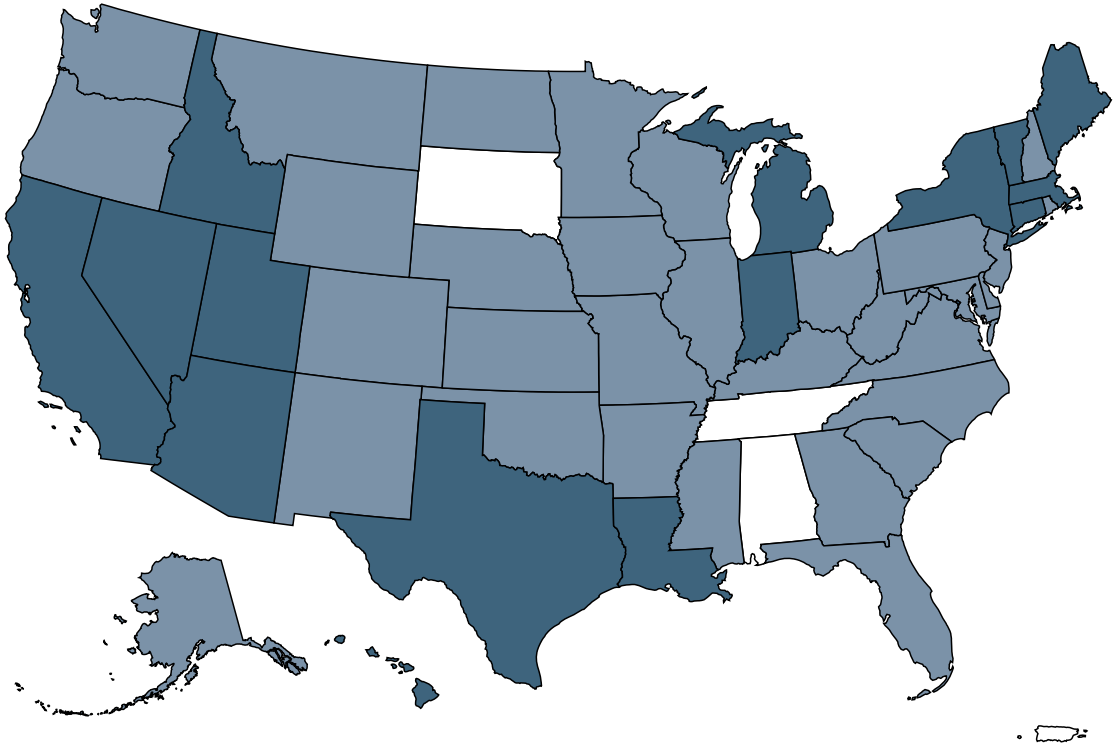


Figure: Map of U.S. states with net metering (blue) that are in the process of developing a successor for net-metering (darker blue).

Research Question

What is the value of (distributed) solar and wind to the electricity system?

Research Question

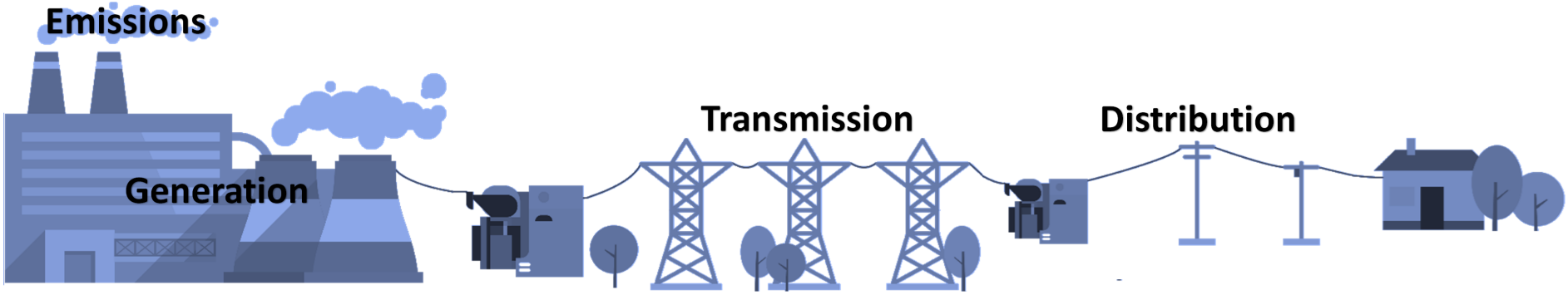
What is the value of (distributed) solar and wind to the electricity system?

- What are their full social costs and benefits in *all* stages of the electricity supply chain?

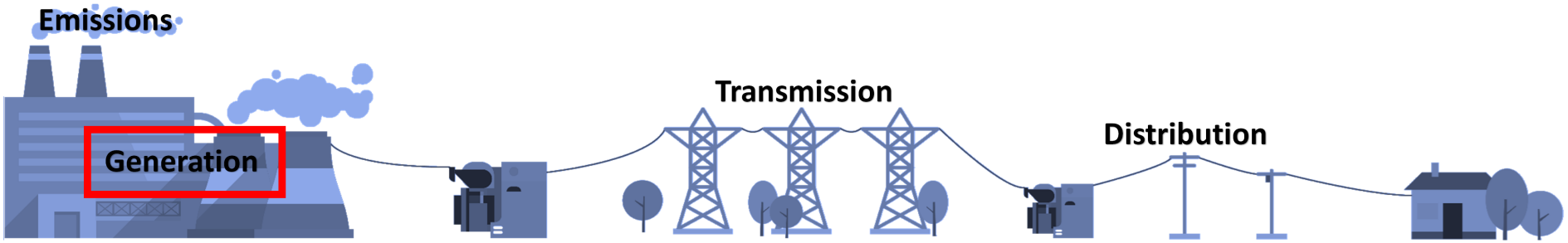
Research Question

What is the value of (distributed) solar and wind to the electricity system?

- What are their full social costs and benefits in *all* stages of the electricity supply chain?



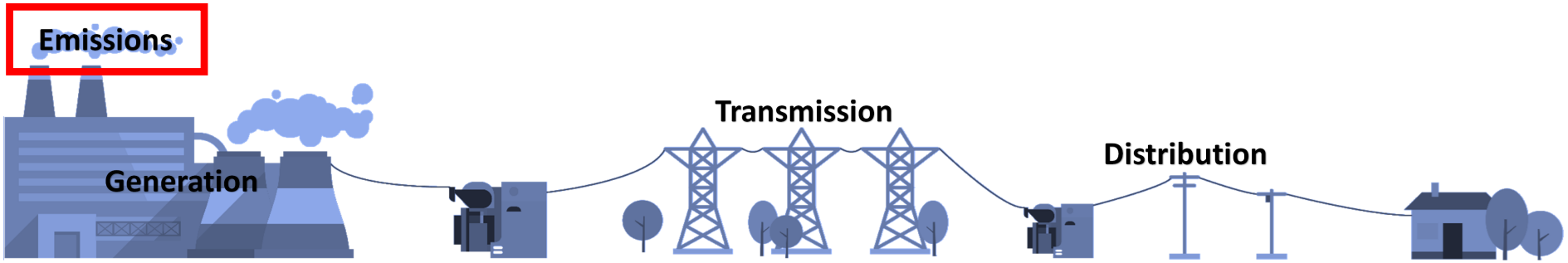
Adding renewables to the electricity system: What happens?



GENERATION

- What is the value of the replaced electricity generation plants in the energy market?
- How much does the need for installed generation capacity change?
- Do solar and wind generation change the cost of ancillary services, like balancing the system and the reserve capacity needed?

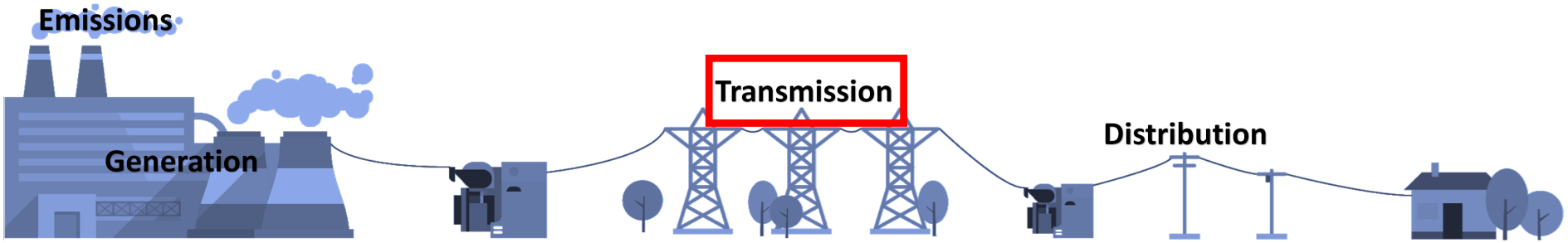
Adding renewables to the electricity system: What happens?



EMISSIONS

- What are the avoided emissions of the replaced fossil fuel generation?
- What are the environmental benefits of the avoided emissions?

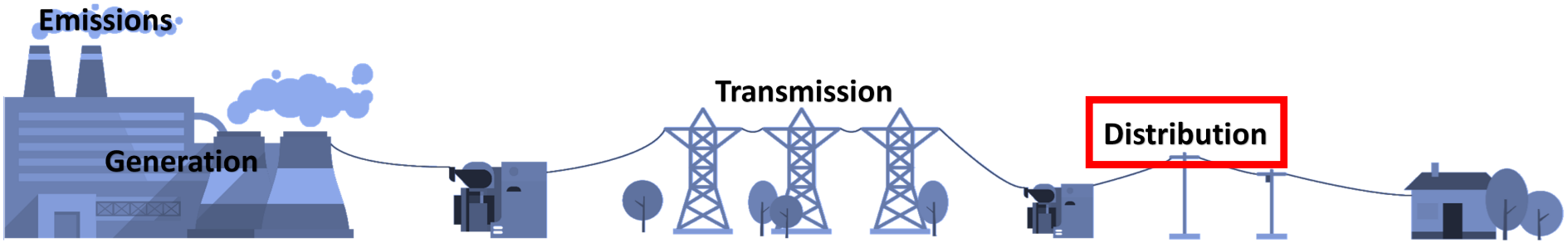
Adding renewables to the electricity system: What happens?



TRANSMISSION

- Do solar and wind generation change the cost of congestion and losses in the transmission network?

Adding renewables to the electricity system: What happens?



DISTRIBUTION

- Does distributed solar generation decrease peak loading on local lines and transformers?
- Do they lead to more or less local interruptions?
- Do they affect power quality?

Contributions

1. Most prior studies of solar and wind generation have focused on estimating in much detail a specific effect in a specific region.
   $\longrightarrow$ **Quantify in all stages of the electricity supply chain and in all liberalized electricity markets in the United States.**

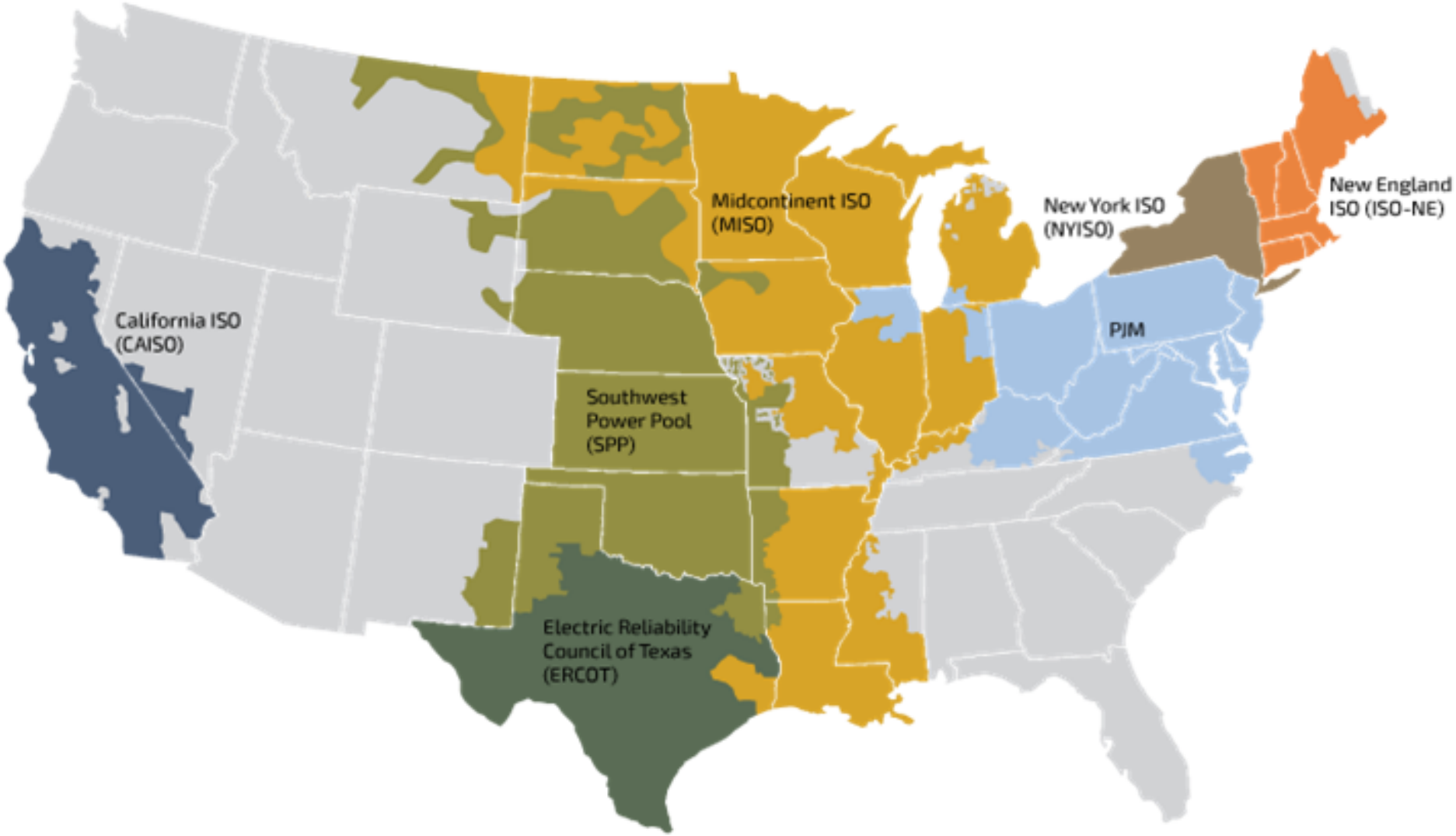
2. Prior multi-region studies (Callaway et al., 2017; Sexton et al., 2018) have used detailed hourly irradiance and wind speed data.
   $\longrightarrow$ **Use hourly 2014-2018 data of actual solar and wind output.**

3. A blind spot in the literature is the effect of intermittent renewable generation on the distribution network.
   $\longrightarrow$ **Estimate the effect on the distribution network in Connecticut.**

General methodology and literature

	CAISO	ISONE	NYISO	ERCOT	MISO	PJM	SPP
Capacity	Callaway, Fowlie and McCormick, JAERE, 2017 (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	Cohen et al., 2016 (2011-2012, hourly) data+simulations						

7 ISO (independent system operator) regions in the USA



Hourly observational data: 2014-2018

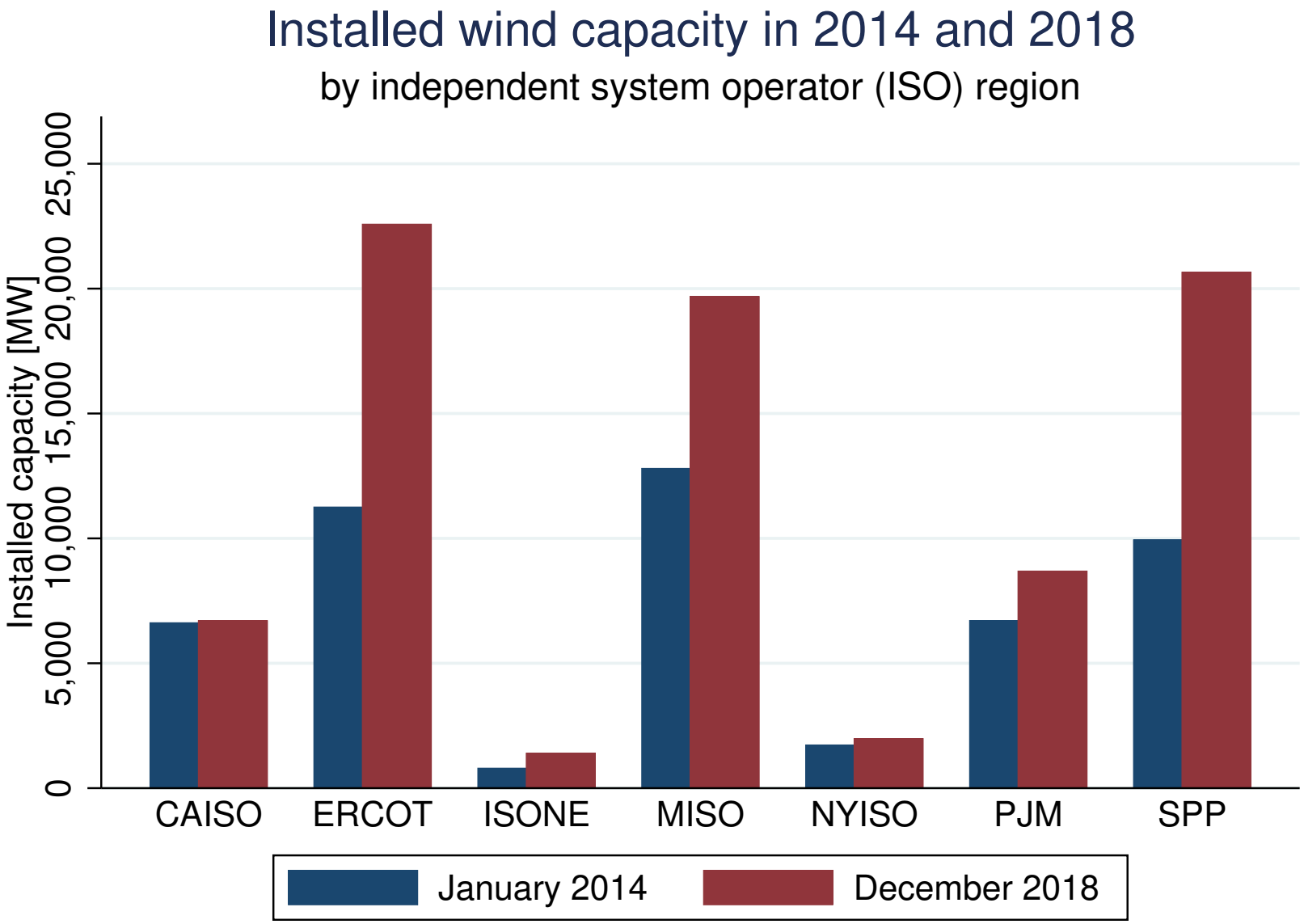
For each of the seven U.S. independent system operator regions:

1. **Generation**
   - Fuel mix: conventional + wind + solar
   - Load
   - Day-ahead hub (locational marginal) prices
   - Forward capacity market prices
   - Reserve price & quantity
   - Regulation/balancing price & quantity
2. **Transmission**
   - Congestion
   - Losses

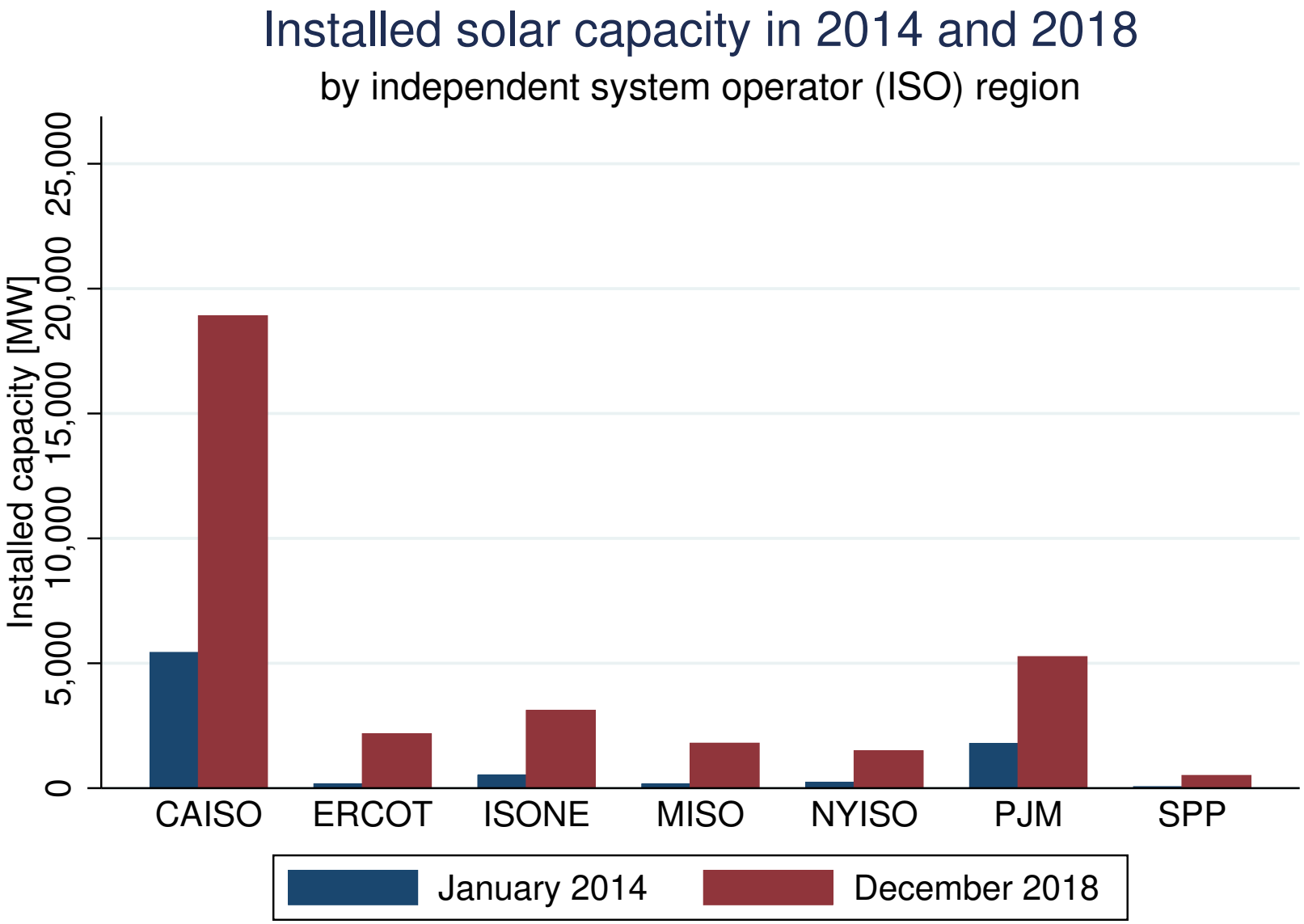
Hourly observational data

3. **Distribution** (for one utility only)
   - Subcircuit-level network metrics: line loading, voltage, interruptions
   - Database of all solar installations in Connecticut
4. **Emissions**
   - AP2 (Muller, 2014)
   - Continuous Emission Monitoring System (CEMS) Database?

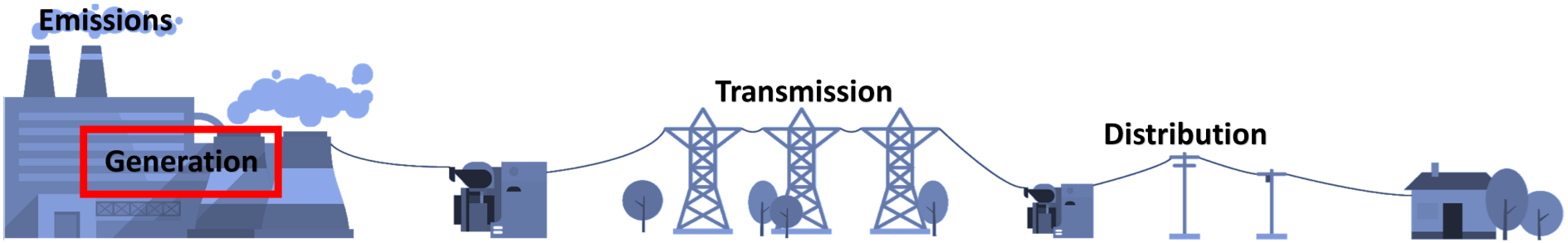
Installed **wind** capacity in 2014 and 2018



Installed **solar** capacity in 2014 and 2018



(1) Energy: Methodology



1. **Energy**: calculate the market value of electricity generated

$$\frac{\sum_t^T p_{it} \cdot q_{solar,it}}{\sum_t^T q_{solar,it}} \quad \text{and} \quad \frac{\sum_t^T p_{it} \cdot q_{wind,it}}{\sum_t^T q_{wind,it}} \tag{1}$$

where p_{it} is the price and q_{it} is the generation at time period t in ISO zone i.

(1) Energy: Results

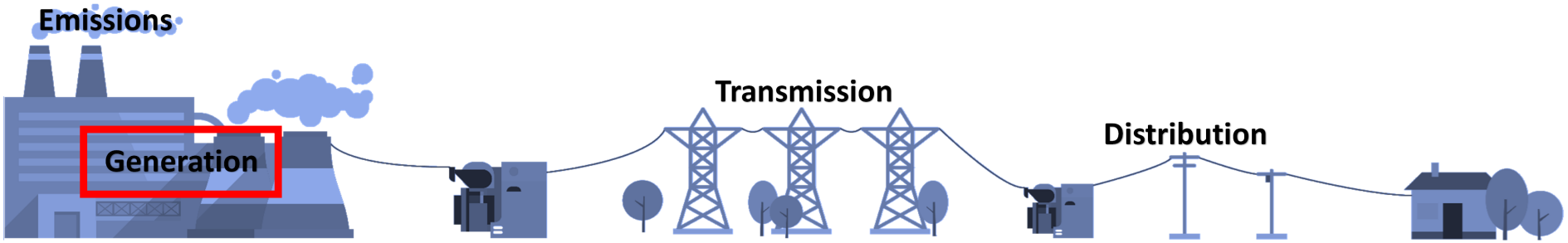
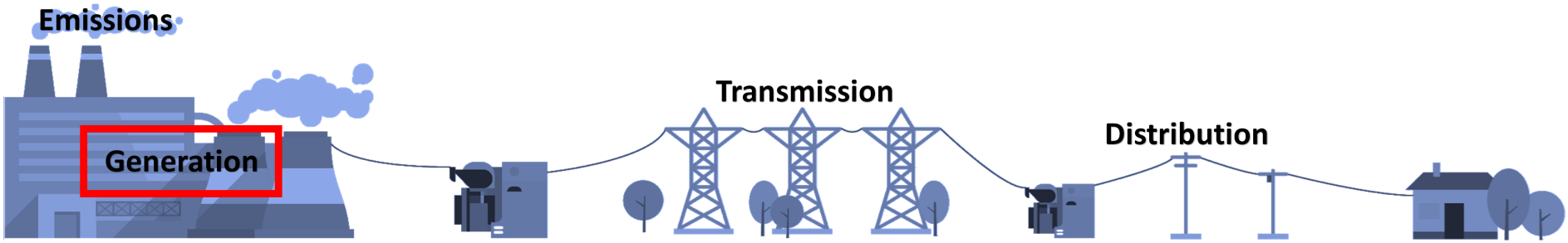


Table: Energy value of wind and solar generation (2014-2018 average).

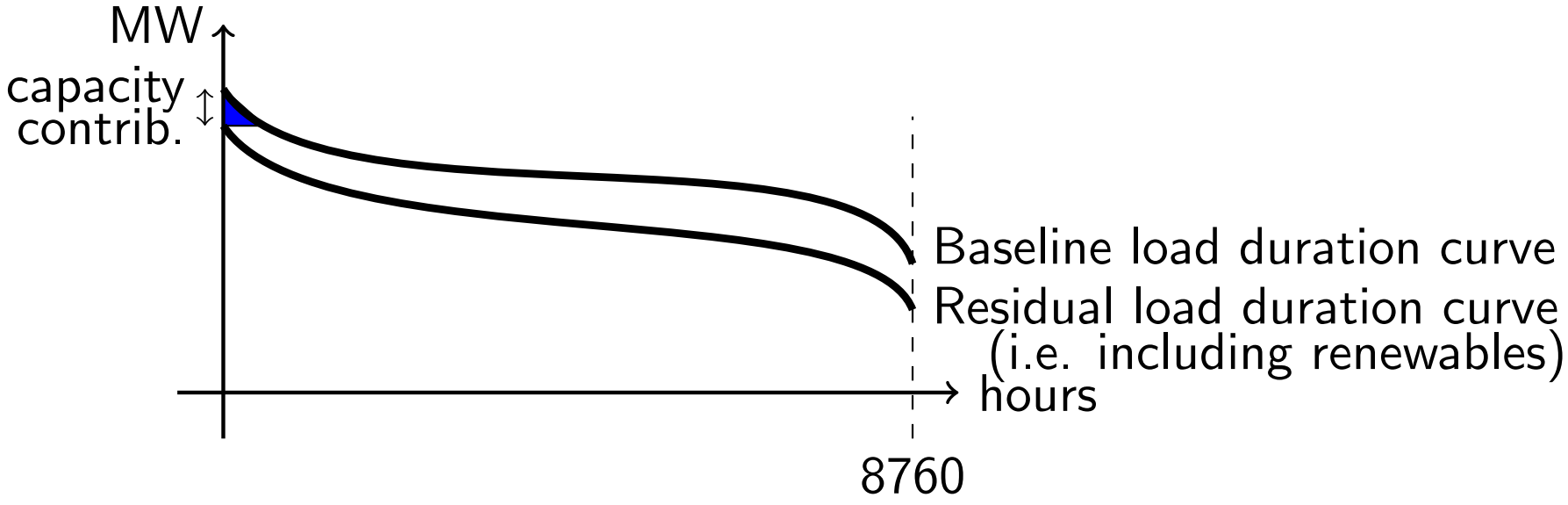
$/MWh	CAISO	ERCOT	ISONE	MISO	NYISO	PJM	SPP
Wind	**36.50**	25.67	**48.24**	29.39	45.72	**36.71**	23.48
Solar	34.15	**37.56**	41.14	/	/	35.05	**30.60**

Note: MISO and NYISO solar generation data are not available (Respectively 170-1,800 MW and 235-1,500 MW installed capacity in 2014-2018.).

(2) Capacity: Methodology



2. **Capacity**: calculate the contribution to the decrease of yearly peak load and valued at 60,000$/MW-year.



(2) Capacity: Results

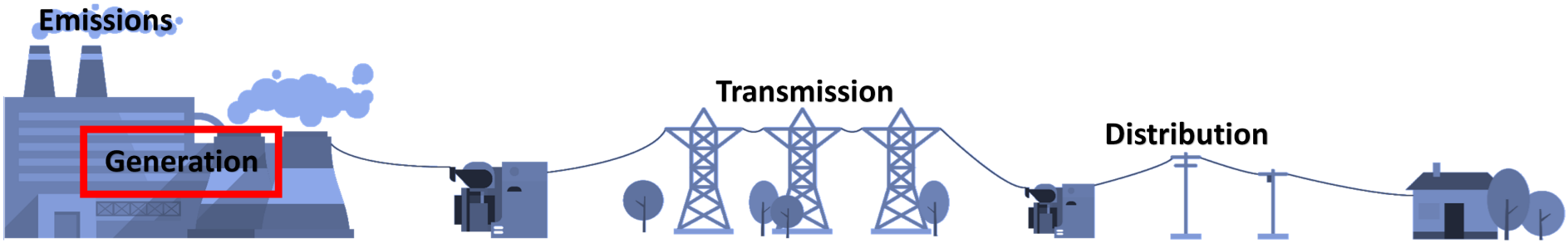
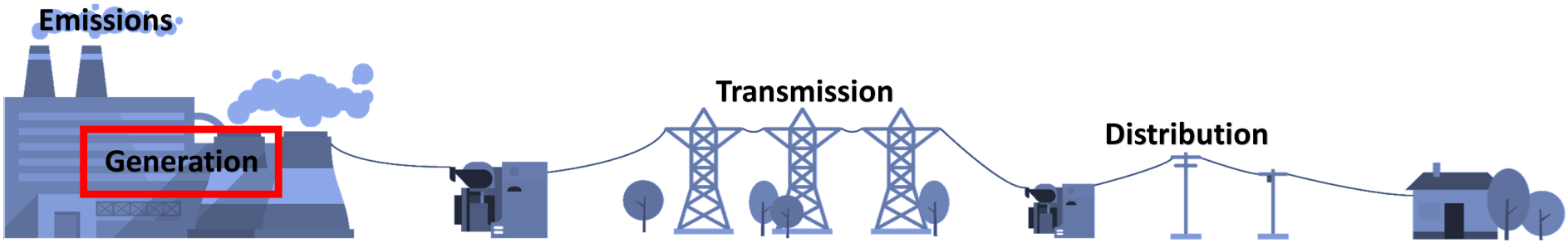


Table: Capacity value of wind and solar generation (2014-2018 average).

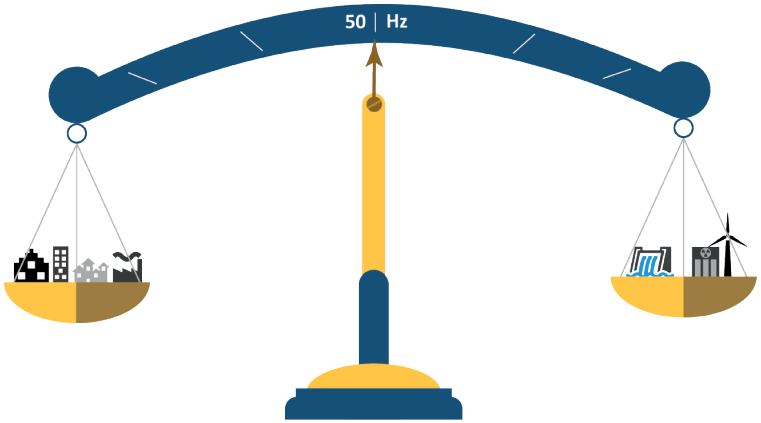
$/MWh	CAISO	ERCOT	ISONE	MISO	NYISO	PJM	SPP
Wind	**16.82**	1.40	2.42	1.48	2.49	1.49	1.79
Solar	5.60	**18.75**	**15.66**	/	/	**22.51**	**22.81**

Note: MISO and NYISO solar generation data are not available (Respectively 170-1,800 MW and 235-1,500 MW installed capacity in 2014-2018.).

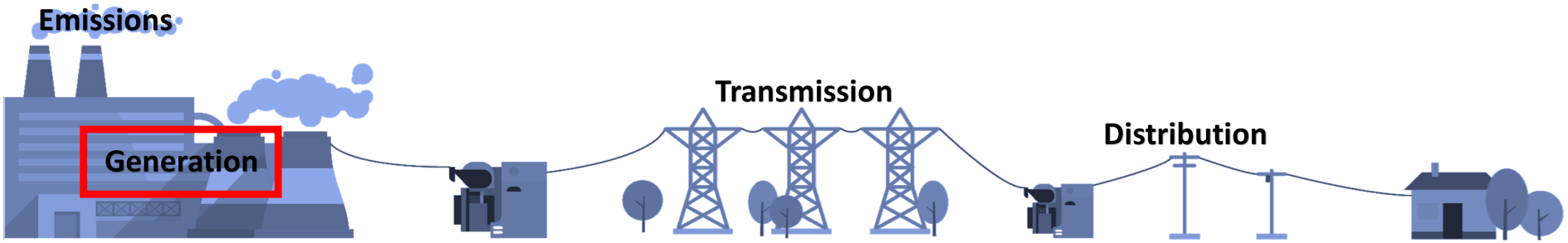
(3) Ancillary services = reserves and regulation



- Reserves = ensuring enough generation capacity to deal with real-time imbalances (forecast errors, outages, line failures, etc.)
- Regulation = balance supply and demand in real time



(3) Ancillary services: Methodology



3. **Ancillary services**: estimate how the cost of reserves and regulation change in response to renewable generation

$$cost_{ancillary,it} = \beta_{solar,i} q_{solar,it} + \beta_{wind,i} q_{wind,it} + \sum_{n=1}^{3} \beta_{load,i} load_{it}^{n} \quad (2)$$
$$+ p_{commodity,it} + \delta_{hmy,i} + \epsilon_{it}$$

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

(3) Ancillary services: Results

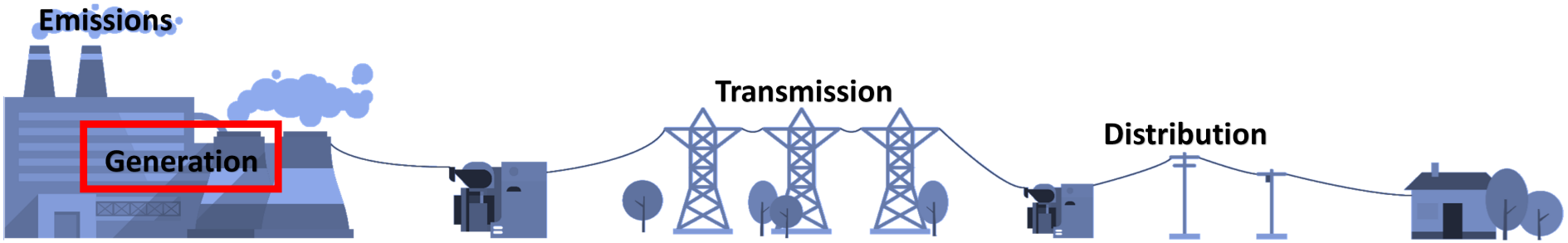


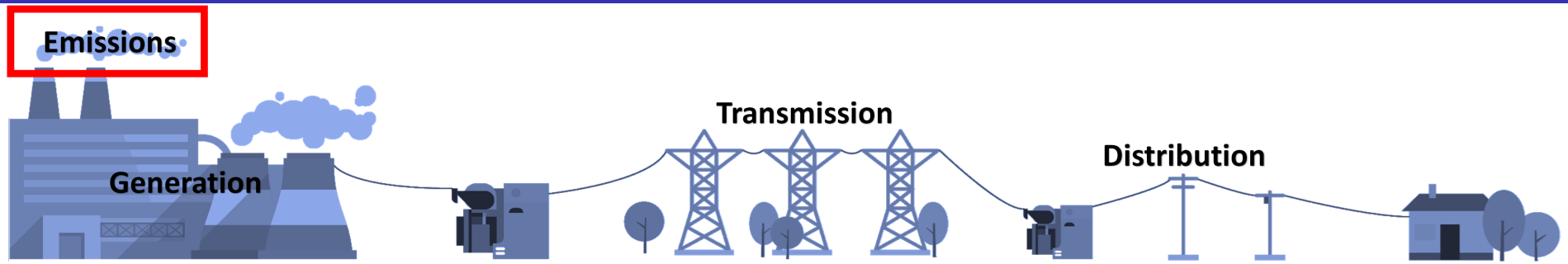
Table: Solar and wind generation generally **decrease** the total cost of reserves and regulation (2014-2018 average).

$/MWh	CAISO	ERCOT	ISONE	PJM
Solar	0.08	-7.78	-3.28***	-1.11
Wind	0.09	-0.87***	-3.46***	-0.70***
Total decrease of ancillary service costs		-14%	-0.7%	-6.6%

Note: p<0.05 (*), p<0.01 (**), p<0.001 (***)

Decrease is entirely because of effect on prices, not on quantity.

(4) Emissions: Methodology



1. **Emissions**: estimate the marginal changes of conventional generation in response to renewable generation (Cullen, 2013; Novan, 2015)

$$q_{conventional,it} = \beta_{solar,i} q_{solar,it} + \beta_{wind,i} q_{wind,it} + \sum_{n=1}^{3} \beta_{load,i} load_{it}^{n} \quad (3)$$
$$+ p_{commodity,it} + \delta_{hmy,i} + \epsilon_{it}$$

Technologies sum to one

2. Monetize the resulting emission changes using AP2 (Muller, 2014)

(4) Emissions: Results

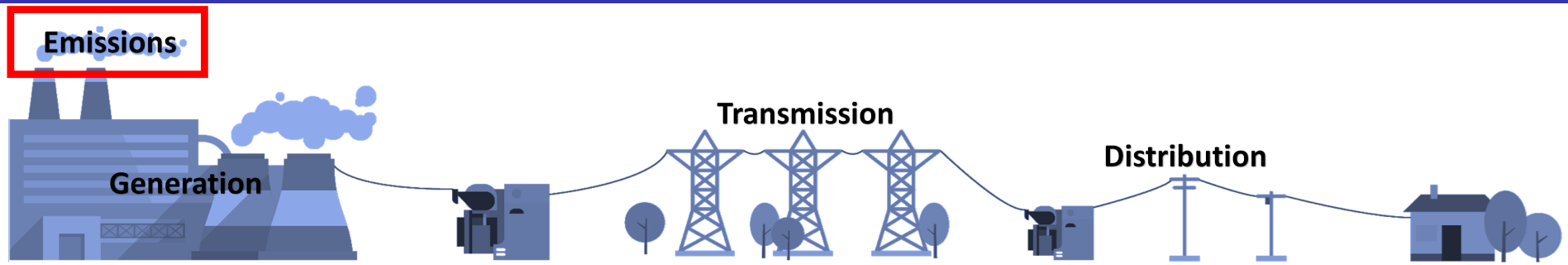
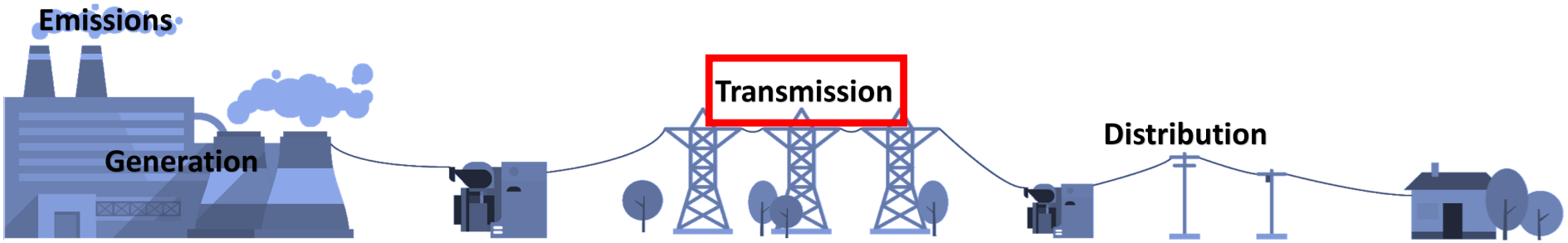


Table: Effect of 1 MW of wind and solar generation (2014-2018 average)

MW/MW	ERCOT		PJM	
	Wind	Solar	Wind	Solar
Coal	**-0.27**	**-0.34**	**-0.47**	0.06
Gas	**-0.71**	**-0.61**	**-0.39**	**-0.96**
Hydro	0	-0.01	0	-0.12
Nuclear	0	**-0.10**	-0.04	**-0.08**
Other	0	0	-0.12	0.08
TOTAL	-0.99	-1.06	-1.02	-1.02
VALUE [$/MWh]	27.1	26.7	34.8	20.3

All results

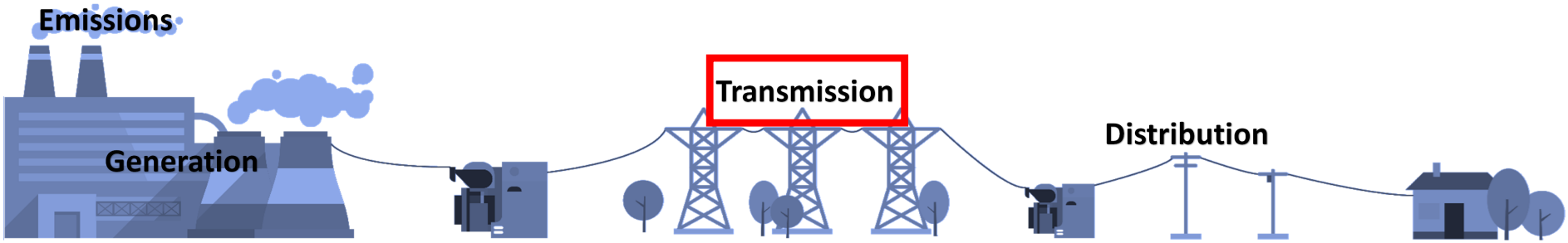
(5)(6) Transmission congestion and losses: Methodology



- **Congestion and losses**: estimate how much their costs change in response to renewable generation

$$cost_{losses/congestion,it} = \beta_{solar,i} q_{solar,it} + \beta_{wind,i} q_{wind,it} + \sum_{n=1}^{3} \beta_{load,i} load_{it}^{n} + p_{commodity,it} + \delta_{hmy,i} + \epsilon_{it} \quad (4)$$

(5)(6) Transmission congestion and losses: Results

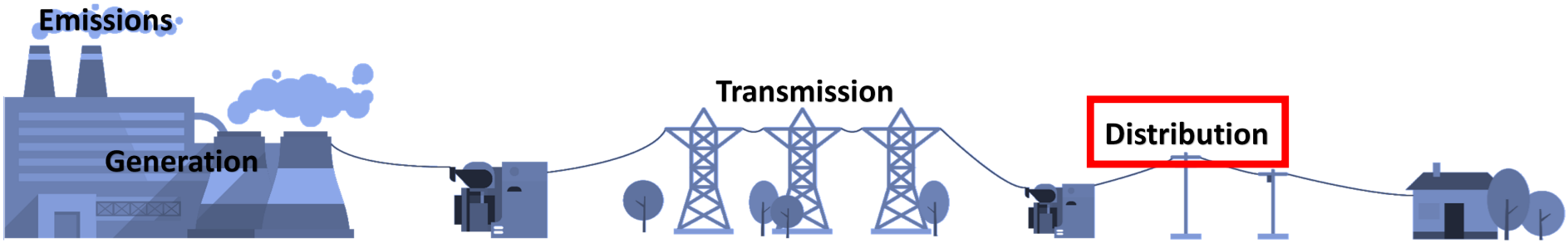


Effect is highly significant, positive or negative, but very small: [-0.0063,0.0078]. Varies substantially depending on where the renewables are located.

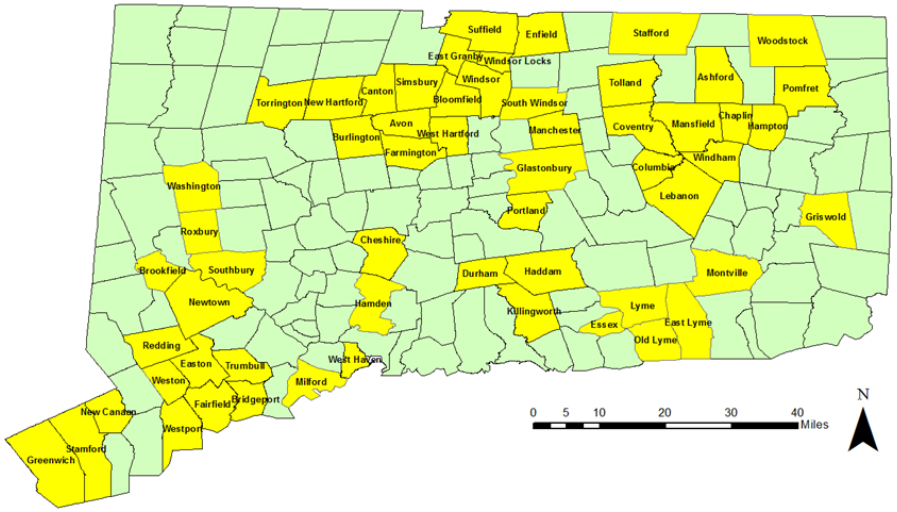
Table: Average congestion and losses (2014-2018 average, day-ahead)

$/MWh	CAISO	ERCOT	ISONE	MISO	NYISO	PJM	SPP
Congestion	0.73	1.36	0.03	0.66	1.14	5.54	0.27
Losses	1.27	/	0.07	0.18	1.19	0.10	0.19

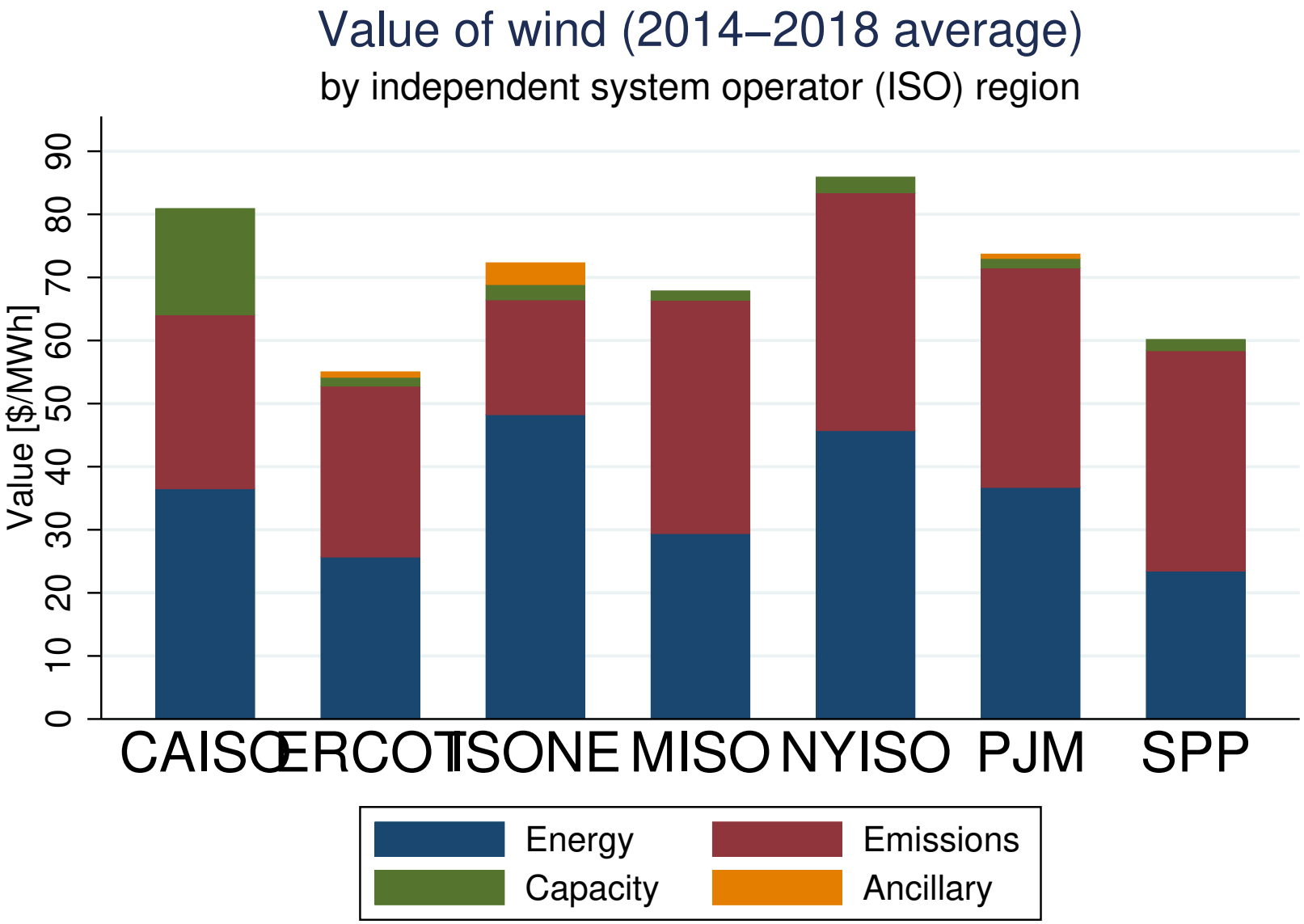
(7) Distribution: Methodology



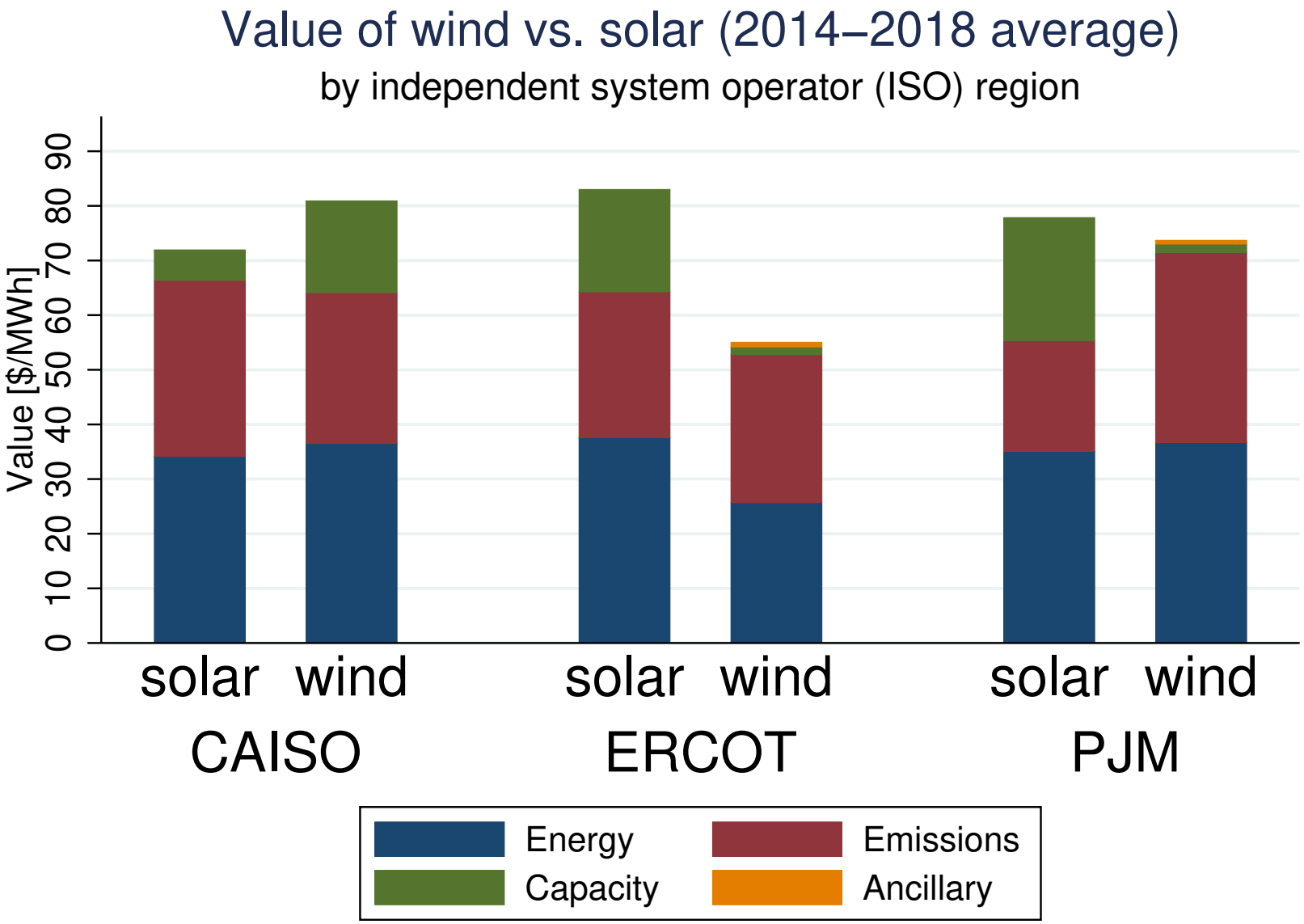
- Randomized controlled trials of the Solarize campaigns in Connecticut. Compare changes in (peak) line loading, voltage and interruptions between treated and control towns, using subcircuit-level data from a local utility.



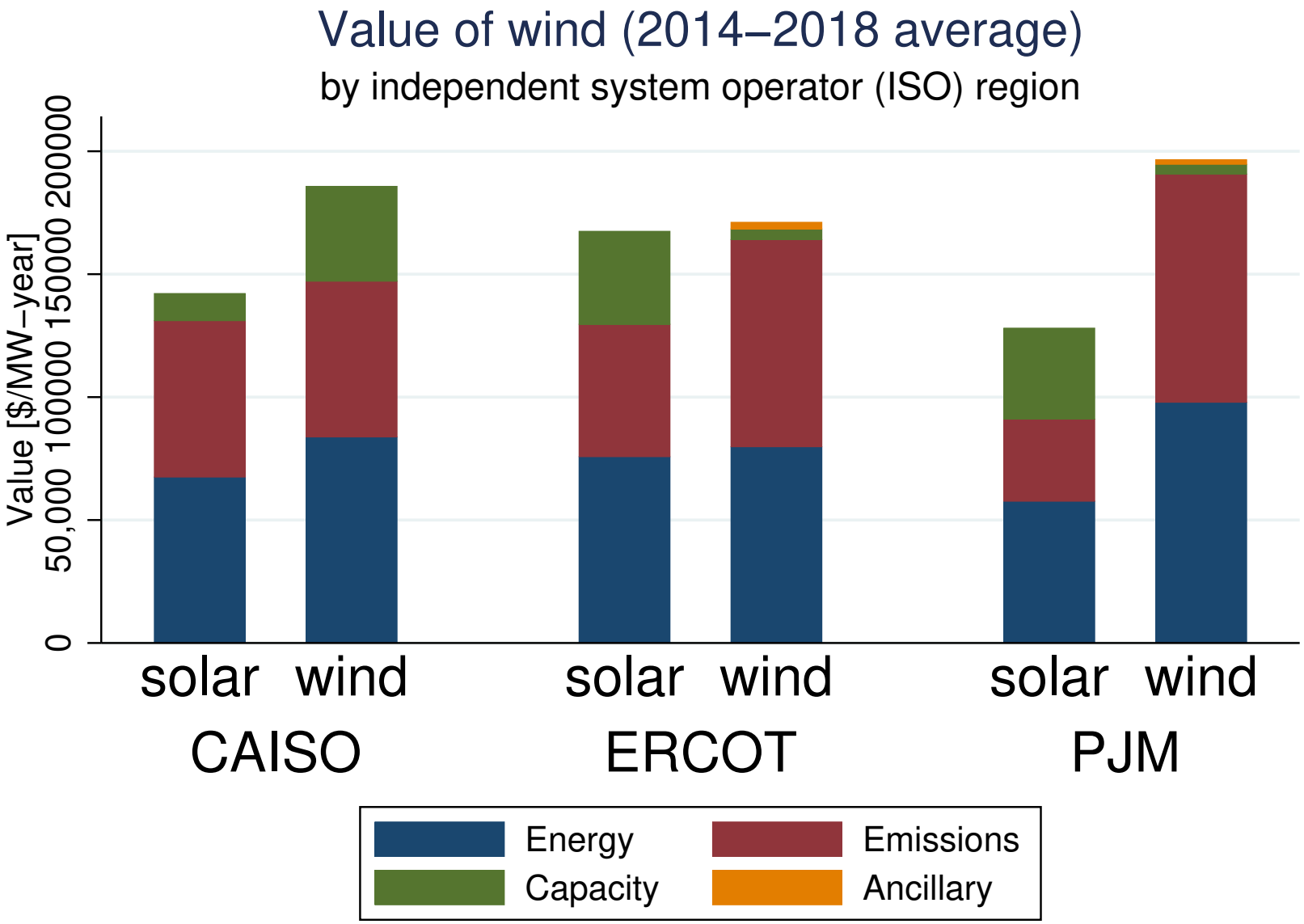
Results: Wind [$/MWh]



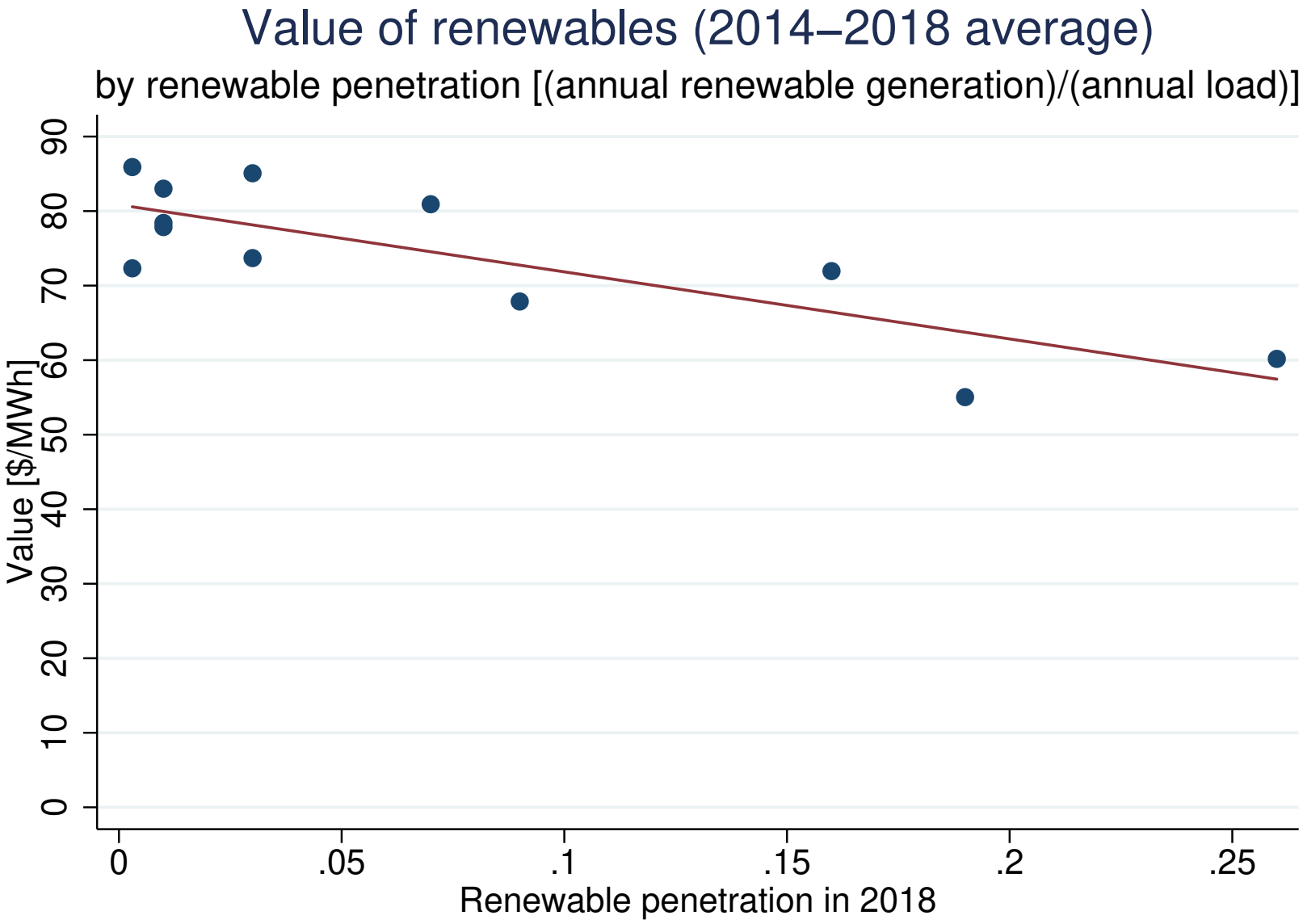
Results: Solar vs. wind [$/MWh]



Results: Solar vs wind [$/MW-year]



Results: value of renewables by renewable penetration



Summary of findings

1. Importance of value categories: Energy $>$ Emissions $\geq$ Capacity $>$ ancillary services $>$ transmission ≈ 0
2. Expressed per MWh generated: solar $\gtrapprox$ wind
   - $[70 - 85]$ \$/MWh for solar vs [55-85] \$/MWh for wind
3. Expressed per capacity installed: wind $\gtrapprox$ solar
   - $[130,000 - 160,000]$ \$/MW-year for solar vs [160,000-200,000] \$/MWh for wind \$/MW-year
4. Solar and wind have significant but very small effect on transmission network
5. Some evidence that value decreases when the penetration level increases

(4) Emissions: Results wind sum to one

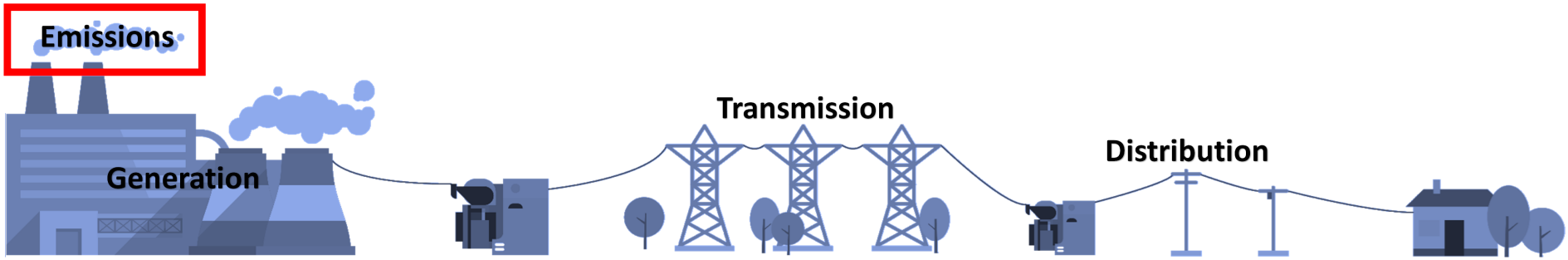


Table: Effect of 1 MW of wind generation on different generation technologies + exchange (2014-2018 average).

MW/MW	CAISO	ERCOT	ISONE	MISO	NYISO	PJM	SPP
Coal	-0.70	-0.27	0.02	-0.53	-0.01	-0.47	-0.53
Gas		-0.71	-1.00	-0.36	-0.23	-0.39	-0.38
Exchange	-0.26	/	0.03	-0.07	-0.40	-0.04	-0.09
Other	-0.04	0	-0.07	-0.03	-0.25	-0.12	-0.01
TOTAL	-1.00	-0.99	-1.02	-0.98	-0.89	-1.02	-1.00

Back

(4) Emissions: Monetized results wind

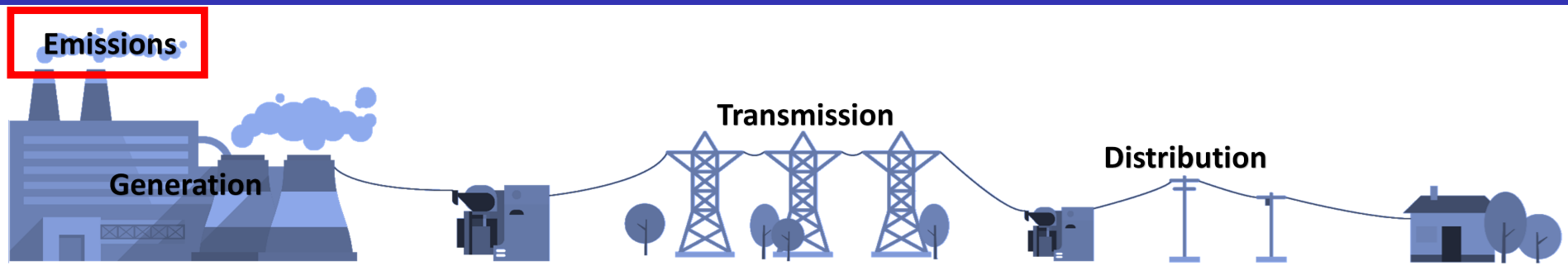


Table: Avoided emissions monetized using AP2 annual estimates, assuming 2018 ISO-average CEMS generation technology emissions (2014-2018 average).

$/MWh	CAISO	ERCOT	ISONE	MISO	NYISO	PJM	SPP
PM2.5	9.0	2.5	4.0	2.8	15.2	4.5	1.4
SO_2	1.7	0.8	0	2.9	2.1	3.7	1.3
NO_X	0.2	1.3	0	2.0	0.1	1.0	2.7
CO_2	16.7	22.5	14.2	29.3	20.2	25.2	29.6
TOTAL	**27.6**	**27.1**	**18.2**	**37**	**37.7**	**34.8**	**34.9**

Back