# Causal effects of **R**enewable **P**ortfolio **S**tandards on renewable investments and generation

## The role of heterogeneity and dynamics

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# Background

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## Renewable Portfolio Standards (RPS)

- **state-level** policy from 1991 (Iowa) Fig1 Map
- 30 states and Washington D.C (most 2000-2009)
- 70% of the US population & 64% of total generation capacity (2019)
- apply to 58% of total retail electricity sales
- more than 70 proposals for a national portfolio standard (2020)

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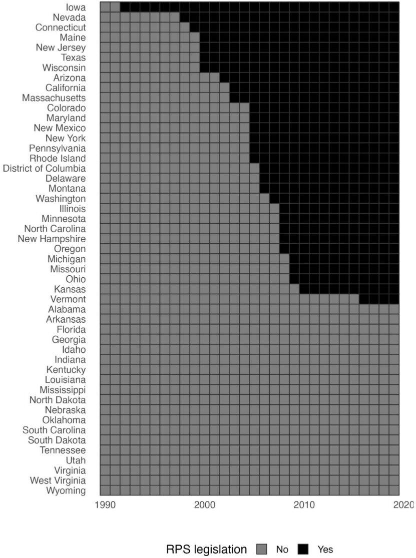
## Renewable Energy Credit (REC)

- 1 MWh of electricity generates from renewable source = 1 REC
- **Interstate Sales**: purchase electricity or **"unbundled"** RECs
- **Spillover**: incentive investments in renewables outside of the regulated state An Example

# RPS Status by State

Background Data



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    - dynamics: annual percentage requirement increases gradually (until reaches mandated goal)
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- **Effective Standard**: much lower (allow existing renewable generation to qualify for compliance)
- **Sources**: wind and solar ✔, hydroelectric and nuclear ✔ ✗
- **Encourage Strategy**: charges and financial penalties
- **Monitor by RECs**: issued by regional authorities that encompass multiple states (trade mostly within a region)

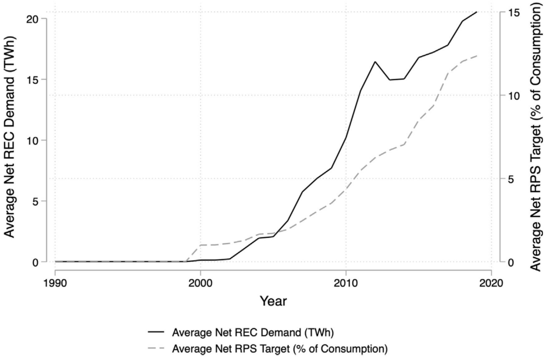
# More Details about RPS

## Examples

- California's RPS mandates that 60% of retail electricity sales come from renewable generation sources by 2030 and has interim targets of 44% by 2024 and 52% by 2027.
- Although California's standard was 20% of total retail electricity sales in 2010, its effective standard was approximately 17% of sales after accounting for eligible existing generation.
- some states such as California exempt publicly owned utilities from the RPS standard, while others such as Colorado set separate, lower standards for publicly owned utilities.
- Delaware enforce RPS policies by charging a fee ("Alternative Compliance Payment") for each unit of renewable generation, while other states such as California allow regulators to levy financial penalties on non-compliant utilities.

# Stringency of RPS over time

details




- **Net RPS Target**: measure the percent of applicable retail electricity sales required to be generated by renewable sources
- **Net REC Demand** (= total renewable capacity mandated - existing supply of RECs): measure regulatory stringency

# Literature Review

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- **Other Reduced-Form**
  - **IV** (Interstate sales of wholesale electricity markets): RPSs induce out-of-state emissions reductions through RECs (Feldman and Levinson, 2023), (Hollingsworth and Rudik, 2019)
  - **Synthetic Control Method**: ambiguous impact on renewables investments (Upton Jr and Snyder, 2017)

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  - **Synthetic Control Method**: ambiguous impact on renewables investments (Upton Jr and Snyder, 2017)
- **General Equilibrium Model**
  - deliver large resource booms or large emissions savings but not both (Bento et al., 2018)
  - effect on renewable capacity investments depends on transmission costs and natural endowments (Fullerton and Ta, 2022)

# Research Question

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  - RPS policies are **not randomly** assigned across states (Lyon, 2016)
  - **Dynamic** and **Heterogeneous** effects across states (policy design & renewable resource endowments)
- **Contribution**
  - recent data up to 2019 (latter 2010s period is critical)
  - seperate wind and solar: differences in declining cost trends and innovation (Wiser et al., 2023)
  - dynamic impacts in longer-term (11 year)
  - **leverages robust estimator** **(Callaway and Sant'Anna, 2021)**

# Data Source

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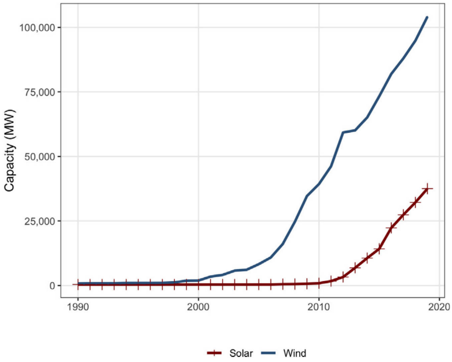
  - total cumulative installed capacity over time by source (wind, solar, coal and gas)
- Actual Generation of Electricity by Source
  - EIA Form 906
  - annual data on generation at the power plant level

# Trends in renewable electricity generation capacity (MW)

solar ATT




- similar pattern, roughly linear (wind: early 2000s, solar: 2010)
- **localized** incentives for diffusion
  - reduction in levelized costs of operation
  - federal and state-level production tax credits

# Data Source & Main Variables

| Variable | Units | Source |
|---|---|---|
| Transmission lines | km per km^2 | Homeland Infrastructure Foundation-Level Data (HIFLD) |
| Wind speed | meters per second | NREL Wind Integration National Dataset (WIND) |
| Solar irradiance | kWh / m^2 /year | NREL Physical Solar Model version 3 Global Horizontal Irradiance Multi-year Annual Average |
| Installed capacity | MW | EIA Form EIA-860 |
| Generation | GWh | EIA Form EIA-906 |
| GDP per capita | $ per person | Bureau of Economic Analysis (BEA) dataset SAGDP2N |
| Electricity price | all end-use, $ / kWh | EIA State Energy Data System (SEDS) |
| Electricity consumption | Bil. kWh | EIA State Energy Data System (SEDS) |
| House LCV score | Scale $[0, 100]$ | League of Conservation Voters (LCV) Scorecard |
| Senate LCV score | Scale $[0, 100]$ | League of Conservation Voters (LCV) Scorecard |
| Fraction counties non-attainment | Share $[0, 1]$ | Environmental Protection Agency (EPA) Greenbook |

- RPSs are more likely to be adopted in states that scored higher in the League of Conservation Voters (LCV) score index.

# Summary Statistics (1990)

| | RPS states | Non RPS states | Difference |
|---|---|---|---|
| **A. Infrastructure & Endowments** | | | |
| Transmission lines (km per km^2) | 0.16 | 0.14 | 0.02 |
| Wind speed (meter per second) | 6.3 | 6.1 | 0.2 |
| Solar irradiance (kWh / m^2 /year) | 4.3 | 4.6 | -0.2 |
| **B. Installed Capacity (MW)** | | | |
| Wind | 26.0 | 0.0 | 26.0 |
| Solar | 13.4 | 0.0 | 13.4 |
| Coal | 5,500.6 | 7,164.8 | -1,664.2 |
| Gas | 4,182.7 | 2,873.30 | 1,309.4 |
| Total | 15,694.1 | 14,394.0 | 1,300.10 |
| **C. Generation (GWh)** | | | |
| Wind | 183 | 0 | 183 |
| Solar | 24 | 0 | 24 |
| Coal | 58,930 | 74,690 | -15,761 |
| Gas | 18,468 | 9,714 | 8,754 |
| Total | 64,289 | 57,571 | 6,718 |
| **D. Other Predictors** | | | |
| GDP per capita | 42,278 | 34,145 | 8,132*** |
| Electricity price (all end-use, $ / kWh) | 0.12 | 0.10 | 0.02*** |
| Electricity consumption (Bil. kWh) | 59.6 | 46.3 | 13.4 |
| House LCV score | 62.1 | 41.7 | 20.4*** |
| Senate LCV score | 62.3 | 34.4 | 27.9*** |
| **Observations** | 30 | 19 | |

- marked differences between states adopting RPSs and states never adopting them

# causal effect on Deployment and Generation

## Canonical Equation

Difference-in-differences design with a TWFE estimator Dynamic TWFE

$$y_{it} = \beta RPS_{it} + X'_{it}\theta + \gamma_i + \delta_t + \varepsilon_{it}$$

- $y_{it}$ denotes utility-scale wind or solar electric capacity installed (or generation)
- $X_{it}$ is a vector of state-specific time varying control variables
- $\gamma_i$: state fixed effects
- $\delta_t$: the year fixed effects
- $\beta$: the **average treatment effect on the treated (ATT)** of an RPS policy on the outcomes (utility-scale wind and solar capacity and generation)
- $\beta$ not guaranteed to recover an interpretable causal parameter

(Rios-Avila et al., 2022)

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$$ATT_{g,t} = \mathbb{E}\left[\frac{G_g}{\mathbb{E}[G_g]}(Y_t - Y_{g-1} - \mathbb{E}[Y_t - Y_{g-1}|X, G_g = 0])\right]$$

- $G_g$: equal to one if a state first implemented an RPS at period $g$
- $Y_t$: potential outcome at event-time period $t$
- $Y_{g-1}$: the potential outcome in period $g-1$
- $ATT_{g,t}$: **compare** the differential outcomes of states in adoption cohort $g$ between $t$ and the period prior to RPS **to** the same differential in states which are not yet treated by $g$

# impacts of RPS intensity

**Binary Indicator ⇒ continuous measure of treatment**

Measure RPS intensity by calculating the total demand for RECs in each state (Feldman and Levinson, 2023) Schematic

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$$Net - RPS_{it} = \max\left(0, RPS_{it} - EligibleRenewables_{i,\tau i-1}\right)$$

$$Net - Out - of - State - REC - Demand_{it} = \sum_{j \in TP_i} \max\left(0, RPS_{jt} - Renewables_{jt}\right)$$

- Net in-state demand = gross statutory RPS requirement less eligible renewable generation produced in the year before RPS
- Net out-of-state demand for RECs = the sum of the RPS goal where state $i$ can sell RECs to, less those states' contemporaneous renewables generation (Hollingsworth and Rudik, 2019)
- total demand for RECs = in-state + out-of-state demand (binarize to 1 when exceeds sample average level)

# Estimated ATT (wind)

| | (1) | (2) | (3) |
|---|---|---|---|
| **Panel A: Capacity (MW)** | | | |
| Overall ATT (cohort) | 652 | 475 | 1220** |
| | (405) | (389) | (410) |
| Overall ATT (year) | 394 | 306 | 713* |
| | (219) | (222) | (278) |
| 1-5 years post | 241* | 158 | 241 |
| | (113) | (119) | (149) |
| 6-11 years post | 575 | 469 | 1210** |
| | (353) | (352) | (452) |
| **Panel B: Generation (GWh)** | | | |
| Overall ATT (cohort) | 3260 | 2250 | 6950** |
| | (2240) | (2110) | (2270) |
| Overall ATT (year) | 1740 | 1330 | 3720* |
| | (1140) | (1070) | (1500) |
| 1-5 years post | 1090* | 680 | 1110 |
| | (534) | (569) | (695) |
| 6-11 years post | 2550 | 2070 | 6490* |
| | (1850) | (1720) | (2580) |
| **Controls** | | | |
| Endowments | | Yes | Yes |
| Sociopolitical | | | Yes |
| Observations | 1380 | 1380 | 1380 |

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- RPS policy increases installed wind capacity by 1220 MW on average
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- larger impact for 6–11 years after RPS (than 1-5)
- 1% increase in the RPS target implies the share of capacity increases by 0.41%
- e.g. 6490 GWh
  - 176% of mean wind generation
  - 20% of mean coal generation (among RPS states, 2019)

- $***p < 0.001$, $**p < 0.01$, $*p < 0.05$.
- Standard errors are computed using a multiplier bootstrap method, clustering at the state level.

# Dynamic Effects (wind)

- subset for which have 11 years of (pre-) & (post-) RPS
  - point $\Rightarrow$ event time-specific treatment effect
  - length of tickers $\Rightarrow$ 95% CI

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- subset for which have 11 years of (pre-) & (post-) RPS
  - point ⇒ event time-specific treatment effect
  - length of tickers ⇒ 95% CI
- long-lasting change (to the electricity sector)
  - **pre**: parallel trends (credible ATT)
  - **post**: significant only 5–7 years, roughly linear treatment effects, no sign of reverting back

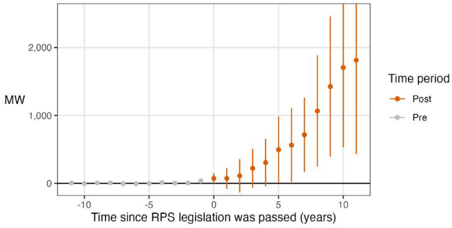


Figure: installed wind capacity

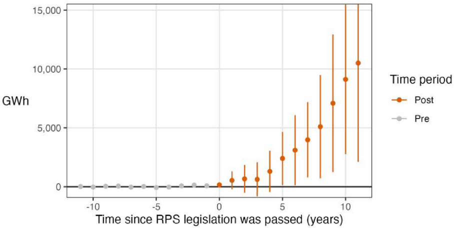


Figure: wind electricity generation

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| Overall ATT (cohort) | 201* | 235** | 155 |
| | (92.8) | (85.9) | (106) |
| Overall ATT (year) | 50.1 | 71.1 | 43.0 |
| | (53.7) | (51.4) | (51.3) |
| 1-5 years post | 2.14 | 3.65* | 1.51 |
| | (1.92) | (1.68) | (1.93) |
| 6-11 years post | 98.3 | 139 | 84.7 |
| | (101) | (100) | (99.2) |
| **Panel B: Generation (GWh)** | | | |
| Overall ATT (cohort) | 762* | 902* | 676 |
| | (375) | (354) | (409) |
| Overall ATT (year) | 119 | 195 | 114 |
| | (145) | (139) | (139) |
| 1-5 years post | 2.38 | 8.61* | 1.78 |
| | (5.40) | (4.13) | (5.57) |
| 6-11 years post | 236 | 382 | 227 |
| | (275) | (273) | (273) |
| **Controls** | | | |
| Endowments | | Yes | Yes |
| Sociopolitical | | | Yes |
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  - smaller estimates than their wind counterparts
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  - vary in statistical precision across specifications
  - much occur between 6-11 years
- 1% increase in the RPS target implies the share of capacity increases by 0.02%
- Lagged Investment Trends
  - **wind**: occurred since 2000 (economically attractive and lower risk than solar) (Wiser et al., 2011)
  - **solar**: similar accumulation since 2010

# Estimated ATT (solar)

| | (1) | (2) | (3) |
|---|---|---|---|
| **Panel A: Capacity (MW)** | | | |
| Overall ATT (cohort) | 201* | 235** | 155 |
| | (92.8) | (85.9) | (106) |
| Overall ATT (year) | 50.1 | 71.1 | 43.0 |
| | (53.7) | (51.4) | (51.3) |
| 1-5 years post | 2.14 | 3.65* | 1.51 |
| | (1.92) | (1.68) | (1.93) |
| 6-11 years post | 98.3 | 139 | 84.7 |
| | (101) | (100) | (99.2) |
| **Panel B: Generation (GWh)** | | | |
| Overall ATT (cohort) | 762* | 902* | 676 |
| | (375) | (354) | (409) |
| Overall ATT (year) | 119 | 195 | 114 |
| | (145) | (139) | (139) |
| 1-5 years post | 2.38 | 8.61* | 1.78 |
| | (5.40) | (4.13) | (5.57) |
| 6-11 years post | 236 | 382 | 227 |
| | (275) | (273) | (273) |
| **Controls** | | | |
| Endowments | | Yes | Yes |
| Sociopolitical | | | Yes |
| Observations | 1380 | 1380 | 1380 |

- **positive but insignificant**
  - smaller estimates than their wind counterparts
  - vary in statistical precision across specifications
  - much occur between 6-11 years
- 1% increase in the RPS target implies the share of capacity increases by 0.02%
- Lagged Investment Trends
  - **wind**: occurred since 2000 (economically attractive and lower risk than solar) (Wiser et al., 2011)
  - **solar**: similar accumulation since 2010

- $***p < 0.001$, $**p < 0.01$, $*p < 0.05$.
- Standard errors are computed using a multiplier bootstrap method, clustering at the state level.

# Dynamic Effects (solar)

- subset for which have 11 years of (pre-) & (post-) RPS
    - point ⇒ event time-specific treatment effect
    - length of tickers ⇒ 95% CI

# Dynamic Effects (solar)

- subset for which have 11 years of (pre-) & (post-) RPS
  - point ⇒ event time-specific treatment effect
  - length of tickers ⇒ 95% CI
- **Very small** change (to the electricity sector)
  - **pre**: parallel trends (credible ATT)
  - **post**: small and indistinguishable from zero

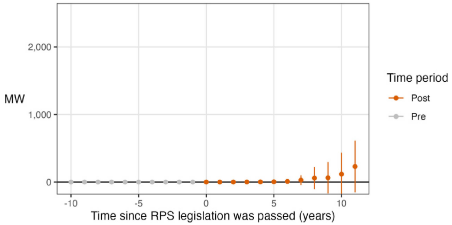


Figure: installed solar capacity

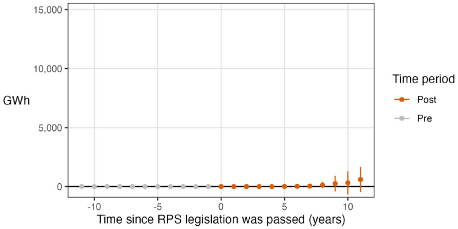


Figure: solar electricity generation

# Robustness Check

- **Alternative Control Groups**
  - never treated states vs. never and not yet treated

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  - (net REC demand) above the sample average vs. being positive

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- **Treatment Definitions**
  - (net REC demand) above the sample average vs. being positive

| Dependent variable | Balanced | Control | Independent variable | Solar | Wind |
|---|---|---|---|---|---|
| **Capacity (MW)** | **Yes** | **NYT** | **RPS Legislation** | **43<br>(51.3)** | **713*<br>(278)** |
| **Generation (GWh)** | **Yes** | **NYT** | **RPS Legislation** | **114<br>(139)** | **3720*<br>(1500)** |
| Capacity (MW) | Yes | NT | RPS Legislation | 43<br>(51.3) | 739**<br>(278) |
| Capacity (MW) | No | NYT | RPS Legislation | 284<br>(243) | 1980*<br>(869) |
| Capacity (MW) | Yes | NYT | Net REC demand (average) | 353<br>(454) | 1120*<br>(543) |
| Capacity (MW) | Yes | NYT | Net REC demand (positive) | 114<br>(97.8) | 671*<br>(323) |
| Generation (GWh) | Yes | NT | RPS Legislation | 114<br>(139) | 3830*<br>(1510) |
| Generation (GWh) | No | NYT | RPS Legislation | 1400<br>(1090) | 11700*<br>(5060) |
| Generation (GWh) | Yes | NYT | Net REC demand (average) | 1410<br>(1800) | 5620*<br>(2830) |
| Generation (GWh) | Yes | NYT | Net REC demand (positive) | 369<br>(351) | 3480<br>(1800) |

# Robustness Check (Cont'd)

- 2 years of **Anticipation Effects** details

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  - TWFE regression using OLS (net REC demand & binary RPS)

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- **Estimator**
  - TWFE regression using OLS (net REC demand & binary RPS)

| Dependent variable | Anticipation | Drop states | Cohort Group | Method | Independent Variable | Solar | Wind |
|---|---|---|---|---|---|---|---|
| **Capacity (MW)** | **No** | **No** | **1-Year** | **C+S** | **RPS Legislation** | **43 (51.3)** | **713* (278)** |
| **Generation (GWh)** | **No** | **No** | **1-Year** | **C+S** | **RPS Legislation** | **114 (139)** | **3720* (1500)** |
| Capacity (MW) | Yes | No | 1-Year | C+S | RPS Legislation | 43 (51.3) | 809** (301) |
| Capacity (MW) | No | Yes | 1-Year | C+S | RPS Legislation | 43 (94.2) | 681 (479) |
| Capacity (MW) | No | No | 3-Year | C+S | RPS Legislation | 145 (122) | 1220** (467) |
| Capacity (MW) | No | No | - | TWFE | Net REC demand (TWh) | 2.4 (1.67) | 14.1 (18.3) |
| Capacity (MW) | No | No | - | TWFE | RPS Legislation | -5.85 (3.31) | 90.9* (39.1) |
| Generation (GWh) | Yes | No | 1-Year | C+S | RPS Legislation | 118 (137) | 4190* (1660) |
| Generation (GWh) | No | Yes | 1-Year | C+S | RPS Legislation | 106 (247) | 4860 (2910) |
| Generation (GWh) | No | No | 3-Year | C+S | RPS Legislation | 633 (500) | 6900* (2690) |
| Generation (GWh) | No | No | - | TWFE | Net REC demand (TWh) | 5.74 (3.37) | 59.5 (99.5) |
| Generation (GWh) | No | No | - | TWFE | RPS Legislation | -14.4 (7.73) | 536* (211) |

# Discussion

**Estimation of the contribution of RPS**

- ATT on wind capacity approximately $\approx$ 1000 MW (11 years post RPS)
- $29 \times 1000$MW $\approx$ 29GW, almost 30% of current aggregate wind capacity

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## Policy Implications

- Clean Energy Standard proposed by Biden (2021) shares many features with RPSs
  - may promote investments in wind & solar production capacity and generation
- whether investments sufficient?
  - for energy sector to reach zero emissions by 2035

*CES: a technology-neutral portfolio standard that requires that a certain percentage of utility sales be met through "clean" zero- or low-carbon resources, such as renewables, nuclear energy, coal or natural gas fitted with carbon capture, and other technologies.*
*As with an RPS, eligible technologies are awarded credits per MWh of generation that can be traded, which provides an efficient, market-based solution to meet a standard. (Source: RFF)*

# Potential Caveats

**Main Results**

- RPS dramatically increased wind capacity investments and generation
  - this increase persists up to 11 years
- RPS takes time to affect renewable capacity installations and generation (6–11 years)
- no evidence on solar capacity

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- RPS dramatically increased wind capacity investments and generation
  - this increase persists up to 11 years
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- no evidence on solar capacity

**Potential Caveats?**

- More heterogeneity in policy design Map
- data can't be well-suited for solar investments (timing) Trend
- Be careful of interpretation of different DiD estimators Misinterpretation

# Takeaways

**For Research**

- Heterogeneity and Dynamic Effects are really important!
- In China: revisit some "Pilot" Policies
    - ETS? Water Right Trading? Low-Carbon City?
    - "Green" Credits (REC) in China

# Takeaways

## For Research

- Heterogeneity and Dynamic Effects are really important!
- In China: revisit some "Pilot" Policies
  - ETS? Water Right Trading? Low-Carbon City?
  - "Green" Credits (REC) in China

## For Researchers

- Possible to make correct identification using limited, coarse observations (1380 here)
- Refer to "cutting-edge" econometrics strategies!
  - Causal Inference framework matters
- Re-evaluate some Policies in China.
  - `R` package for `did` estimation: click here!

# Appendix: the Distribution of RPS

Background

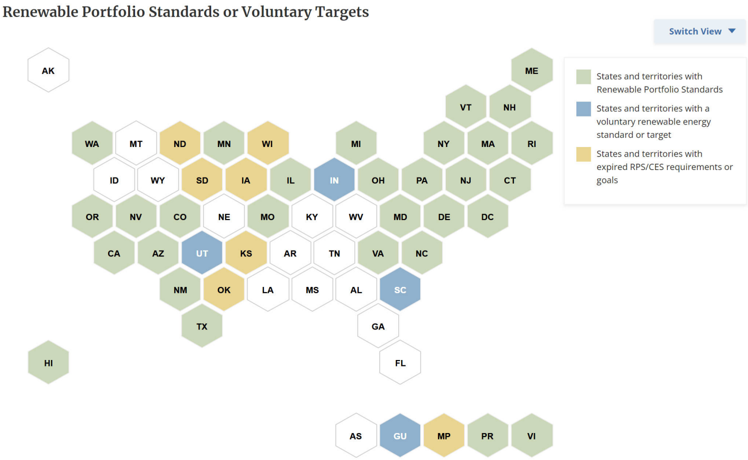



Figure: Renewable Portfolio Standards or Voluntary Targets

Source: National Conference of State Legislatures

# Appendix: Emissions savings versus resource booms

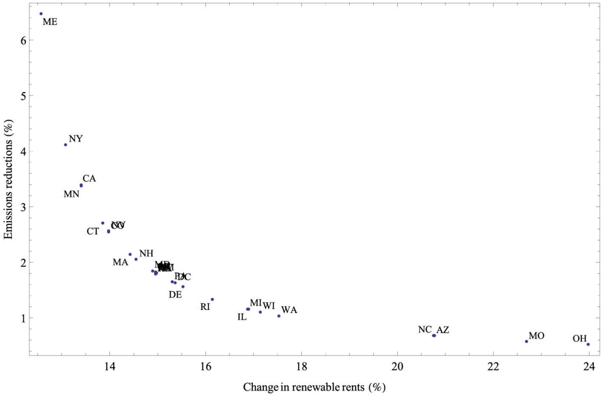
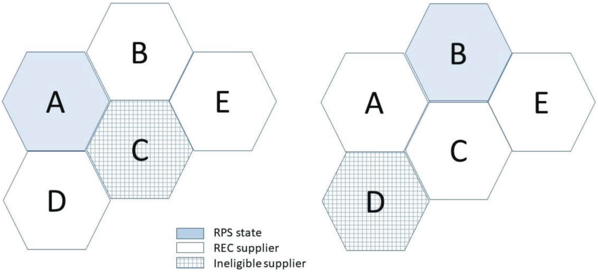



Figure: Change in emission savings and renewable rents by state due to 10% increase in RPS

Source: (Bento et al., 2018)

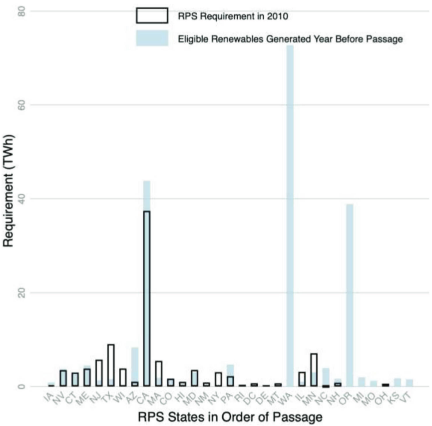
# Appendix: A Schematic of REC Market (Feldman and Levinson, 2023)

RPS intensity



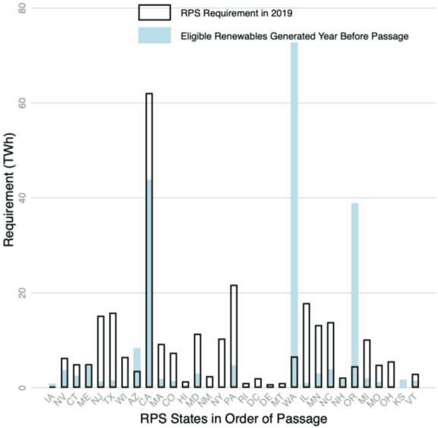

- **Left**: A purchase RECs from B, D, and E
- **Right**: B purchase RECs from A, C, and E
- eg: when calculating D's net out-of-state REC demand, we include A's requirement but not B's.

# Appendix: Net in-state demand (2010) (Feldman and Levinson, 2023)




- most states' RPS goals were already being met by the renewables they were generating before enactment

# Appendix: Net in-state demand (2019) (Feldman and Levinson, 2023)




- most states' RPSs required some new renewables, at least relative to their original levels.

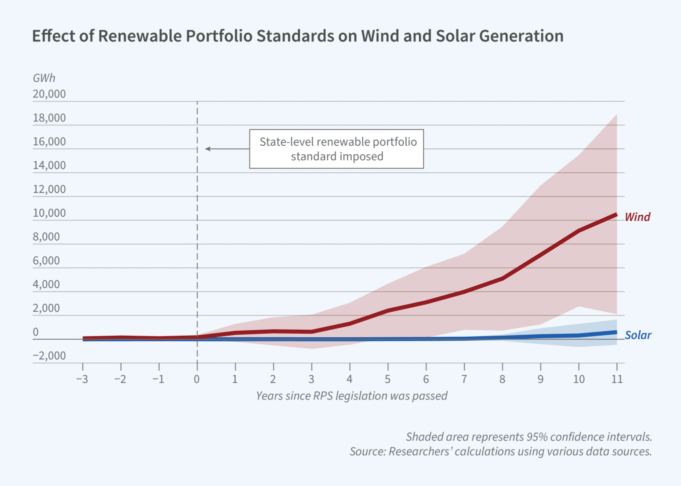
# Appendix: Endogenous Nonadditionality (Feldman and Levinson, 2023)

## Example

Background

- In 2010 Nevada was requiring that 3.5 TWh of electricity sales come from renewable sources.
- But Nevada's RPS had been enacted in 1997, and the year before that, it was already producing 3.7 TWh of renewables, more than its RPS requirement in 2010. None of the renewables generated in Nevada before 2010 should be attributed to its RPS.
- some of Nevada's renewables growth before 2010 might, in theory, be attributable to RPSs in nearby states like California and Arizona.
- Nevada utilities might generate renewable energy for the purpose of selling unbundled RECs to those other states.
- **What makes policy evaluation tricky** is that Nevada's renewables growth after 2010 might be attributable both to its own RPS, which increased to 6.3 TWh by 2019, and to RPSs in nearby states.

# Appendix: Combined Figure




Source: NBER Digest (Nov.2023)

# Appendix: "Dynamic" Variations of the TWFE specification

$$
\begin{aligned}
Y_{i,t} = \alpha_i + \alpha_t + \gamma_k^{-K} D_{i,t}^{<-K} + \sum_{k=-K}^{-2} \gamma_k^{lead} D_{i,t}^k \\
+ \sum_{k=0}^{L} \gamma_k^{lags} D_{i,t}^k + \gamma_k^{L+} D_{i,t}^{>L} + \varepsilon_{i,t}
\end{aligned}
$$

- with the **event study** dummies $D_{i,t}^k = \mathbf{1}\{t - G_i = k\}$, where $G_i$ indicates the period unit i is first treated (Group).
- $D_{i,t}^k$ is an indicator for unit $i$ being $k$ periods away from initial treatment at time $t$.
- $\gamma$'s cannot be rigorously interpreted as reliable measures of "dynamic treatment effects". (Sun and Abraham, 2021)

# Appendix: "Beyond 2030" in the UK

## 拟投资5000多亿元，英国将进行史上最大电网变革

英国国家电网计划，到2035年，英国电力系统将接入86 GW的海上风电。这已超过了当前全球海上风电的装机总量。

## ESO publishes "Beyond 2030" – a £58bn investment plan in the future of Britain's energy system

Future Network Development / 19 Mar 2024 - 3 minute read

Source: ESO (Electricity System Operator for Great Britain)

# Appendix: Misinterpretation of DiD estimators

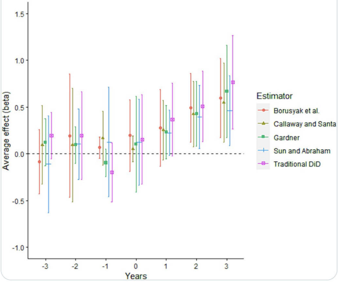
**Ashvin Gandhi** @ashdgandhi · Jan 23

I have refereed multiple papers where the authors implemented CSDID and didn't realize that the graph actually shows clear pre-trends. In fact, I have been guilty of this misinterpretation more than once as well.

**Ashvin Gandhi** @ashdgandhi · 16h

Asking for more than one alternative DD estimator should immediately disqualify a reviewer.

> **Journal of Corporate Finance** @JCorpFin · Mar 30
>
> Wait, is that FIVE DiD estimators in one graph?😍😍😍
> x.com/JCorpFin/statu...




1 1 17 5.7K

Source: Ashvin Gandhi's Twitter

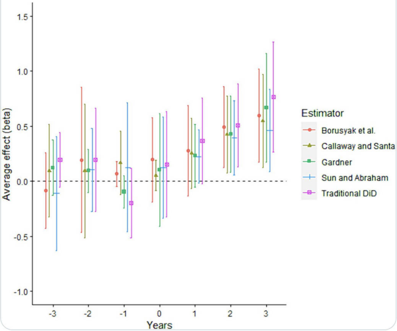
# Appendix: Misinterpretation of DiD estimators (Cont'd)

**Kirill Borusyak** @borusyak · 17h

Another instance when researchers are allowed - even encouraged - to be mindless about empirical methods

**Journal of Corporate Finance** @JCorpFin · Mar 30

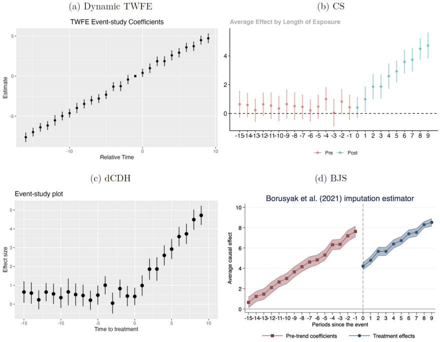
Wait, is that FIVE DiD estimators in one graph?😍😍😍
x.com/JCorpFin/statu...




9 12 208 66K

Source: Kirill Borusyak's Twitter

# Appendix: Misinterpretation of DiD estimators (Cont'd)


Source: Jonathan Roth's Twitter (Roth, 2024) Caveats

# Appendix: Details from (Callaway and Sant'Anna, 2021)

## Treatment Effects in DiD Designs with Multiple Periods ATT

## Framework

- focus on a panel data case.
- consider a **random** sample (iid):

$$\{(Y_{i,1}, Y_{i,2}, ..., Y_{i,\tau}, D_{i,1}, D_{i,2}, ..., D_{i,\tau}, X_i)\}_{i=1}^{n}$$

  where $D_{i,t} = 1$ if unit $i$ is treated in period $t$ and 0 otherwise.
- $G_{i,g} = 1$ if unit $i$ is first treated at time $g$, and zero otherwise ("Treatment starting-time" / "Cohort dummies")
- $C = 1$ is a "never-treated" cimparison group (not required, though)
- **Staggerd treatment adoption**: $D_{i,t} = 1 \Rightarrow D_{i,t+1} = 1$, for $t = 1, 2, ..., \tau$. (**Irreversibility**, or units do not "forget" about the treatment experience)

# Appendix: Details from (Callaway and Sant'Anna, 2021)

## Framework (Cont'd)

- **Potential outcomes**:

$$Y_{i,t} = Y_{i,t}(0) + \sum_{g=2}^{T} (Y_{i,t}(g) - Y_{i,t}(0)) \cdot G_{i,g}$$

  - $Y_{i,t}(0)$: unit i's untreated potential outcome at time $t$ if they remain untreated through time period $\tau$
  - $Y_{i,t}(g)$: potential outcome that unit $i$ would experience at time $t$ if they were to first become treated in time period $g$

# Appendix: Details from (Callaway and Sant'Anna, 2021)

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  - $Y_{i,t}(g)$: potential outcome that unit $i$ would experience at time $t$ if they were to first become treated in time period $g$

- **Parameter of interest**:

$$ATT(g,t) = \mathbb{E}[Y_t(g) - Y_t(0) | G_g = 1], \text{ for } t \geqslant g$$

  - Average treatment effect for the group of units first treated at time period $g$, in calendar time $t$

# Appendix: Details from (Callaway and Sant'Anna, 2021)

## Framework (Cont'd) Robust

- **Limited Treatment Anticipation**: there is a known $\delta \geqslant 0$ s.t.

$$\mathbb{E}[Y_t(g)|X, G_g = 1] = \mathbb{E}[Y_t(0)|X, G_g = 1] \quad a.s.$$

for all $g \in \mathcal{G}$, $t \in 1, ..., \mathcal{T}$ such that $\underbrace{t < g - \delta}_{\text{"before effective starting date"}}$.

- For simplicity, let's take $\delta = 0$, which is arguably the norm in the literature.
- If units anticipate treatment by two period, this assumption would hold with $\delta = 2$.
- Generalized propensity score uniformly bounded away from 1:

$$p_{g,t}(X) = P(G_g = 1|X, G_g + (1 - D_t)(1 - G_g) = 1) \leqslant 1 - \epsilon \quad a.s.$$

# Appendix: Details from (Callaway and Sant'Anna, 2021)

**Framework (Cont'd)**

- **Parallel Trend Assumption (based on a "never-treated" group)**: For each $t \in \{2, ..., \tau\}$, $g \in G$ such that $t \geqslant g$,

$$\mathbb{E}[Y_t(0) - Y_{t-1}(0) | X, G_g = 1] = \mathbb{E}[Y_t(0) - Y_{t-1}(0) | X, C = 1] \;\; a.s.$$

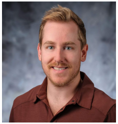
- **Parallel Trend Assumption (based on "Not-Yet-Treated" Groups)**: For each $(s, t) \in \{2, ..., \tau\} \times \{2, ..., \tau\}$, $g \in G$ such that $t \geqslant g$, $s \geqslant t$.

$$\begin{aligned} &\mathbb{E}[Y_t(0) - Y_{t-1}(0) | X, G_g = 1] \\ &\qquad = \mathbb{E}[Y_t(0) - Y_{t-1}(0) | X, D_s = 0, G_g = 0] \quad a.s. \end{aligned}$$

# Appendix: About the Researchers

## Olivier Deschenes

- "My recent research is focused on estimating the impacts of climate change on human health and economic productivity in the U.S. and around the world using historical data."



## Christopher Malloy

- "In my current work, I use applied empirical methods and causal inference to understand the effect of assigning liability for low probability, high severity events on firm precaution to prevent such events."

## Gavin McDonald

- "The tools he uses include ... program impact evaluation and econometrics, decision support tool web app development, and big data and machine learning."

*Thank You!*

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