Can Distributed Intermittent Renewable Generation Reduce Future Grid Investments? Evidence from France

Based on Astier, Rajagopal and Wolak
(published in the Journal of the European Economic Association)

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- Intermittent wind and solar energy are major technologies proposed to achieve these goals.

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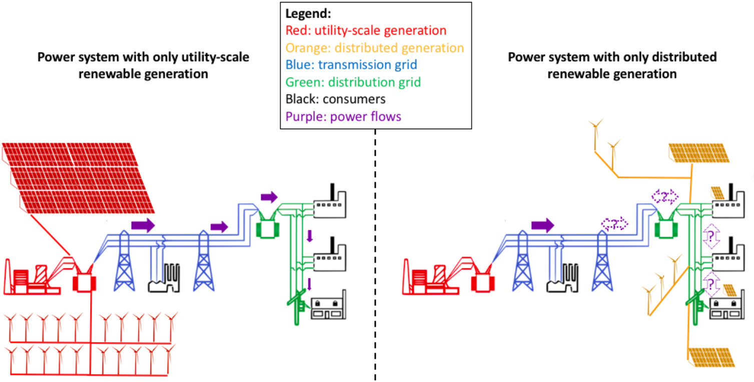
- Intermittent wind and solar energy are major technologies proposed to achieve these goals.

Policy question: to achieve these goals at least cost to consumers, should investments in wind and solar should occur in distribution grid or transmission grid?

Grid-scale vs distributed units



Levelized cost of distributed versus grid scale solar

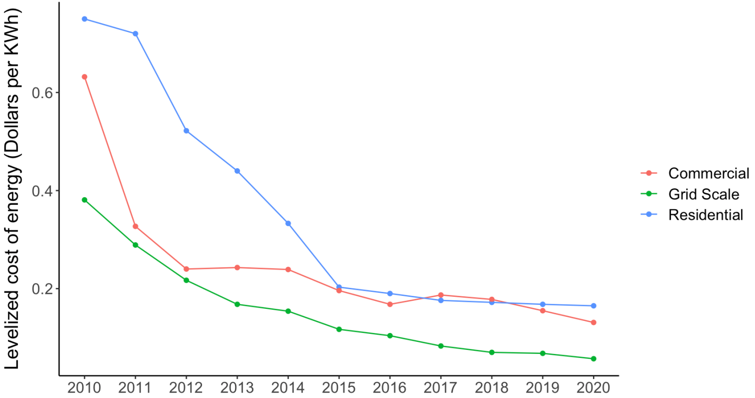


Figure: Levelized Cost of Energy (LCOE) for grid-scale units (global capacity-weighted average) and distributed solar generation units (average for France) from 2010 to 2020 ($/KWh). Source: adapted from IRENA.

The case for distributed wind and solar

- The case for distributed wind and solar investments relative to grid scale generation investments relies on two arguments:
  - distributed wind and solar reduces need for distribution network upgrades;
  - distributed wind and solar does not incur transmission and distribution network losses.

- However, typical transmission and distribution losses are not big enough to close the LCOE gap.

⇒ Substantial network investment savings from distributed investments are needed to rationalize significantly higher subsidies for distributed generation.

The New York Times

How New York City Is Turning Its Thousands of Roofs Into Power Providers

Manhattan now has the country's biggest array of solar panels on an apartment complex. The Bronx could soon have a bigger one.

"even though not enough energy is generated to power all of the complex, the solar energy will take pressure off the power distribution network on hot summer days when demand from Con Edison's customers is peaking"

(source: https://www.nytimes.com/2019/07/10/nyregion/nyc-solar-power.html)

Research gap

- The extent to which distributed generation "*takes pressure off the power distribution network*" or reduces the need for distribution network investments is highly debated, particularly for distribution network-connected solar facilities: estimated benefits can differ by an order of magnitude depending on who assesses them. Example

- Evidence typically comes from simulation models applied to hypothetical distribution network or a small number of actual distribution networks.

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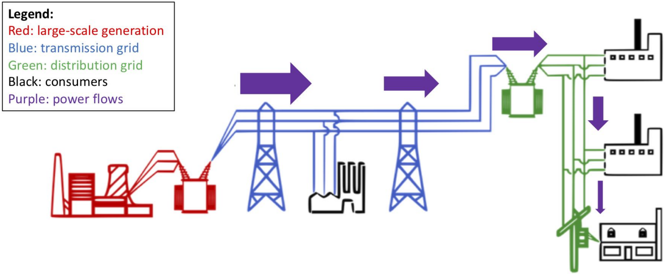
- Evidence typically comes from simulation models applied to hypothetical distribution network or a small number of actual distribution networks.

⇒ Empirical evidence based on actual power flows into distribution network is largely nonexistent.

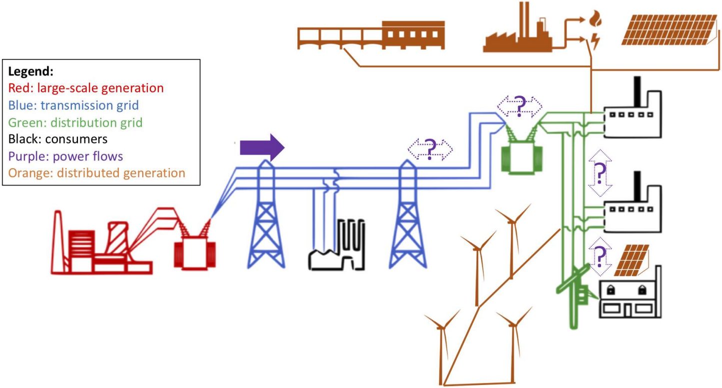
Conventional electricity supply industry

One-way energy flows from generation units to final consumers.



Distributed generation

Distributed generation units are small power plants that connected to distribution grid close to consumers that can reduce transmission and distribution network flows.

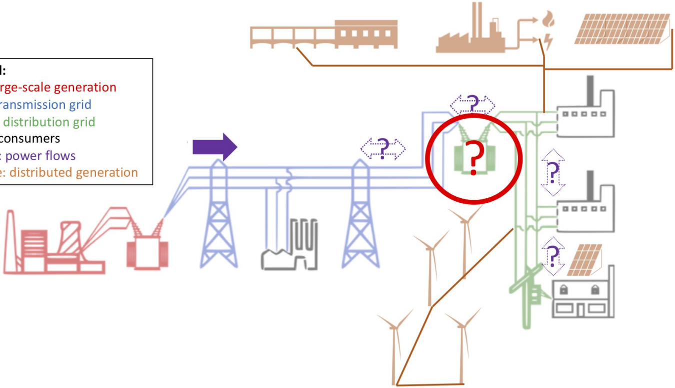


Approach followed in the paper

- The authors look at 5 types of distributed generation technologies: PV, wind, small hydro, renewable thermal, and non-renewable thermal.
- They explore empirically whether and for which technologies distributed generation investments may reduce the need for future network expansions, based on data for France between 2005 and 2018.

Methodology

Legend:
Red: large-scale generation
Blue: transmission grid
Green: distribution grid
Black: consumers
Purple: power flows
Orange: distributed generation

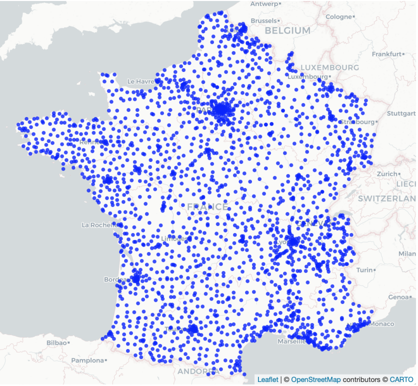


Focus on hourly energy flows at distribution sub-stations, that are the interface between the transmission and distribution grids.

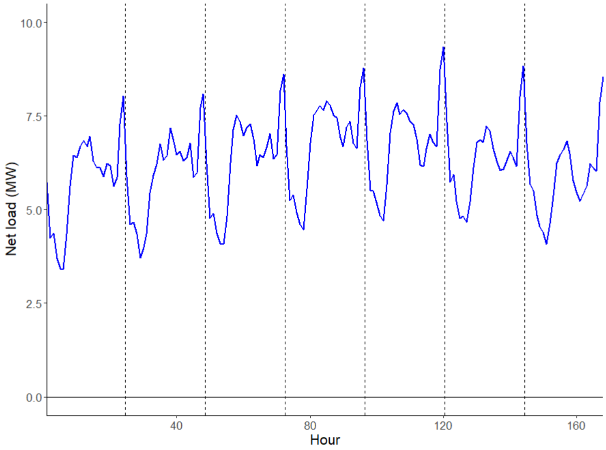
Dataset 1 - Distribution sub-station hourly load levels

Hourly sub-station net load levels:

- for 2,000+ sub-stations;
- between 2005 and 2018.



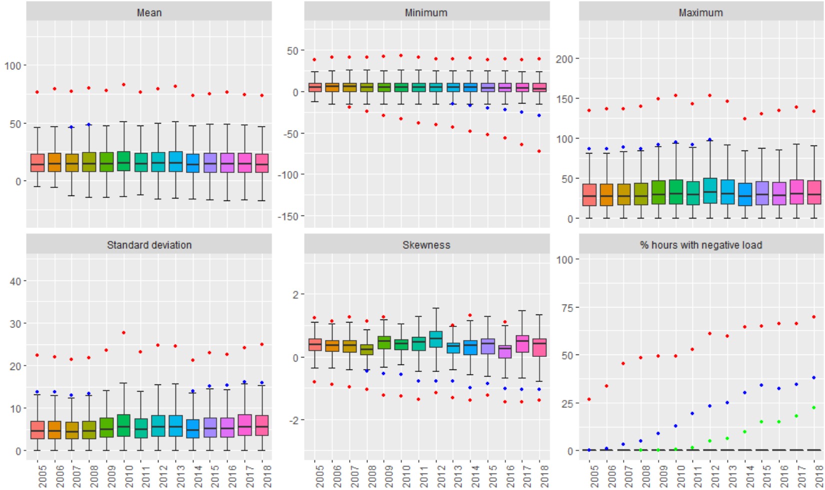
Dataset 1 - Raw data



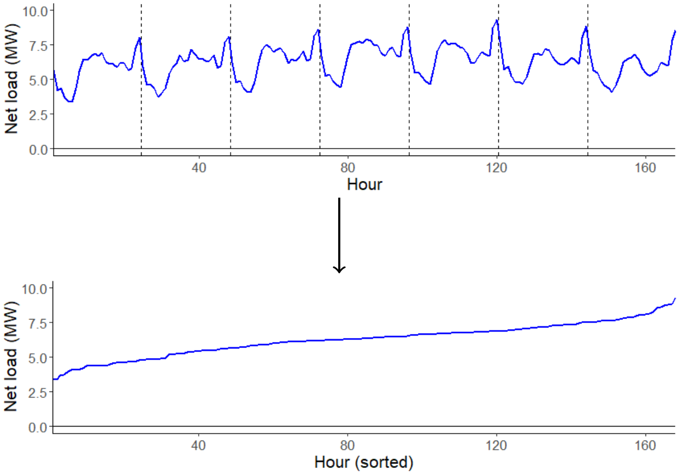
Hourly load levels for a given sub-station in a given week

$\Rightarrow$ raw data is composed 250+ million observations.

Dataset 1 - Main summary statistics

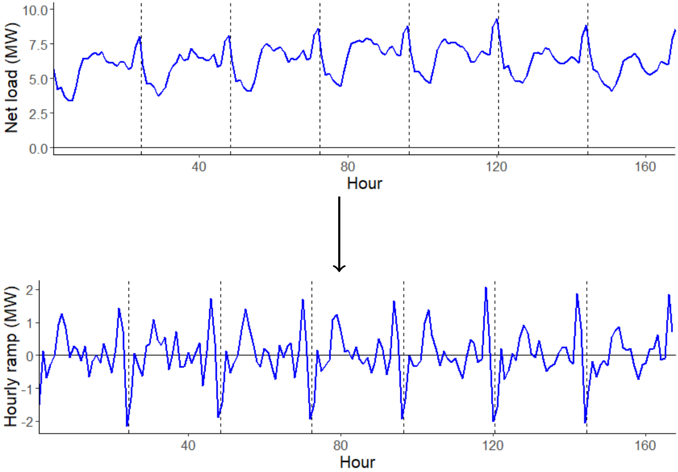


Dataset 1 - Load duration curve



⇒ Keep track of quantiles of annual load duration curves for *each sub-station in each year*.

Hourly ramps



Dataset 2 - Distributed generation capacities

- Information about the universe of power plants in France is publicly available;
- Authors are able to match with great accuracy distributed generation capacities to the upstream distribution substation to which they connect.

Details

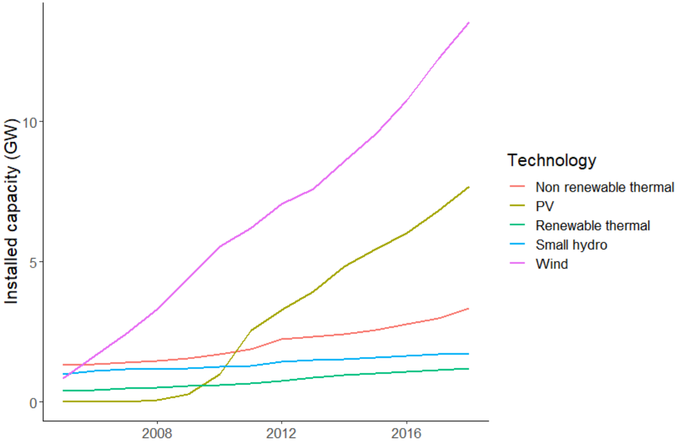
Dataset 2 - Summary statistics

The unit of observation is a given sub-station in a given year between 2005 and 2018 (30,000+ observations).

Statistic	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max	Total 2018 (% inventory)
Wind	3.114	11.499	0	0	0	189	13,567 (96.8%)
PV	1.392	3.829	0	0.01	1.2	101	7,695 (99.0%)
Small hydro	0.641	2.642	0	0	0	63	1,717 (86.1%)
Renewable thermal	0.354	1.709	0	0	0	35	1,198 (96.0%)
Non renewable thermal	0.974	2.743	0	0	0	45	3,334 (93.3%)

First columns: summary statistics of sub-station level installed capacities (in MW) by technology. Last column: total capacity by technology as of 2018 in our final dataset, both in absolute value and as a percentage of the total capacity listed in the public inventory of power plants.

Growth in distributed generation



Installed distributed generation capacities in mainland France (in final dataset).

Final dataset

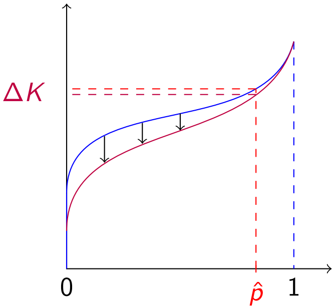
Combining both datasets, the dataset used in the empirical analysis combines for each of the 2,000+ sub-stations and each year from 2005 to 2018:

- The installed capacity $K_{t,s,y}$ of distributed generation units of technology t (for sub-station s at the end of year y);
- Any statistic $Y_{s,y}$ that may be computed from the annual hourly net load levels at the sub-station. Focus on attention on:
  - the main quantiles of the annual distribution of hourly net load levels, which add up to the load duration curve;
  - the main quantiles of the annual distribution of hourly ramps, which add up to the ramp duration curve.

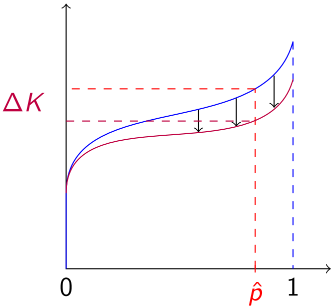
Load duration curve and capacity savings

Adding 1 MW of a given distributed generation technology will affect the shape of load duration curve (resp. ramp duration curve).

A given distributed generation technology is likely to help defer grid investments if it has a significant impact on the top quantiles:

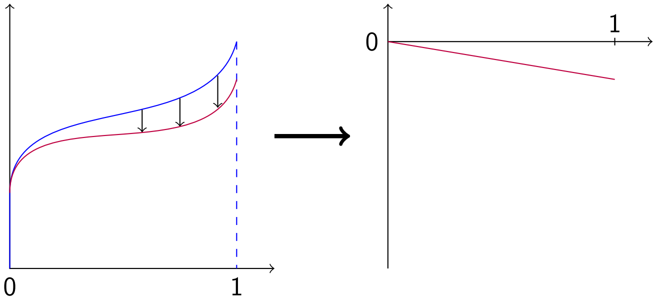


Small capacity savings



Large capacity savings

Quantile impact functions



Change in the load duration curve Quantile impact function

Estimating quantile impact functions

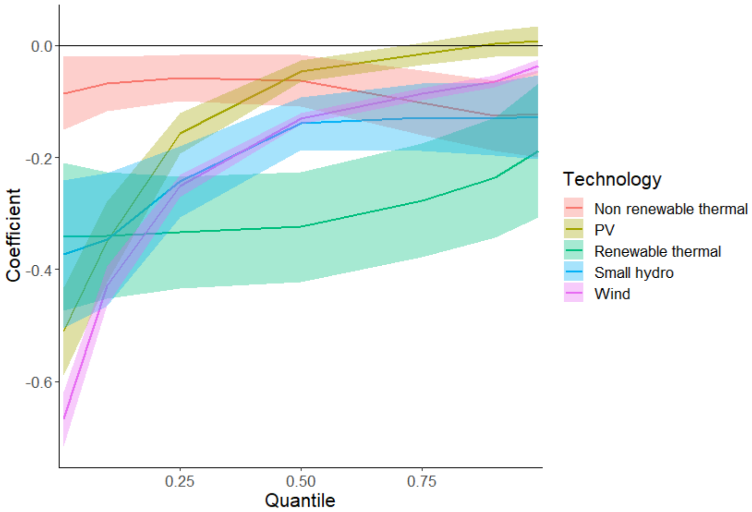
For each duration curve, authors use a seemingly unrelated regressions framework with a two-way fixed-effect specification. For quantile q, they estimate:

$$Q_{q,s,y} = \sum_t \beta_{q,t} K_{t,s,y} + \delta_{q,s} + \delta_{q,y} + \epsilon_{q,s,y}$$

where $Q_{q,s,y}$ is the q-th quantile of the annual distribution of hourly net load levels (resp. hourly ramps) for sub-station s in year y.

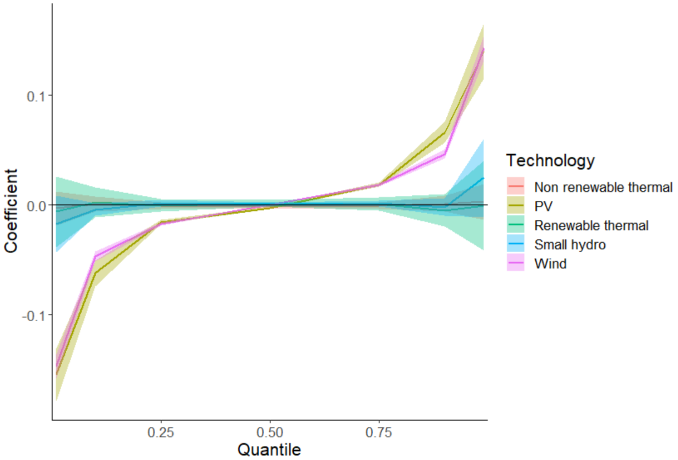
$\Rightarrow$ Fixing a given technology t and a given duration curve of interest, the 7-tuple $(\hat{\beta}_{0.01,t}, \hat{\beta}_{0.1,t}, \hat{\beta}_{0.25,t}, \hat{\beta}_{0,5,t}, \hat{\beta}_{0.75,t}, \hat{\beta}_{0.9,t}, \hat{\beta}_{0.99,t})$ then corresponds to the estimated quantile impact function for that technology and duration curve.

Estimated impacts on the load duration curve



Reported 95% confidence intervals are based on robust (HC1) standard errors clustered at the sub-station level.

Estimated impacts on hourly ramps

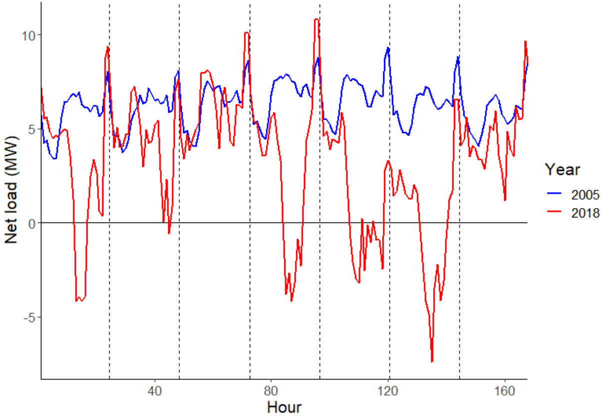


Reported 95% confidence intervals are based on robust (HC1) standard errors clustered at the sub-station level.

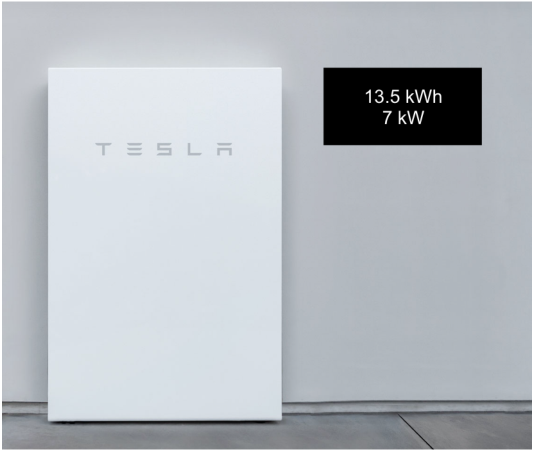
Placebo test

Anecdotical illustration

Observed changes for a given week at a given sub-station where PV and wind distributed generation grew from 0 to 10+ MW between 2005 and 2018.



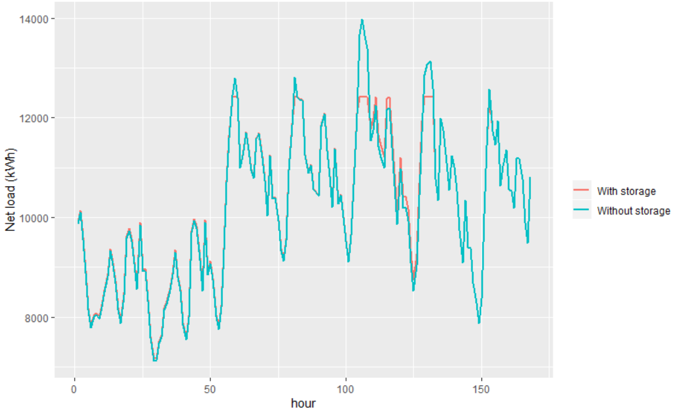
Renewable distributed generation and battery storage



(source: www.tesla.com)

Optimistic assumptions

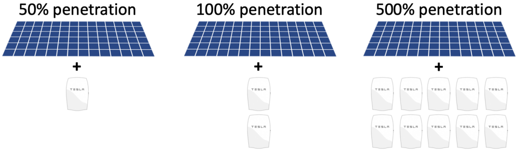
- Weekly peak-shaving operations:



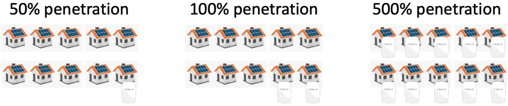
- Perfect foresight of net load;
- Lossless (dis)charge;
- No limitations in the number of refresh cycles.

Storage penetration scenarios

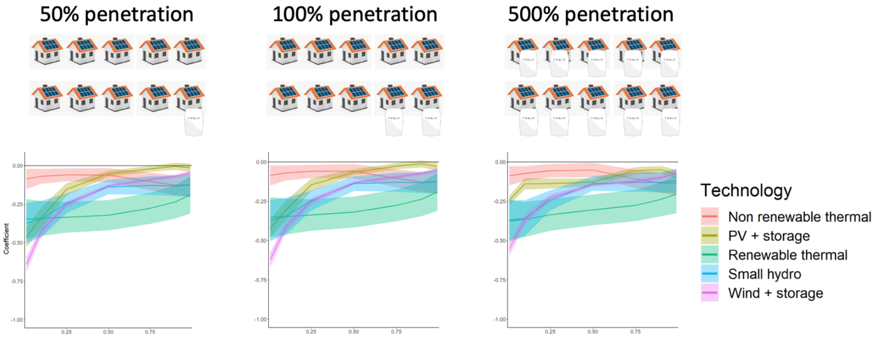
The authors assume that for each kW of either wind or solar installed, X % kWh of battery storage is simultaneously connected to the same substation. They consider 3 different penetration levels:



or equivalently:



Storage analysis results - graph



Note: the 500% case corresponds to installing roughly one Tesla PowerWall 2 Battery for every 3 kW of intermittent distributed generation. Intuition

Main take-aways

- Distributed wind and PV are found to:
  1. have respectively a small or negligible impact on the maximum net hourly load levels observed on distribution grids;
  2. contribute to increase in the occurrence of hours with excess local generation and large hourly ramps.

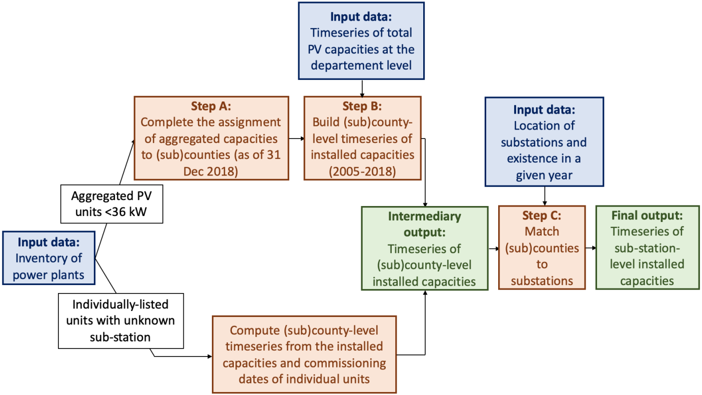
  $\Rightarrow$ At least for the case of France, benefits from deferring future grid expansions cannot rationalize a substantial policy support for distributed wind and solar generation over utility-scale generation.

- In contrast, investments in thermal and small hydro units are found to lead to significant reductions in peak net loads
- Substantial investments in storage are necessary for wind and solar investments to deliver comparable peak net load reductions

Back-up slides

Distributed generation - assignment procedure

For units whose upstream sub-station is unknown (yellow and red slices), we implement a sensible procedure to assign them to sub-stations.



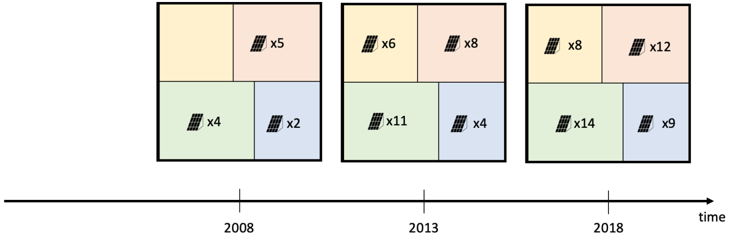
⇒ obtained results hold independently of how (or even whether) we perform this assignment.

General idea behind our assignment procedure

- Our assignment procedure leverages the fact that we observe the location of distributed generation units down to the (sub)county level;
- Mainland France is divided into 30,000+ counties ("communes"), and the most populated of them are further divided into sub-counties ("maille IRIS");
- We use a spatial division of mainland France into 45,508 spatial units (with a mean surface of 11.9 km^2), that is one order magnitude higher than the number of sub-stations.

Small PV installations and confidentiality

For confidentiality reasons, most small (< 36kW) PV units are aggregated at the finest level of spatial aggregation (sub-county, county or departement) that makes it possible to group at least 10 installations together.



department	11	18	17
county	NA	NA	NA
county	NA	NA	12 (2018)
county	NA	11 (2013)	14 (2013)
county	NA	NA	NA

Observed in 2018 registry

Step A (only needed for aggregated PV units): Spatial assignment as of 2018

- 74% of the total capacity from aggregated PV units consist in county or sub-county observations;
- The remaining 26% are located at the departement level;
- We further know that units aggregated at the department level cannot be located in (sub)counties for which an aggregated PV observation exist;

$\Rightarrow$ for each departement, we thus allocate capacities aggregated at the departement-level uniformly across counties for which no aggregated PV observation exists.

Step B (only needed for aggregated PV units): Going back in time

- From Step A, we observe (or have inferred) the capacity $W_{c,d}$ of aggregated PV units in (sub)county c of departement d *as of 31 December 2018*;
- Because the composition of aggregated units have changed over time, they do not have a commissioning date and a constant capacity;
- We use a third dataset (provided by the French Department of Energy) to retrieve the total capacity $K_{d,y}$ of aggregated PV installations in departement d at the end of year y;
- Finally, we postulate that the capacity $K_{c,d,y}$ in (sub)county c of departement d in year y was:

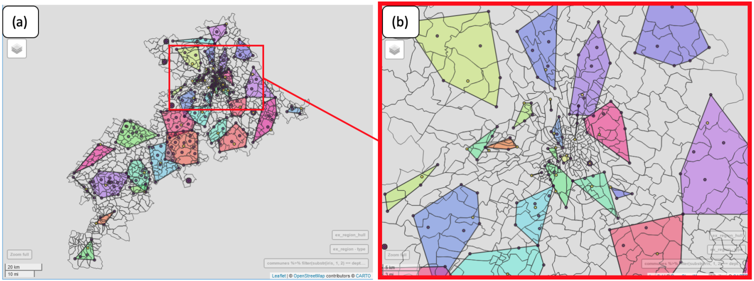
$$K_{c,d,y} \equiv K_{d,y} \frac{W_{c,d}}{\sum_{c' \in d} W_{c',d}}$$

NB: other approaches to extrapolate were found to yield fairly similar results.

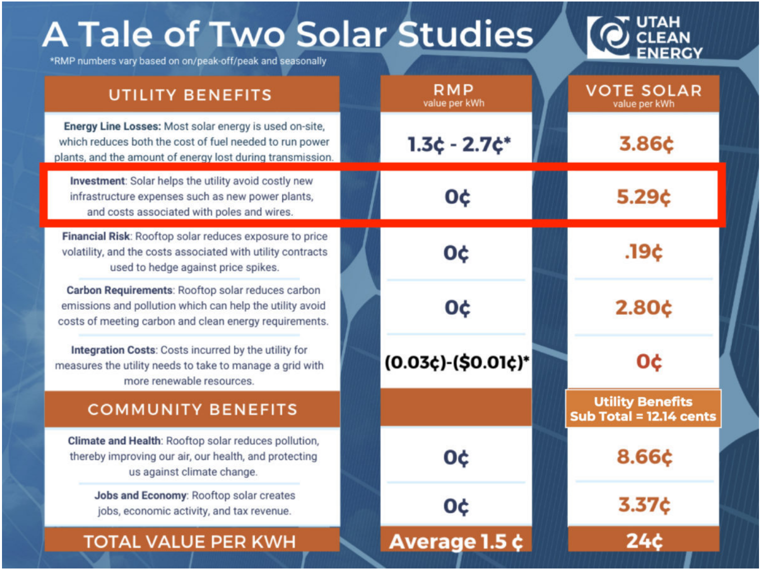
Step C (all DG units with unknown sub-station): matching counties to sub-stations

We observe (or have inferred for aggregated PV) (sub)county-level timeseries of installed capacities by technology.

In this last step, we use the known connections DG units – sub-stations to infer which sub-station is most likely to supply a given (sub)county.



Back



A Tale of Two Solar Studies

UTAH CLEAN ENERGY

*RMP numbers vary based on on/peak-off/peak and seasonally

UTILITY BENEFITS	RMP value per kWh	VOTE SOLAR value per kWh
Energy Line Losses: Most solar energy is used on-site, which reduces both the cost of fuel needed to run power plants, and the amount of energy lost during transmission.	1.3¢ - 2.7¢*	3.86¢
Investment: Solar helps the utility avoid costly new infrastructure expenses such as new power plants, and costs associated with poles and wires.	0¢	5.29¢
Financial Risk: Rooftop solar reduces exposure to price volatility, and the costs associated with utility contracts used to hedge against price spikes.	0¢	.19¢
Carbon Requirements: Rooftop solar reduces carbon emissions and pollution which can help the utility avoid costs of meeting carbon and clean energy requirements.	0¢	2.80¢
Integration Costs: Costs incurred by the utility for measures the utility needs to take to manage a grid with more renewable resources.	(0.03¢)-($0.01¢)*	0¢
COMMUNITY BENEFITS		Utility Benefits Sub Total = 12.14 cents
Climate and Health: Rooftop solar reduces pollution, thereby improving our air, our health, and protecting us against climate change.	0¢	8.66¢
Jobs and Economy: Rooftop solar creates jobs, economic activity, and tax revenue.	0¢	3.37¢
TOTAL VALUE PER KWH	Average 1.5 ¢	24¢

Source: Wesoff, Eric. "*Utah utility Rocky Mountain Power and solar advocates aren't even close on the value of rooftop PV sent to the grid*", PV magazine, 2020. Back

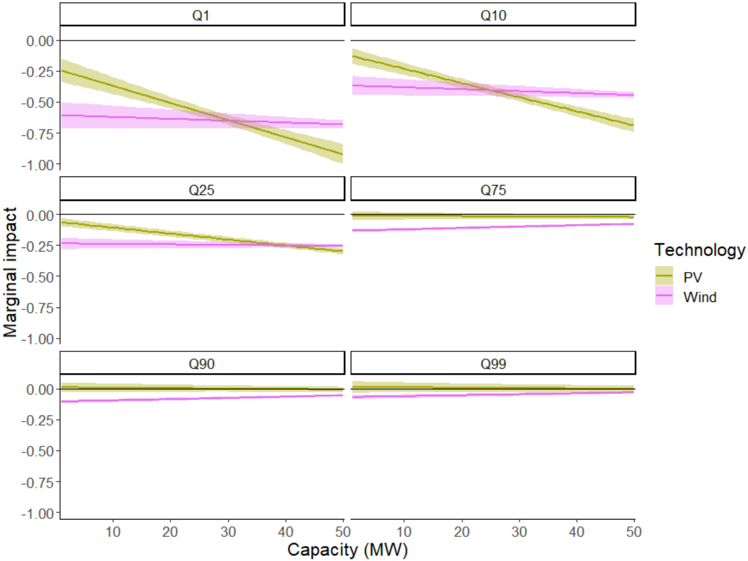
Non-constant marginal impact of distributed generation capacities?

We also estimate a quadratic specification:

$$Y_{q,s,y} = \sum_t \alpha_{q,t} K_{t,s,y} + \sum_t \beta_{q,t} K^2_{t,s,y} + \delta_s + \delta_y + \epsilon_{s,y} \tag{1}$$

If $\beta_{q,t}$ is statistically different from zero, the marginal impact of technology t on quantile q is not constant with respect to installed distributed generation capacities.

Results for the load duration curve

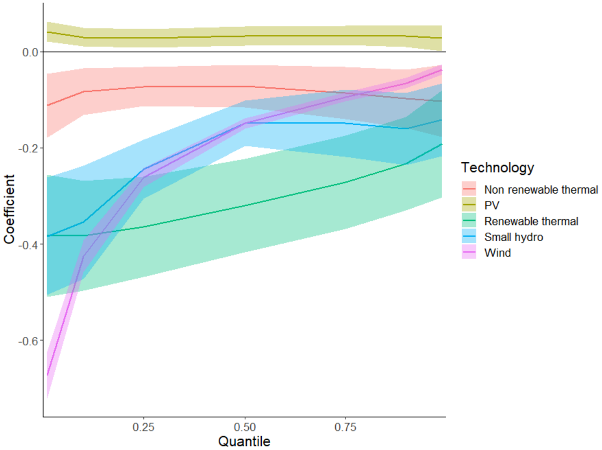


Placebo Test for Rooftop Solar

If restrict analysis to hours of day with no sun, additional 1 MW of solar capacity should have no effect on net demand

- Restrict hours used to compute both load duration curve and ramp duration curve to 11 pm to 5 am each day;
- Compute annual load duration curve and ramp duration curve for these hours only;
- Repeat above analysis.

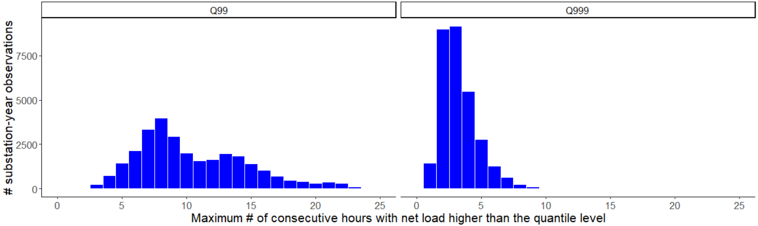
Load duration curve test for rooftop solar



⇒ possible evidence for a small solar rebound.

Back

Hourly ramps



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