Evaluating the Impact of Renewable Power

BREAD-IGC Virtual PhD Course on Environmental Economics

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ICREA-IAE and Northwestern

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I. Introduction
Renewable expansion is key to mitigating climate change

- Electricity is a major source of GHG emissions (e.g., 25% in the US)
- Another large source is transportation, which can be electrified soon
Renewables are cost effective!

Capacity-weighted average construction costs for electricity generators (2013–2018)
dollars per kilowatt

- **solar photovoltaic**
  - 2013: $4,000
  - 2018: $1,848

- **onshore wind turbines**
  - 2013: $3,500
  - 2018: $1,382

- **natural gas**
  - 2013: $3,000
  - 2018: $2,000

Northwestern
Challenge 1: Intermittency

Timing

- Wind and solar power cannot be “turned on” based on demand.
- Need to adjust operations to be ready to cover when these sources are not available.
- Can increase volatility and uncertainty in the market.
Challenge 2: Existing networks were not built for renewables

Geography

- Conventional power plants can be placed near demand centers
  - Minimal transmission lines were required to connect supply and demand

- By contrast, renewables are often best generated in remote locations
  - Renewable-abundant regions are not well integrated with demand centers
II. The cost-benefit of renewables
Renewables have become the cheapest source of energy in many countries

- Great reductions in costs, large climate benefits.
- Technological improvements that increase performance and reduce volatility.
- Very cheap, but without grid investments/batteries, it can quickly lead to saturation.
- Costs for storage and grid expansion need to be benchmarked against clear benefits of increased renewable power.

Economics can be helpful at providing a systematic cost-benefit analysis.
Costs and benefits: quantitative analysis

Costs

- Cost of panels/wind mills
- Costs to incumbents
- Intermittency
- Transmission investments

Benefits

- Price reductions
- Pollution reductions
- GHG reductions
- Resilience
- Investment spillovers
Methodologies

Regression methods

- Main variables of interest: emissions, prices, costs, etc.
- Main independent variable: level of wind and solar (production/capacity).
- Temporal aggregation: typically hourly or daily

Structural methods

- Modeling tools to simulate impact of renewables
- Temporal aggregation: typically hourly
- To understand past outcomes and consider counterfactual/future scenarios
- Focus: Investment/transmission considerations, market power, alternative reliability policies, etc.
III. Case study from Spain: Intermittency
Question: What have been the impacts of wind generation in the last decade?

Methodology: Regression analysis of hourly operational data (prices, congestion costs, emissions benefits, etc.).

Finding: Consumers have been better off, even after accounting for the cost of the subsidies. Market design can impact these benefits.

Co-authors: Claire Petersen and Lola Segura-Varo
We get hourly data from the Spanish electricity market (2009-2018). Data from REE and OMIE.

- Data include: market prices, intermittency costs, congestion, and other reliability services, emissions data (tons/CO2), subsidies received (millions), etc.

- We **quantify the impact of wind** on these variables:
  - Benefits: emissions reductions, reduced use of fuels, price reductions for consumers.
  - Costs: increased costs of intermittency (paid by consumers and by wind farms), price reductions for consumers.
Identification strategy

- Given randomness in wind forecasts, we run a regression of the impacts of wind on these variables.
- **Spline approach** to look at the impact at different quintiles:

\[ Y_t = \beta_0 + \sum_{q=1}^{5} \beta_q W_{qt} + \gamma X_t + \epsilon_t , \]

where \( W_{qt} \) are spline bins according to the quintiles of the wind variable.
- Examine *average* predicted costs as well as *marginal effects*. 
Note on endogeneity

Wind production can be endogenous due to:
- Curtailment.
- Strategic behavior.

Use forecasted wind either directly or as an instrument to actual production.

<table>
<thead>
<tr>
<th>VARIABLES</th>
<th>(1) Wind Forecast</th>
<th>(2) Wind Forecast</th>
<th>(3) IV Forecast</th>
<th>(4) IV Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forecasted wind (GWh)</td>
<td>0.191 (0.0162)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final wind production (GWh)</td>
<td></td>
<td>0.152 (0.0140)</td>
<td>0.182 (0.0150)</td>
<td>0.188 (0.0189)</td>
</tr>
<tr>
<td>Observations</td>
<td>83,840</td>
<td>83,841</td>
<td>83,840</td>
<td>81,348</td>
</tr>
<tr>
<td>R-squared</td>
<td>0.561</td>
<td>0.557</td>
<td>0.079</td>
<td>0.079</td>
</tr>
</tbody>
</table>
Emphasis on operational costs

- In the literature, often large emphasis on the costs of intermittency from renewable resources.
- Focus on the paper to quantify intermittency costs in the market.
- *Has wind contributed to large increases in operational costs?*
- We identify intermittency costs as the (accounting) costs of providing congestion management, reliability services, balancing, etc.
Results for operational costs

- Operational costs go up with more wind.
- However, they don’t increase dramatically.
- Marginal effects don’t increase.
Decomposition of operational costs

- We quantify effects to different operational services.
- Congestion goes up with wind.
Results for prices

- Wind reduces prices in the market.
- Effect is one order of magnitude larger than the effect on operational costs.
Putting all effects together for welfare

■ Consumer surplus
  ► Benefit: reduced price.
  ► Cost: subsidy, costs of intermittency paid by consumers.

■ Producer surplus
  ► Benefit: subsidy, reduced fossil fuel costs.
  ► Cost: reduced price, costs of intermittency paid by wind farms.

■ Emissions reductions
  ► Above and beyond what is already internalized by EU-ETS.
  ► For alternative values of SCC.

■ Cost of investment.
  ► For alternative LCOE values.
Welfare effects of wind by group

- Marginal increases in wind benefit consumers more than they hurt them, even if they have to pay subsidies.
- Biggest losers are traditional producers of electricity.
- Wind farms receive large revenues, key for welfare is how that compares with costs.
- Intermittency has modest overall effects.
Cost-benefit for different SCC and LCOE

- Overall cost benefit sensitive to assumptions on the cost and benefits of wind power.
- LCOE = (mostly) capital costs of wind.
- SCC = social cost of carbon, global environmental benefits.
- Intermittency has some impacts, but does not affect qualitative findings.
Wind investments had a positive impact on welfare for reasonable SCC.

On average, policy benefited both consumers and producers.

Details on market design and compensation can substantially impact winners and losers.

Sometimes perceived as a costly mistake, but a huge early success in climate policy that has lead to over 20% of generation in Spain being from wind.
IV. Case study from Chile: Transmission
A case study from Chile

- The Chilean context provides a unique case study.
- Chile has large solar resources, but best spots disconnected from demand centers (Antofagasta and Atacama desert).
- Chile successfully connected these areas via ambitious grid projects in 2017 and 2019.
- We provide a *dynamic* quantification of the benefits.
Gonzales, Ito, and Reguant (2023)

- Gonzales, Ito, and Reguant (2022) quantify the value of transmission infrastructure in Chile.

- Question: What is the cost benefit of the expansion project?

- Tools: event study + structural model of the Chilean electricity market.

- Some key findings:
  - We highlight the dynamic benefits of grid expansion, enabling increased renewable expansion.
  - The cost of transmission can be quickly recovered, even when ignoring the added climate change benefits.
Summary of the paper in a picture

- Demand in region A
- Demand in region B
- Autarky
- Trade *
- Trade **
- Gains from trade without solar investment
- Solar investment
- Cost savings with solar investment
- p_A
- p_B
- c_B
- p^*
- p^{**}
- p_A
- p_{\tilde{A}}
Static impacts: Event study effects of the line

\[ c_t = \alpha_1 l_t + \alpha_2 R_t + \alpha_3 c^*_t + \alpha_4 X_t + \theta_m + u_t \]

- Our method uses insights from Cicala (2022)
  - \( c_t \) is the observed cost
  - \( c^*_t \) is the nationwide merit-order cost (least-possible dispatch cost under full trade in Chile)
  - \( l_t = 1 \) after the interconnection; \( R_t = 1 \) after the reinforcement
  - \( X_t \) is a set of control variables; \( \theta_t \) is month fixed effects
  - \( \alpha_1 \) and \( \alpha_2 \) are the impacts of interconnection and reinforcement
### Static impacts: Event study effects of the line

<table>
<thead>
<tr>
<th></th>
<th>Hour 12</th>
<th>All hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (After the interconnection)</td>
<td>-2.42</td>
<td>-2.07</td>
</tr>
<tr>
<td>1 (After the reinforcement)</td>
<td>-0.96</td>
<td>-0.61</td>
</tr>
<tr>
<td>Nationwide merit-order cost</td>
<td>1.12</td>
<td>1.03</td>
</tr>
<tr>
<td>Coal price [USD/ton]</td>
<td>-0.03</td>
<td>-0.01</td>
</tr>
<tr>
<td>Natural gas price [USD/m(^3)]</td>
<td>-10.36</td>
<td>-0.65</td>
</tr>
<tr>
<td>Hydro availability</td>
<td>0.43</td>
<td>0.00</td>
</tr>
<tr>
<td>Scheduled demand (GWh)</td>
<td>-0.51</td>
<td>-0.01</td>
</tr>
<tr>
<td>Sum of effects</td>
<td>-3.38</td>
<td>-2.68</td>
</tr>
<tr>
<td>Mean of dependent variable</td>
<td>35.44</td>
<td>38.63</td>
</tr>
<tr>
<td>Month FE</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Sample size</td>
<td>1033</td>
<td>1033</td>
</tr>
<tr>
<td>(R^2)</td>
<td>0.94</td>
<td>0.97</td>
</tr>
</tbody>
</table>
Does this static event study analysis get the full impact?

- Our theory suggested:

  ➤ Yes if solar investment occurs *simultaneously* with integration
  ➤ No if solar investment occurs in *anticipation* of integration
Solar investment occurred in anticipation of integration

- Solar investment began after the announcement of integration in 2014
- These solar entries depressed the local price to near zero in 2015-2017
Solar investment occurred in anticipation of integration.

However, more and more new solar plants entered the market:

- Investment occurred in the anticipation of the profitable environment.
- Static analysis does not capture the full impact of market integration.
- We address this challenge in the next section.
Buidling a model to get at the full effect

- Impacts of the grid can be static and dynamic:
  - Production benefits: more solar can be sent to the demand centers, prices in solar regions go up.
  - Investment benefits: more solar power is built.

- We highlight that an event study is likely to capture only the first kind of effects (e.g., around time of expansion).

- We build a model of the Chilean electricity market to quantify the benefits of market integration including its investment effects.
A structural model to study a dynamic effect on investment

- We divide the Chilean market to five regional markets with interconnections between regions (now expanding to 11)

- Model solves constrained optimization to find optimal dispatch that minimizes generation cost

- Constraints:
  1. Hourly demand = (hourly supply - transmission loss)
  2. Supply function is based on plant-level hourly cost data
  3. Demand is based on node-level hourly demand data
  4. Transmission capacity between regions:
     - Actual transmission capacity in each time period
     - Counterfactual: As if Chile did not integrate markets
The structural model solves this constrained optimization

\[
\begin{align*}
\text{Min} \quad & C_t = \sum_{i \in I} c_{it} q_{it}, \\
\text{s.t.} \quad & \sum_{i \in I} q_{it} - L_t = D_t, \quad q_{it} \leq k_i, \quad f_r \leq F_r.
\end{align*}
\]

(1)

**Variables:**
- \(C_t\): total system-wise generation cost at time \(t \in T\)
- \(c_{it}\): marginal cost of generation for plant \(i \in I\) at time \(t\)
- \(q_{it}\): dispatched quantity of generation at plant \(i\)
- \(L_t\): Transmission loss of electricity
- \(D_t\): total demand
- \(k_i\): the plant’s capacity of generation
- \(f_r\): inter-regional trade flow with transmission capacity \(F_r\)
Dynamic responses are solved as a zero-profit condition

\[ E \left[ \sum_{t \in T} \left( \frac{p_{it}(k_i)q_{it}(k_i)}{(1 + r)^t} \right) \right] = \rho k_i \quad (2) \]

- where:
  - NPV of profit (left hand side) = Investment cost (right hand side)
  - \( \rho \): solar investment cost per generation capacity (USD/MW)
  - \( k_i \): generation capacity (MW) for plant \( i \)
  - \( p_{it} \): market clearing price at time \( t \)
  - \( q_{it} \): dispatched quantify of generation at plant \( i \)
  - \( r \): discount rate

- This allows us to solve for the profitable level of entry for each scenario
We calibrate the model with detailed market data

- **Network model**
  - k-means clustering of province prices into 5 zones, observed flows between clusters to set transmission.

- **Supply curve**:
  - based on observed production and/or observed reported costs.

- **Demand**:
  - based on nodal level data, aggregated to clusters.

- **Solar potential**:
  - based on days without transmission congestion.

- **Cost of solar**:
  - based on zero profit condition.
The cost and benefit of the transmission investments

- Cost of the interconnection and reinforcement
  - $860 million and $1,000 million (Raby, 2016; Isa-Interchile, 2022)

- Benefit—we focus on three benefit measures
  - Changes in consumer surplus
  - Changes in net solar revenue (\(= \) revenue \(-\) investment cost)
  - Changes in environmental externalities
Cost-benefit results

<table>
<thead>
<tr>
<th>Table: Cost-Benefit Analysis of Transmission Investments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Modelling assumptions</strong></td>
</tr>
<tr>
<td>Investment effect due to lack of integration</td>
</tr>
<tr>
<td><strong>Benefits from market integration (million USD/year)</strong></td>
</tr>
<tr>
<td>Savings in consumer cost</td>
</tr>
<tr>
<td>Savings in generation cost</td>
</tr>
<tr>
<td>Savings from reduced environmental externality</td>
</tr>
<tr>
<td>Increase in solar revenue</td>
</tr>
<tr>
<td><strong>Costs from market integration (million USD)</strong></td>
</tr>
<tr>
<td>Construction cost of transmission lines</td>
</tr>
<tr>
<td>Cost of additional solar investment</td>
</tr>
<tr>
<td><strong>Years to have benefits exceed costs</strong></td>
</tr>
<tr>
<td>With discount rate = 0</td>
</tr>
<tr>
<td>With discount rate = 5.83%</td>
</tr>
<tr>
<td>With discount rate = 10%</td>
</tr>
<tr>
<td><strong>Internal rate of return</strong></td>
</tr>
<tr>
<td>Lifespan of transmission lines = 50 years</td>
</tr>
<tr>
<td>Lifespan of transmission lines = 100 years</td>
</tr>
</tbody>
</table>
Assessing the cost-benefit

- With the model, we can compute the benefits of the line, with and without investment effects.
- We find that investment effects are key to justify the cost of the line.
- The line was also very attractive from a consumer welfare perspective, even at 5.83% discount rate (Chile’s official rate).
- Political economy makes renewable expansion “easy” in Chile.
- How to reduce political economy challenges in other jurisdictions?
V. Conclusion
Evaluating the energy transition

- Renewable power provides a unique opportunity to decarbonize electricity generation.
- We used economics to evaluate the impacts of renewables in two countries that have experienced a tremendous transformation.
- Challenges and concerns, e.g., due to intermittency and transmission, but overall success stories.

More details?
- Measuring the Impact of Wind Power and Intermittency, with Claire Petersen and Lola Segura, revise and resubmit at *Energy Economics*.