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Ph.D. (c) Miguel Castro
Michigan State University
castrom9@msu.edu
Introduction

• **What is the value of intermittent renewable energy (IRE) sources, such as wind and solar?**
  • Reduce grid-level electricity generation costs and emissions.
  • Cyclical and random intermittency—difficult to integrate them to electric grids

• **Need to account for the dynamic interactions between storage capacity and emissions regulations in assessing the value of intermittent renewables.**
  • Previous studies have explored:
    • the costs of intermittency (Gowrisankaran et al, 2015),
    • the impact of storage on generation and investment in generating capacity (De Sisternes et al., 2016),
    • the value of wind generation in the presence of storage under market power (Sioshansi, 2011),
    • the long-term dynamic effects of carbon taxes on electricity markets (Cullen and Reynolds, 2016).
Introduction

• This research explores the dynamic value of intermittent renewable energy contingent on storage and emissions taxes
  • Using a stylized Social Planner Dynamic model of the Texas (ERCOT) electricity market that simulates allocations, welfare and emissions (CO_{2}, NOx, and SO_{2}) for different storage and renewable energy levels.
  • Assessment of wind power values under different scenarios combining storage availability and emissions taxes

• Storage capacity and emissions taxes are complements in driving the value of wind.
  • Energy is allocated when it is most socially valuable.
  • Wind power first best value doubles its LCOE but second best does not.
  • Storage first best value (economic welfare) covers its cost but a second best does not
  • Simply taxing emissions leads to a larger welfare gain than planned storage (324 MW) in ERCOT.
Wind has grown from 8-11% as share of total load (electricity demand), on avg, between 2011-2015.

Goal of incorporating 324 MWh of storage by 2020.
Cycles of wind power and storage dynamics

Average hourly load and wind generation in Texas for 2015

Storage helps smoothing demand and wind power cycles

Empirical Model.

\[
\begin{align*}
\text{Max}_{f, h} \left[ \sum_p \int_0^{f_ip + r_ip + h_ip} \left( a_p - b_p \cdot q_ip \right) dq_ip - \sum_p d \cdot e^{g f_ip} \right] \\
\text{s.t. } s_{t+1} = s_t - h_t \cdot (1 - \eta \cdot \lfloor 1^{h_ip < 0} \rfloor), \quad s_0 = 0, \quad h_t \leq s_t \leq s_{\text{max}} \quad r_ip \sim \text{iid}(n_p, \sigma_p^2)
\end{align*}
\]

Solve for optimal daily expected fossil generation, surplus, storage, welfare \( E(W_i^*) = E[S_i^* - (\text{MSC}(f_i^*) - \text{MC}(f_i^*)) \) and emissions \( E(Em_i(f_i^*)) \) using Monte Carlo simulations.

- Calibrate demand, marginal private and social costs using hourly data on load, generation, heat rate and emissions from EPA-CEMs, EIA and ERCOT. Marginal dmg estimates from social cost of carbon (US IAWG, 2015), SO\(_2\) and NO\(_x\) smoke stack emissions (Muller and Mendehlson, 2009)

- Draw \( r_ip \) from hourly wind power deciles uniform distribution and solve the maximization problem with CONOPT. (1000 draws)

- Simulate the heterogeneous generation effects of an increase in wind power capacity with decile regressions
Empirical model

The curves represent the wholesale electricity market private marginal cost and the social costs.

The most parsimonious calibration results use the exponential function.
Empirical Model.

Compute the marginal value of increasing wind power and storage under different emissions taxes and storage scenarios

1. No storage, no tax (baseline) $v_o(r_t)$
2. No storage, tax on all emissions $v_1(r_t)$
3. Storage, no tax $v_2(r_t)$
4. Storage, tax on all emissions $v_3(r_t)$

<table>
<thead>
<tr>
<th></th>
<th>No tax</th>
<th>With tax</th>
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<tbody>
<tr>
<td>Value of wind</td>
<td>$E \left( \frac{v_o(r_t + \Delta r_t) - v_o(r_t)}{\Delta r_t} \right)$</td>
<td>$E \left( \frac{v_1(r_t + \Delta r_t) - v_o(r_t)}{\Delta r_t} \right)$</td>
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<tr>
<td>Value of wind with storage</td>
<td>$E \left( \frac{v_2(r_t + \Delta r_t) - v_2(r_t)}{\Delta r_t} \right)$</td>
<td>$E \left( \frac{v_3(r_t + \Delta r_t) - v_2(r_t)}{\Delta r_t} \right)$</td>
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<tr>
<td>Value of storage</td>
<td>$E \left( \frac{v_2(r_t + \Delta sto) - v_o(r_t)}{\Delta storage} \right)$</td>
<td>$E \left( \frac{v_3(r_t + \Delta sto) - v_1(r_t)}{\Delta storage} \right)$</td>
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Levying emissions taxes decreases power arbitraging of coal offpeak power for natural gas peak power.

For 2015 wind power generation (11% of Load) and demand levels, the ideal storage/arbitrage is around 700 MWh more than double the official 2020 planned levels (324 GWh).
Preliminary results

Storage alone slightly increases the value of intermittent renewables (1.66 USD/MWh avg)

The largest increase in value comes from correcting the emissions externalities when allocating power.

Wind power first best value (165 USD/MWh) doubles its LCOE but second best does not (40 USD/MWh)

Estimates consider the benefits of avoided fossil generation cost, emissions offsets and arbitrage.
Preliminary results

Storage first best value (USD/kWh 472.91) covers its cost but a second best (adoptiong storage without emissions taxes) does not (USD/kWh 15).

The second best value is low due to the damages from substituting peak gas generation with off peak coal excessively when we don’t take into account their emissions externalities.
Two period model of storage, intermittent renewable energy and carbon taxes

Cyclical intermittency of renewable energy creates arbitrage incentives.

Taxing emissions leaves no room for deadweight losses that could be exacerbated by arbitraging.
Theoretical model of renewable energy and storage.

\[ \text{Max}_{f,h} = E_{op} \sum_{t=p,op} \beta^t \left[ \int_0^{f_t+r_t(\text{Cap})+h_t} P_t(Q_t) dq - C_t(f_t) - \tau e_t(f_t) \right] \]

s.t: \[ s_{t+1} = s_t - (1 - \eta \ast [1]^{h_{ip}<0})h_t, \quad s_0 = 0, \quad |h_{ip}| \leq |h_{max}| \]

- \( f_t \) fossil generation
- \( r_t \) is renewable generation, \( \text{Cap} \) renewable energy capacity, \( \eta \) storage efficiency
- \( h_t > 0 \) (discharge) \( h_t < 0 \) (recharge)
- \( \tau \) marginal damage of emissions

Optimal fossil fuel condition: \( P_t(Q_t) \geq C_t(f_t) + \tau e_t(f_t) \)

No arbitrage condition: \( P_t(Q_t) \leq \beta E_t[P_{t+1}(Q_{t+1})] \)

- Two periods: offpeak (op) and then peak (p).
- Peak demand is larger but, on average, there is more renewable power at the offpeak: \( E[r_{op}(\text{Cap})] > E[r_p(\text{Cap})] \)
- Renewables are a cyclic stochastic function of capacity: The random components are recurring iid variables for both periods.
15-18 minutes. 12 slides
Less text on slides

Theoretical framework. Set up results to explain main findings.
  Complementarity storage and taxes.
  Why largest value increase with tax? 4 times!
  Tax, reduction arbitrage free level,
  Increase emissions?

Social Merit order reordering plants show color in curves

Graph bar 12-24 bins storage. Wave curves with std. error bands
  Tax reduces need for storage, avoid coal arbitrage but complements in
  value IRE
Value IRE curve 11-15-20-25%. Compare only external benefits Novan

Increase value IRE and storage not enough to cover inv. Costs yet? Dispatch and
  carbon structure Texas. Compare to value only emissions Novan

Storage modelling mainly deals with smoothing daily cycles not short term
  randomness.
  Finding emissions? No carbon tax, storage.

Next steps? Operation reserves, Markov switching?
Preliminary results

Graph 6. Fossil generation and ideal storage allocation by period of the day.

In the scenarios with storage, all fossil generation tends to converge to the same level throughout the day (arbitraging of prices).

For 2015 wind power levels (11% of Load) the ideal storage/arbitrage levels range between 6.600 and 6.681 MW, on average, for the scenarios with and without tax respectively.

Levying emissions taxes decreases the optimal storage IRE (0.5-2 USD/MWh).

The largest increase in value is due to correcting for the emissions externality when allocating generation.
Proposed next steps

• Develop a new scenario with a tax on CO$_2$ only and not on local pollutants.

• Assess arbitrage levels and mg values of IRE and storage for different wind integration (12%-30% range, intervals of 5%) and storage adoption levels (324 MW-6600MW).

• Model more detailed time granularity of arbitrage decisions (12 or 24 bins within a day). Sensitivity analysis elasticity of D.

Use a time series unsupervised clustering methodology (Hidden Markov Models and Markov switching with 2015 data) to implement a detailed (realistic) simulation of the time horizon of the dynamic programming and value of wind power and storage.

• Incorporate operation reserves requirements in order to capture the increasing costs of wind power intermittency
Preliminary results

Levying emissions taxes decreases power arbitraging of coal offpeak power (hours 0-5) for natural gas peak power (18-22).

For 2015 wind power generation (11% of Load) and demand levels, the ideal storage/arbitrage is 16.9 and 20.6 GWh with and without emissions taxes, respectively. This is much larger than the official 2020 planned levels (0.3 GWh).
Data and methods

Wind generation explained by Wind Capacity WC plus hour and day effects.

\[ WG_t = \alpha + \sum_{h=0}^{23} \beta_{hw} \text{HOUR}_h \text{WC}_t + \alpha_d + \varepsilon_t \]

Different decile regressions for each period.

Decile generation effects of increasing wind capacity

WG. Wind generation explained by Wind Capacity WC plus hour and day effects. Different decile regressions for each period.
Wind has grown from 8-12% as share of total load (electricity demand), on avg, between 2011-2015.

Source: ERCOT, 2016
Background
Wind has grown from 8-12% as share of total load (electricity demand), on avg, between 2011-2015.

Goal of incorporating 324 MW of storage by 2020.
Average hourly load and wind generation in Texas for 2015

Substitution of off-peak, high-carbon coal generation for on-peak, low-carbon natural gas generation
Theoretical model of IRE and storage.

\[ \text{Max}_{f,h} = E_o \sum_{t=0}^{T} \beta^t \left[ \int_0^{Q_i} P_t(f_t + r_t(Cap) + h_t) dq - C_t(f_t) - \tau e_t(f_t) \right] \]

s.t: \[ s_{t+1} = \eta s_t - h_t \]

\[ s_t \geq 0 \]

\[ h_t < 0 \text{ (recharge),} \]

\[ \tau \text{ marginal damage of emissions } e_t(f_t) \]

IRE is a stochastic function of capacity \[ r_t = r_t(Cap) \]

Assume two periods (offpeak and then peak). Peak demand is larger but there is more IRE generation at the offpeak.

EXPLAIN ALL VARIABLES ABOVE!!

No constraints on storage/ideal arbitrage. Using backward induction, total welfare is:

\[ v_o^*(s_t, r_t) = \left\{ \int_0^{Q_i} P_o(f_o^*(Cap,\eta) + r_o + h_o^*(Cap,\eta)) dq - C_o(f_o^*(Cap,\eta)) - \tau e_o(f_o^*(Cap,\eta)) + \beta E_o \left[ \int_0^{Q_i} P_p(f_p^*(Cap,\eta) + r_p - \eta h_o^*(Cap,\eta)) dq - C_p(f_p^*(Cap,\eta)) - \tau e_p(f_p^*(Cap,\eta)) \right] \right\} \]

Assuming no uncertainty the value of IRE is given by:

\[ \frac{\partial v_o(r_t)}{\partial \text{Cap}} = \frac{\partial h_o^*}{\partial \text{Cap}} (P_o(\ast)(1-\eta)) + \frac{\partial r_o}{\partial \text{Cap}} P_o(\ast) + \beta \frac{\partial r_p}{\partial \text{Cap}} P_p(\ast) \]

Adding IRE capacity increases net welfare as long as the marginal value of generation increases overcomes storage losses.
Sustainable Energy

Tesla Just Added a Huge Stack of Batteries to the California Power Grid

Impressive as they are, the giant lithium-ion batteries probably aren’t the key to our energy future.

by Jamie Condliffe January 30, 2017

Tesla has just given California’s power grid a bit of backup.

A Texas startup's big energy idea: storing electricity underground

Quidnet Energy wants to make solar and wind energy more accessible by turning abandoned oil and gas wells into energy storage vaults.
Introduction

- What is the value of intermittent renewable energy (IRE) sources, such as wind and solar?
  - Reduce grid-level electricity generation costs and emissions.
  - Cyclical and random intermittency—difficult to integrate them to electric grids (Joskow, 2011; Baker et al., 2013).

- Assess the value of intermittent renewables by developing a stylized, welfare-maximizing dynamic model of the Texas (ERCOT) electricity market.
  - Previous studies (Sioshansi, 2011; Carson and Novan, 2013; Gowrisankaran et al, 2015; Cullen and Reynolds, 2016; De Sisternes et al., 2016) have not accounted for the dynamic interactions between storage capacity and emissions regulations in assessing the effect of intermittent renewables on welfare.

- Storage capacity and emissions taxes are complements in driving the value of wind.
- Compute the ideal storage-arbitrage levels for ERCOT
- Adopting large levels of storage, even with emissions taxes, can lead to an increase in pollution due to the substitution of off-peak, high-carbon coal generation for on-peak, low-carbon natural gas generation
Dynamic model of electricity generation and emissions

\[
Max_{f,h} = E_0 \sum_{t=0}^{T} \beta^t \left[ \int_0^{Q_i} P_t(f_t + r_t + h_t) dq - C_t(f_t) \right]
\]

s.t: \[ s_{t+1} = \eta s_t - h_t \]
\[ s_t \geq 0 \]

Using the Bellman equation (assuming linear Demand and Costs):

\[
v(s_t, r_t) = \max_{f,s} \left\{ \int_0^{Q_i} P_t(f_t + r_t + h_t) dq - C_t(f_t) + \beta E_t(v(s_{t+1}, r_{t+1}) | t) \right\}
\]

At the interior solution

Optimal fossil fuel condition: \[ P_t(f_t + r_t + h_t) = C_t'(f_t) \]

Storage/Arbitrage: \[ P_t(f_t + r_t + h_t) = \beta E_t(P_{t+1}(f_{t+1} + r_{t+1} + h_{t+1}) + G(\eta, h_{t+2}, h_{t+3}, ..., h_T)) \]

Where: \( f_t \) fossil fuel, \( h_t \) storage action level, Intermittent renewable energy \( r_t \)
Assuming no losses, total load is \( Q_t = f_t + r_t + h_t \)
St is the storage level

Simulate the effects of electricity storage and environmental taxes on generation, emissions, and the value of wind generation.

Renewable energy is modelled as a cyclic stochastic process (iid) with recurring realizations every day for each period \( t \).
Data and methods

4 time periods of the day (0-5, 6-11, 12-17, 18-23).

The curves represent the wholesale electricity market private marginal cost and the social costs.

The scheduler job is to dispatch plants according to the merit order based on private and social costs.

The most parsimonious calibration results use the exponential function. $R^2 > 0.98$
Data and methods

EPA and EIA hourly data for 2015 (8760 observations for 136 power plants)

Marginal damages:
*social cost of carbon (US IAWG, 2015),
*SO2 and NOx smoke stack emissions (Muller and Mendehlson, 2009)

I calibrate the Marginal Social Cost of electricity generation for the wholesale market using hourly plant level emissions
Data and methods

\[ \text{Decile}_\tau (WG_i | X_i) = \alpha(\tau) + WC_i \beta_1(\tau) + \text{Hour} \beta_2(\tau) + \text{Day} \beta_3(\tau) \]

WG. Wind generation explained by Wind Capacity WC plus hour and day effects.
Different decile regressions for each period.
Simulations and intended results

- Compute allocations, emissions and welfare for different storage levels (ERCOT planned 324 MW up to ideal) and renewable energy levels (12-30%) under the following scenarios:
  a. No storage, no tax
  b. No storage, tax on all emissions (CO2, NOx and SO2)
  c. Storage, no tax
  d. Storage, tax on all emissions (CO2, NOx and SO2)
Monte Carlo simulation implementation

\[
Max_{f,s} = \left[ \sum_p \int_0^{Q_i} a_p - b_p \left( f_{ip} + r_{ip} + s_{ip} \right) dq - \sum_p d \cdot e^{g f_{ip}} \right]
\]

\[s.t: \sum_i s_{ip} = 0 \quad r_i \sim \text{iid} \left( \bar{r}_i, \sigma_i^2 \right) \quad |s_i| \leq smax\]

*Assume all information on wind generation is revealed at the start of the day

*For each random draw \((i)\), based on wind power deciles for each representative hour, solve the maximization problem with GAMS-CONOPT

* 1000 random draws

---

**No storage scenarios**

- Find optimal expected fossil gen \(E(f_i^*)\) and welfare in the case of the model with MSC \(E(W_i^*)\).

- For the model with no emissions taxes the optimization renders the surplus \(S^*\) and we compute welfare subtracting the externality:
  \[E(W_i^*) = E[S_i^* - (MSC(f_i^*) - MC(f_i^*))]\]

- Compute emissions using the polynomial fn.
  \[E(Em_i(f_i^*))\]

**Storage scenarios**

- For the case of ideal storage, solve the maximization problem without any constraint on \(s_i\). For the ERCOT planned storage, constrain \(s_i \leq 324\)

- Similarly, find optimal expected fossil gen, storage, surplus and welfare.

- Compute emissions using the polynomial fn.
Preliminary results

Fossil generation and ideal storage allocation by period of the day

In the scenarios with storage, all fossil generation tends to converge to the same level throughout the day (arbitraging of prices).

For 2015 wind power levels (11% of Load) the ideal storage/arbitrage levels range between 6.600 and 6.681 MW, on average, for the scenarios with and without tax respectively.

Levying emissions taxes decreases the optimal storage

Graph 24, 12 bars charging action, curve value IRE
Preliminary results

In 2015, the full economic value of wind power was around 140 USD/MWh (current situation with neither storage nor tax).

Adding emissions taxes triples the value of wind capacity and generation.

Adding ideal storage means a six fold increase and combining storage and taxes yields a nine fold increase.

Need to consider operation reserve costs.
Thank you

Simulate the effects of electricity storage and environmental taxes on generation, emissions, and the value of wind generation.

Dynamic model of electricity generation and emissions

\[
Max_{f,h} = E_0 \sum_{t=0}^{T} \beta^t \left[ \int_0^{Q_i} P_t(f_t + r_t + h_t) dq - C_t(f_t) \right]
\]

s.t: \[ s_{t+1} = \eta s_t - h_t \]
\[ s_t \geq 0 \]

Using the Bellman equation (assumer linear Demand and Costs):

\[
v(s_t, r_t) = max_{f, s} \left\{ \int_0^{Q_i} P_t(f_t + r_t + h_t) dq - C_t(f_t) + \beta E_t(v(s_{t+1}, r_{t+1}|t) \right\}
\]

At the interior solution:

Optimal fossil fuel condition: \[ P_t(n_t^{FF} + n_t^{RE} + h_t) \leq C_t(n_t^{FF}) \]

And arbitrage

\[
P_t(n_t^{FF} + n_t^{RE} + h_t) \leq \beta E_t(P_{t+1}(n_{t+1}^{FF} + n_{t+1}^{RE} + h_{t+1})|t \in \{peak, off peak\})
\]

Where: \( f_t \) fossil fuel, \( h_t \) storage action level, Intermittent renewable energy \( r_t \)
Assuming no losses, total load is \( Q_t = f_t + r_t + h_t \)
St is the storage level

Simulate the effects of electricity storage and environmental taxes on generation, emissions, and the value of wind generation.

Renewable energy is modelled as a cyclic stochastic process (iid) with recurring realizations every day for each period t.

Renewable energy is modelled as a cyclic stochastic process (iid) with recurring realizations every day for each period t.
Simulations and intended results

- Compute allocations, welfare and emissions for the social planner problem for different storage levels (ERCOT planned 324 MW and ideal welfare maximizing level) and renewable energy levels (2015 and up to 30% of total demand) under 6 scenarios:
  a. No storage, no tax
  b. No storage, tax on CO2 only
  c. No storage, tax on CO2, NOx and SO2
  d. Storage, no tax
  e. Storage, tax on CO2 only
  f. Storage, tax on CO2, NOx and SO2

- Assess the dynamic value of increasing 1 MW storage capacity vs 1 MW wind capacity for the above scenarios.
  - Externality reduction (emissions), merit order effect (fossil fuel substitution and cost reduction) and storage contribution captured in the welfare increase between the expected outcome with baseline wind vs the simulated outcome with increased capacity:
    \[ E\left(W_i^*(wind + \delta MW)\right) - E\left(W_i^*(wind_0)\right) \]
    \[ \frac{\delta MW}{\delta MW} \]
Data and methods: MC simulation for dynamic value of wind

\[ \text{Max}_{f,s} = \left[ \sum_{i} \int_{0}^{Q_i} a_i - b_i \ast (f_i + r_i + s_i) dq - \sum_{i} d \ast e^{g f_i} \right] \]

s.t: \[ \sum_{i} s_i = 0 \]
\[ r_i \sim iid(\bar{r}_i, \sigma_i^2) \]
\[ |s_i| \leq smax \]

*For each random draw (i), based on wind power deciles for each representative hour, solve the maximization problem with GAMS-CONOPT

No storage scenarios

- Find optimal expected fossil gen \( E(f_i^*) \) and welfare in the case of the model with MSC \( E(W_i^*) \).
- For the model with no emissions taxes the optimization renders the surplus \( S^* \) and we compute welfare subtracting the externality:
  \[ E(W_i^*) = E[S_i^* - (MSC(f_i^*) - MC(f_i^*))] \]
- Compute emissions using the polynomial fn.
  \[ E(Em_i(f_i^*)) \]

Storage scenarios

- For the case of ideal storage, solve the maximization problem without any constraint on \( s_i \). For the ERCOT planned storage, constrain \( s_i \leq 324 \)
- Similarly, find optimal expected fossil gen, storage, surplus and welfare.
- Compute emissions using the polynomial fn.
Implementing storage and emissions taxes lead to the most efficient outcome by properly accounting for the externality related deadweight loss and for the flexibility in allocating energy when it is most valuable.
Preliminary results

Fossil generation and 324 MW of storage allocation by period of the day

With constrained storage we see a smaller reduction in fossil generation.
Preliminary results

Adding a tax decreases all emissions in all scenarios.

Ideal storage scenarios
Having storage in addition to emissions taxes increases all emissions slightly since the benefits of arbitraging electricity compensate for the externality damages caused by substituting peak gas generation with base coal generation.

Only NOx emissions increase in the scenario with storage compared to the current baseline. Arbitraging coal for gas steam turbines (large Nox emissions factor, 1.6 lbs/MWh).
If we are not willing to assume that all information on wind generation is revealed at the start of the day, then the true optimal solution is found with

\[ v(s_t, r_t) = \max_{f,s} \left\{ \int_0^{Q_i} [a_i - b_i * (f_i + r_i + h_i)] dq - c f_i^2 + \beta E_t(v(s_{t+1}, r_{t+1})|t) \right\} \]

And the difference between the static and dynamic optimization results is the option value related to using storage. Charging/discharging now vs waiting for stochastic realizations and postponing the decision to future periods.

Using expected realization, the certainty equivalent result with linear demand and costs give an option value of around USD 1 million or 1.13% of total welfare.

Optimal storage increases from 5.9 GW to 6.4 GW, incentive to charge more given uncertainty in wind power realizations.
Next steps

• Run several simulations with incremental levels of storage (from 0 to ideal) to plot the value of wind power for different wind integration levels (12%-30% range)

• Constraint on borrowing electricity throughout time! In option value solution

• Why with iid is there an option value?!

• Incorporate operation reserves cost to add detail on the increasing costs wind power intermittency
  • Startup and ramping costs, coal power plants might change Marginal Cost Curve (Dr. Herriges, argument)

• Run Monte Carlo simulations for wind power realizations with the dynamic solution (option value) for ideal storage levels.
• Texas electricity grid and market (ERCOT) >1% hydropower, and marginal imports

• Wind has grown from 8-12% share of total load, on avg, between 2011-2015

• Ideal case study to simulate effects of future storage

• Goal of incorporating 324 MW of storage by 2020

• Emerging initiatives and technologies for storage

• SHOW LOAD IN GRAPH, INTUITION, HIGHER LOAD PEAK AND LESS WIND.
An electric grid powered primarily by renewable energy is one of the proposed alternatives for reducing air pollution and GHG.

There are some encouraging efforts:

* Several state level renewable portfolio standard policies RPS and feed in tariff schemes
* CAISO goal of integrating 33% RE generation by 2020

Solar went from 1% to 7% and wind from 3% to 6% between 2011-2015 in California
Literature review

• Short run benefits of IRE: displaced generation (merit order effect) and emissions.

• Benefits reduced by intermittency of wind and solar power—both cyclical and random—can make it difficult to integrate these sources into conventional electric grids (Joskow, 2011; Baker et al., 2013).

• Storage can ease IRE integration and increase the benefits but it could also lead to an increase in total CO₂ emissions, by facilitating the substitution of off-peak, high-carbon coal generation for on-peak, low-carbon natural gas generation (Carson and Novan, 2013).
Literature review

• Previous literature:
  • costs of intermittency (Gowrisankaran et al, 2016),
  • the impact of storage on generation and investment in generating capacity (De Sisternes et al., 2016),
  • the value of wind generation in the presence of storage under market power (Sioshansi, 2011),
  • and the long-term dynamic effects of carbon taxes on electricity markets (Cullen and Reynolds, 2016).

• Need to account for the interactions between storage capacity and emissions regulations in assessing the performance of intermittent renewables.
Static version of dynamic intraday storage problem

If we are willing to assume that all information on wind generation is revealed at the start of the day, we get:

\[ \text{Max}_{f,s} = E_0 \sum_{t=0}^{T} \beta^t \left[ \sum_{i=1}^{Q_i} P_i (f_i + r_i + s_i) da - \sum_{i=24} C(f_i) \right] \]

s.t. \[ \sum_{i=1}^{4} s_i = 0 \quad \text{(storage lasts no longer than a day)} \]

\[ r_i \sim iid(\bar{n}_i, \sigma^2_i) \]

\[ |s_i| \leq \text{smax} \quad \text{In the case of constrained storage} \]
Using the demand bins, I obtain the deciles of wind power generation for each period in day based on 2015 data.

These deciles are used in a Monte Carlo simulation aimed at finding the expected welfare and allocations of 1000 random draws.

In order to simulate the differentiated impact of increasing wind capacity on generation throughout the day, I use decile regressions of wind power generation on installed capacity:
For example at the second period, the value function looks like:

\[
v(s_1, r_1) = \max_{f, h} \int_0^T \left[ a_1 - b_1 \left( f_1 + r_1 + h_1 \right) \right] dq - c f_1^2
\]

\[
+ \beta E_t \left[ \left\{ \begin{array}{l}
a_2(f_2 + r_2 + h_2) - \frac{b_2}{2} \left( f_2 + r_2 + h_2(s_2, r_2) \right)^2 - c \left( \frac{a_2 - b_2 \left( r_2 + h_2(s_2, r_2) \right)}{2c + b_2} \right)^2 + \\
\beta E_t \left[ \left\{ \begin{array}{l}
a_T \left( a_T + 2c \left( r_T + s_T - \eta h_2(s_2, r_2) \right) \right) - b_T \left( a_T + 2c \left( r_T + s_T - \eta h_2(s_2, r_2) \right) \right) \right] \right) - c \left( \frac{a_T - b_T \left( r_T + s_T - \eta h_2(s_2, r_2) \right)}{2c + b_T} \right)^2
\end{array} \right) \right) \right) \right) \right)
\]

We solve all the way to the first period and we will find the optimal allocations and welfare (value function at initial time period).
Static version of dynamic intraday storage

Effect of tax and renewable generation change on eq (given usual cost and demand function assumptions):

\[
\begin{bmatrix}
\frac{\delta f_o^*}{\delta \tau} & \frac{\delta f_o^*}{\delta r_o} \\
\frac{\delta f_p^*}{\delta \tau} & \frac{\delta f_p^*}{\delta r_o} \\
\frac{\delta s_o^*}{\delta \tau} & \frac{\delta s_o^*}{\delta r_o}
\end{bmatrix}
= \left(-\frac{1}{\det > 0}\right) \begin{bmatrix}
(C''P_o' + C''P_p' - P_p'P_o')e_o' - P_p'P_o'e_p' & 2P_p'P_o'r^2 - C''P_o'^2 - C''P_p'P_o' \\
(C''P_o' + C''P_p' - P_p'P_o')e_p' - P_p'P_o'e_o' & 2P_p'P_o'r^2 - C''P_p'P_o' \\
P_p'P_o'(e_o' + e_p') - C''P_p'e_p' & C''^2P_o'^2 - C''P_p'P_o' - C''P_o'^2
\end{bmatrix}
\]

Adding or increasing emissions taxes on fossil generation, decrease its allocation on both periods and affect the optimal storage.

In this case, offpeak storage so was defined to be negative charging period. Thus an increase means that the optimal recharge actually decreases. Overall, charging capacity decreases with an emissions tax in order to prevent emissions arbitraging between periods (coal for gas)

Increasing offpeak renewable energy (ro) decreases fossil generation (merit order effect) and increases the negative amount (recharge) stored in the offpeak (so) due to the change in relative peak and offpeak prices (indirect merit order effect).