Accommodating Renewable Generation Sources on the Grid

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Growth of wind and solar generation

- Wind and solar PV are now the main sources of new generating capacity additions to grids in many developed countries
  - Wind: mostly wholesale level, solar PV:mostly the retail level
- In many cases, they are supported by:
  - Investment tax credits
  - Renewable energy mandates
  - Production subsidies or tax credits
  - Subsidized grid expansions and distribution system upgrades
  - Exemptions from planning, zoning, wildlife, site remediation and other laws
- But there have also been large reductions in their levelized costs (LCOE) through learning by doing, and also explicit R&D
Wind lowers wholesale prices when generating
Negative prices

- Wind generation *production* subsidies can give negative wholesale prices
  - Generators will bid up to the negative of the explicit or implicit production subsidy to be allowed to generate
- Negative prices should also reduce average wholesale prices
- But negative prices also impose costs on thermal generators that have inflexible output or substantial ramping costs
- More generally, the merit order effect is a short-run phenomenon
  - Reduced revenue to thermal capacity leads to plant exit or discourages entry
European real household electricity prices 2007-2016

\[ p = 0.158 - 0.156 N - 0.067 HL + 0.131 GT + 0.164 W + 0.253 S + 0.054 E \]

- \( p \) = Real household electricity price per kWh for households consuming 5–15MWh pa
- \( N \) = nuclear capacity as fraction of total
- \( HL \) = large hydro (>10MW) capacity as fraction of total
- \( GT \) = gas turbine capacity as fraction of total
- \( W \) = wind capacity as fraction of total
- \( S \) = solar (thermal + PV) capacity as fraction of total
- \( E \) = 1 if former east European country, 0 otherwise

- \( R^2 \) (overall) = 0.5335, \( R^2 \) (within) = 0.4996, \( R^2 \) (between) = 0.5414
- Fraction of variance due to country effects = 0.7654
- Joint test of significance of coefficients \( \chi^2(6) = 224.23 \)

- 23 countries in sample: Austria, Belgium, Bulgaria, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Lithuania, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom
Australian retail electricity, gas prices

Source: Australian Bureau of Statistics, and Department of Environment and Energy
Australian gas price and gas use in electricity generation

Source: Australian Bureau of Statistics, and Department of Environment and Energy
Systemic issues with wind generation

- Time of day correlation with load
- Seasonal correlation with load
- Short-term instability
  - Frequency control
  - South Australian episodes following both high and low wind speeds
  - Texas events with passing cold fronts
- Remoteness and long transmission links
  - CREZ zones in Texas – $7 billion transmission upgrade
  - Transmission system fragility in Australia
  - Capacity factors on transmission links
Typical wind power curve 1500kW rating
Systemic issues with solar PV

- Wholesale versus retail competition with natural gas in NW Australia
- Economics of wholesale versus retail competition
  - Why isn’t it like growing your own tomatoes?
  - Fixed costs rolled into marginal charge
  - Equity aspect and why high demand customers install PV
  - A fixed plus a variable charge is common for club goods
- Exacerbated by net metering
- Costs of network upgrades to accommodate solar
- In some parts of Australia:
  - No more solar PV is allowed to be installed
  - “Belly of the duck” is about to hit the ground
  - Excessive voltages from solar power are raising costs for some non-PV customers and have damaged their appliances
Are LCOE calculations misleading?

- LCOE implicitly assumes that the value of the generated power is irrelevant to the competitiveness of the different sources
  - But as Joskow has noted, the critical issue is value of output minus cost
- Papers by Hirth and others have shown that the wholesale prices that renewable generators receive decline as more renewable generators using the same energy source are added to a system
  - Renewable generation “fouls its own nest”
- In addition, as the share of wind in particular rises, short-run variability of its output imposes grid stabilization and reserve power plant costs that are not part of the LCOE calculation
Dynamics of renewables entry

- In a recent paper, Green and Léautier develop a simple theoretical model to examine systemic effects of subsidized renewable energy (RE).
  - They show that the subsidy needed to support RE can spiral out of control.
- All RE of a given type receives low prices when that RE is generating.
  - This also tends to displace thermal capacity via the merit order effect.
- When RE is not generating, electricity demand falls as the subsidy-inclusive electricity price rises, which further reduces thermal capacity.
- If RE capacity becomes large enough, a discontinuity occurs when no thermal technology is generating at those times when RE is generating.
- Baseload then stops setting marginal prices when RE is generating and the required subsidy to RE rises dramatically.
Backup for renewables is the key issue

- What about the Denmark success story?
  - Large scale hydro ("the Scandinavian battery") provided critical support
  - Trade can be an alternative to "domestic backup"
  - Even so, Denmark often sells when the price is low, buys when its high

- Pumped storage
  - Currently 99% of bulk electricity storage
  - Approximately 80% round-trip efficiency
  - Topography is a critical limitation

- Batteries
  - 50% higher LCOE than pumped storage under generous assumptions
  - Some problems: Leakage, deterioration over time
  - More suited to provide ancillary services than seasonal storage
  - Mining boom in Australia for battery materials – what does it tell you?
Natural gas as backup

- Texas (ERCOT) experience with wind has been more favorable than the European and Australian experiences discussed earlier
  - More than 22GW wind; 0.46GW non-dispatchable and 0.09GW dispatchable hydro; 1.75GW of solar; less than 0.09GW of battery storage
  - About 66.5GW of thermal; of which 5.06 is nuclear; 14.25 is coal; remainder mostly natural gas
- Critical supporting factor: Low cost natural gas
- Australian expansion of RE coincided with opening to LNG exports and simultaneous bans on onshore natural gas E&P in much of SE Australia
- In Europe, natural gas prices from Russian imports are also high
US and Texas electricity rates

Source: Energy Information Administration
Real electricity rates and natural gas prices

Source: Energy Information Administration
Henry Hub versus UK NBP price

Source: Energy Information Administration
Long-run transition from fossil fuels

- Simplified model of transition to non-fossil fuel generation
- Study was done using 2016 data from ERCOT
- Take EIA representative technology costs for onshore wind, nuclear, natural gas (CC and GT) and pumped storage
  - Since Texas is not suitable for pumped storage, this effectively assumes that battery cost and performance can be improved to pumped storage levels
  - Also note that nuclear LCOE was much higher than wind LCOE
Wind capacity factor and ERCOT load, 2016

Source: ERCOT
**Solutions for costs in long-run systems without natural gas**

<table>
<thead>
<tr>
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<th>WACC 0.05</th>
<th>WACC 0.075</th>
<th>WACC 0.10</th>
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<td><strong>Nuclear and storage</strong></td>
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<tr>
<td>Annual cost ($b)</td>
<td>29.875</td>
<td>39.798</td>
<td>50.286</td>
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<td>Average cost (¢/kWh)</td>
<td>11.46</td>
<td>15.27</td>
<td>19.293</td>
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<tr>
<td><strong>Wind and storage</strong></td>
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<td>Annual cost ($b)</td>
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<tr>
<td>Average cost (¢/kWh)</td>
<td>15.13</td>
<td>19.49</td>
<td>24.171</td>
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</table>

- Key explanation: Wind plus storage system needs 2x storage
  - With nuclear, storage smooths load; with wind both load and generation
  - Effectively storage has to cover load *minus* generation at all times
Storage with nuclear
Storage with wind

![Graph showing energy stored or produced from storage (GWh) over time.](image)
Natural gas included in the system

- Now solve a linear program to minimize costs subject to
  - Demand and storage constraints, and
  - A reserve plant margin constraint (10% above maximum hourly load)
- Scale up actual 2016 hourly wind generation amounts with capacity
- Choice variables:
  - Multiple for wind capacity and outputs
  - Capacities of other types of plants and their hourly outputs
  - Electricity used in pumping or generated from stored water in each hour
Hourly load and example solution for outputs
Transition with WACC = 7.5%
Transition with WACC = 7.5% (detail)
Transition with WACC = 10% (detail)
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Transition with WACC = 5%

Cost or fuel use relative to 2016 natural gas price

Multiple of 2016 natural gas price

Capacity (GW)
- Storage
- Nuclear
- GT
- CC

Cost or fuel use relative to 2016 natural gas price
- cost
- fuel use
## Constraining wind capacity to zero

<table>
<thead>
<tr>
<th>r = .075</th>
<th>( p_{NG} = 9.22 )</th>
<th>( p_{NG} = 9.40 )</th>
<th>( p_{NG} = 10.12 )</th>
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<tbody>
<tr>
<td></td>
<td>( \omega ) free</td>
<td>( \omega = 0 )</td>
<td>( \omega ) free</td>
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<tr>
<td>Average cost (¢/kWh)</td>
<td>8.11</td>
<td>8.11</td>
<td>8.20</td>
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<tr>
<td>CC capacity (GW)</td>
<td>52.040</td>
<td>54.188</td>
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<td>GT capacity (GW)</td>
<td>25.405</td>
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<td>Wind capacity (GW)</td>
<td>6.428</td>
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<td>Nuclear capacity (GW)</td>
<td>0</td>
<td>0</td>
<td>10.265</td>
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<tr>
<td>Fuel used (10(^15)BTU)</td>
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<td>2.234</td>
<td>1.228</td>
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<table>
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<th>r = .10</th>
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<th>( p_{NG} = 11.57 )</th>
<th>( p_{NG} = 12.29 )</th>
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<tr>
<td></td>
<td>( \omega ) free</td>
<td>( \omega = 0 )</td>
<td>( \omega ) free</td>
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<tr>
<td>Annual cost ($b)</td>
<td>34.440</td>
<td>34.580</td>
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<tr>
<td>Average cost (¢/kWh)</td>
<td>9.80</td>
<td>9.84</td>
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<tr>
<td>CC capacity (GW)</td>
<td>42.583</td>
<td>53.660</td>
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<td>Wind capacity (GW)</td>
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<tr>
<td>Nuclear capacity (GW)</td>
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<td>0</td>
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<tr>
<td>Fuel used (10(^15)BTU)</td>
<td>1.503</td>
<td>2.236</td>
<td>1.407</td>
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Some key implications

- At 7.5% or 10% WACC, wind becomes competitive first
  - When natural gas backup is relatively cheap, wind plus gas is less costly
- Whilst only natural gas is used, the elasticity of cost with respect to $p_{NG}$ is more than 40x elasticity of fuel use
- Entry of wind and/or nuclear displace CC more than GT
- Nuclear is more effective at cutting natural gas use than is wind
  - GT capacity, and CC/GT capacity factors, are higher with wind
- Total system capacity is much higher with wind than nuclear
- Substantial wind capacity is included over a small range of $p_{NG}$ prices
  - Even so, constraining wind to zero does not raise costs very much
World primary energy consumption by source

Source: BP Statistical Review of World Energy
Expected energy demand growth is where low cost is important
Can nuclear power be the long-run solution?

- Major advantage: high energy density
- But large nuclear plants are expensive and risky for utilities to build, and current plants have proliferation and waste disposal risks
- Technological developments that could make nuclear less costly, safer (passive control) or eliminate most waste (including Pu by-products)?
  - Small scale modular plants
  - Thorium-based reactors, including the dual fluid reactor
  - ITER or other (private) controlled hydrogen fusion efforts
  - Fusion of boron or other elements higher up the periodic table
  - Laser separation of isotopes
- We also need electric vehicles to displace combustion engine vehicles
- Air transport – maybe hydrogen?