Effect of resource availability and grid integration on wind energy development

GOKUL IYER, HAEWON MCJEON, AND LEON CLARKE

Snowmass meeting
GCAM: The Global Change Assessment Model

- GCAM is a **global integrated assessment model**
- GCAM links **Economic, Energy, Land-use, and Climate** systems
- Emissions of **16 greenhouse gases and short-lived species**: CO$_2$, CH$_4$, N$_2$O, halocarbons, carbonaceous aerosols, reactive gases, sulfur dioxide.
- Runs through **2095 in 5-year time-steps**.
- GCAM is implemented using **object-oriented programming**, providing a robust and flexible platform for future work.
- Documentation available at: [wiki.umd.edu/gcam](http://wiki.umd.edu/gcam)

- **14 Region Energy/Economy Model Regions**
- **151 Agriculture and Land Use Model Regions**

**Started in 1978** – a DOE-SC investment to address the need for an explicit research tool to assess the link between human energy systems and carbon emissions (part of the Carbon Cycle Program back then).

- **1984 first integration of GCAM** (then called Edmonds-Reilly) with the DOE carbon cycle model.
- Formerly known as **MiniCAM**

July 22, 2013
Some Themes from Last Year’s Talk
The bias against high wind speeds in the reanalysis dataset limits the estimates of the cheapest wind.
Sensitivity of wind energy potential

- Wind Speed
- Roughness
- Turbine Height
- Turbine Density
- Land Suitability
- Turbine Cost
- Finance Rate
- Transmission Cost

Deviation of Wind Potential from Central Scenario (pWh)

- Optimistic: <$0.06/kWh, <$0.09/kWh
The bias against high wind speeds in the reanalysis dataset limits the estimates of the cheapest wind.

In three of the four comparison regions examined in this study, the CFSR data set used here missed 90% of the area with winds power class 5 and above.

Wind energy supplies at less than 9 cents/kWh are quite large in many regions relative to projected electricity demand. In other regions, wind supplies are more constrained.
Wind integration in GCAM
For the U.S., GCAM splits the load duration curve into four segments.

- The load duration curve divided into 4 segments: off-peak, intermediate, subpeak, and peak
  - Note that the load duration curve does not currently respond to changes in demand sectors.
- We have built a prototype implementation of this approach internationally, but we are currently using a single market with two wind options.
  - One issue is how to think about load duration curves outside of the U.S.

Illustrative conception of load duration curve.
Baseload generation supplies to all four sectors; intermediate to three, sub-peak to two, and peak to one.

Each technology is assigned to a specific horizontal segment:

- For example, nuclear power supplies only to baseload; wind supplies baseload; solar PV w/o storage supplies subpeak; CSP w/ thermal storage is intermediate.
- Some technologies (gas, coal) can supply more than one segment, but with different capacity factors.

System storage (modeled as battery) buys from one vertical segment and sells to another.
Backup requirements for intermittent resources

- Increasing wind penetration means you need more backup generation
- We typically assume gas turbine backup, but we have assumed storage based backups as well.
  - Backup requirements increase with increase in share of renewables (not just wind)

<table>
<thead>
<tr>
<th>Backup requirement</th>
<th>Base case</th>
<th>Mid-share (share =0.5)</th>
<th>Capacity limit (share =0.9)</th>
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<tbody>
<tr>
<td>Backup Ratio</td>
<td>25%</td>
<td>0.9</td>
<td>0.5</td>
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\[ Backup Ratio = \frac{1}{1 + e^{Midshare - elecshare}} \]
Renewable initiatives Scenarios
No Policy

- Standard model assumptions (business as usual)
- No carbon price
- Standard wind supply curve

No Policy Electricity generation mix

| Year | Coal|w/ CCS | Coal|w/o CCS | Oil|w/ CCS | Oil|w/o CCS | Gas|w/ CCS | Gas|w/o CCS | Biomass|w/ CCS | Biomass|w/o CCS | Nuclear | Hydro | Wind | Solar | Geothermal |
|------|-------|--------|--------|--------|--------|--------|--------|--------|---------|---------|---------|---------|-------|-------|-------|-----------|
| 2010 |       |        |        |        |        |        |        |        |         |         |         |         |       |       |       |           |
| 2020 |       |        |        |        |        |        |        |        |         |         |         |         |       |       |       |           |
| 2030 |       |        |        |        |        |        |        |        |         |         |         |         |       |       |       |           |
| 2040 |       |        |        |        |        |        |        |        |         |         |         |         |       |       |       |           |
| 2050 |       |        |        |        |        |        |        |        |         |         |         |         |       |       |       |           |
| 2060 |       |        |        |        |        |        |        |        |         |         |         |         |       |       |       |           |
| 2070 |       |        |        |        |        |        |        |        |         |         |         |         |       |       |       |           |
| 2080 |       |        |        |        |        |        |        |        |         |         |         |         |       |       |       |           |
| 2090 |       |        |        |        |        |        |        |        |         |         |         |         |       |       |       |           |
| 2100 |       |        |        |        |        |        |        |        |         |         |         |         |       |       |       |           |

Characterized by rapid development of fossil fuels

And growth in emissions
Flagship

- Standard model assumptions
- Carbon Price policy

![Carbon Price Chart]

Carbon Price in 2005 $/tCO₂
Standard model assumptions

Carbon Price policy

Standard wind supply curve
New Wind

- Wind supply curve based on NREL estimates of Wind power potential
  - Based on the NCAR’s Climate Four Dimensional Data Assimilation (CFDDA) database

- Protected, urban, and high-elevation areas are excluded in the data

- Data by country, resource quality and distance to nearest large load or power plant

Assumes turbines are operational all the time and that no energy is lost due to closeness of turbines.
- Standard model assumptions

- Carbon price policy
  - Same as “Flagship”

- Nuclear phase-out and no CCS
Increasing wind penetration means you need more backup generation.

We typically assume gas turbine backup, but we have assumed storage based backups as well.

- Backup requirements increase with increase in share of renewables (not just wind)

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**Backup Ratio**

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\text{Backup Ratio} = \frac{1}{1 + e^{\text{Midshare} - \text{elecshare}}}
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Backup Ratio = \( \frac{1}{1 + e^{\text{Midshare} - \text{elecshare}}} \)
Increasing wind penetration means you need more backup generation.

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![Backup requirements chart](chart.png)

Backup Ratio = \( \frac{1}{1 + e^{\text{Midshare} - \text{elecshare}}} \)

- Base case:
  - Mid-share (share = 0.5): 25%
  - Capacity limit (share = 0.9): 29%

- Generous:
  - Mid-share (share = 0.5): 35%
  - Capacity limit (share = 0.9): 39%

- Strict:
  - Mid-share (share = 0.5): 15%
  - Capacity limit (share = 0.9): 19%

More backup required for a given share of renewables.
Results
Global Electricity generation

- **Flagship**
  - More wind

- **Generous RE Integration**
  - Less wind

- **Nuke phase-out, no CCS**
  - Dramatic expansion of renewables

- **Strict RE Integration**
  - Less wind
Global wind Electricity generation

Wind electricity generation

- Flagship
- New Wind
- No Policy
- RE
- Generous RE Integration
- Strict RE Integration

Less wind with new curve because new supply curve has lower resource for a given price
Global wind Electricity generation

Wind electricity generation

[1EJ]

- Flagship
- New Wind
- No Policy
- RE
- Generous RE Integration
- Strict RE Integration

More wind in generous integration
Global wind Electricity generation

Wind electricity generation

- Flagship
- New Wind
- No Policy
- RE
- Generous RE Integration
- Strict RE Integration

Less wind in strict integration
Global wind Electricity generation

Wind electricity generation

- Flagship
- New Wind
- No Policy
- RE
- Generous RE Integration
- Strict RE Integration

Increased demand for wind with nuke phase out and no CCS
Effect of new supply curves on regional wind electricity generation

USA wind electricity

<table>
<thead>
<tr>
<th>Year</th>
<th>USA Wind Supply Curves</th>
<th>Price (2010 cents/kWh)</th>
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<tbody>
<tr>
<td>2010</td>
<td>Flagship</td>
<td>5</td>
</tr>
<tr>
<td>2020</td>
<td>New Wind</td>
<td>5</td>
</tr>
<tr>
<td>2030</td>
<td>Flagship</td>
<td>6</td>
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<tr>
<td>2040</td>
<td>New Wind</td>
<td>7</td>
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<tr>
<td>2050</td>
<td>Flagship</td>
<td>8</td>
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<tr>
<td>2060</td>
<td>New Wind</td>
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<td>2070</td>
<td>Flagship</td>
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China wind electricity

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<td>New Wind</td>
<td>3</td>
</tr>
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<td>2030</td>
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Less wind with new curve

Because new curve has less resource for a given price
Effect of integration limits on regional Wind electricity generation

Generous RE Integration

- Western Europe
- Southeast Asia
- Middle East
- Latin America
- Korea
- Japan
- India
- Former Soviet Union
- Eastern Europe
- China
- Canada
- Australia_NZ
- Africa
- USA

2050

Strict RE Integration

- Western Europe
- Southeast Asia
- Middle East
- Latin America
- Korea
- Japan
- India
- Former Soviet Union
- Eastern Europe
- China
- Canada
- Australia_NZ
- Africa
- USA

2100

Change in wind electricity generation wrt Flagship case

Integration limits make a bigger difference in 2100.
Effect of integration limits on regional Wind electricity generation

Generous RE Integration

- Western Europe
- Southeast Asia
- Middle East
- Latin America
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- Eastern Europe
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- USA

Strict RE Integration

- Western Europe
- Southeast Asia
- Middle East
- Latin America
- Korea
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- India
- Former Soviet Union
- Eastern Europe
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- Canada
- Australia_NZ
- Africa
- USA

Change in wind electricity generation wrt Flagship case

Restricting integration makes more difference
Effect of integration limits on regional Wind electricity generation

**Generous RE Integration**

- Western Europe
- Southeast Asia
- Middle East
- Latin America
- Korea
- Japan
- India
- Former Soviet Union
- Eastern Europe
- China
- Canada
- Australia_NZ
- Africa
- USA

**Strict RE Integration**

- Western Europe
- Southeast Asia
- Middle East
- Latin America
- Korea
- Japan
- India
- Former Soviet Union
- Eastern Europe
- China
- Canada
- Australia_NZ
- Africa
- USA

**Change in wind electricity generation wrt Flagship case**

- Generous integration does not matter for some big players
Effect of integration limits on regional Wind electricity generation

Generous RE Integration
- Western Europe
- Southeast Asia
- Middle East
- Latin America
- Korea
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- India
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- Eastern Europe
- China
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Strict RE Integration
- Western Europe
- Southeast Asia
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- Eastern Europe
- China
- Canada
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Change in wind electricity generation wrt Flagship case

Makes a bigger difference because share of renewables is as high as 30%
## Regional Change in Wind Production

### Advanced Resource

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<thead>
<tr>
<th>Region</th>
<th>2095</th>
<th>2050</th>
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<tbody>
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<td>China</td>
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### Advanced Intermittency

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The new supply curve shifts to the left (but we need to check this out more thoroughly)
- Increased wind generation cost
- Reduced wind generation

The influence of integration constraints interacts critically with supplies. Expanded integration is generally more important later in the century when production is higher and for regions with higher low-cost supplies.

In GCAM, you’ll use it if you need it. With phase out of nuclear and no CCS, development of wind energy increases significantly.
The End