High Penetration of Renewable Energy: Possible Scenarios, Implications, and Best Practices from International Experience

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To what extent can renewable energy technologies commercially available today meet the U.S. electricity demand over the next several decades?
Challenges for Intermittent Renewables

• Wind and solar are not “dispatchable”

• Is intermittency well-timed with demand?
  - Seasonally
  - Daily

• Is supply predictable?
  - Weekly
  - Hourly
    - Minutes to seconds

• Is supply where you need it?

• Large area footprint—objections to siting.
Areas of largest central tendency of wind power resource are also areas that experience the strongest and most expansive coincident intermittency.
The effects of correlated wind at different locations on ramping requirements

Total California Wind Generation

Figure 2.4: California wind power ramps from five diverse locations and total
Regional Supply...and Demand Centers

Figure B: Wind Availability and Demand Centers in the U.S.
Regional Differences in the US

Degree of Anti-Coincidence

Fraction of Grid Points in Midwest with Power (1979)

Less than 40% of the Midwest area is typically able to produce wind power. There’s a high variability in the winter and low coverage in the summer (sometimes zero).

East/West Coast benefit from anti-coincidence and significant offshore resources with high power density.
“Availability” = \frac{\text{# Hours with power density} \ > \ 200 \ \text{W/m}^2}{\text{Total number of hours}}

Wind “Episode” defined as continuous period that power density > 200 W/M²

Generally speaking, where wind power is “available” corresponds to where continuous episodes are prolonged.

Largest availability and episode length is in offshore resources.
Daily load and intermittency—sometimes it works, and sometimes it doesn’t.

Figure 2.3: Wind and load ramps on the Alberta interconnected electric system\textsuperscript{15}
Solar, more predictable/regular, except for clouds

Figure 2.9: Parabolic trough CSP plant on a sunny day (Sampling time of 10 sec.)

Figure 2.10: Parabolic trough CSP plant on a partly-cloudy day (Sampling time of 10 sec.)
How to use intermittent renewables and assure supply

• Choose anti-coincident sites—larger area grid interconnects.
• Balance anti-coincident renewables—wind-solar.
• Build excess capacity at high supply/low demand periods and “spill” excess.
• Balance with dispatchable renewables—hydro, geothermal.
• Storage—pumped hydro, Compressed air, battery
• Balance with a dispatchable generation plant, e.g. natural gas turbine or combined cycle
• Ramp base load coal or nuclear
## Levelized Cost of Electricity Alternatives w/o subsidies, 2010

<table>
<thead>
<tr>
<th>Units</th>
<th>Pulverized Coal</th>
<th>NGCC</th>
<th>NGCC with CCS</th>
<th>IGCC with CCS</th>
<th>Advanced Nuclear</th>
<th>NGCC with CCS</th>
<th>IGCC with CCS</th>
<th>Advanced Nuclear</th>
<th>Solar PV</th>
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<tbody>
<tr>
<td>1</td>
<td>&quot;Overnight&quot; Capital Cost</td>
<td>$/kW</td>
<td>2049</td>
<td>892</td>
<td>1781</td>
<td>3481</td>
<td>3521</td>
<td>1812</td>
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<td>2</td>
<td>Total Capital Requirement</td>
<td>$/kW</td>
<td>2377</td>
<td>964</td>
<td>1995</td>
<td>4177</td>
<td>4930</td>
<td>5109</td>
<td>6144</td>
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<td>3</td>
<td>Capital Recovery Charge Rate</td>
<td>%</td>
<td>10.6%</td>
<td>10.6%</td>
<td>10.6%</td>
<td>10.6%</td>
<td>10.6%</td>
<td>10.6%</td>
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<tr>
<td>4</td>
<td>Fixed O&amp;M</td>
<td>$/kW</td>
<td>25.9</td>
<td>11.0</td>
<td>18.8</td>
<td>43.5</td>
<td>84.8</td>
<td>5.5</td>
<td>11.0</td>
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<td>5</td>
<td>Variable O&amp;M</td>
<td>$/kWh</td>
<td>0.0043</td>
<td>0.0019</td>
<td>0.0028</td>
<td>0.0042</td>
<td>0.0005</td>
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<td>6</td>
<td>Project Life</td>
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<td>20</td>
<td>20</td>
<td>20</td>
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<tr>
<td>7</td>
<td>Capacity Factor</td>
<td>%</td>
<td>85%</td>
<td>85%</td>
<td>80%</td>
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<td>85%</td>
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<tr>
<td>8</td>
<td>(Capacity Factor Wind)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>9</td>
<td>(Capacity Factor Biomass/NGCC)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>10</td>
<td>Operating Hours</td>
<td>hours</td>
<td>7446</td>
<td>7446</td>
<td>7008</td>
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<td>7446</td>
<td>3066</td>
<td>7008</td>
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<td>11</td>
<td>Capital Recovery Required</td>
<td>$/kWh</td>
<td>0.03</td>
<td>0.01</td>
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<td>0.06</td>
<td>0.07</td>
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<td>12</td>
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<td>0.003</td>
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<td>0.00</td>
<td>0.0062</td>
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<td>13</td>
<td>Heat Rate</td>
<td>BTU/kWh</td>
<td>8740</td>
<td>6333</td>
<td>7493</td>
<td>8307</td>
<td>10488</td>
<td>0</td>
<td>7765</td>
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<td>14</td>
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<td>$/MMBTU</td>
<td>1.40</td>
<td>6.08</td>
<td>6.08</td>
<td>1.40</td>
<td>0.63</td>
<td>1.03</td>
<td>6.08</td>
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<tr>
<td>15</td>
<td>(Fraction Biomass/NGCC)</td>
<td>%</td>
<td>8.8%</td>
<td>8.2%</td>
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<td>16</td>
<td>Fuel Cost per kWh</td>
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<td>0.0122</td>
<td>0.0385</td>
<td>0.0456</td>
<td>0.0116</td>
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<td>17</td>
<td>Levelized Cost of Electricity</td>
<td>$/kWh</td>
<td>0.03</td>
<td>0.01</td>
<td>0.03</td>
<td>0.06</td>
<td>0.07</td>
<td>0.07</td>
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<tr>
<td>18</td>
<td>Markup Over Coal</td>
<td></td>
<td>1.00</td>
<td>1.03</td>
<td>1.57</td>
<td>1.71</td>
<td>1.64</td>
<td>1.43</td>
<td>1.58</td>
</tr>
</tbody>
</table>

**Notes:**
- **Wind beats coal**
- **But low capacity factor means...**
- **Capital recovery per kWh is more costly...**
- **Back-up may need to operate rarely...**
- **But low fuel cost but high capital recovery cost...**
- **Bottom line, wind 43% more expensive...**
- **Low fuel cost but high capital recovery cost...**

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*Source: NATIONAL RENEWABLE ENERGY LABORATORY*
RE Futures is an analysis of the U.S. electric sector focused on 2050 that explores:

1. Whether the U.S. power system can supply electricity to meet customer demand with high levels of renewable electricity, including variable wind and solar generation.
2. Grid integration using models with unprecedented geographic and time resolution for the contiguous U.S.
3. Synergies, constraints, and operational issues associated with a transformation of the U.S. electric sector.
# Renewable Electricity Futures Scope

<table>
<thead>
<tr>
<th>RE Futures does....</th>
<th>RE Futures does not...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identify commercially available RE generation technology combinations that meet up to 80% or more of projected 2050 electricity demand in every hour of the year.</td>
<td>Consider policies, new operating procedures, evolved business models, or market rules that could facilitate high levels of RE generation.</td>
</tr>
<tr>
<td>Identify electric sector characteristics associated with high levels of RE generation.</td>
<td>Fully evaluate power system reliability.</td>
</tr>
<tr>
<td>Explore a variety of high renewable electricity generation scenarios.</td>
<td>Forecast or predict the evolution of the electric sector.</td>
</tr>
<tr>
<td>Estimate the associated U.S. electric sector carbon emissions reductions.</td>
<td>Assess optimal pathways to achieve a low-carbon electricity system.</td>
</tr>
<tr>
<td>Explore a select number of economic, environmental and social impacts.</td>
<td>Conduct a comprehensive cost-benefit analysis.</td>
</tr>
<tr>
<td>Illustrate an RE-specific pathway to a clean electricity future to inform the development of integrated portfolio scenarios that consider all technology pathways and their implications.</td>
<td>Provide a definitive assessment of high RE generation, but does identify areas for deeper investigation.</td>
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</tbody>
</table>
**Modeling Framework**

**Black & Veatch**
- Technology Teams
- Flexible Resources
- End-Use Electricity
- System Operations
- Transmission

**Technology cost & performance**
- Resource availability
- Demand projection
- Demand-side technologies
- Grid operations
- Transmission costs

**Implications**
- GHG Emissions
- Water Use
- Land Use
- Direct Costs

**ReEDS**
- (Capacity expansion)

**ABB inc. GridView**
- (Hourly production cost)

**SolarDS**
- (Rooftop PV market penetration)

**rooftop PV penetration**

**2050 mix of generators**

does it balance hourly?

**High resolution modeling using 134 nodes & hourly time steps**

**Capacity & Generation 2010-2050**

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**GHG Emissions**
- Water Use
- Land Use
- Direct Costs
Scenario Framework

Reference Scenario
- Low-Demand Baseline

Exploratory Scenarios
Impact of Increasing Renewable Electricity Penetration
- 30%
- 40%
- 50%
- 60%
- 70%
- 80%
- 90%

Core 80% RE Scenarios
- 80% RE-NTI
- 80% RE-ITI
- 80% RE-ETI
- Constrained Transmission
- Constrained Flexibility
- Constrained Resources

Impact of System Constraints

Impact of Technology Improvement (TI)

Sensitivity Scenarios
- Alternative Fossil Baselines
- Impact of Fossil Cost Assumptions
- 80% RE
- Higher Fossil Fuel Costs
- Lower Fossil Fuel Costs
- Higher Fossil TI

High-Demand Baseline
Impact of Demand Growth Assumptions
- High-Demand 80% RE

Renewable Technology Improvement Assumptions Color-Coding
- No Technology Improvement (NTI)
- Incremental Technology Improvement (ITI)
- Evolutionary Technology Improvement (ETI)
General Assumptions

- **Energy Efficiency**: Most of the scenarios assumed significant adoption of energy efficiency (including electricity) measures in the residential, commercial, and industrial sectors.

- **Transportation**: Most of the scenarios assumed a shift of some transportation energy away from petroleum and toward electricity in the form of plug-in hybrid or electric vehicles, partially offsetting the electricity efficiency advances that were considered.

- **Grid Flexibility**: Most scenarios assumed improvements in electric system operations to enhance flexibility in both electricity generation and end-use demand, helping to enable more efficient integration of variable-output renewable electricity generation.

- **Transmission**: Most scenarios expanded the transmission infrastructure and access to existing transmission capacity to support renewable energy deployment. Distribution-level upgrades were not considered.

- **Siting and Permitting**: Most scenarios assumed project siting and permitting regimes that allow renewable electricity development and transmission expansion with standard land-use exclusions.
Renewable Resources and Technologies

- Biopower ~100 GW
  - Stand-alone
  - Cofired with coal

- Solar CSP ~37,000 GW
  - Trough
  - Tower
  - With thermal storage

- Geothermal ~36 GW
  - Hydrothermal

- Hydropower ~200 GW
  - Run-of-river

- Solar PV ~80,000 GW
  - Residential
  - Commercial
  - Utility-scale
  - (rooftop PV ~700 GW)

- Wind ~10,000 GW
  - Onshore
  - Offshore fixed-bottom

- Current Total US Installed Capacity of all Types: ~ 1000 GW

- Only currently commercial technologies were modeled (no EGS, ocean, floating wind) with incremental and evolutionary improvements.

- RE characteristics including location, technical resource potential, and grid output characteristics were considered.
Key Results

A Transformation of the U.S. Electricity System

RE generation from technologies that are commercially available today, in combination with a more flexible electric system, is more than adequate to supply 80% of total U.S. electricity generation in 2050—while meeting electricity demand on an hourly basis in every region of the country.
Renewable generation resources could adequately supply 80% of total U.S. electricity generation in 2050 while balancing hourly supply and demand.
The abundance and diversity of RE resources can support multiple combinations of RE technologies to provide 80% generation by 2050.

- Technology deployment depends on scenario assumptions, but in all cases examined, RE resources existed to compensate for assumed variations in access to transmission, grid flexibility, resource availability, technology costs, and electricity demand.
- Constraints to transmission result in greater PV, offshore wind, and biopower deployment.
- Constraints to system flexibility result in greater dispatchable technology deployment, e.g., storage and CSP with thermal storage.
- Constraints to resource accessibility result in greater wind and solar deployment.

Low-Demand ranges encompass results for Technology Improvement and Constrained scenarios.
All regions of the country could contribute substantial renewable electricity supply in 2050.

80% RE-ITI scenario
A more flexible electric power system is needed to enable electricity supply-demand balance with high levels of RE generation

System flexibility can be increased using a broad portfolio of supply- and demand-side options, including:

- Flexible generators (particularly natural gas)
- Dispatchable renewables (e.g., biopower, geothermal, CSP with storage and hydropower)
- Demand response (e.g., interruptible load)
- Controlled charging of electric vehicles
- Storage
- Curtailment
- Transmission
- Geospatial diversity of the variable resources to smooth output
- Coordinating bulk power system operations across wider areas
Electricity supply and demand can be balanced in every hour of the year in each region with 80% electricity from renewable resources.*

*Full reliability analysis not conducted in RE Futures
System flexibility provided through increased ramping and startup-shutdown of conventional generators, particularly in low-demand periods.
Dispatchable renewable generators and storage provide system flexibility by shifting operation to periods of high net load

Source: Denholm, .... (2012)

Dispatch of CSP with thermal storage in Western Interconnection (80% RE ITI)
In most 80%–by-2050 RE scenarios, 110-190 million MW-miles of new transmission lines are added.

AC-DC-AC interties are expanded to allow greater power transfer between asynchronous interconnects.

However, 80% RE is achievable even when transmission is severely constrained (30 million MW-miles)—which leads to a greater reliance on local resources (e.g. PV, offshore wind).

Annual transmission and interconnection investments in the 80%-by-2050 RE scenarios range from $5.7B-8.4B/year, which is within the range of recent total investor-owned utility transmission expenditures.

High RE scenarios lead to greater transmission congestion, line usage, and transmission and distribution losses.
Regional renewable electricity supply in 2050 – constrained transmission scenario

Constrained Transmission scenario
### 80% RE Scenario Results Comparison *(under RE-ITI technology assumption)*

<table>
<thead>
<tr>
<th></th>
<th>80% RE-ITI</th>
<th>Constrained Transmission</th>
<th>Constrained Flexibility</th>
<th>Constrained Resources</th>
<th>High-Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>% variable generation</td>
<td>43%</td>
<td>47%</td>
<td>39%</td>
<td>47%</td>
<td>49%</td>
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<tr>
<td>New Transmission</td>
<td>119 million MW-miles</td>
<td>28 million MW-miles ~</td>
<td>132 million MW-miles ~</td>
<td>188 million MW-miles ~</td>
<td>182 million MW-miles ~</td>
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<tr>
<td>T&amp;D Losses</td>
<td>8.6%</td>
<td>8.3% ~</td>
<td>9.0%</td>
<td>9.5%</td>
<td>8.9% ~</td>
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<tr>
<td>Operating Reserve Reqt.</td>
<td>96 GW</td>
<td>114 GW ~</td>
<td>128 GW ~ ~ ~ ~ ~ ~</td>
<td>99 GW ~ ~ ~ ~ ~ ~</td>
<td>143 GW ~ ~ ~ ~ ~ ~</td>
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<tr>
<td>Interruptible Load</td>
<td>38 GW</td>
<td>48 GW ~ ~ ~ ~ ~ ~ ~</td>
<td>28 GW ~ ~ ~ ~ ~ ~ ~</td>
<td>38 GW ~ ~ ~ ~ ~ ~ ~</td>
<td>64 GW ~ ~ ~ ~ ~ ~</td>
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<tr>
<td>Curtailment (% of var gen)</td>
<td>5.6%</td>
<td>8.6% ~ ~ ~ ~ ~ ~ ~</td>
<td>7.0% ~ ~ ~ ~ ~ ~ ~</td>
<td>6.2% ~ ~ ~ ~ ~ ~ ~</td>
<td>7.1% ~ ~ ~ ~ ~ ~</td>
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<td>Storage</td>
<td>122 GW</td>
<td>129 GW ~ ~ ~ ~ ~ ~ ~</td>
<td>152 GW ~ ~ ~ ~ ~ ~ ~</td>
<td>131 GW ~ ~ ~ ~ ~ ~ ~</td>
<td>136 GW ~ ~ ~ ~ ~ ~</td>
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Red arrows indicate magnitude and direction of change relative to the 80% RE-ITI scenario.
High renewable electricity futures can result in deep reductions in electric sector greenhouse gas emissions and water use.

80% RE scenarios lead to:
- ~80% reduction in 2050 generation from both coal-fired and natural gas-fired sources
- ~80% reduction in 2050 GHG emissions (combustion-only and life cycle)
- ~50% reduction in electric sector water use
- Gross land use totaling <3% of contiguous U.S. area; other related impacts include visual, landscape, noise, habitat, and ecosystem concerns.

### Gross Land Use Comparisons (000 km²)

<table>
<thead>
<tr>
<th>Category</th>
<th>Land Use (000 km²)</th>
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<tbody>
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<td>Biomass</td>
<td>44-88</td>
</tr>
<tr>
<td>All Other RE</td>
<td>52-81</td>
</tr>
<tr>
<td>All Other RE (disrupted)</td>
<td>4-10</td>
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<tr>
<td>Transmission &amp; Storage</td>
<td>3-19</td>
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<tr>
<td>Total Contiguous U.S.</td>
<td>7,700</td>
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<td>2009 Corn Production*</td>
<td>350</td>
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<td>Major Roads**</td>
<td>50</td>
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<tr>
<td>Golf Courses **</td>
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*USDA 2010, **Denholm & Margolis 2008
Incremental cost associated with high RE generation is comparable to published cost estimates of other clean energy scenarios

- Comparable to incremental cost for clean energy and low carbon scenarios evaluated by EIA and EPA
- Reflects replacement of existing generation plants with new generators and additional balancing requirements (combustion turbines, storage, and transmission) compared to baseline scenario (continued evolution of today’s conventional generation system)
- Assumptions reflect incremental or evolutionary improvements to currently commercial RE technologies; they do not reflect U.S. DOE activities to further lower these costs.
Future Work Needed

• A comprehensive cost-benefit analysis
• Comprehensive power system reliability analysis
• Market Design, Institutional, and other structural areas...
• Deeper analysis of advanced technologies, including supply and demand-side flexibility