Envisioning a Renewable Electricity Future for the United States

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GCEP Net Energy Analysis Workshop

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Stanford University, CA
Today’s discussion

- Current status of U.S. renewables
- Motivation for studying high RE futures
- Renewable Electricity Futures study + updates
- Brief look at new Wind Vision Study
- Conclusions
Renewables currently make up a small fraction of total U.S. electricity generation

- In 2013, ~12% of total generation from RE sources
- ~6% from non-hydro RE

Source: data from EIA electric power monthly
Renewables currently make up a small fraction of total U.S. electricity generation

- In 2013, ~12% of total generation from RE sources
- ~6% from non-hydro RE

U.S. RE [wind] penetration considerably lower than other countries (although some states—IA, SD, KS—have comparable ~20+% levels)

Source: data from EIA electric power monthly

Source: Berkeley Lab estimates based on data from Navigant, EIA, and elsewhere
Renewables currently make up a small (but growing) fraction of total U.S. electricity generation.

**Wind**

Source: 2013 Wind Technologies Market Report

**Solar PV**

Source: Tracking the Sun VII
Regional and instantaneous penetration levels can be much higher.

**Bonneville Power Administration**
Record Wind Output: 4,512 MW on 2/22/2013
Percent of Generation: 39.9% on 10/20/2012

**Xcel Energy Colorado**
Record Wind Output: 1,874 MW on 5/24/2013
Percent of Demand: 60.5% on 5/24/2013

**MISO**
Record Wind Output: 10,012 MW on 11/23/2012
Percent of Demand: 25% on 11/23/2012

**CAISO**
Record Wind Output: 4,196 MW on 4/7/2013
Percent of Generation: 17.5% on 4/7/2013

**ERCOT**
Record Wind Output: 10,296 MW on 3/26/2014
Percent of Demand: 39.7% on 3/31/2014

**SPP**
Record Wind Output: 7,202 MW on 3/18/2014
Percent of Demand: 33.4% on 4/6/2013

Source: AWEA 2014
Regional and instantaneous penetration levels can be much higher

Bonneville Power Administration
Record Wind Output: 4,512 MW on 2/22/2013
Percent of Generation: 39.9% on 10/2/2013

Source: AWEA 2014

Xcel Energy Colorado
Record Wind Output: 1,874 MW on 5/24/2013
Percent of Demand: 33.5% on 5/24/2013

Source: CAISO 2013

MISO
Record Wind Output: 10,012 MW on 11/23/2012
Percent of Demand: 101.8% on 11/23/2012

Source: MISO 2013

The Duck Curve

CAISO
Record Wind Output: 4,196 MW on 4/7/2013
Percent of Generation: 17.5% on 4/7/2013

Source: CAISO 2013

ERCOT
Record Wind Output: 10,296 MW on 3/26/2014
Percent of Demand: 39.7% on 3/31/2014

Source: ERCOT 2014

SPP
Record Wind Output: 7,202 MW on 3/18/2014
Percent of Demand: 33.4% on 4/6/2013

Source: AWEA 2014
RE technical potential is significantly greater than electricity demand in the U.S.

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

**Hydropower ~200 GW**
- Run-of-river

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

**Solar PV ~80,000 GW**
- Rooftop PV ~700 GW
- Residential
- Commercial
- Utility-scale

**Geothermal ~36 GW**
- Hydrothermal

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

Current total installed capacity in the U.S. is ~1000 GW
Annual electricity demand in the U.S. is <4,000 TWh
RE technical potential is significantly greater than electricity demand in the U.S. – especially true for solar

Meeting all of U.S. demand with current PV technologies would require about 103-214 m² per person.

U.S. area per capita (m²):
- Total: 30,914
- Roofs: 65
- Golf Courses: 34
- Corn Ethanol 219
RE technology costs/prices continue to decline

Wind

Solar PV

Source: Tracking the Sun VII

Residential & Commercial PV (Median Values)

Median prices for systems installed in 2013 (n=50,614):
- $4.7/W (≤10 kW)
- $4.3/W (10-100 kW)
- $3.9/W (>100 kW)

Source: 2013 Wind Technologies Market Report

Source: Tracking the Sun VII
RE technologies have very low life cycle GHG emissions and water requirements

+ other potential social and environmental benefits
  - air pollution (SO2, NOx, PM)
  - energy resiliency?
  - fuel diversity?
  - net energy?
But can we really have a grid mostly reliant on RE?

Why not?

...the diffuse and remote nature of the resource?

...the sun doesn’t always shine and the wind doesn’t always blow so massive amounts of storage will be needed?

...massive amounts of backup will be very costly and generate lots of emissions?

...our grid can take up some (<20%) RE but beyond that it will break?

Using advanced models, NREL scenario analysis and integration studies are designed to rigorously tackle some of these issues
RE Futures (NREL 2012) is a U.S. DOE-sponsored collaboration with more than 110 contributors from 35 organizations including national labs, industry, universities, and non-governmental organizations.

And recently (3/12/2015) released DOE Wind Vision (energy.gov/windvision)
Modeling Framework

SolarDS
(rooftop PV market penetration)

ABB inc.
GridView
(hourly production cost)

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

ReEDS
(capacity expansion)

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

Implications
GHG Emissions
Water Use
Land Use
Direct Costs

Capacity & Generation 2010-2050

2050 mix of generators
does it balance hourly?

rooftop PV penetration

High resolution modeling using 134 nodes & hourly time steps

Implications
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Capacity & Generation 2010-2050

2050 mix of generators
does it balance hourly?

rooftop PV penetration

High resolution modeling using 134 nodes & hourly time steps
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.
Transitioning from today’s system to one with 80% RE generation will largely avoid future fossil fuel-based electricity generation.

**Under High (or BAU) Demand Growth**

- **High-Demand Baseline**
  - Offshore Wind
  - Onshore Wind
  - Rooftop PV
  - Utility PV
  - CSP
  - Hydropower
  - Geothermal
  - Biomass
  - NG-CT/OGS
  - NG-CC
  - Coal
  - Nuclear

- **High-Demand 80% RE-ITI**
  - Offshore Wind
  - Onshore Wind
  - Rooftop PV
  - Utility PV
  - CSP
  - Hydropower
  - Geothermal
  - Biomass
  - NG-CT/OGS
  - NG-CC
  - Coal
  - Nuclear
Transitioning from today’s system to one with 80% RE generation will largely avoid future fossil fuel-based electricity generation.

**Under Lower Demand Growth (or higher energy efficiency)**

![Graph showing annual generation comparison between Low-Demand Baseline and Low-Demand 80% RE-ITI.](image-url)
All RE technologies will be relied upon, but especially variable generation (wind and solar PV): 49-55% VG penetration levels

• >1000 GW of RE capacity will be needed (>40 GW per year in the 2040s) to achieve 80% RE by 2050
• Type and amount of RE chosen will depend strongly on
  o Future technology cost and performance improvements
  o Resource accessibility (e.g. siting)
  o Ability to develop new transmission infrastructure
  o Flexibility of the future grid
All regions of the country could contribute substantial renewable electricity supply in 2050.
Electricity supply and demand can be balanced in every hour of the year in each region with 80% electricity from renewable resources*.
Electricity supply and demand can be balanced in every hour of the year in each region with 80% electricity from renewable resources.*

Peak →

Baseline scenario

Off-Peak →

80% RE-ETI scenario

*Full reliability analysis not conducted in RE Futures
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
A more flexible electric power system is needed to enable electricity supply-demand balance with high levels of RE generation.
Installed capacity is sufficient to meet summer afternoon peak demand from diverse reserves.

Firm capacity provided by some RE generators, conventional generators, and storage.
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 et al. (2012)

Dispatch of CSP with thermal storage in Western Interconnection (80% RE ITI)
Coordination across wider areas and faster markets help to manage variability (see WWSIS 2, Energy Imbalance Market, & other studies for additional examples)

Constrained Transmission Scenario (Worst 4 days)
Curtailment can be used strategically to reduce variability in the net load

- 8-10% of wind, solar, hydropower curtailed in 2050 under 80% RE scenarios
- Curtailment can be reduced through increased transmission capacity, more-flexible generators, storage, and demand-side applications (e.g., controlled PHEV charging)
As RE deployment increases, additional transmission infrastructure is required

- In most 80%-by-2050 RE scenarios, 113-158 million MW-miles of new transmission lines are added.
- However, 80% RE is achievable even when transmission is severely constrained (39 million MW-miles)—which leads to a greater reliance on local resources (e.g. PV, offshore wind).
High renewable electricity futures can result in deep reductions in electric sector greenhouse gas emissions and water use. 80% RE scenarios lead to:

- ~70-80% reduction in 2050 generation from both coal-fired and natural gas-fired sources
- ~70-80% 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>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<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>
</tr>
<tr>
<td>Transmission &amp; Storage</td>
<td>3-19</td>
</tr>
<tr>
<td>Total Contiguous U.S.</td>
<td>7,700</td>
</tr>
<tr>
<td>2009 Corn Production*</td>
<td>350</td>
</tr>
<tr>
<td>Major Roads**</td>
<td>50</td>
</tr>
<tr>
<td>Golf Courses **</td>
<td>10</td>
</tr>
</tbody>
</table>

*USDA 2010, **Denholm & Margolis 2008
Side note: WWSIS2 (2013) examined costs of cycling, emissions impacts of cycling, and compare wind and solar impacts

Key finding: Emissions impacts of cycling are relatively small

- Modeled 33% combined wind/solar scenarios in the Western Interconnection
- Used commercial software PLEXOS to model grid operations on 5 minute basis
Incremental cost associated with high RE generation is comparable to published cost estimates of other clean energy scenarios

- 80% RE scenarios are estimated to have similar incremental cost compared with EIA and EPA scenarios that have similar levels of carbon emission reductions
- With updated technology costs, fossil fuel price projections, and retirements, incremental costs for 80% RE are estimated to be lower
Hot off the press on March 12: Wind Vision Study

- Documentation of the current state of wind...
- Exploration of the potential pathways for wind...
- **Quantification of the costs, benefits, and other impacts associated with continued deployment and growth of U.S. wind power**; and
- Identification of actions and future achievements that could support continued growth...
Summary of cost/benefits/impacts of transitioning to 35% wind by 2050

Note: Results represent the present value of incremental costs or benefits (impacts) of the Study Scenario relative to the Baseline Scenario. Central estimates are based on Central Study Scenario modeling assumptions. The electricity system cost range reflects incremental expenditures (including capital, fuel, and operations and maintenance for transmission and generation of all technologies modeled) across a series of sensitivity scenarios. Air pollution and GHG estimates are based on the Central Study Scenario only, with ranges derived from the methods applied and detailed in the full report.
### Summary of cost/benefits/impacts of transitioning to 35% wind by 2050

<table>
<thead>
<tr>
<th>System Costs</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>$149 billion (3%) lower cumulative electric sector expenditures</td>
<td>14% reduction in cumulative GHG emissions (12.3 gigatones CO₂ equivalents), saving $400 billion in avoided global damages</td>
</tr>
</tbody>
</table>

#### Additional Impacts

<table>
<thead>
<tr>
<th>Energy Diversity</th>
<th>Jobs</th>
<th>$</th>
<th>Land Use</th>
<th>Public Acceptance and Wildlife</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased wind power adds fuel diversity, making the overall electric sector 20% less sensitive to changes in fossil fuel costs.</td>
<td>Approximately 600,000 wind related gross jobs spread across the nation.</td>
<td>$1 billion in annual land lease payments</td>
<td>Less than 1.5% (106,000 km²) of contiguous land area of the U.S. occupied by wind power plants</td>
<td>Careful siting, continued research, thoughtful public engagement, and an emphasis on optimizing coexistence can support continued responsible deployment that minimizes or eliminates negative impacts to wildlife and local communities</td>
</tr>
<tr>
<td>The predictable, long-term costs of wind power create downward price pressure on fossil fuels that can cumulatively save consumers $280 billion from lower natural gas prices outside the electric sector.</td>
<td>$440 million annual lease payments for offshore wind plants</td>
<td>Less than 0.04% (3,300 km²) of contiguous U.S. land area impacted by turbine pads, roads, and other associated infrastructure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>More than $3 billion in annual property tax payments</td>
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</table>

Note: Cumulative costs and benefits are reported on a Net Present Value basis for the period of 2013 through 2050 and reflect the difference in impacts between the Central Study Scenario and the Baseline Scenario. Results reported here reflect central estimates within a range; see Chapter 3 for additional detail. Financial results are reported in 2013$ except where otherwise noted.

1. Electric sector expenditures include capital, fuel, and operations and maintenance for transmission and generation of all technologies modeled, but excludes consideration of estimated benefits (e.g., GHG emissions).
2. Mortality is the incidence of disease or rate of sickness in a population.
3. Water consumption refers to water that is used and not returned to the source. Water withdrawals are eventually returned to the water source.
Conclusions

• Extensive analysis has demonstrated the feasibility of deriving up to ~20% of the nation’s electricity from wind and solar with little cost penalty, significant emissions reductions, and no impact on reliability.
• At ~20-35%, some changes to systems operation are likely needed (e.g. increased cooperation across large areas).
• Detailed and rigorous explorations beyond ~35% have only recently started, but early results indicate:
  o It is possible, but many more sources of grid flexibility (e.g. DR, storage, transmission) will be needed.
  o While marginal benefits of RE begin to decrease due to the limited correlation of supply/demand, an RE-heavy pathway to achieve deep environmental and social benefits appears to be viable.
A future U.S. electricity system that is largely powered by renewable sources is possible, and further work is warranted to investigate this clean generation pathway.
Questions?

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