Boosting Wind and Solar Energy: Opportunities and Technological Challenges

Lucy Pao
Palmer Endowed Chair Professor
Electrical, Computer, & Energy Engineering

University of Colorado Boulder
How much power do you use?

Mobile phone
~ 1 W

Laptop
~ 10 W

TV
~ 100 W

Coffee machine

Toaster

Oven

Dishwasher

Electric kettle

~ 1000 W

( $10^3 \text{ W} = 1 \text{ kW}$ )

Area heater

Vacuum

Iron

Hair dryer

Clothes dryer

Electric vehicle charging
~ 1 kW to 100 kW

$10^6 \text{ W} = 1 \text{ MW}$

~ Small Town

$10^9 \text{ W} = 1 \text{ GW}$

~ City

[ images from overstock.com, pcworld.com, apple.com, tesla.com ]
Units of Power and Energy

Energy

1 kWh = 1 kW for 1 hour

- Dishwasher: ~ 1000 W
- Coffee machine: ~ 1000 W
- Electric kettle: 10^3 W = 1 kW
- Air conditioner: ~ 10^6 W = 1 MW
- Microwave: ~ 1 kW
- Oven: ~ 1 kW
- Toaster: ~ 1 kW
- Hair dryer: ~ 1 kW
- Clothes dryer: ~ 1 kW
- Electric vehicle charging: ~ 1 kW to 100 kW

10^6 W = 1 MW ~ Small Town
10^9 W = 1 GW ~ City

[ images from overstock.com, pcworld.com, apple.com, tesla.com ]
Renewable Energy & The Power Grid

Hydro

Wind

Solar PV

Grid Integration

[ images from constructionreviewonline.com, proprofs.com, gapenergysolutions.com, resilience.org ]
How does hydropower work?

[ image from Hydropower 101 on yourtube.com ]
How much hydropower is there?

- End-of-2017 global installed hydropower capacity was 1,267 GW; expected to increase 3% annually over next 25 years.

- EU has 293 GW

- Austria has 14 GW

[ end-of-2017 data from hydropower.org ]
Hydropower Advantage: if there is sufficient water, it can control the amount of power generated in a similar way as with coal or natural gas.

[ image from Hydropower 101 on youtube.com ]
Renewable Energy & The Power Grid

Hydro

Wind

Solar PV

Grid Integration

[ images from constructionreviewonline.com, proprofs.com, gapenergysolutions.com, resilience.org ]
How does wind power work?

- Goal is to maximize power generation

[ figure from www.energyland.emsd.gov.hk based upon original from US Dept. of Energy ]
End-of-2017 global installed wind capacity was 539 GW; average annual growth of 16% over last decade.

EU has 169 GW; average annual growth of 10%.

Austria has 2.8 GW; average annual growth of 11%.

How much wind power is there?

- China: 36%
- US: 17%
- Germany: 9%
- India: 6%
- Spain: 4%
- France: 3%
- UK: 3%
- Brazil: 2%
- Italy: 2%
- Other: 16%
- Canada: 2%
- Austria: 14 GW

Hydro:
- World: 1267 GW
- EU: 293 GW
- Austria: 14 GW

[data from gwec.net, navigant.com, and 2017 Wind Technologies Market Report (LBNL)]
Renewable Energy & The Power Grid

Hydro

Wind

Solar PV

Grid Integration

[ images from constructionreviewonline.com, proprofs.com, gapenergysolutions.com, resilience.org ]
How does solar PV work?

- PV panel consists of layers of material that produce electricity when light shines on it.
- Lower-end PV solar cells now achieve about 14-17% efficiency.
- Higher-end solar cells can achieve about 20-30% efficiency.
- Research laboratories have demonstrated > 40%.
- Goal is to maximize power generation.

[en.wikipedia.org/wiki/Solar_cell]
End-of-2017 global installed solar PV capacity was 403 GW; average annual growth of 38% over last decade

- EU has 107 GW; average annual growth of 26%
- Austria has 1.25 GW; average annual growth of 44%

How much solar PV power is there?

[ Data from iea-pvps.org ]
Growth of Hydro, Wind, and Solar PV

- **Global Installed Capacity (GW)**

<table>
<thead>
<tr>
<th>Year</th>
<th>Hydro</th>
<th>Wind</th>
<th>Solar PV</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017</td>
<td>1000</td>
<td>500</td>
<td>300</td>
</tr>
<tr>
<td>2018</td>
<td>1200</td>
<td>600</td>
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<td>2019</td>
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<tr>
<td>2025</td>
<td>2600</td>
<td>1300</td>
<td>1100</td>
</tr>
</tbody>
</table>
Wind and Solar PV Penetration

Approximate Wind Penetration, end of 2017
Approximate Solar PV Penetration, end of 2017

[Source: 2017 Wind Technologies Market Report, Lawrence Berkeley National Lab]

[2017 solar data from ieapvps.org]
Renewable Energy & The Power Grid

[ images from constructionreviewonline.com, proprofs.com, gapenergysolutions.com, resilience.org ]
Power Systems

Most traditional power plants have synchronous generators.

When power demanded and power generated are approximately equal, synchronous generators on a network tend to stabilize each other.

Large mismatches between demanded and generated power causes destabilization of the grid.

[Based upon a slide from Mark Ahlstrom of WindLogics]
Grid Frequency Fluctuations

\[ f_{\text{grid}} = 50 \text{ Hz} \]

[Slide courtesy of Jacob Aho]
Frequency Drops if Electrical Power Generated < Electrical Load

\[ f_{grid} = 50 \text{ Hz} \quad f_{grid} < 50 \text{ Hz} \]

[Slide courtesy of Jacob Aho]
Frequency Rises if Electrical Power Generated > Electrical Load

\[ f_{grid} = 50 \text{ Hz} \quad f_{grid} < 50 \text{ Hz} \quad f_{grid} > 50 \text{ Hz} \]

[Slide courtesy of Jacob Aho]
Traditionally, generation is controlled to match varying load

- Operational reserves needed
- Imbalance causes frequency variations on utility grid
Balancing Electrical Generation and Load

- Traditionally, generation is controlled to match varying load
  - Operational reserves needed
  - Imbalance causes frequency variations on utility grid

Large frequency fluctuations can cause load shedding, or even blackouts
Wind turbines and solar PV arrays are typically decoupled from the grid through their power electronics:

- In the past, wind and solar generally have not participated in “balancing services”
- Creates increased burden on remaining generating units
How does wind power work?

Goal is to maximize power generation

[ figure from www.energyland.emsd.gov.hk based upon original from US Dept. of Energy ]
How does solar PV work?

- PV panel consists of layers of material that produce electricity when light shines on it
- Lower-end PV solar cells now achieve about 11-15% efficiency
- Higher-end solar cells can achieve about 20-30% efficiency
- Research laboratories have demonstrated > 40%
- Goal is to maximize power generation

[en.wikipedia.org/wiki/Solar_cell]
Possible Solution: APC of Wind and Solar

- **Active Power Control of Wind and Solar PV Power Plants**
  - De-rate wind and solar power plants
  - Enable wind turbines and solar photovoltaic panels to follow changing power reference commands

[figure from a presentation by A. Kowli, original from SVK (Swedish national grid)]
Wind Turbine Field Test Results

Freq Deviation [Hz]

-0.15
-0.1
-0.05
0

Power [kW]

550
540
530
520
510
500

Time [s]

0
50
100
150
200

Commanded Power
Generated Power
Rated Power
Ideal Field Test Input
Solar PV Array Field Test Results

[ 2016 – 2017, Hoke, Shirazi, Chakraborty, Muljadi, Maksimovic ]

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**Diagram:**
- **X-axis:** Time [s]
- **Y-axis:** Freq Dev [Hz] and Power [kW]
- **Graphs:**
  - **Line:** Actual Frequency Deviation
  - **Dashed Line:** Ideal Frequency Deviation
  - **Line:** Commanded Power
  - **Dashed Line:** Estimate of Possible Power
  - **Line:** Generated Power

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Other Possible Solutions

- Curtail wind and solar as needed
- More transmission lines
- Improved wind and solar forecasts
- Demand-side management
  - Thermal storage
  - Time-of-use pricing and “optimal” pricing strategies
- Storage (at GWh scale)
  - Expensive
  - Effect of millions of electric vehicles, whose batteries can be either a load or a supply

[figure from a presentation by A. Kowli, original from SVK (Swedish national grid)]
Pumped Hydro as a Means of Storage

[ image from antinuclear.net ]
While there are many challenges, there are many solution possibilities.
Acknowledgments

Research supported by:

[Logos of ARPA-E, NSF, NREL, Envision, and Hanse-Wissenschaftskolleg Institute for Advanced Study]

as well as other industry (who wish to remain anonymous)
Current students, recent postdoc:

David Pasley joined in August 2018

Lucy Pao

Christopher Bay (2017-2018)

Michael Sinner

Daniel Zalkind

R. Arnold Braker

Nikhar Abbas

Acknowledgments

Sarah Pao Radzihovsky

Daughter:

April 2018
Vielen Dank!