lecture 3. Systems Integration of Renewable Energy Sources

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March 2021
The Agenda Today

Part 1: Renewable Energy Systems
- Energy and climate change (continue)
- Global trends in penetration of renewable energy
- Potentials and challenges

Part 2: Energy storage systems
Terminology (reminder)

Primary energy: raw, unprocessed

Final energy: ready to be used

Energy system

Fuel extraction & imports → Fuel processing & transformation → Fuel storage → Demand

Electricity sector
- Thermal power
- Nuclear
- Hydropower
- Wind and solar

Central heating
- Fuel boilers
- Electric boilers
- Heat pumps
- Solar thermal

Power to x

Distributed Energy Technologies

Industry (feedstock)
Buildings
Transport

Renewable energy sources

Fuels

Electricity

District heating

Renewables
Renewable energy systems
Energy Consumption History (recap)

• World primary energy use in 2015
• Huge dependence on fossil fuels
Greenhouse Effect

Greenhouse gases: CO2, CH4, N2O, O3, CFC, H2O vapor

Image: http://steemit.com/

Image: http://pinterest.com/charleswelsh
Global Carbon Cycle

- Carbon pools: oceans, soils, plants, earth’s crust
- Human induced GHGs the biggest imbalance in the cycle

*Human induced GHGs = 7.7 Pg or Gt (billion tonnes)*

Image: http://pinterest.com/charleswelsh
Temperature Rise

- The target: try to keep the temperature rise well below $2^\circ C$ by the year 2100.
Climate Change Effects

Question:
discuss the main climate change Impacts and consequences in your group

Image: http://vox.com
Climate Change Effects (cont.)

- Direct effects:
  - Higher temperatures
  - Agriculture failure
  - Altered weather patterns
  - Homelessness
  - Ocean acidification
  - Marine ecosystem shift
  - Sea level rise

- Indirect effects:
  - Mass migration
  - Economic disruption
  - Malnutrition
  - Social unrest
  - Displacement
  - Infectious disease spread

Image: http://ecological.blog.com
GHGs may generate a Hothouse

- Hothouse state:
  Human is not able to stop the process ➔ Domino Effect

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**Environment**

**Earth at risk of entering ‘hothouse’ state from which there is no return, scientists warn**

‘In the context of the summer of 2018, this is definitely not a case of crying wolf... the wolves are now in sight’

Josh Gabbatiss, Science Correspondent | @josh_gabbatiss | 4 hours ago | 15 comments
"If there are to be problems, may they come during my life-time so that I can resolve them and give my children the chance of a good life."

Kenyan proverb
Measures for reducing carbon footprint

Renewable Energy in the Energy Mix

- Available and replaceable in a sustainable way

Types of renewable energy:
- Solar
- Wind
- Biomass
- Hydro
- Geo-thermal
- Ocean/wave/tidal
- …

Share from Global Final energy, Image: http://reneweconomy.com
Renewable Energy Potential

- World annual energy needs: 16 TW-yr
- Solar and wind two biggest renewable energy resources
Solar PV

- Small-scale: household
- Large scale: solar PV farms
- Modular, quick, no water needs, maintenance-free
- Distributed and off-grid generation
- Often peak-demand following
- Economically competitive:
  In many places in the world, the cheapest option for new capacity

Globally 627 GW installed by 2019

Solar PV Capacity Additions

- 40% growth in 2019 compared to 2018
- As cheap as 0.014 $/kWh: a choice also for developing countries

https://ren21.net
Wind Power

- Modular and distributed
- Onshore and offshore
- Large scale production (wind farms)
- Economically competitive
- Technology improvements (higher capacity factor, bigger turbines)
- 651 GW global capacity by 2019
- China the leading country
- India, the third country in capacity additions in 2019
Investments in New Power Capacity

FIGURE 52. Global Investment in New Power Capacity, by Type (Renewables, Coal, Gas and Nuclear Power) 2019

- **Renewables (excluding hydropower >50 MW)**: 282 billion USD, 71.2%
- **Coal**: 37 billion USD, 9.3%
- **Natural gas**: 47 billion USD, 11.9%
- **Nuclear**: 15 billion USD, 3.8%

Share of Wind and Solar in Electricity

- RE more in the electricity sector
- 60% of electricity in Denmark from mainly wind and solar
Levelized Cost of Electricity (LCOE)

- Indicator for the cost of one unit of electricity generated by a power plant
- Net present value (NPV) of the costs over lifetime divided by total electricity generated

$$\text{LCOE} = \frac{\text{NPV of Total Costs Over Lifetime}}{\text{NPV of Electrical Energy Produced Over Lifetime}}$$

$$\text{LCOE} = \sum \frac{I_t + M_t + F_t}{(1 + r)^t} \frac{E_t}{(1 + r)^t}$$

I: investment costs
M: maintenance costs (disposal, etc.)
F: fuel costs
E: total electricity generated
## LCOE of Renewables vs. Conventional

Selected renewable energy generation technologies are cost-competitive with conventional generation technologies under certain circumstances.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Renewable Energy</th>
<th>Conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar PV—Rooftop Residential</td>
<td>$151</td>
<td>$242</td>
</tr>
<tr>
<td>Solar PV—Rooftop C&amp;I</td>
<td>$75</td>
<td>$154</td>
</tr>
<tr>
<td>Solar PV—Thin Film Utility Scale</td>
<td>$32</td>
<td>$42</td>
</tr>
<tr>
<td>Wind</td>
<td>$28</td>
<td>$54</td>
</tr>
<tr>
<td>Gas Peaking</td>
<td>$150</td>
<td>$190</td>
</tr>
<tr>
<td>Nuclear</td>
<td>$29</td>
<td>$192</td>
</tr>
<tr>
<td>Coal</td>
<td>$33</td>
<td>$152</td>
</tr>
<tr>
<td>Gas Combined Cycle</td>
<td>$44</td>
<td>$68</td>
</tr>
</tbody>
</table>

Image: Lazard Consultancy
Challenges in Integration of Renewables

• Question:

what are the main challenges in increasing the share of renewables in our final energy use?
Some Intermittency Challenges

- Variable renewable energy (solar and wind)
- Temporal and locational variability
- Need for huge backup capacity in high shares of VRE
- Grid connection (windy areas far from the grid)
- Reliability, firm capacity (e.g., peak time): backup capacity
- Capacity credit (capacity value): capacity available at peak time (wind and solar = 10-15%)
- Ramp-up and ramp-down of thermal plants = additional cost for them
What’s the challenge?

• Challenge in large scale integration of variable renewable energy (wind, PV)

https://uncomfortableknowledge.com/decarbonization-of-electricity-production/
Energy storage systems

“I can't change the direction of the wind,
but I can adjust my sails to always reach my destination.”

Attributed to Jimmy Dean
Solutions for Intermittency Challenge

- **Grid interconnectivity**: connecting homes/communities/cities/countries together to balance variability
- **Electricity storage**: storing excess electricity to be used later
- **Demand response**: changing electricity demand to respond to variability
- **Power-to-heat**: converting electricity to heat
- **Power-to-fuel**: converting electricity to fuels (like hydrogen, methane, etc.)
- ...
What is electricity storage?

Storing electricity to be used later (in the same form) at a reasonable response time

• Electricity storage = electrical energy storage (EES)

Electricity storage in this study:
Stationary, grid-connected, Utility scale (medium to large scale), rechargeable

Not including:
Electric vehicles (dump charge), energy management, fuel storage, residential scale end-user, etc.
Functionality of EES (in general)

1. **Charge**: receiving power, converting it to a type of storable energy

2. **Storage unit**: storing energy and preventing from losing its value over time

3. **Discharge**: converting energy back into power, when required
Motivation for further research on EES

- Variable renewables and need for integrating them
- Deregulated markets and high capital cost for peak demands
- High investment costs of grid infrastructure for reliability improvement
- Price improvement of EES technologies (e.g., batteries)
- Smart energy systems and the need for smart use of energy …
Electricity storage technologies

• Mechanical:
  - Pumped hydro-electricity storage (PHS)
  - Compressed air energy storage (CAES)
  - Flywheel

• Electrochemical:
  - Batteries (lead-acid, NaS, Li-ion, etc.)
  - Flow batteries (e.g. VRFB)

• Other (chemical, electromagnetic, …)
  - Hydrogen storage, SMES
  - Ultracapacitors, etc.

Source: SBC ENERGY Institute
Pumped hydropower storage (PHS)

- The most common EES
- The largest PHS is 3000 MW (Bath County PHS, USA)

+ High efficiency (75-85%)
+ No fuel and emissions
+ Long discharge time (8-24 hr)
+ Low O&M requirements
+ Low generating costs
+ Long lifetime

- Large and long projects
- Site-specific
- Environmental permitting
- Capital intensive
EES technologies: Prospects for PHS

- Underground PHS, sea water reservoir, multi-purpose reservoir, pressurized water (Link to a PHS project, Link to the video of a pressurized PHS)

www.gravitypower.net

Yanbaru Okinawa PHS, Agency of Natural Resources and Energy, Japan
Compressed air energy storage (CAES)

- Second commercial technology for large-scale storage
- Two operating plants worldwide: 320 MW in Germany and 110 MW in USA
- Pressurized air is stored in salt caverns, natural aquifers, depleted gas reservoirs or aboveground vessels
- Advanced CAES without fuel needs
  + Long discharge time
  + Proven and commercial technologies
  + Large scale plants possible

- Fuel and emissions (conventional CAES)
  - Rather low efficiency (42% without and 54% with recuperator)
- Costs uncertain if fueled with natural gas

PG&E (www.pge.com)
Flywheel energy storage

- Commercially available
- Based on the use of rotational energy
- Suitable for power quality services and ride-through
- Applicable to mobile services (rail vehicles and automobile industry)

+ High efficiency (85%) and long life cycles
+ Low response time (millisecond)
+ No fuel, spill, hazard,…
+ Scalable, 20 MW plant in New York for frequency regulation

Not suitable for energy-related services
Electrochemical batteries

• A wide range of technologies available (based on material and process): lead-acid, Ni-Cd, Li-ion, NaS, ZEBRA, etc.

• Suitable both for power and energy-related services

• Most concerns related to toxicity, material intensity, air conditioning needs, etc.

• From rather low efficiency to improved efficiency (e.g., Li-ion)

• Limited life cycle and lifetime resulting in high replacement costs (e.g., lead-acid)

• Large batteries so far around 30-40 MW
  (70 MW NaS project in future to Italy)

34 MW NaS battery connected to 51 MW wind farm, NGK Insulator, Japan
Hydrogen energy storage

- By electrolysis process, water is decomposed to hydrogen and oxygen
- Hydrogen storage in tanks, reservoirs, even natural gas pipelines (up to 5%)
- Stored hydrogen can be utilized in fuel cells or thermal engines

+ Long-term storage
+ Technology available
+ Different energy carriers
+ High energy density

- Low efficiency (35-42%)
- High capital and O&M costs

Source: FuelCellToday
Power to gas energy storage

- Hydrogen reacts with CO2 and produces synthesized methane (natural gas)
- Can be integrated with carbon capture and storage (CCS) processes

+ Different technologies available for storage, transfer, and conversion back to power
+ Long-term storage
+ Different energy carriers
+ High energy density
- Low efficiency (32-40%)
- Expensive

Source: Sterner, 2009
Think more about power to gas!

- A full range of energy carriers (power, heat, and transport fuel)
- Increasing system flexibility, is it an ultimate solution?
- New concepts: sail energy, wind fuel, power fuel, etc.
Electricity storage in power systems

• In late 1880s, EES were the original solution for night-time load in New York City private area (lead-acid battery)

A) Without EES

B) With EES
Group exercise: benefits (services) of storage

• Discuss with your group members:

  - **What** are the use cases and benefits of electricity storage?
  
  - **Who** benefits from storage in that service? (e.g., electricity generator, system operator, end user, etc.)
Applications of electricity storage

- Wholesale energy services (bulk storage, arbitrage, ancillary services, and frequency regulation)
- Renewable integration
- T&D support
- Distributed EES

18 applications with different requirements
Applications of electricity storage \(^{(2)}\)

- Benefits of EES should be first monetized/valued
- Benefits depend on the market design

Source: Electric Power Research Institute (EPRI)
Energy Arbitrage

• Charging in low power prices to sell at peak times ➔ power price difference must be higher than marginal costs of EES

• Daily charge/discharge cycles or longer periods (from weekends to weekdays)

• Knowledge or estimation of day-ahead power prices

➔ What is the impact of EES on power prices?

(self-competition)
Role of storage in balancing markets

- Balancing market are growing as a result of higher RE integration
- In balancing market, EES can make revenues both in charging (down-regulation) and discharging (up-regulation)
- Some EES technologies are able to charge/discharge simultaneously
Aggregation of benefits of storage

- EES potential for several applications ➔ aggregation of benefits

Goal: Making business model

Source: Electric Power Research Institute (EPRI)
Gas turbine vs. electricity storage

1. Application in power regulation

100 MW gas turbine

- 50 MW Range
- 10 minute ramp
- 50 MW flexible range
- 20-30% useable hours/year
- Emissions

Source: EPRI

100 MW EES (efficient use)

- 200 MW Range
- + Second time ramp
- ++ 200 MW flexible range
- + 95% useable hours
- + Reduction of emissions
- + Fast project implementation

2. Application for peaking plants (CF=5%):

LCOE for gas turbine 360, and for lead-acid battery 280-320 €/MWh

➔ It’s not always correct to compare the costs in €/kW or €/MWh (what criterion so!?)
Challenges and limitations of energy storage

- Today, lack of information regarding economy of EES is a barrier
- No free markets in some services that EES is a good candidate
- Regulatory supports should be defined by cost-benefit analysis
- Other system-level impacts of EES should be evaluated (RES integration)
- Effect of high penetration of EES in energy markets (self-competition)
- Scheduling, forecasting, and allocation in aggregation of the benefits
- Toxicity, material intensity, and environmental impacts of EES
Final notes

• EES is not a panacea ➔ comparison with alternatives required

• More commercialization is needed to evaluate costs/benefits in practice

• Economic features of EES should be clarified for defining business models (ownership structure) and regulatory incentives

• Other alternatives and their impact on the development of EES ➔ for example, “smoothing effect” of renewables in large-scale integration

• Impact of EU-level power markets with high capability of power exchange

• System-level impacts of EES and study of its socio-environmental benefits
Further reading

• Our world in data (very useful visuals): https://ourworldindata.org/renewable-energy

• Database of EES projects worldwide: http://www.energystorageexchange.org/projects


• Gravity-based EES by rail vehicles (see the video): http://www.aresnorthamerica.com/

• Mountain Gravity Energy Storage: https://doi.org/10.1016/j.energy.2019.116419
Further reading: policy and economics

- Some articles related to policy, regulation, and market-economics of energy storage:


  - When I showed the slide related to (Vanadium- Redox) flow batteries, some of you looked a little skeptic. See how politicians think about it: https://www.youtube.com/watch?v=iBgENqVLJLs
• Thank you for your attention!