ECE 333 – GREEN ELECTRIC ENERGY

1. Introduction and Overview

George Gross
Department of Electrical and Computer Engineering
University of Illinois at Urbana–Champaign


GWh

<table>
<thead>
<tr>
<th>Year</th>
<th>Generation (GWh)</th>
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</thead>
<tbody>
<tr>
<td>2009</td>
<td>891</td>
</tr>
<tr>
<td>2010</td>
<td>1,299</td>
</tr>
<tr>
<td>2011</td>
<td>1,818</td>
</tr>
<tr>
<td>2012</td>
<td>4,327</td>
</tr>
<tr>
<td>2013</td>
<td>9,036</td>
</tr>
<tr>
<td>2014</td>
<td>17,691</td>
</tr>
<tr>
<td>2015</td>
<td>24,893</td>
</tr>
<tr>
<td>2016</td>
<td>36,054</td>
</tr>
<tr>
<td>2017</td>
<td>53,287</td>
</tr>
<tr>
<td>2018</td>
<td>63,825</td>
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<tr>
<td>2019</td>
<td>71,937</td>
</tr>
<tr>
<td>2020</td>
<td>90,891</td>
</tr>
</tbody>
</table>
PV SOLAR CAPACITY PRICE DECLINE

Source: Bloomberg New Energy Finance
2020 US SOLAR PV STATUS

- **US** installed 19.2 $GW_{dc}$ of solar $PV$ capacity in 2020, a 43% increase over the amount installed in 2019.
- The $PV$ capacity represents almost 43% of the 2020 added **US** electricity generation capacity.
- The **US** cumulative operational solar $PV$ capacity exceeds 100 $GW_{dc}$.
- The implementation of *concentrated solar power* ($CSP$) – often referred to as solar thermal – plants is growing considerably more slowly both in the **US** and the rest of the world.
2020 US SOLAR PV STATUS

- The 2021 Q1 was the US solar industry’s largest Q1 ever with over 5 GW$_{dc}$ new solar PV capacity.
- Potential headwinds loom on the horizon for the foreseeable future as the COVID-19 pandemic fallout threatens project schedules due to labor shortage/supply chain problems that lead to construction delays, work stoppages, permitting delays, reduced customer demand and a more challenging financing access environment; as a result, solar growth may slow.
UTILITY PV INSTALLATIONS VS. CONTRACTED PIPELINE

Source: Wood Mackenzie and SEIA; available online at https://www.seia.org/solar-industry-research-data
ANNUAL US UTILITY RENEWABLE CAPACITY ADDITIONS: 2010 – 2020


cumulative in GW

cumulative
solar

wind

GW

cumulative in GW

0 5 10 15 20 25 30 35 40


0 20 40 60 80 100 120 140 160

wind

solar

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CLEAN POWER CAPACITY GROWTH BY STATE

operational clean energy capacity by state

Source: American clean power 2021, Q1; available at https://cleanpower.org/wp-content/uploads/2021/05/CPQ-2021Q1_public.pdf; p. 6
ANNUAL NORTH AMERICAN T & D INVESTMENTS: 2010 – 2020

Source: Hitachi ABB Power Grids Velocity Suite available at: https://www.tdworld.com/transmission-reliability/article/21171011/a-stronger-more-resilient-electric-grid-requires-more-transmission-investments0

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LEADING NATIONS’ RENEWABLE ENERGY GENERATION 2020


% share of total generation

- **wind power**
- **solar PV**

DK | UY | IE | DE | EL | ES | UK | PT | AU | NL | HN | SE | BE | CL | NI | IT

% share of total generation
US ANNUAL AND CUMULATIVE UTILITY BATTERY STORAGE CAPACITY GROWTH

Source: American clean power 2021, q1; available at https://cleanpower.org/wp-content/uploads/2021/05/CPQ-2021Q1_public.pdf; p. 20

cumulative storage capacity (MW)

annual storage capacity additions (MW)
GLOBAL ENERGY STORAGE INSTALLED CAPACITY TECHNOLOGIES: 2019 – 2020

2019
- 92.6% (pumped storage: 4.6%)
- 85%

2020
- 90.3% (pumped storage: 6.9%)
- 90%


Legend:
- Pumped storage
- Molten salt storage
- Lithium-ion storage
- Other electrochemical storage
- Other energy storage
NATIONAL SOLAR DATABASE

In 2020, US geothermal units produced about 0.5% of the total US electricity generation.

Total 2020 installed US geothermal capacity was 3,673 MW; generation in 2020 was 16,930 GWh.

Geothermal generation has experienced slow growth in recent years.

Geothermal prices exceed wind/solar prices.
GEOTHERMAL PRODUCTION
GEOTHERMAL PLANTS
US GEOTHERMAL RESOURCES

Source: NREL; available at https://www.nrel.gov/gis/assets/images/geothermal-identified-hydrothermal-and-egs.jpg
US GEOTHERMAL ENERGY STATUS

Source: IRENA, https://www.irena.org/geothermal

installed capacity in MW

nameplate capacity
winter net capacity
summer net capacity
mean net generation

0 1,000 2,000 3,000 4,000

displayed capacity in MW

1,000 2,000 3,000 4,000

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TOP TEN GEOTHERMAL CAPACITY COUNTRIES IN 2020

GEOTHERMAL POWER INSTALLED COSTS, c.f.s AND LCOE: 2010 – 2020

GEOTHERMAL POWER TOTAL INSTALLED COSTS: 2007–2021

CAPACITY FACTORS OF GEOTHERMAL POWER PLANTS: 2007–2021

LCOE OF GEOTHERMAL POWER PROJECTS: 2007–2021

World biomass installed capacity is 146 GW and the 2016 generation was 504 TWh.

The US grid-connected installed biomass capacity is 16.0 GW.

China, US and Brazil are the three largest biofuel producers in the world.

World biofuels production capacity is 144 billion l/y.
GLOBAL FUEL ETHANOL PRODUCTION: 2020

Source: Center for Sustainable Systems University of Michigan, available at http://css.umich.edu/factsheets/biofuels-factsheet

US 15.78 (54)
Brazil 8.57 (30)
China 0.90 (3)
Europe 1.44 (5)
r. o. w. 2.34 (8)
YEARLY ETHANOL AND BIODIESEL PRODUCTION: 2001–2019

Source: Center for Sustainable Systems University of Michigan, available at http://css.umich.edu/factsheets/biofuels-factsheet
BIOENERGY INSTALLED COSTS, c.f.s AND LCOE: 2010 – 2020

BIOENERGY PROJECTS c.f.s. IN 2020

TOTAL INSTALLED COSTS OF BIOENERGY PROJECTS IN 2020

ANNUAL SOLAR AND BIOMASS CAPACITY: 2014 – 2017

Source: EIA, Electric Power Monthly, data published in May 9, 2018, Today in Energy; available online at https://www.eia.gov/todayinenergy/detail.php?id=36132
ANNUAL SOLAR & BIOMASS ENERGY PRODUCTION: 2014 – 2017

Source: EIA, Electric Power Monthly, data published in May 9, 2018, Today in Energy; available online at https://www.eia.gov/todayinenergy/detail.php?id=36132
The major capital cost items for a biomass power system include the fuel storage and fuel handling equipment, the combustor, boiler, prime mover, generator, controls, stack, and emissions control equipment.

US biomass resources deploy direct combustion as the most common method of heat production.

Small-scale biomass electric plants installed cost range is 3,000 – 4,000 $/kW and levelized costs of energy of 80 – 150 $/MWh.
NEW WORLDWIDE CLEAN ENERGY INVESTMENT: Q1/2006 – Q2/2020

Source: Bloomberg New Energy Finance; available at https://about.bnef.com/clean-energy-investment/
NEW WORLDWIDE CLEAN ENERGY INVESTMENT BY REGION: Q1/2006 – Q2/2021

NEW WORLDWIDE CLEAN ENERGY INVESTMENT BY SECTOR: Q1/2006 – Q2/2021

NEW ANNUAL GLOBAL CLEAN ENERGY INVESTMENT BY REGION: 2006 – 2020

Source: Bloomberg New Energy Finance; available at https://about.bnef.com/clean-energy-investment/
NEW CLEAN ENERGY INVESTMENT BY CHINA: Q1/2006 – Q2/2020

Source: Bloomberg New Energy Finance; available at https://about.bnef.com/clean-energy-investment/
NEW CLEAN ENERGY INVESTMENT BY INDIA: Q1/2006 – Q2/2020

Source: Bloomberg New Energy Finance; available at https://about.bnef.com/clean-energy-investment/
NET ANNUAL RENEWABLE CAPACITY ADDITION: 2018 – 2021


- net capacity additions in GW
- bioenergy
- solar PV
- wind
- hydro

Asia Pacific
- 2018
- 2019
- 2020
- 2021

Americas
- 2018
- 2019
- 2020
- 2021

Europe
- 2018
- 2019
- 2020
- 2021

others
- 2018
- 2019
- 2020
- 2021

NET ANNUAL RENEWABLE CAPACITY ADDITION: 2018 – 2021

ANNUAL GLOBAL POWER SECTOR INVESTMENT: 2011 – 2021

Source: IEA analysis based on EIA 2021, available at https://iea.blob.core.windows.net/assets/01e998-8611-45d7-acab556422575a/ElectricityMarketReportJuly2021.pdf; p. 31

2019 US $ billion

- fossil fuel power
- nuclear
- renewable power
- electricity networks
- battery storage

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GLOBAL RENEWABLE INVESTMENT: 2011 – 2020


2% increase from 2019 to 2020

- China
- Other developing and emerging countries
- European Union and United Kingdom
- United States
- Other developed countries
## TRENDS IN GLOBAL RENEWABLE INVESTMENT: A COMPARISON


<table>
<thead>
<tr>
<th>Technology</th>
<th>New Annual Investment (Billion USD)</th>
<th>Change relative to 2010</th>
<th>Change relative to 2019</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar power</td>
<td>0 20 40 60 80 100 120 140 160</td>
<td>+64%</td>
<td>+12%</td>
</tr>
<tr>
<td>Wind power</td>
<td>0 40 80 120 160</td>
<td>+60%</td>
<td>-6%</td>
</tr>
<tr>
<td>Biomass and waste</td>
<td>0 4 8 12 16 20</td>
<td>-39%</td>
<td>-3%</td>
</tr>
<tr>
<td>Small-scale hydropower</td>
<td>0 1.7 5.0</td>
<td>-82%</td>
<td>-48%</td>
</tr>
<tr>
<td>Biofuels</td>
<td>0 1.7</td>
<td>-91%</td>
<td>-65%</td>
</tr>
<tr>
<td>Geothermal power</td>
<td>0 1.0</td>
<td>-73%</td>
<td>-30%</td>
</tr>
<tr>
<td>Ocean power</td>
<td>0 0.0</td>
<td>-100%</td>
<td>—</td>
</tr>
</tbody>
</table>

**Source:** REN 21 at https://www.ren21.net/wp-content/uploads/2019/05/GSR2021_Full_Report.pdf; p.188
IMPACTS OF RENEWABLES

MW

ture chronological load

modified chronological load

capacity of the time-dependent resource

energy generated by time-dependent resource
ELECTRIC SYSTEM INFRASTRUCTURE

Central Generating Station
Step-Up Transformer
Control Center
Residential Data Concentrator
Micro-turbine
Photo voltaics
Batteries
Residential
Gas Turbine
Receiving Station
Gas Turbine
Recip Engine
Cogeneration
Industrial
Commercial
Flywheel
Commercial
Recip Engine
Fuel cell
Commercial
Data network Users

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TWENTY-FOUR HOUR PROFILE

Source: California ISO data for 08/08/13
WEEKLY LOAD CYCLE

Source: California ISO data from 08/05/13 to 08/11/13
THE WEEKLY LOAD SHAPE

load

- **total available**
- **reserves margin**
- **base load**
- **intermediate**
- **peak**

**Mon** | **Tue** | **Wed** | **Thu** | **Fri** | **Sat** | **Sun**
CALIFORNIA SUMMER LOAD: TYPICAL DAILY SHAPE

Source: California ISO data for 07/20/21
ONTARIO DAILY WIND POWER OUTPUT

MW
700
600
500
400
300
200
100
0

hour

Source: IESO
PV POWER OUTPUT OF 1–MW CdTe ARRAY IN GERMANY

Source: CAISO
PV POWER OUTPUT AT THE NEVADA 70 – kW POLYCRYSTALLINE ARRAY

Data collected on a 10 – second basis

Source: CAISO
AUGUST 21, 2017 SOLAR ECLIPSE

'000s of megawatts, Pacific daylight time

PEAK OF ECLIPSE IN CALIFORNIA

Day of eclipse

Day before eclipse

Source: California ISO
KEY CHALLENGES IN RENEWABLE EXPANSION

- Integration into the grid
  - interconnection
  - grid capability
  - reliability issues
  - power quality

- Competitiveness of technology costs

- Environmental issues, e.g., recycling

- Development of lower-cost storage technology
KEY CHALLENGES IN RENEWABLE EXPANSION

❑ Formulation of appropriate policies at the
  - federal;
  - state; and
  - local

levels

❑ Regulatory accommodation via
  - smoother permitting processes
  - assurances of back up power provision
  - implementation of “green power” differential
US 2020 BILLION – DOLLAR WEATHER AND CLIMATE DISASTERS

Central Severe Weather
July 10–11

Western Wildfires,
California, Oregon,
Washington Firestorms
Fall 2020

Western / Central
Drought and Heatwave
Summer-Fall 2020

Central and Eastern
Severe Weather
May 3–5

Central, Southern,
and Eastern Severe Weather
April 27–30

South Texas Hail Storms
May 27

Hurricane Hanna
July 25–26

Hurricane Delta
October 9–11

Hurricane Zeta
October 28–29

South Central and Ohio Valley
Severe Weather
March 27–28

Southeast Tornadoes and
Northern Storms and Flooding
January 10–12

Tennessee Tornadoes and
Southeast Severe Weather
March 2–4

South, East and
Northeast Severe Weather
February 5–7

Hurricane Isaias
August 3–4

South, Central and Eastern
Severe Weather
May 20–23

Southeast and Eastern
Tornado Outbreak
April 12–13

Tropical Storm Eta
November 8–12

Source: NOAA; available at https://www.ncdc.noaa.gov/billions/

This map denotes the approximate location for each of the 22 separate billion-dollar weather and climate disasters that impacted the United States during 2020.
US 2021 BILLION – DOLLAR WEATHER AND CLIMATE DISASTERS

Source: NOAA; available at https://www.ncdc.noaa.gov/billions/

This map denotes the approximate location for each of the 8 separate billion-dollar weather and climate disasters that impacted the United States January–June 2021.
FROM 2011 TO 2019, 121 COAL-FIRED POWER PLANTS WERE REPURPOSED TO USE OTHER TYPE OF FUELS: 49.2 GW OF COAL FROM THE TOTAL 316.8 GW COAL CAPACITY AT THE START OF 2011 WAS RETIRED.

OF THE 121 PLANTS, 103 WERE CONVERTED TO OR REPLACED BY NATURAL-GAS-FIRED PLANT:

14.3 GW CAPACITY CONVERTED THE BOILER TO BURN NATURAL GAS.
THE *US* VANISHING COAL PLANTS

- 15.3 GW capacity of natural gas combined cycle (*NGCC*) replaced 7.9 GW coal capacity

- The switch from coal to natural gas was driven by

  - stricter emission standards;

  - low natural gas prices; and,

  - more efficient gas turbine technology
US COAL TO NATURAL GAS CONVERSION: 2011 – 2019

Source: EIA August 5, 2020; available at https://www.eia.gov/todayinenergy/detail.php?id=44636

Source: EIA August 5, 2020; available at https://www.eia.gov/todayinenergy/detail.php?id=44636

- replacement by NGCC
- conversion to natural gas boiler
- outright retirement

GW
COAL PLANT RETIREMENTS CONTINUE

Source: EIA, Today in Energy, September 1, 2020; available online at https://www.eia.gov/todayinenergy/detail.php?id=44976

- retired as of June 2020
- planned for retirement

GW
COAL PLANT RETIREMENTS

Source: S&P Global Market Intelligence; available on-line at
While the US remains the world’s premier oil and gas producer, Trump has tried to stop the coal decline but without much success:

- retirements of mostly 50+ years-old plants continued
- thousands of miners lost jobs
- integration of renewable resources – principally solar – at deeper penetrations
Today, coal powers less than 20\% of *US* electricity consumption.

Climate change concerns, the movement away from coal by many advanced economies and the push by states and cities to limit future fossil resource reliance are key drivers and so is the improved economics of solar and wind power.
Kentucky Coal Mining Museum in Harlan County switches to solar power

(Washington Post, April 6 2017)
GLOBAL COAL-FIRED GENERATION CAPACITY: 2019 – 2021

China

r. o. w.

installed capacity in GW

2019 2020 2021

GAS-FIRED POWER GENERATION CAPACITY ADDITION: 2020 – 2022

COURSE OBJECTIVES

❑ Acquaint students with key basic physical principles used in renewable energy generation

❑ Stress the importance of economics – including the role of incentives – and environmental aspects in electricity developments; also, the role in job creation by the renewable sector is critical

❑ Provide a good understanding of impacts of market forces on shaping the electricity business
COURSE OBJECTIVES

- Expose students to some major national and international developments in renewable energy systems and their effective integration into today’s power grids.

- Explain the exciting developments in the energy sector and the role electricity plays in addressing global warming issues.
ECE 333: KEY ASPECTS

- Understanding of the basic scientific principles underlying renewable resources is essential.

- Awareness of the role that renewables can play in effective climate change activities is important.

- Challenges in the integration of renewables are huge in nearly every dimension.
TOPICAL OUTLINE

- General overview of electricity demand, supply, industry structure, interconnected system operations and state of technology

- Nature/role of renewable generation resources

- Review of concepts in electric circuit analysis

- Engineering aspects of renewable resource generation technologies: wind energy conversion
TOPICAL OUTLINE

systems; thermodynamics considerations; solar resource and solar array systems; economics of renewable technologies; environmental issues

- The roles of energy storage resources and their deployment in grids with integrated renewable

- The demand picture: the nature of electrical loads; time dependence and periodicity; price impacts
TOPICAL OUTLINE

- Demand management and energy conservation; efficiency improvements; price-responsive demand; load management; and the role of new technologies
- Electricity market basics
- Integration of renewable generation into the grid
- The policy and regulatory dimensions
GRADING POLICY

- The course grade is based on the performance of the student in the quizzes, the midterm exams, and the final exam.

- Students will be assigned homework but will not need to hand them in as they are not graded.

- The problems in the short quizzes in class will be based on the homework assignment problems.
## Proposed Grading Policy Table

<table>
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<tr>
<th>component</th>
<th>percentage</th>
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<td>homework</td>
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</tr>
<tr>
<td>quizzes</td>
<td>15</td>
</tr>
<tr>
<td>two midterm exams</td>
<td>40</td>
</tr>
<tr>
<td>final</td>
<td>45</td>
</tr>
<tr>
<td>total</td>
<td>100</td>
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</table>
Suddenly, knowing a lot about the U.S. power grid became sexy at cocktail parties.