1. Introduction and Overview

George Gross

Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign

RENEWABLE ENERGY SYSTEMS

- We focus on the technical, economic and environmental aspects of renewable and alternative energy systems to obtain an understanding of their role in meeting society’s electricity needs
- We analyze a wide range of renewable energy supply issues
- The course provides a basis to understand the distinctive scientific principles of renewable
RENEWABLE ENERGY SYSTEMS

energy and the ability to provide an assessment of the economics and environmental impacts of renewable energy

- The course covers the basics of energy generation from renewable sources, the needed thermodynamics background, the structure and nature of the electric transmission grid, the integration of renewable resources into the grid in terms of technical, environmental and economic aspects and the regulatory framework for electricity

OUTLINE OF INTRODUCTION

- The importance of electricity
- The US electricity industry – past and present
- Electricity generation
- Nature of electric demand
- The energy supply and demand picture
- A brief overview of renewables
- Course outline
CRITICAL IMPORTANCE OF ELECTRICITY

- Energy is the *lifeblood* of modern society
- The importance of electricity is on the rise
- Efficient and environmentally sensitive electricity services are key requirements for the nation’s global competitiveness
- The electric power industry is one of the world’s largest industrial sectors; the 2014 *US* revenues from retail sales were circa $400 billion

ENERGY CONSUMPTION AND ELECTRICITY USE

*energy / GNP ratio* (index is 100 for the year 1900) *electricity as a percentage of total energy consumed*

*electricity will continue to substitute for less efficient and less productive energy forms*
ELECTRIC POWER SECTOR $CO_2$
EMISSIONS

US $CO_2$ EMISSIONS: 1990 – 2017


Source: https://www.eia.gov/electricity/annual/pdf/epa.pdf; issued November 2016

Page 4
THE WORLD ECONOMIES RELY ON ABUNDANT AND AFFORDABLE ELECTRICITY

ELECTRICITY AND ENERGY

- While the main focus of the course is on green resources, we need to also understand both the energy context and the policy context, within which such resources are planned and operated.

- Energy obtained from various sources is converted into electricity; electric energy is not used in
ELECTRICITY AND ENERGY

that form but is converted into other energy forms, such as light, sound and mechanical energy

- As more energy is consumed as electricity, the focus on the environmental impacts is driving the changes underway in the energy infrastructure, given the universal interest to effectively address the impacts of climate change

IMPACTS OF ELECTRICITY

- The National Academy of Engineering, the US’s most prestigious collection of outstanding engineers, named electrification – the development of the vast networks of electricity that power the world – the most important of the twenty engineering achievements that have had the greatest impact on the quality of life in the twentieth century
IMPACTS OF ELECTRICITY

- Electricity ranked ahead of the automobile, airplane, safe and abundant water, electronics, computers and space exploration
- The widespread electrification implemented in the twentieth century gave us energy for our cities, factories, farms and homes, forever changing the lives of people

THE BEGINNINGS

- Commercial use of electricity began in the late 1870’s with the development of arc lamps for street lighting and lighthouse illumination
- The first complete electric power system, comprising a generator, cable, fuse, meter and loads, is considered to be Edison’s Pearl Street Station in New York in 1882
  - DC system with a DC generator supply
  - 59 customers within a 1 – mile radius area
THE BEGINNINGS

☐ Actually, George Roe had founded in 1879 an electric company in San Francisco, which later became part of *PG&E*

☐ this was the first entity in the nation to offer central station electric service to the public

☒ two brush arc–light dynamos supplied 21 lights to serve from sundown to midnight – Sundays and holidays excluded – for $10 per lamp per week
Frank Sprague developed *electrical motors* in 1884; within a short time, he incorporated them into the electricity system.

The major limitations of *DC* systems became apparent by 1886:

- inability to deliver power over longer distances
- need for high voltages for longer distance transmission so as to reduce the associated losses but, considerably lower voltages for generation and consumption.

Gaulard and Gibbs developed the *transformer* and *AC transmission*, the forerunners of the *AC* transmission systems in use today.

George Westinghouse immediately bought *US rights* to the Gaulard and Gibbs technology.

In 1889, the *first AC transmission line in North America* – a single phase 4–*kV, 21–km* line – was put into operation to link Willamette Falls to Portland.
MAJOR DEVELOPMENTS

- A key and important development was Tesla’s invention of induction motors and polyphase systems.
  - Westinghouse purchased the rights to Tesla’s inventions on AC motors, generators, transformers and transmission systems.
  - Westinghouse was the key driver of the construction of the basis of today’s AC grid.

- AC won out over DC because
  - The ease of transformation of voltage levels thereby providing the flexibility to use different voltage levels for generation/transmission and consumption.
  - The increased simplicity of AC over DC generators.
  - The increased simplicity and lower costs of AC over DC motors.

- AC replaced DC over a very brief time period.
MAJOR DEVELOPMENTS

- In 1893, the first three-phase transmission line in North America went into service; it was a $2.3-kV$, 12-$km$ line in Southern California.
- Niagara Falls was connected to Buffalo – a 30-$km$ distance – using AC since DC was not practical.

TECHNOLOGICAL DEVELOPMENTS

- Pressures to transmit larger amounts of power over larger distances led to higher voltages:
  - early systems: 12, 44 and 66 $kV$ (RMS line-to-line)
  - 1922: 165 $kV$
  - 1923: 220 $kV$
  - 1935: 287 $kV$
  - 1953: 330 $kV$
  - 1965: 500 $kV$
  - 1966: 735 $kV$ (Hydro Quebec)
  - 1969: 765 $kV$ (American Electric Power)
TECHNOLOGICAL DEVELOPMENTS

- Standardization of voltage levels led to voltage classifications
  - 115, 138, 161 and 230 kV are high voltage (HV)
  - 345, 500 and 765 kV are extra high voltage (EHV)
- The development of mercury arc valves in the early 1950’s made HVDC economical in specific cases: transmission of larger blocks of power over longer distances

- Eventually, the various frequencies in use – 25, 50, 60, 125 and 133 Hz – became standardized to 60 Hz in North America; there are many parts of the world where the frequency is 50 Hz today
- DC becomes economic over AC for distances greater than
  - 500 km for overhead lines
  - 50 km for underground/submarine cables
THE US TRANSMISSION GRID

Legend
- Cooperatives
- Federal
- Independent Transmission Companies
- Other Public Power
- Shareholder-Owned

THE ELECTRIC POWER GRID

INDUSTRY STRUCTURE

- Brutal and inefficient competition was rife in electricity
  - 24 central station power companies were established in Chicago between 1887 and 1893
  - Exhaustive duplication and fierce competition led to high costs

- Samuel Insull built a monopoly over all central station production in Chicago and is considered the father of the regulated monopoly:
  “exclusive franchises should be coupled with the conditions of public control, requiring all charges for services to be based on a cost plus a reasonable profit”
- In 1907, New York and Wisconsin set up their regulatory commissions to regulate electricity
THE VERTICALLY INTEGRATED UTILITY INDUSTRY STRUCTURE

COMPETITION IN THE GENERATION MARKET

- The 1978 Public Utility Regulatory Policies Act (PURPA) unleashes competition through the introduction of qualifying facilities (QFs)
- PURPA mandates each investor–owned utility to purchase power at avoided cost from QFs located in its service territory
- PURPA implementation was left to individual states resulting in non-uniform implementations
- The once fledgling private power enterprises constitute today a multibillion dollar industry whose role in the electricity business is of paramount importance
ENERGY SOURCES OF NUG CAPACITY

- natural gas: 59.0%
- coal: 17.8%
- other: 3.1%
- oil: 5.7%
- nuclear: 8.3%
- hydro: 2.1%
- wind: 1.7%
- geothermal: 0.7%
- waste: 1.5%
- natural gas

Source: 1993 Capacity and Generation of Non-Utility Sources of Energy, Edison Electric Institute

GROWING IMPACT OF NUG ENERGY

Source: http://www.eia.doe.gov/cneaf/electricity/epmtable1_1.html; Issued 2010

**NUG ENERGY**

![Energy Bar Chart](source_image)

**DIVERSITY OF THE US ELECTRICITY INDUSTRY**

![Diversity Bar Chart](source_image)

*Source: EIA, January, 2017*

**total number** = 3,473
THE US ELECTRICITY INDUSTRY

- The 811 rural electric coops stem from the New Deal years – a result of the drive to supply electricity to everyone and everywhere
- The 287 “other providers” include 89 “facilities” of co-generators and other industrial generators and 198 “other entities” of marketers – entities that sell delivery or energy services, but not both
- The 6 federal power marketing agencies (FPMAs) include Bonneville Power and TVA

THE US ELECTRICITY INDUSTRY

- The 261 investor–owned utility companies (IOUs) represent the predominant part of the industry because nearly three fifths of all electricity sales come from these entities
- The 1,948 publicly owned electric utilities are the most numerous members of the industry: they represent non-profit, customer-owned government agencies at the local and state levels
- The 166 non–utility companies are, typically, not state–regulated entities
2017 US ELECTRICITY CUSTOMERS

Total consumers: 151.86 million

<table>
<thead>
<tr>
<th>Type</th>
<th>Million Customers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>132.69</td>
</tr>
<tr>
<td>Commercial</td>
<td>18.35</td>
</tr>
<tr>
<td>Industrial</td>
<td>0.82</td>
</tr>
<tr>
<td>Other</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

Source: EIA, EPM with data for January 2018, rel. March 2018, Table 5.7: Number of Ultimate Customers Served by Sector, p. 133.

RETAIL SALES OF ELECTRICITY TO END–USE SECTOR CUSTOMERS

Total 2016: 3,757 TWh
Total 2017: 3,707 TWh

<table>
<thead>
<tr>
<th>Sector</th>
<th>GWh 2016</th>
<th>GWh 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>1,409,340</td>
<td>1,398,551</td>
</tr>
<tr>
<td>Commercial</td>
<td>1,366,195</td>
<td>1,354,325</td>
</tr>
<tr>
<td>Industrial</td>
<td>973,682</td>
<td>946,577</td>
</tr>
<tr>
<td>Transportation</td>
<td>7,503</td>
<td>7,606</td>
</tr>
</tbody>
</table>

PERCENT CUSTOMERS SERVED BY ELECTRICITY PROVIDERS

- IOUs 57.80%
- non-utility 0.30%
- federal 0.80%
- coop 11.4%
- other 14.80%
- public 14.90%

Source: http://www.eia.gov/electricity/state/unitedstates/Table 9

TV POPULATION IN US HOMES

- no television
- one or two televisions
- three or more televisions

RISING NUMBER OF COMPUTERS IN HOUSEHOLDS


TOTAL RESIDENTIAL ENERGY USE

PREVALENT HEATING SOURCES IN US HOUSEHOLDS

![Graph showing the percentage of heating sources from 1993 to 2009.](image)


US CONVENTIONAL ELECTRICITY GENERATION SOURCES

![Map showing conventional electricity generation sources in the US.](image)

2001 – 2017 GENERATION CAPACITY ADDITIONS

Source: EIA, http://www.eia.gov/electricity/annual/html/epa_04_06.html; issued December 2017

2017 GENERATION BY SOURCE

AMEREN ILLINOIS ENERGY SOURCES OF ELECTRICITY SUPPLIED IN 2017

- Coal: 50%
- Nuclear: 16%
- Natural gas: 20%
- Wind: 9%
- Hydro: 1%
- Oil: 3%

Source: Ameren IP, April 2018

2017 AMEREN ILLINOIS POWER AVERAGE ELECTRICITY EMISSIONS / WASTE

<table>
<thead>
<tr>
<th>Output</th>
<th>Average amount per MWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>1,373 lb</td>
</tr>
<tr>
<td>Nitrogen oxides</td>
<td>0.72 lb</td>
</tr>
<tr>
<td>Sulfur dioxide</td>
<td>1.38 lb</td>
</tr>
<tr>
<td>High–level nuclear waste</td>
<td>0.0009 lb</td>
</tr>
<tr>
<td>Low–level nuclear waste</td>
<td>0.0002 ft^3</td>
</tr>
</tbody>
</table>

Source: Ameren IP, data for the 12 months ending December 31, 2016
ENVIRONMENTAL ASPECTS

- The electricity industry is the most highly visible stationary source of pollution
- In big picture terms, the US electric power industry is responsible for about
  - 3/4 of $SO_X$ emissions
  - 1/3 of $CO_2$ and $NO_X$ emissions
  - 1/4 of particulate matter and toxic heavy metals emissions

US LAWS ON ENVIRONMENTAL PROTECTION

Number of laws
ACRONYM SOUP

- **NIMBY**: Not In My Back Yard
- **NOOS**: Not on Our Street
- **LULU**: Locally Undesirable Land Use
- **NOPE**: Not on Planet Earth
- **NIMTOO**: Not in My Term of Office
- **SLAPP**: Strategic Lawsuits Against Public Participants
- **CAVE**: Citizens Against Virtually Everything
- **BANANA**: Build Absolutely Nothing Anywhere Near Anyone

ENERGY EFFICIENCY

WE’LL PAY YOU IF WE CAN DO THIS TO YOUR SPARE REFRIGERATOR.

- You’ll save your spare refrigerator yourself. If you believe how wasteful it is. An average one wastes a whopping $100 a year in energy costs.* If you let us recycle it, not only will you get rid of an old energy guzzler, you’ll get a $50 savings bond from Edison or CPF. To qualify, it must be in working order and used as a second refrigerator for the last six months. *So for your $50 savings bond, call Edison or CPF at 1-800-234-9722. Or visit our TDD accessible number 1-800-354-9710. It pays to recycle your spare refrigerator.
ECONOMIC DEVELOPMENT

Time to make a quantum leap! It's time to make it in Texas.

If you compete in the high tech, food, aircraft manufacture or plastics industries, EU Electric can help you make it in Texas. Everything you need, in one convenient location, couldn't be better. Texas is one of the states people want to move to. We've got low cost land. Low cost labor. Low cost taxes. Our people are well trained in transportation with access to rail, truck, commerical freight and highway services. And our utilities, like electricity, are reliable and reasonable. So get a jump on your competition, get on down here. We have a wealth of real estate, space and property to put along. Contact John Proctor at 1-800-431-4400. Fax 219-958-9476.

EU ELECTRIC
We put a lot of energy into business.

THE ENERGY UNIT PREFIX

<table>
<thead>
<tr>
<th>prefix</th>
<th>symbol</th>
<th>value</th>
<th>exponent</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>kilo</td>
<td>k</td>
<td>thousand</td>
<td>$10^3$</td>
<td></td>
</tr>
<tr>
<td>Mega</td>
<td>M</td>
<td>million</td>
<td>$10^6$</td>
<td></td>
</tr>
<tr>
<td>Giga</td>
<td>G</td>
<td>billion</td>
<td>$10^9$</td>
<td></td>
</tr>
<tr>
<td>Tera</td>
<td>T</td>
<td>trillion</td>
<td>$10^{12}$</td>
<td></td>
</tr>
<tr>
<td>Peta</td>
<td>P</td>
<td>quadrillion</td>
<td>$10^{15}$</td>
<td></td>
</tr>
<tr>
<td>Exa</td>
<td>E</td>
<td>quintillion</td>
<td>$10^{18}$</td>
<td></td>
</tr>
</tbody>
</table>
ENERGY AND POWER UNITS

- Energy is expressed in a wide variety of units:
  - Joules
  - quads
  - Watt-hours
  - BTUs
  - calories

- Fuel supply are expressed in barrels, tons oil equivalent (toe), BTUs, calories or cubic feet for gas and acre feet for water

- In round numbers:
  - the US annually consumes 100 quads of energy
  - the US installed electric generation capacity is about 1,000 GW
  - the Champaign electrical load is about 300 MW

THE GLOBAL ENERGY DEMAND

- We view the electric energy within the global energy context

- We discuss the key aspects of demand
  - population growth
  - future demand growth

- We examine the energy supply picture and the impacts on green house gases
WORLD POPULATION

1990: 5.3 billion
2017: 7.6 billion
2030: 8.6 billion
2050: 9.8 billion
2100: 11.2 billion

Source: United Nations Department of Economic and Social Affairs, Population Division, World Population Prospects: The 2017 Revision

DEMOGRAPHIC TRANSFORMATIONS

2015 – 7.35 billion
Asia: 60%
Europe: 16%
Africa: 16%
Latin America & Caribbean: 9%
Oceania: 5%

2060 – 10.18 billion
Asia: 52%
Europe: 28%
Africa: 16%
Latin America & Caribbean: 8%
Oceania: 4%

Source: UN, Population Division; http://esa.un.org/unpd/wpp/Excel-Data/population.htm
GLOBAL LACK OF ELECTRICITY ACCESS


GLOBAL LACK OF CLEAN COOKING ACCESS

Source: REN 21
1980 – 2011 ENERGY DEMAND VS. GDP PER CAPITA

Source: EIA and the World Bank

1980 – 2011 ENERGY DEMAND TRENDS

Source: EIA, 2010; data exclude biomass
EVOLUTION OF THE MAIN SOURCES OF US ENERGY CONSUMPTION

Source: Steve Chu and Arun Majumdar, "Opportunities and challenges for a sustainable energy future," Nature, August 2012


### 2012 WORLD PRIMARY ENERGY CONSUMPTION

<table>
<thead>
<tr>
<th>source</th>
<th>generation (PJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>solid fuels</td>
<td>156,171</td>
</tr>
<tr>
<td>liquid fuels</td>
<td>172,935</td>
</tr>
<tr>
<td>natural gas</td>
<td>125,063</td>
</tr>
<tr>
<td>hydroelectric power</td>
<td>34,796</td>
</tr>
<tr>
<td>nuclear power</td>
<td>23,462</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td><strong>522,370</strong></td>
</tr>
</tbody>
</table>

Source: BP Statistical Review of the World 2013

---

### PREDOMINANCE OF OIL AND GAS

![Graph showing the predominance of oil and gas in world energy consumption]

PREDOMINANCE OF OIL AND GAS

Source: http://www.exxonmobil.com/corporate/Newsroom/Publications/eTrendsSite/chapter1.asp

IEA ELECTRICITY GENERATION AND CO2 FORECASTS

Source: Steve Chu and Arun Majumdar, "Opportunities and challenges for a sustainable energy future," Nature, August 2012
GLOBAL MEAN TEMPERATURE

The change over the period 1860-2000 is about 0.7 °C

Source: IPCC Fourth Assessment Report

KEELING CURVE

Source: Mauna Loa Observatory, Hawaii
COMPELLING EVIDENCE

natural forcing only

natural (solar + volcanic) forcing alone does not account for warming in the past 50 years

anthropogenic forcing only

natural + anthropogenic forcing

adding human influences (greenhouse gases + sulfate aerosols) brings the models and observations into pretty close agreement

1980 – 2008 CO₂ EMISSIONS VS. GDP PER CAPITA

Source: EIA and GGDC
**CO₂ EMISSIONS FORECAST**

![Graph showing CO₂ emissions forecast](image)

*Source: The Outlook for Energy: A View to 2040, pg. 34*

**EMISSION HETEROGENEITIES**

![Graph showing emission heterogeneities](image)

*Source: International Energy Agency*

---

Page 37
China consumed 48% of 2010 global coal production.


CRUDE OIL PRICES 1861-2016

Source: BP Statistical Review of World Energy 2017
MISALIGNMENT OF SUPPLY AND DEMAND


MAJOR CHALLENGES IN ENERGY

- **Energy security**: fuel supply resources for the future
- **Economic growth**: accommodation of the developing nations’ needs
- **Environmental effects**: global warming and emission control
- **Electricity system reliability**: assurance of integrity of electric power infrastructure
SUSTAINABILITY

Sustainable development refers to living, production and consumption in a manner and at a level that meets the needs of the present without unduly impacting the ability of future generations to meet their own needs.

The World Commission on Environment and Development set up by the UN issued a seminal report in 1987; the so-called Brundtland Report entitled *Our Common Future* established the concept and definition of sustainable development:

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts:

- the concept of needs, in particular the essential needs of the world's poor, to which overriding priority should be given; and
- the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs."
The major thrust of the report was to explicitly recognize the scale and unevenness of economic development and population growth continue to place unprecedented pressures on the planet’s land, water and other natural resources and without constraints are severe enough to wipe out regional populations and, over the long term, to lead to global catastrophes.

Sustainability is a key guiding principle in policy formulation in many nations, states and localities.

ROLE OF RENEWABLES IS OF GROWING IMPORTANCE
### 2017 GENERATION BY SOURCE

- **Coal**: 30.1%
- **Natural gas**: 31.8%
- **Hydro**: 7.5%
- **Petroleum/other gases**: 0.9%
- **Nuclear**: 20.1%
- **Other renewable sources**: 9.6%

**Source:** EIA March 29, 2018, https://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf; issued March, 2018

### 2017 NET GENERATION OF RENEWABLE ENERGY SOURCES

- **Wind**: 37.5%
- **Hydroelectric**: 44.1%
- **Wood & wood-derived fuels**: 4.0%
- **Other biomass**: 4.4%
- **Geothermal**: 2.4%
- **Solar**: 7.7%

**Source:** EIA March 29, 2018, https://www.eia.gov/totalenergy/data/monthly/pdf/mer.pdf; issued March, 2018
2017 RENEWABLE ENERGY SHARE OF GLOBAL ELECTRICITY GENERATION

73.5% Non-renewable electricity

26.5% Renewable electricity

16.4% Hydropower

5.6% Wind power

2.2% Bio-power

1.9% Solar PV

0.4% Ocean, CSP and geothermal power


US POPULATION DENSITY AND RENEWABLE RESOURCE LOCATIONS

Source: http://www.census.gov/popest/data/maps/2009/PopDensity_09.jpg
DENSITY MAP OF FUTURE WIND AND SOLAR INSTALLED CAPACITY ADDITIONS


RENEWABLE PORTFOLIO STANDARDS (RPS)

Source: http://www.dsireusa.org/resources/detailed-summary-maps; February 2017
2005 – 2017 GLOBAL WIND CAPACITY


2017 TOP 10 COUNTRIES IN TOTAL INSTALLED WIND CAPACITY

world total: 539,123 MW

2017 INSTALLED WIND CAPACITY

Europe 33.01 %
Asia 42.36 %
North America 19.52 %
Africa & Middle East 0.84 %
Latin America & Caribbean 3.32 %
Pacific 0.95 %

total installed capacity: 539,581 MW

1998 – 2017 INSTALLED US WIND CAPACITY ADDITIONS


US WIND DEVELOPMENTS IN 2016

- Installed power capacity exceeded the US hydro capacity in 2016 so as to make wind the largest capacity RER with 52,000 turbines
- Added wind capacity in 2016 was 8,203 MW
- Total installed wind capacity in 2016 is 82,143 MW
- The US wind industry provides employment to 102,500 persons
- Wind turbine technician is the fastest growing job in the US
In late 2016, Block Island – the first, offshore US wind farm with a 5–turbine 30–MW nameplate capacity –began operations off the RI coast.

Wind generated energy reduced 9 % of electric power energy $CO_2$ emissions – 159 million mt – and saved 87 billion gallons of water consumption.

Corporate interest in wind – not driven by RPS requirements – continued to remain high.
US WIND ENERGY INDUSTRY MANUFACTURING FACILITIES

Source: AWEA 2017 Annual Market Report Executive Summary

2017 US WIND GENERATION SHARE OF STATE CONSUMPTION

total 2017 generation: 254,000 GWh
2017 generation share: 6.3%

Source: AWEA at https://www.awea.org/2017-market-reports
WIND ENERGY REDUCES US GHG EMISSIONS


158.6 million metric tons of CO₂

SOLAR ENERGY

Images From: http://www.scientificamerican.com/article.cfm?id=how-to-use-solar-energy-at-night
2009 – 2017 GLOBAL CUMULATIVE PV CAPACITY

GLOBAL ADDED PV CAPACITY:
2000 – 2018

The global solar cumulative capacity reached 405.4 GW in 2017. The addition of 98.9 GW represents a 30% year-on-year growth over the 76.6 GW installed in 2016. China installed 34.5 GW to continue as the dominant solar nation in the world. Europe’s share remained at 22% of the global PV capacity with 8.6 GW added capacity.

**US Annual Solar Capacity Additions**

Source: [https://www.seia.org/solar-industry-research-data](https://www.seia.org/solar-industry-research-data)

**US Annual PV Solar Capacity Additions and Prices**

Source: SEIA/UTM Research U.S. Solar Market Insight Lawrence Berkeley National Laboratory Tracking the Sun

![Graph showing solar utility scale generation from 2009 to 2017](source: http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm? t=epmt_1_01_a)

NATIONAL SOLAR DATABASE

![Map of national solar database](source: http://www.seia.org/research-resources/national-solar-database; issued 2016)
### Top 10 States with Installed Solar PV Capacity in 2017

- **FL**: 1,430 MW
- **GA**: 1,566 MW
- **UT**: 1,599 MW
- **TX**: 1,874 MW
- **MA**: 2,011 MW
- **NJ**: 2,390 MW
- **NV**: 2,595 MW
- **AR**: 3,400 MW
- **NC**: 4,308 MW
- **CA**: 21,074 MW

Source: 2017 data; available at [https://www.seia.org/solar-industry-research-data](https://www.seia.org/solar-industry-research-data)

### US Solar PV Capacity 2018 Q1

- **Total 2012 – 2017**: 44.2 GWdc

- **39%**: California
- **38%**: North Carolina
- **9%**: Nevada
- **5%**: Arizona
- **5%**: Massachusetts
- **4%**: All Others

Source: SEIA/GTM Research US Solar Market Insight Q1 2018
PV SOLAR RESOURCE MAP FOR THE US, SPAIN AND GERMANY

US – GERMANY COMPARISON

<table>
<thead>
<tr>
<th>attribute</th>
<th>US</th>
<th>Germany</th>
<th>ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>population (million)</td>
<td>321</td>
<td>82</td>
<td>3.9</td>
</tr>
<tr>
<td>area (mi²)</td>
<td>3,119,884</td>
<td>137,882</td>
<td>22.6</td>
</tr>
<tr>
<td>peak load (GW)</td>
<td>777</td>
<td>80</td>
<td>9.7</td>
</tr>
<tr>
<td>annual energy (billion kWh)</td>
<td>3,963</td>
<td>544</td>
<td>7.3</td>
</tr>
<tr>
<td>installed wind capacity (MW)</td>
<td>65,877</td>
<td>39,223</td>
<td>1.7</td>
</tr>
</tbody>
</table>

In 2011, US geothermal resources produced an estimated 16.7 million MWh. Total installed US geothermal capacity in 2011 reached 3,500 MW. Geothermal generation has experienced slow growth over the last 10 years averaging 1.2%/y. Geothermal power prices are 4 – 6 ¢/kWh.

Source: National Geographic

U.S.’s first geothermal power plant, Mayacama Mountains, California, turned 50 in 2009


Geothermal Plants

ECE 333 © 2002 – 2018 George Gross, University of Illinois at Urbana-Champaign, All Rights Reserved.
GEOTHERMAL PRODUCTION

2016 BIOMASS / BIOFUELS STATUS

- World biomass installed electricity capacity is 112 GW with 504 TWh generation
- The US grid-connected installed capacity is 13.2 GW
- US and Brazil are the largest biofuel producers
- World biofuels production capacity is 135 billion l/y
BIOENERGY AND BIOFUEL


YEARLY ETHANOL AND BIODIESEL PRODUCTION

**DOE BIOMASS/BIOFUELS GOALS**

- Competitive electricity by 2020
- Ethanol production resources to be at the target of 1.07 $/g$ by 2020

**DOE WIND PROGRAM GOALS**

- 3 ¢/kWh in classes 4 and above onshore wind areas
- 5 ¢/kWh for off-shore regions
DOE SOLAR PROGRAM GOALS

- Photovoltaics: 6¢/kWh by 2020
- Concentrating solar power/troughs: 5¢/kWh by 2012

Q3 2012 LEVELIZED COSTS OF ENERGY

RENEWABLE ELECTRICITY GENERATION

Source: http://www.ft.com/cms/s/0/67b20418-60cc-11e6-ae3f-77baadeb1c93.html#axzz4HoYP7PrE

IMPACTS OF RENEWABLES

true chronological load
modified chronological load

capacity of the time-dependent resource
energy generated by time-dependant resource
ELECTRIC SYSTEM INFRASTRUCTURE

Residential Data Concentrator
Central Generating Station
Step-Up Transformer
Control Center
Distribution Substation
Receiving Station
Central Generating Station
Step-Up Transformer
Control Center
Distribution Substation
Receiving Station

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

total available

load

reserves margin

intermediate peak

base load
CALIFORNIA SUMMER LOAD: TYPICAL DAILY SHAPE

KEY CHALLENGES IN RENEWABLE EXPANSION

- Integration into the grid
  - interconnection
  - grid capability
  - reliability issues
  - power quality
- Competitiveness of technology costs
- Environmental problems
- Development of storage technology
**CAISO APRIL 2005 DAILY WIND PATTERNS**

*MW*

![Graph of CAISO April 2005 Daily Wind Patterns](image)

Source: CAISO

---

**ONTARIO DAILY WIND POWER OUTPUT**

*MW*

![Graph of Ontario Daily Wind Power Output](image)

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

(Chart showing power output over time with data collected on a 5-minute basis)

**PV POWER OUTPUT AT THE NEVADA 70 – kW POLYCRYSTALLINE ARRAY**

(Chart showing power output over time with data collected on a 10-second basis)
KEY CHALLENGES IN RENEWABLE EXPANSION

- Government policies at the
  - federal
  - state
  - local
- Regulatory accommodation
  - permitting processes
  - back up power
  - “green power” differential


ROOFTOP SOLAR IN THE US

EIA indicates that rooftop solar electricity represents less than 0.25% of the US electric generation.

Government incentives aimed at promoting solar energy have made the installation of rooftop solar widespread in the Western states – CA, AZ, CO, NV.

Incentives include tax credits, installment cost rebates and net metering for customers with rooftop solar panels.

At present, 43 states, the District of Columbia and 4 territories offer net metering.
**ROOFTOP SOLAR IN THE US**

- Under net metering – a billing mechanism that credits solar energy system owners for excess energy injected into the grid – customers only pay for the electricity consumed in excess of what they feed into utility, the so-called *net energy*

- The implementation of net metering varies from one jurisdiction to another

Source: http://www.seia.org/policy/distributed-solar/net-metering

---

**US NET METERING STATUS**

Source: http://www.dsireusa.org/resources/detailed-summary-maps/; July 2017

- 38 states + DC, AS, USVI, & PR have mandatory net metering rules

- State-developed mandatory rules for certain utilities (38 states + DC + 3 territories)

- No statewide mandatory rules, but some utilities allow net metering (2 states)

- State-wide distributed generation compensation rules other than net metering (7 states + 1 territory)

US Territories

AS PR

VI GU

---
OPPOSITION TO GREEN POWER POLICIES

- Notwithstanding the growing importance of green energy, opponents of government policies that stimulated this growth are pushing to roll back those incentives and mandates.

- Energy markets are strongly driven by policies and the various attempts to weaken or eliminate green energy mandates and incentives creates new sources of uncertainty, whose effects are to chill markets and reduce investment momentum.

- Ohio has enacted a bill – Senate Bill 310 – shelving requirements for utilities to ramp up the use of renewable energy and energy efficiency; in effect the bill provides a two-year freeze on the RPS requirements in Ohio to have 25% of the consumption supplied by renewable resources.
COURSE OBJECTIVES

- Acquaint students with key basic physical principles used in renewable energy
- Stress the importance of economics and environmental aspects in electricity developments
- Expose students to some major developments in renewable energy systems and their integration into the power grid
- Provide a good understanding of impacts of market forces on shaping the electricity business
- Expose students to the exciting developments in the energy sector

ECE 333: KEY ASPECTS

- Understanding of the scientific principles underlying renewable resources is essential
- Awareness of the role that renewables can play is important
- Challenges in the integration of renewables are huge in nearly every aspect
TOPICAL OUTLINE

- General overview of electricity demand, supply, industry structure, interconnected system operations and state of technology
- Nature/role of each renewable generation resource
- Review of concepts in electric circuit analysis
- Engineering aspects of renewable resource generation technologies: wind energy conversion systems; thermodynamics considerations; solar resource and solar array systems; economics of renewable technologies; environmental aspects
- The roles of energy storage resources and their deployment in grids with integrated renewable
- The demand picture: the nature of electrical loads; time variation, periodicity and price dependence aspects
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 electricity policy and regulatory dimensions

GRADING POLICY

- The course grade is based on the performance of
  the student in the quizzes, the two midterms 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 will be selected
  from the homework assignments
### GRADING POLICY TABLE

<table>
<thead>
<tr>
<th>component</th>
<th>percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>homework</td>
<td>0</td>
</tr>
<tr>
<td>quizzes</td>
<td>15</td>
</tr>
<tr>
<td>midterm exams</td>
<td>20 x 2 = 40</td>
</tr>
<tr>
<td>final</td>
<td>45</td>
</tr>
<tr>
<td>total</td>
<td>100</td>
</tr>
</tbody>
</table>