Next three lectures:

Pros and cons of meeting energy needs by means other than combustion of fossil fuel

We’ll begin by going over a few Course Logistics

Lecture 19
25 April 2017
Course Logistics

• Problem Set #4 will be posted by start of class Thursday
  − Due Tues, 9 May (two weeks from today)
  − Of course, last problem set
  − Will conduct review on Wed, 10 May so there will be only 1 day to accept late submissions

• Grad Student Projects:
  − Had presented due date of Wed, 10 May, 6:00 pm in class several times, but website gives due date of Mon, 15 May (which is during finals)
  − Another possibility is Fri, 12 May (Reading Day)
  − Would like super-quick meeting of 633 students immediately after class to finalize due date
  − Delighted to provide comments on either a draft of the paper and/or presentation provided. I have at least 2 days prior to due date

• Final Exam
  − Wed, 17 May, 10:30 am to 12:30 pm
  − This room
  − Format similar to prior exams
  − Closed book, no notes
  − Slight emphasis on material covered since last exam, but entire course will be covered on the final exam
  − Lecture on 11 May 2017 (Thurs) will be a class review/final exam prep
Follow-up from Tuesday

- Graph showing historical emissions of CO\textsubscript{2} and population growth.
  - Two axes: Emission (Gt CO\textsubscript{2} yr\textsuperscript{-1}) and Population (Billion).
  - Key events marked:
    - 1st Oil Shock
    - 2nd Oil Shock
    - US-USSR-Europe Growth
    - China Growth
    - Market Crash
    - 80s Recession
    - Steel Manufacture
    - WWI
    - WWII
    - Great Depression

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Follow-up from Tuesday

[Graph showing historical emissions and population growth with key events marked such as World Wars, oil shocks, and population milestones.]
Nomenclature

Power (energy/time):
- TW : Terra Watt; $10^{12}$ W
- GW : Giga Watt; $10^9$ W
- MW : Mega Watt; $10^6$ W
- kW : Kilo Watt; $10^3$ W

$W = 1$ joule /sec

Solar arrays are “sized” in terms of kW

Energy (Power $\times$ time):
- kW hr : $10^3$ W delivered continuously over an hour
- mW hr : $10^6$ W delivered continuously over an hour

Output of solar arrays are metered in terms of kW hr
In 2005, world obtained:

~80% of its energy &
~66% of its electricity
from combustion of fossil fuels
In 2013, world still obtained ~80% of its energy from combustion of fossil fuels
In 2014, world still obtained ~67% of its electricity from combustion of fossil fuels.
World *Electricity* Generating Capacity:

Power (energy/time)

<table>
<thead>
<tr>
<th>Total Source</th>
<th>GW (year 2017)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>1,928</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>1,589</td>
</tr>
<tr>
<td>Hydro-electric</td>
<td>1,114</td>
</tr>
<tr>
<td>Wind</td>
<td>460</td>
</tr>
<tr>
<td>Liquid Fossil Fuel</td>
<td>402</td>
</tr>
<tr>
<td>Nuclear</td>
<td>386</td>
</tr>
<tr>
<td>Solar</td>
<td>247</td>
</tr>
<tr>
<td>Other Renewable (Biomass)</td>
<td>142</td>
</tr>
<tr>
<td>Geothermal</td>
<td>17</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>6285</strong></td>
</tr>
</tbody>
</table>

Source: [https://www.eia.gov/outlooks/ieo/ieo_tables.cfm](https://www.eia.gov/outlooks/ieo/ieo_tables.cfm)
World *Electricity* Generating Capacity:

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U.S. *Electricity* Supply: 2016

http://www.c2es.org/technology/overview/electricity

U.S. obtains ~64% of its electricity from fossil fuels & ~14% from hydro, wind, biomass, and solar
Maryland obtains ~52% of its electricity from fossil fuels & ~9% from hydro, wind, biomass, and solar
Market Force #1: Cost of Fossil Fuel ↑

https://mellanosternidag.wordpress.com/2014/12/29/oljepriset/
Residential Electricity Cost, United States

http://www.eia.doe.gov/forecasts/steo/report/electricity.cfm
U.S average residential retail price of electricity: 12.67 cents per kilowatt-hour in 2015

https://commons.wikimedia.org/wiki/File:Average_Residential_Price_of_Electricity_by_State.svg
Price of Electricity varies a lot Internationally

Price of Electricity varies a lot Internationally

Average electricity prices in US cents/kWh (2011 ppps)

ppps: purchasing power parities

Market Force #2: Cost of Electricity from Renewables

2015 US Average Cost of Electricity: ~12.7 cents per kw-hour

Hydro

- World’s largest renewable energy source for production of electricity
  - 17% of world’s electricity needs
  - Nearly 100% of electricity in Norway, Uruguay, and Paraguay
  - Canada: nearly 50% US: ~7% in 2005 as well as today

- Technology very mature

- Only ~20% of world overall potential being tapped

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**Figure 8.2** Percentage of electricity produced from hydroelectric in different countries. (Source: CIA World Factbook, December 2003.)

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**Hydro: 17.7 % of world electricity capacity**
Largest Capacities:

- **Itaipú, Paraná River, South America: 14,000 MW**
  - Built 1975 to 1991
  - Volume of iron and steel: enough to build 380 Eiffel Towers
  - Volume of concrete: 15 × that of Channel Tunnel between France and England

- **Three Gorges Dam, Yangtze River, China: 22,500 MW**
  - Fully operational in 2012
  - Cost: $22.5 billion or 1 million $ / MW
  - Largest construction project in China since Great Wall
  - 1 million people displaced
  - Now provides _____ of China’s electricity needs

In 2012, the Three Gorges Dam in China took over the #1 spot of the largest hydroelectric dam (in electricity production), replacing the Itaipú hydroelectric power plant in Brazil and Paraguay.

Three Gorges Dam has a generating capacity of 22,500 megawatts (MW) compared to 14,000 MW for the Itaipú Dam.

But, over a year-long period, both dams generate about the same amount of electricity because seasonal variations in water availability on the Yangtze River in China limit power generation at Three Gorges Dam for a number of months during the year.

Capacity Factor = \( \frac{93.5 \text{ TWh}}{(197 \text{ TWh})} = 0.47 \)

• Three Gorges Dam, Yangtze River, China: 22,500 MW
  – Fully operational in 2012
  – Cost: $22.5 billion or 1 million $ / MW
  – Largest construction project in China since Great Wall
  – 1 million people displaced
  – Now provides ~1.7% of China’s electricity needs

Capacity Factor, Various Energy Sources

[Graph showing capacity factors for various energy sources, including Solar PV, Nuclear, Solar Thermal, Biomass, Geothermal, Integrated Gasification Combined Cycle, Wind Offshore, Coal, Hydropower (new), Hydro, MSW-Landfill Gas, Wind, Combined Cycle Gas Turbine, and Combustion Turbine.]

http://www.nrel.gov/analysis/tech_cap_factor.html
Environmental Ledger

• Positive:
  – No NO\textsubscript{x} and SO\textsubscript{x} during operation
  – CO\textsubscript{2} release only during construction (page 90, Olah et al.)

• Negative:
  – Flooding: over 1 million people displaced by Three Gorge Dam
  – Soil fertility: High Aswan Dam in Egypt has resulted in fertile silt collecting at bottom of Lake Nassar, necessitating use of $1\times10^6$ tons of fertilizer
  – GHG emissions from lost forest and decaying biomass under dammed water

http://ga.water.usgs.gov/edu/hywowworks.html

http://www.springerlink.com/content/k30639u4n8pl5266/
http://www.newscientist.com/article.ns?id=dn7046
Hydro

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Top Hydropower Producing States, 2013

- Over half of the total U.S. hydroelectric capacity for electricity generation concentrated in three States (Washington, Oregon, and California)
- ~30% in Washington, location of the largest hydroelectric facility: Grand Coulee Dam.

http://www.eia.doe.gov/kids/energy.cfm?page=hydropower_home-basics-k.cfm
Wind

- Fastest growing renewable resource: 30% per year from 1992 to 2007

- Germany: 44,470 MW capacity, generating 13.3% of country’s electricity in 2015
  - Europe dominates wind energy turbine market

- Turbine capability has increased dramatically past 20 years:
  - Went from 20 m diameter generating 20-60 kW to 100 m diameter generating 2 MW

About 7.3% of world electricity production capacity right now
Wind Power Potential, World

• Wind power varies as \([\text{Wind Velocity}]^3\):
  – Installation benefits from accurate knowledge of wind fields

![Wind Power Potential, World](image)

Figure 2. Map of wind speed extrapolated to 80 m and averaged over all days of the year 2000 at sounding locations with 20 or more valid readings for the year 2000. Archer and Jacobson, *JGR*, 2006

• Potential electricity generation from "sustainable Class 3 winds" is 72 Terawatts!

• Installation of ~5 Terawatts (current global electricity capacity) requires harnessing only a fraction of this potential with current turbine technology
Wind

- Wind power varies as \([\text{Wind Velocity}]^3\):
  - Betz law: http://en.wikipedia.org/wiki/Betz%27_law
  - Installation benefits from accurate knowledge of wind fields

Figure 13. Wind Resource Potential

Wind Power Potential, Maryland

http://www.eere.energy.gov/windandhydro/windpoweringamerica/images/windmaps/md_50m_800.jpg
Wind Power, Pros & Cons

Environmental Ledger

• Positive:
  – No emissions
  – Land on wind farm can be used for agriculture or livestock

• Negative:
  – Lightning strikes, turbine break/failure, or leaking fluid can lead to fire
  – Long-term performance of turbines not well established
  – Public resistance to visual impact or noise:
    June 29, 2003 - After a wind project was proposed several miles off the coast of Cape Cod, some environmentalists raised objections, as did U.S. Senator Ted Kennedy who owns a summer home in the area
    [link](http://www.cbsnews.com/stories/2003/06/26/sunday/main560595.shtml)
Geothermal

- US largest producer of geothermal electricity (absolute amount):

- El Salvador derives largest percentage of electricity from geothermal:

Olah et al., Beyond Oil and Gas: The Methanol Economy, 2009.
• Geothermal electricity growing rapidly:

but total production capacity, about **17 GW (or 17,000 MW) in 2012**, represents only 0.3% of total world *electricity* generation capacity.

Olah *et al.*, *Beyond Oil and Gas: The Methanol Economy*, 2009.
Geothermal

• Temperature of source critical:
  – dry steam (T > 220°C) most profitable
  – hot water (150 to 300°C) can generate electricity using “flash steam”
    (depressurization and boiling)
  – low temperature (T < 150°C) used for heat (Iceland) or to extract H₂ from H₂O or fossil fuels

Where will favorable conditions for geothermal most likely be found?

Figure 7.4 Cost and performance of 1 MW binary power plants as a function of geofluid temperature in degrees Celsius (°C).

Geothermal

• Margins of tectonic plates most favorable

(1) Geothermal fields producing electricity
(2) mid-oceanic ridges crossed by transform faults (long transversal fractures)
(3) subduction zones, where the subducting plate bends downwards and melts in the asthenosphere (~100 to 200 km below surface)

http://iga.igg.cnr.it/geo/geoenergy.php
Geothermal

- Temperature of source critical:
  - dry steam ($T > 220^\circ C$) most profitable
  - hot water (150 to 300$^\circ C$) can generate electricity using “flash steam” (depressurization and boiling)
  - low temperature ($T < 150^\circ C$) used for heat (Iceland) or to extract $H_2$ from $H_2O$ or fossil fuels

Map of U.S. Water Temperature

http://www1.eere.energy.gov/geothermal/geomap.html
Geothermal

• Everything you ever wanted to know about Geothermal electricity:

• Claim: geothermal is a largely untapped resource for electricity in the US
  – improvements in deep drilling and management of water flow within wells needed

• Strong association of electricity production and price:

GETEM: Geothermal Electric Technology Evaluation Model
EGS: Enhanced Geothermal Systems: i.e., engineered reservoirs that have been
created to extract economical amounts of heat from geothermal resources

![Graph showing predicted supply curves using the GETEM model](image-url)

Figure 9.8 Predicted supply curves using the GETEM model for identified EGS sites associated
with hydrothermal resources at depths shallower than 3 km. The base case corresponds to today’s technology
and the 5-, 15-, 25-, and 35-year values correspond to the state of technology at that number of years into
the future.
Solar PV

- Sun delivers about 10,000 times more energy than world consumption
- Photovoltaic: converts solar energy into electricity
  - photovoltaic effect: Nobel Prize in 1921 went to __________
  - solar cells developed in 1960s for military and satellites
  - crystals from silicon, cadmium, copper, arsenic, etc
  - efficiency increased from 15% in mid-1970s to ~25% today
- PV capacity increased 30% per year from 1997 to 2007:

Figure 8.10 Cumulative installed photovoltaic (PV) power in reporting IEA countries. IEA-photovoltaic power systems programme.

Olah et al., Beyond Oil and Gas: The Methanol Economy, 2009.
Solar PV Cost

Graph shows the cost of solar PVs, representing total capital and operating costs over the lifetime of the panels, divided by the total electricity generated in kWh.

Data from US DOE Solar Energy Technologies Program

https://energyonesolar.com/residential-rural-solar-energy/

Analysis shows production costs drop by ~16% for each doubling of capacity
Solar PV Cost

How Cheap Can Solar Get?

When solar reaches 2% of 2015 global electricity demand

- This is a future model of solar prices.
- Assumes 16% cost reduction of new solar electricity per doubling of scale.
- Solar costs unsubsidized.
- Natural gas prices do not include carbon pollution externalities.

New Natural Gas Electricity Price

Average Solar - Medium Sunlight Locations

Lowest Cost Solar - Sunniest Locations

Graph by Ramez Naam rameznaam.com/tag/solar/

2015: Solar is 1% of global electricity

2020?

2028?

2035?

5 Doublings, from 200GW in 2015 to 6,400 GW at a future point. 20 years? Difficult to Estimate.

Cumulative Worldwide GW of Solar Deployed


Analysis based on production costs dropping by ~16% for each doubling of capacity
Route 1 (south of campus), just south of the new Whole Foods 22.7 kW system (power) has generated 175,574 kW-hours (energy) since 22 July 2010

http://www.universityparksolar.com  &  http://www.youtube.com/watch?v=khQsTJz2BkM
Solar PV Efficiency

Operational for:
2010: 205
2011: 365
2012: 366
2013: 365
2014: 365
2015: 365
2016: 366
2017: 115
Total: 2512 days

\[22.7 \text{ kW} \times 2512 \text{ days} \times 24 \text{ hrs/day} = 1.37 \times 10^6 \text{ kW hr}\]

Capacity Factor = \[\frac{1.76 \times 10^5 \text{ kW hr}}{1.37 \times 10^6 \text{ kW hr}}\]

Financial return = \[1.76 \times 10^5 \text{ kW hr} \times 0.13 \$/	ext{kW hr}\]
64.8 kW × 1290 days × 24 hrs/day = 2.0 × 10^6 kW hr
Capacity Factor = 2.51×10^5 kW hr / 2×10^6 kW hr =
Financial return = 2.51×10^5 kW hr × 0.13 $/kW hr =
Solar PV Efficiency

<table>
<thead>
<tr>
<th>Material</th>
<th>Laboratory Efficiency</th>
<th>Production Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monocrystalline Silicon</td>
<td>24 %</td>
<td>14 to 17 %</td>
</tr>
<tr>
<td>Polycrystalline Silicon</td>
<td>18 %</td>
<td>13 to 15%</td>
</tr>
<tr>
<td>Amorphous Silicon</td>
<td>13 %</td>
<td>5 to 7 %</td>
</tr>
</tbody>
</table>

Limited Efficiency

Limited spectral range of effective photons (depends on material used)

Surplus energy transformed into heat

Optical losses from shadowing and/or reflection

http://www.solarserver.com/knowledge/basic-knowledge/photovoltaics.html
Concentrated Solar Power (CSP)

• Parabolic mirrors heat fluid that drives Stirling engine
  – Fluid is permanently contained within the engine's hardware
  – Converts heat to energy
  – Theoretical efficiencies often challenging to achieve

• Highest electrical efficiencies for solar → lowest costs!
  http://www.powerfromthesun.net/Book

Kramer Junction, Calif
  Fully operational in 1991: 350 MW capacity
  Low output in 1992 due to Pinatubo aerosol!
  Present operating cost: ~11 ¢ / kWh

Nevada Solar One
  Output: 64 MW capacity / 134,000 MW-hr / year
  Could supply all US electricity needs
  if built over a ~ 130 mile × 130 mile area
  Construction cost: ~$2 / kW-hr for one yr’s prod
Nevada Solar One

Project capacity: 64 MW (power = energy / time)

Project output for 2012 to 2015: 118,000 MW-hr (energy, or power × time)

Number of hours in year = 365x24 = 8760

Capacity Factor = 118,000 MW-hr / (64 MW × 8760 hr) =

Nevada Solar One's production is as follows (values in GW-h).[20]

<table>
<thead>
<tr>
<th>Year</th>
<th>Solar</th>
<th>Fossil</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>41.21</td>
<td>0.38</td>
<td>41.59</td>
</tr>
<tr>
<td>2008</td>
<td>122.69</td>
<td>0.91</td>
<td>123.31</td>
</tr>
<tr>
<td>2009</td>
<td>120.65</td>
<td>2.43</td>
<td>123.07</td>
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<td>2010</td>
<td>133.00</td>
<td>1.16</td>
<td>134.16</td>
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<tr>
<td>2011</td>
<td>128.26</td>
<td>1.99</td>
<td>130.26</td>
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<tr>
<td>2012</td>
<td>128.94</td>
<td>1.39</td>
<td>130.33</td>
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<tr>
<td>2013</td>
<td>112.79</td>
<td>2.31</td>
<td>115.10</td>
</tr>
<tr>
<td>2014</td>
<td>116.23</td>
<td>2.58</td>
<td>118.80</td>
</tr>
<tr>
<td>2015</td>
<td>105.65</td>
<td>2.14</td>
<td>107.79</td>
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http://en.wikipedia.org/wiki/Nevada_Solar_One#Production

Fossil backup, night time preservation, and morning pre-heating, is provided by natural gas and provides up to 2% of total output.
Nevada Solar One / US Energy Needs

US Electricity Consumption is $3913 \, \text{TW-hr}$ or $3913 \times 10^6 \, \text{MW-hr}$

Nevada Solar One output: $118,000 \, \text{MW-hr}$

Nevada Solar One size = 0.6 square mile: (i.e., about 0.78 by 0.78 miles)

To meet US Energy Needs, would need $\frac{3913 \times 10^6 \, \text{MW-hr}}{118,000 \, \text{MW-hr}}$ or $3.3 \times 10^4$ more area

$0.6 \, \text{square mile} \times 3.3 \times 10^4 = 2 \times 10^4$ square miles

$[2 \times 10^4 \, \text{square miles}]^{1/2} = 141 \text{ by 141 miles}$

Cost: $\frac{2 \, \text{KW-hr} \times 3913 \, \text{TW-hr} \times (10^{12} \, \text{W/TW})}{(10^3 \, \text{W/KW})} = \$7.8 \times 10^{12}$

or $7.8$ trillion dollars

US GDP in 2016 was $18.6$ trillion dollars