Topic 01 –

INTRODUCTION AND FRAMEWORKS
WHY WE STUDY ENERGY
WHAT IS ENERGY REALLY?

- “The ability to do work”
  - Create Product, GDP
- Leverages human capital
- Foundation of modern industrial society - 17 Billion horses
  - Thought: 1 hp = 11 people-power

- The business of energy is fundamentally about “energy services”

- Energy is best understood as a set of interconnected systems.
HOWEVER, POTENTIAL TURBULENCE AHEAD...
YOUR MOTIVATIONS FOR COURSE

(AKA “BURNING QUESTIONS”)

Please Submit 2-3 of these (along with name, photo, and brief background) to me by email this week!!
HOW WE WILL STUDY ENERGY SYSTEMS
# BASICS QUESTIONS ON ENERGY SYSTEMS

<table>
<thead>
<tr>
<th>Category</th>
<th>Questions</th>
<th>Additional Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical</td>
<td>What is energy?</td>
<td>How is it measured?</td>
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<tr>
<td></td>
<td>Where does it come from?</td>
<td>Are there undesirable emissions or outcomes from the process?</td>
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<td>How is it transformed?</td>
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<td></td>
<td>Where is it consumed?</td>
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<tr>
<td>Economic</td>
<td>How much is needed?</td>
<td>Will it run out?</td>
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<td></td>
<td>What does it cost?</td>
<td>Are all of the costs and benefits observed and accounted for?</td>
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<tr>
<td></td>
<td>What is it worth?</td>
<td></td>
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<tr>
<td>Market</td>
<td>How is it transacted?</td>
<td>Which technology will win in the marketplace?</td>
</tr>
<tr>
<td></td>
<td>Which input is cheaper today?</td>
<td>What risks exist in the current system, and who bears them?</td>
</tr>
<tr>
<td></td>
<td>Which input will be cheaper tomorrow?</td>
<td>Will an emerging technology disrupt the existing marketplace?</td>
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<td></td>
<td>What is it worth to end users?</td>
<td></td>
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<tr>
<td>Social</td>
<td>How do energy endowments impact political interactions?</td>
<td>How should scarce resources be allocated?</td>
</tr>
<tr>
<td></td>
<td>How do political interactions impact energy production and use?</td>
<td>Who should bear the risks of energy choices?</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Is energy access a basic right?</td>
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</tbody>
</table>
LOOKING AT ACTORS AND CONFLICTS

- Constraints within the system
- Stakeholder Tensions abound:
  - Economy vs. Environment
  - Social vs. Economic
  - Environment vs. Society

- We will use a full suite of innovation tools to view the tension & constraints as well as potential solutions.

FUNDAMENTAL TENSION IN ENERGY

**Innovation**
- Entrepreneurship
- Profit-Motive
- Invention
- Necessity
- Efficiency
- Opportunity

**Depletion**
- Absorption
- Peak Production
- Constraints
- Selfishness
- Market Failures
- Tradeoffs
**Systems Thinking**

*Systems thinking*[is] a way of thinking about, and a language for describing and understanding, the forces and interrelationships that shape the behavior of systems.

This discipline helps us to see how to change systems more effectively, and to act more in tune with the natural processes of the natural and economic world.

- Peter Senge, *The Fifth Discipline Fieldbook*

<table>
<thead>
<tr>
<th>Marginal Analysis</th>
<th>Systems Thinking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static</td>
<td>Dynamic</td>
</tr>
<tr>
<td>Local</td>
<td>Global</td>
</tr>
<tr>
<td>Ceteris paribus</td>
<td>All variables can change</td>
</tr>
<tr>
<td>Individual actor</td>
<td>Many actors</td>
</tr>
<tr>
<td>Best used for microanalysis</td>
<td>Best used for complex interactions</td>
</tr>
</tbody>
</table>

Source: thwink.org
<table>
<thead>
<tr>
<th>SYSTEMS</th>
<th>TECHNOLOGY</th>
<th>ECONOMICS</th>
<th>MARKETS</th>
<th>POLICY</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intro</strong> (Chs. 1-3)</td>
<td>System Definitions; Supply Chains</td>
<td>Power to Energy Conversion</td>
<td>Perfect Markets; Fungibility</td>
<td>Demand/Value Calculation</td>
</tr>
<tr>
<td><strong>Grid Management</strong> (Chs. 4-5)</td>
<td>System Purpose</td>
<td>Heat Rates</td>
<td>Supply curve construction; Price Determination</td>
<td>4 part LCOE Model</td>
</tr>
<tr>
<td><strong>Demand Solutions</strong> (Ch. 9)</td>
<td>Stabilizing Loops</td>
<td>Reserve Margins; Time Shifting</td>
<td>Managing Demand; Rebound Effect</td>
<td>Payback Period</td>
</tr>
<tr>
<td><strong>Storage</strong> (Ch. 10)</td>
<td>Stocks, Buffers, and Resilience</td>
<td>Round-trip losses</td>
<td>Market Definition; Economics of Scope</td>
<td>Storage Capital Metrics; LCOS</td>
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<tr>
<td><strong>Distributed Energy</strong> (Chs. 11-12)</td>
<td>Reinforcing Loops; Disruptions</td>
<td>Solar Conversion</td>
<td>Learning; Economics of Scale</td>
<td>Soft Costs; Delivered LCOE</td>
</tr>
<tr>
<td><strong>Transport and Vehicles</strong> (Ch. 13)</td>
<td>Paired Systems</td>
<td>Fleet Efficiency</td>
<td>Short-term vs. Long-term Elasticities</td>
<td>Total Cost of Ownership (TCO)</td>
</tr>
<tr>
<td><strong>Petroleum</strong> (Ch. 14)</td>
<td>Natural System Boundaries</td>
<td>Upstream, Midstream, Downstream</td>
<td>Reserves vs. Resources</td>
<td>Production Cost; Depletion</td>
</tr>
<tr>
<td><strong>Biofuels</strong> (Ch. 16)</td>
<td>Spillover effects</td>
<td>Feedstocks</td>
<td>Complements</td>
<td>Dependent Input Cost</td>
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<tr>
<td><strong>EV and other Motors</strong> (Ch. 17)</td>
<td>Linking Sub-systems</td>
<td>Charging/Fueling Infrastructure</td>
<td>Substitutes</td>
<td>Cost/Mile (CPM); Cycle Cost</td>
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<tr>
<td><strong>Thermal Energy/Natural Gas</strong> (Chs. 17-18)</td>
<td>Measuring and Managing Systems</td>
<td>Heat Temperature; Fuel and Heat Storage</td>
<td>Average vs. Marginal Cost</td>
<td>Cost of Volatility</td>
</tr>
<tr>
<td><strong>Eco-system Linkages</strong> (Ch. 20)</td>
<td>Eco-systems; Sustainable Development</td>
<td>Sources and Sinks</td>
<td>Externalities</td>
<td>Abatement Cost</td>
</tr>
</tbody>
</table>
ASSIGNMENTS AND GRADING

- **Readings – How to approach them?**
  - *Textbook* – *The Energy System (TES)*
  - *Thinking in Systems – Solar Revolution*
  - *Get a news feed!*
  - *Video Links – For Fun and Learning*

- **Class Participation (30%)** - see syllabus

- **Problem Sets (40%)**
  - Course Website for Q&A

- **Final Exam (30%)** – *10 Learning Objectives & Vocab*

- **Grading – Citations – Presentation – Excel**
  - *A’s get reference letters*

- **If you feel lost… My hours, TA hours, Classmates**
TRADITIONAL ENERGY ANALYTICS
THE ENERGY SUPPLY CHAIN

✓ Exploration for and discovery of energy resources

✓ Production or harvesting the energy

   PRIMARY ENERGY SUPPLY

✓ Preparation, transport, or storage

✓ Further processing, purification, and conversion

   SECONDARY ENERGY CARRIERS

✓ Utilization of energy

   FINAL CONSUMPTION

✓ Recovery, destruction or decontamination, or storage of by-products and waste
TRADITIONAL METRICS - NOT VERY HELPFUL

Primary energy use by fuel:
- Gas: 24.6%
- Oil: 36.7%
- Nuclear: 13.6%
- Renewables: 9.0%
- Coal and lignite: 15.8%
- Industrial waste: 0.2%
- Imports-exports of electricity: 0.1%

Final consumption by sector and energy losses (% primary energy consumption):
- Household: 17.3%
- Industry: 15.8%
- Transport: 21.5%
- Agriculture: 1.5%
- Services: 8.2%
- Other sectors: 1.1%
- Transformation losses: 22.0%
- Distribution losses: 1.4%
- Consumption of the energy sector: 5.0%
- Non energy purposes (e.g., chemical industry): 6.2%
CONCEPT: DISAGGREGATING ENERGY DEMAND

**Total energy use (E)** - (Quad. btu, mtoe, EJ, etc.)

1. Population (P) \[E = P \times E/P\]
2. Energy use per capita (E/ P) \[E/P = GDP/P \times E/GDP\]
   1. Income per capita (GDP/ P)
   2. Energy Intensity (E/GDP)
      1. Productivity of energy (GDP/E)
CONCEPT: COMPOUND GROWTH

Compound Growth

To determine future value using compound interest:

\[ FV = PV \cdot (1 + i)^t \]

where \( PV \) is the present value, \( t \) is the number of compounding periods (not necessarily an integer), and \( i \) is the interest rate for that period. Thus the future value increases exponentially with time. The growth rate is given by the period, and \( i \), the interest rate for that period. Alternatively the growth rate is expressed by the interest per unit time based on continuous compounding.

[Source: Wikipedia]

Compound Annual Growth Rate (CAGR)

\[ CAGR(t_0, t_n) = \left( \frac{V(t_n)}{V(t_0)} \right)^{\frac{1}{t_n-t_0}} - 1 \]

\( V(t_0) \) : start value, \( V(t_n) \) : finish value, \( t_n - t_0 \) : number of years.

[Source: Wikipedia]
China and India (etc.) could increase energy use per capita by factor of 5+
Growth of about 2% per annum.

Increase in all fuel sources, led by:
- Natural Gas
- Nuclear

Stratification across uses

SUPPLY MIX HAS BEEN LARGELY STABLE

1. World includes international aviation and international marine bunkers.
2. In these graphs, peat and oil shale are aggregated with coal.
3. Includes geothermal, solar, wind, tide/wave/ocean, heat and other sources.

OVER HISTORY, MORE OF EVERYTHING

The Energy System (Bradford)
REGIONAL VARIATIONS IMPORTANT

Top five countries by total energy supply (TES)

TES by sector (Mtoe), 2018

TES by energy source (Mtoe), 2018

Top five countries by total final consumption (TFC)

TFC by sector (Mtoe), 2018

Industry consumption by sub-sector (Mtoe), 2018

The Energy System (Bradford)
MORE REGIONAL VARIATIONS BY FUEL

Regional consumption pattern 2019
Percentage

North America
S. & Cent. America
Europe
CIS
Middle East
Africa
Asia Pacific

- Oil
- Coal
- Nuclear energy
- Natural gas
- Hydroelectricity
- Renewables

The Energy System (Bradford)
THE ENERGY SYSTEM FRAMEWORK
REALY A SET OF NESTED SYSTEMS

The Energy System (Bradford)
**WITH DETAIL**

- Sub-systems
  - Transportation
  - Electricity
  - Thermal

- More and varied transformations

- But architecture remains
ENERGY, POWER, TRANSFORMATION, AND LOSS
## CONCEPT: METRICS AND CONVERSIONS

### Energy-to-Energy Conversions
- Always balanced

### Volume Conversions
- 1 barrel of oil is equal to 42 US gallons
- Gasoline contains about 132 MJ/US gallon

<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th>TJ</th>
<th>Gcal</th>
<th>Mtoe</th>
<th>MBtu</th>
<th>GWh</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>multiply by:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TJ</td>
<td>1</td>
<td>238.8</td>
<td>238.8 $\times 10^6$</td>
<td>947.8</td>
<td>0.2778</td>
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<tr>
<td>Gcal</td>
<td>4.1868 $\times 10^3$</td>
<td>1</td>
<td>10$^{-7}$</td>
<td>3.968</td>
<td>1.163 $\times 10^{-3}$</td>
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<tr>
<td>Mtoe</td>
<td>4.1868 $\times 10^4$</td>
<td>10$^7$</td>
<td>1</td>
<td>3.968 $\times 10^7$</td>
<td>11,630</td>
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<tr>
<td>MBtu</td>
<td>1.0551 $\times 10^3$</td>
<td>0.252</td>
<td>2.52 $\times 10^8$</td>
<td>1</td>
<td>2.931 $\times 10^4$</td>
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<tr>
<td>GWh</td>
<td>3.6</td>
<td>860</td>
<td>8.6 $\times 10^5$</td>
<td>3412</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

### Metric Prefixes
- [P] 1 000 000 000 000 000 (one quadrillion) $= 1 \times 10^{15}$
- [T] 1 000 000 000 000 (one trillion) $= 1 \times 10^{12}$
- [G] 1 000 000 000 (one billion) $= 1 \times 10^9$
- [M] 1 000 000 (one million) $= 1 \times 10^6$
- [k] 1 000 (one thousand) $= 1 \times 10^3$
- [h] 100 (one hundred) $= 1 \times 10^2$
- [da] 10 (ten) $= 1 \times 10^1$
- [d] 0.1 (one tenth) $= 1 \times 10^{-1}$
- [c] 0.01 (one hundredth) $= 1 \times 10^{-2}$
- [rn] 0.001 (one thousandth) $= 1 \times 10^{-3}$
- [mi] 0.000 001 (one millionth) $= 1 \times 10^{-6}$
- [n] 0.000 000 001 (one billionth) $= 1 \times 10^{-9}$
- [p] 0.000 000 000 001 (one trillionth) $= 1 \times 10^{-12}$
CONCEPT: ENERGY VS. POWER

× Energy (Stock)
  • Volume concept
  • Denominated in Energy amount or Power x Time
    ➢ Joules, Wh, toe, btu, calories

× Power (Flow)
  • TRANSFORMATION of Energy
  • Rate of flow in the system
  • Denominated in energy over a unit of time
    ➢ MW
    ➢ Joules/Second

Applied Energy and Power Examples

? Automobile? Bathtub?
CONCEPT: LAWS OF THERMODYNAMICS

- **First Law**
  - Law of Conservation of Energy
  - Ins and outs must be the same in the end

- **Second Law**
  - “Entropy” increases
  - Energy flows from hot to cold
  - Waste (“Losses?”) accumulate
 Turning fuel into energy/electricity is a multi-step process – each with losses.

 Total energy losses can be as much as 65% (just for generation)

Source: McGraw Hill
Once generated, T&D loses another 10%.

Losses higher in developing world.

Useful energy services versus delivered energy amounts drop further still – 90+ percent.

Total system efficiency to end user is only 30%.

Efficiency to useful energy services can be less than 2%.

Source: German Govt.
TOTAL WELL-TO-WHEELS EFFICIENCY – less than 25%

HYBRIDS ELECTRIC VEHICLES up to 30%

Source: Wang, Argonne
SYSTEM LOSSES NEARLY 60 PERCENT

- Losses significant throughout the system
  - Varies by fuel source and use
- Leverages efficiency arguments

Net Primary Resource Consumption ~97 Quads

Source: Production and end-use data from Energy Information Administration, Annual Energy Review 2002.
*Net fossil-fuel electrical imports.
**Biofuels/other includes wood, waste, alcohol, geothermal, solar, and wind.
“Normative economics and the art of economics... cannot be independent of positive economics. Any policy conclusion necessarily rests on a prediction about the consequences of doing one thing rather than another, a prediction that must be based - implicitly or explicitly - on positive economics.”

- Milton Friedman
Linear extrapolation model
Questions about physical limits, economic impacts, and carbon results

SUPPLY – IEA REFERENCE SCENARIO

Source: IEA
SORRY Y’ALL
RESOURCES CONSTRAINTS DOWN EVERY PATH

- Oil and gas: not enough resources?
- Coal: not enough atmosphere?
- Biomass: not enough land?
- Hydropower & wind: not enough acceptable sites?
- Nuclear fission: too unforgiving?
- Nuclear fusion: too difficult?
- Photovoltaics: not enough money?
- Hydrogen: Only an energy carrier, not a source
- End-use efficiency: Not enough end-user education?

Source: John Holdren
**Thesis** - Knowing how consumer behavior, producer opportunities, and market interactions will naturally evolve is MANDATORY before engaging in either business or policy interventions, or they will almost certainly fail.
ENERGY SYSTEM DYNAMICS