Energy and Society
ER100/PPC184/ER200/PPC284, Fall 2014

Problem Set #2  
Total Points: 100 for ER100/PPC184  120 for ER200/PPC284

Topics covered: Energy and development, Combustion, Exponential growth models

1. “Soft” and “Hard” Energy Paths
Thirty-eight years ago, Amory Lovins wrote his seminal piece describing “hard” and “soft” energy paths. In this question, we would like you to consider Lovins’s arguments in the context of important energy issues today, as well as compare the Lovins paper with some of the articles you’ve read concerning energy and development. [25 points]

a) Describe Lovins’s distinction between hard and soft paths in a few paragraphs using your own language. (It’s OK to take short quotations from Lovins but we’d like to have you explain the concepts in your own words.) [4 points]

ANS: “hard” energy path: Technology and policy choices that aim to increase energy supply through centralized, complex, capital-intensive energy systems.

“soft” energy path: Technology and policy choices that aim to reduce energy demand, with an emphasis on distributed, simple, modular energy systems.

Note that this doesn’t necessarily imply “fossil” versus “renewable” (p. 81). A renewable energy technology (for example, solar photovoltaics) could be implemented in a large-scale centralized manner, and thus could be an example of the “hard path.”

b) Pick a recent article from any major newspaper that addresses a contemporary energy issue and in a short paragraph comment on whether you think the issue is in the “hard-path” or “soft-path” approach. Please start by including a citation for your article, and a sentence summarizing its main point. [6 points]

ANS: Researching for most relevant materials can be time-consuming, and that’s part of the process. If the article comes from New York Times, Wall Street Journal, Economist, Time, etc Timeliness: if the article is published on and after 2010 Proper citation (the information is sufficient to allow easy retrieval)+ summary

c) “Hard” and “soft” are relative terms, and the same energy technology can be applied in ways that are consistent with either the hard- or the soft-path approach. Take the energy issue you worked with in part b) and describe in a sentence or two how the issue might be affected by a “softer” approach (if you identified it as a hard-path approach) or a “harder” approach (if you identified it as a soft-path approach) than what was discussed in the article you read. [4 points]

d) List the five fallacies in the “Mundane Science” article by Kammen and Dove, and discuss any connection between the points raised by Lovins and the five fallacies. [6 points]

ANS: “Mundane science” refers to scientific research directed at problems that affect the day-to-day life of ordinary people, especially the poor. “five fallacies” about mundane science: (1) it’s anti-scientific; (2) it has lower returns than basic research; (3) it’s only an application of basic research; (4) it can’t possibly be objective; (5) it deals with social problems, not technological ones.

Here are some of the overarching connections] Listing any one of the following is OK.

1) We shouldn’t just focus on high-tech, cutting-edge, capital-intensive solutions; we need to also consider more practical solutions at the small- to medium-scale.
2) There are many interesting technical challenges to be solved at the small scale, even though it’s not considered glamorous work. For example, increasing the efficiency of a “simple” cookstove turns out to be a challenging physics problem and it affects a very large population.

3) Small-scale technologies can empower communities through the use of local resources, labor, and expertise. They can be adapted to local conditions and cultures, and don’t create dependence on outside experts.

4) We must recognize the connections between technological problems and social ones, and not behave as though every problem can be solved by the application of more and bigger technology. (However, Kammen and Dove point out, that doesn’t mean every development problem is a purely social one.)

e) The Lovins piece is focused on energy in the context of the United States. How applicable do you believe the concepts and arguments he uses are to energy-impoveryished, developing countries (as in, those countries with average annual per capita energy consumption rates under 1 TOE)? [5 points]

ANS: Lovins argues that through thinking about appropriate scale and better fitting to end use, “soft” technologies achieve greater economy than larger, centralized ‘hard path’ systems by reducing infrastructure costs and distribution losses and by avoiding diseconomies of scale. This argument holds well in developing countries, especially in countries with largely disconnected rural communities where energy service would be better provided in a more distributed way.

2. Exponential growth models
The OECD (or broadly speaking developed) nations’ energy consumption and CO₂ emissions have stabilized in recent years, while those for non-OECD (or broadly speaking developing) nations have been steadily growing. This is of major concern in the context of global coordination in mitigating climate change. BRIC (Brazil, Russia, India, and China) are some of the largest economies in the non-OECD category. The following table is taken from the BP Statistical Review of World Energy. [20 points]

<table>
<thead>
<tr>
<th>million metric tons of CO₂</th>
<th>United States</th>
<th>Brazil</th>
<th>Russia</th>
<th>India</th>
<th>China</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>6377</td>
<td>352</td>
<td>1556</td>
<td>953</td>
<td>3430</td>
</tr>
<tr>
<td>2013</td>
<td>5931</td>
<td>541</td>
<td>1714</td>
<td>1931</td>
<td>9524</td>
</tr>
<tr>
<td>growth rate, r</td>
<td>3.3%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a) Referring to the exponential growth model as \( Q_n = Q_0 \exp(r \times n) \) or \( r = \frac{\ln(Q_n/Q_0)}{n} \), find the rate of growth \( r \) for each country (on an annual percentage basis, up to 3 significant figures) for the CO₂ emissions between 2000 and 2013. Show your working steps and fill the table. [8 points]

ANS: United States: \( \frac{\ln(\frac{5931}{6377})}{2013-2000} = -0.5577\% \approx -0.558\% \)

Brazil: \( \frac{\ln(\frac{541}{352})}{2013-2000} = 3.306\% \approx 3.31\% \)

Russia: \( \frac{\ln(\frac{1714}{1556})}{2013-2000} = 0.7439\% \approx 0.744\% \)

India: \( \frac{\ln(\frac{1931}{953})}{2013-2000} = 5.432\% \approx 5.43\% \)

China: \( \frac{\ln(\frac{9524}{3430})}{2013-2000} = 7.856\% \approx 7.86\% \)

b) Based on your exponential growth model in part a), which year did China pass the United States to be the world's largest carbon dioxide emitter? Which year will India have more annual carbon dioxide than the United States? Note: round the year to the larger integer; if \( n=2022.2, n=2023. \) [8 points]

Note: \( \ln \left( \frac{A}{B} \right) = \ln A - \ln B \)
ANS: Assume in year $n$, the carbon dioxide emissions from China and the U.S. are the same at $Q$:

$$\frac{\ln \left( \frac{Q}{6377} \right) - 0.558\%}{7.86\%} = \frac{\ln \left( \frac{Q}{3430} \right)}{7.86\%}$$

Using $\ln Q = \frac{r_2 \ln(Q_{0-2}) - r_1 \ln(Q_{0-2})}{r_2 - r_1}$

$$\ln Q = \frac{7.86\% \times \ln(6377) - (0.558\%) \times \ln(3430)}{7.86\% - (0.558\%)} = 8.719$$

$$n - 2000 = \frac{8.719 - \ln(3430)}{7.86\%} = 7.4 \quad n=2000+7.4=2008 \text{ (Year 2008, China)}$$

Similarly, assume in year $n$, the carbon dioxide emissions from India and the U.S. are the same at $Q$:

$$\frac{\ln \left( \frac{Q}{6377} \right) - 0.558\%}{5.43\%} = \frac{\ln \left( \frac{Q}{953} \right)}{5.43\%}$$

$$\ln Q = \frac{5.43\% \times \ln(6377) - (0.558\%) \times \ln(953)}{5.43\% - (0.558\%)} = 8.583$$

$$n - 2000 = \frac{8.583 - \ln(953)}{5.43\%} = 31.7 \quad n=2000+31.7=2032 \text{ (Year 2032, India)}$$

c) Are your carbon dioxide emissions projections for China and India realistic? State any two reasons that may not lead to these projections. (Hint: the IPAT equation). [4 points]

ANS: 1) the population growth may de-accelerate in China and India.
2) the economic growth, largely powering the past growing energy consumption, may not sustain at those high levels as the economy transitions to a more developed stage.
3) the energy intensity of the economy in China and India will decrease. As these countries become richer, they have more economic and technological resources to use energy more efficiently. For example, Chinese central government has adopted energy intensity as a key indicator for the local government’ performance.
4) the energy mix (share of different fuels) of the energy system could evolve to be less carbon-intensive. More renewable energy and/or nuclear, and greater energy efficiency measures could be deployed to meet the growing energy demand.

3. Energy, poverty and gender
The chapter “Energy and Poverty” from the 2002 World Energy Outlook, states “…the transition from traditional biomass use to full dependence on modern energy forms is not a straight-line process.” Please write two short paragraphs on each of the following questions. [25 points for ER100/PP184; 35 points for ER200/PP284]

a) Energy Transitions: What is a linear transition model? Using examples from the “Energy and Poverty” chapter and from other readings (e.g. Crewe, Lovins), comment on why energy transitions may not always be linear. In your answer, carry out one small back-of-the-envelope calculation to show how economic trade-offs may influence poor people’s energy choices. For example, you might compare the relative costs of energy (for cooking or heating) delivered by two different technologies. [15 points]

ANS: The “linear” or “energy ladder” model states that as income increases, people will move from less advanced to more advanced fuels in a predictable sequence: dung and residue → wood → charcoal → coal, oil and gas → electricity. However, this is a vast oversimplification. In practice, households usually opt for a mix of fuels, depending on fuel availability and price as well as cultural preferences. Higher income means a wider range of possibilities, including traditional fuels. This is supported by several of our readings (you need to cite at least one article).

- Bose points out that electricity does not substitute for fuel wood in rural India. Most households don’t even own an electric stove; cooking with electricity would be too expensive. Instead, electricity is used for new applications: fans, irons, electric lights, etc. Wood is still the most appropriate cooking fuel and is used alongside electricity.
- Crewe (pp. 72-3) describes the linear energy ladder as one of many racial and gender stereotypes in development work. The ‘ladder’ idea implies that people who use biomass must be poor and backward. But if energy ‘experts’ listened to local users, it would be clear that there are many logical reasons to continue using biomass.
- Lovins’ ideas also cast doubt on the idea of linear transitions. He advocates using a wide diversity of energy sources that are closely matched to end-use needs. For example, he points out (p. 78) that it is wasteful to use electricity for applications like home heating, when we could use a local heat source and thus avoid conversion and transmission losses.

Back-of-the-envelope calculation to explore energy tradeoffs [5 points]:
The possibilities are unlimited, but it was probably easiest to use data from one of the articles we read. [comparison between two technologies 3 points; citing any one source of data/assumption 2 points]
Below is an example for full points:
Daily cost of wood vs. daily cost of LPG in Jaracuaro:

Fuelwood costs 2.67 $ per kg

LPG costs 23.5 $ per kg

Energy content of air dried wood = 15 MJ/kg

Energy content of LPG = 43.1 MJ/kg

(data source for the energy contents is from http://web.mit.edu/mit_energy/resources/factsheets/Units&ConvFactors/MIT%20EnergyClub%20Factsheet.v8.pdf)

Efficiency of LPG stove = 50%

Efficiency of wood stove = 17%

Taking efficiency into account: what is the cost of the energy delivered by the stove?

Wood: 15 MJ/kg × 0.17 = 2.55 MJ/kg @ $0.027/kg = 1.06 $ per MJ delivered

LPG: 43.1 MJ × 0.50 = 21.5 MJ per kg @ $0.235 per kg = 1.09 $ per MJ delivered

So the cost of energy delivered by the two fuels is similar, once end-use efficiency is accounted for. That implies that the main tradeoff is the capital cost of the LPG stove ($50, compared to $10 for a wood stove),
along with considerations such as ease of use and taste of food.

b) Energy Technology Adoption: List at least three factors that are important for increasing energy technology adoption by the rural and urban poor, and provide a one sentence explanation of the importance of each factor. Do you think lessons from cookstove dissemination programs can be applied to other small-scale renewable energy technologies? Justify your answer. [10 points]

**ANS:** Any 3 of the following factors with brief explanation

- Cost of the technology (upfront capital cost, and ongoing fuel cost)
- Availability and reliability of fuel supply
- Ease of use and repair
- Cultural acceptability (e.g. do the tortillas still taste good?)
- Compatibility with existing infrastructure (e.g. kitchen and cookware)
- Conferral of social status
- Other factors, not as often mentioned by users but of great interest to researchers, include:
  - Health, safety, and cleanliness (e.g. particulate emissions)
  - Time savings (unfortunately, women’s time is often undervalued)
  - Efficiency of energy conversion

The lessons from cookstove dissemination programs can certainly be applied to other small-scale renewable energy technologies? Any of the following

- It is not enough for the technology to perform well in a technical sense. It must also fulfill economic, social, and cultural requirements.
- Cost is of utmost importance. No one will use the technology if it's too expensive.
- The technology should be easy to use, and people should be trained how to use it (because even the best technology has few benefits if it is misused).
- The users should be involved in every step of technology development. Beware the advice of ‘experts’ who ignore local expertise.
- The technology should be possible to build and repair locally.
- The technology should be compatible with other household technologies.
- ‘One size doesn’t fit all’: different preferences prevail in different countries. You can’t transplant a standard technology and expect it to succeed.

c) [ER200/PP284 only] From the energy ladder graphics, what inferences can be gleaned about social inequalities that might be inherent in climbing the energy ladder? (Hint: An increase along the y-axis is an increase in cost.) Be sure to use specific material from the readings. [10 points]

**ANS:** You have to cite a reading and specifically mention how the energy ladder is related to energy inequalities from lacking access to modern energy. For full credit, you had to give a specific example of an energy – equality tradeoff; for example, many good answers included references to energy and public health (*the use of wood indoors creates respiratory problems* in women and children; *lack of electricity in hospitals affects health outcomes; lack of lighting and heating in classrooms affects education outcomes*).

4. Combustion and electricity generation

According to the BP Statistical Review of World Energy, fossil fuels (coal, oil, and natural gas) are the dominant (about 86.7%) energy sources for the world’s 12.7 btoe (billion tons of oil equivalent) primary energy consumption in 2013. Similarly in the United States, 86.4% of the 2.27 btoe primary energy consumption is from fossil fuels. In this problem we will examine the energy and carbon emissions from generating electricity using these fuels. Assume energy density for coal and natural gas to be 29.3 MJ/kg and 50.0 MJ/kg respectively. [30 points total for ER100/PP184; 40 points total for ER200/PP284]
a) Based on an approximate formula for coal (CH_{0.8}O_{0.1}), and an approximate formula for natural gas (CH_4), write the balanced combustion equations for each fuel. (Assume complete combustion in oxygen). What is the CO_2 emission factors for coal and natural gas in kg/GJ? [8 points]

**ANS:** Coal: CH_{0.8}O_{0.1} + 1.15O_2 \rightarrow CO_2 + 0.4H_2O

Natural gas: CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O

1.00 kg of coal emits 1.00kg \times \frac{12+16 \times 2}{12+1 \times 0.8+16 \times 0.1} = 3.056kg CO_2

and provides thermal energy of 1.00kg \times \frac{29.3MJ}{kg} \times \frac{GJ}{1000MJ} = 2.93 \times 10^{-2}GJ

with the CO_2 emission factor of \frac{3.056kg}{2.93 \times 10^{-2}GJ} = 104.2kg/GJ \approx 104 kg/GJ

Similarly, 1.00 kg of natural gas emits 1.00kg \times \frac{12+16 \times 2}{12+1 \times 4} = 2.75kg CO_2

and provides thermal energy of 1.00kg \times \frac{50.0MJ}{kg} \times \frac{GJ}{1000MJ} = 5.00 \times 10^{-2}GJ

with the CO_2 emission factor of \frac{2.75kg}{5.00 \times 10^{-2}GJ} = 55.0kg/GJ

b) Assume that the efficiency of a new coal power plant is 33% and that of a natural gas combined cycle plant is 45%. What is the mass of carbon dioxide released per kWh of electricity generated from each plant. In the context of climate change, which one is a cleaner fuel and what attributes of the fuel make it so? [8 points]

**ANS:**

Coal:

\[
\frac{104g}{MJ} \times \frac{1}{33\%} \times \frac{3.6MJ}{kWh} = 1135g/kWh \approx 1100g/kWh or 1.1 kgCO_2/kWh
\]

Natural gas:

\[
\frac{55.0g}{MJ} \times \frac{1}{45\%} \times \frac{3.6MJ}{kWh} = 440g/kWh \approx 440g/kWh or 0.44kgCO_2/kWh
\]

Natural gas is a cleaner fuel than coal in generating electricity, both from a lower CO_2 emission factor (as in part a) and higher efficiency in converting thermal energy to electricity (as in part b).

c) If a household, living in a region powered by coal-fired power plant, consumes 12,000 kWh of electricity per year, what are the annual CO_2 emissions (metric tons) attributed to that household’s consumption? The same household later moved to a greener region, where half of the electricity is generated from natural gas power plant and the other half from non-carbon sources, what are the annual CO_2 emissions (metric tons) with the same annual electricity consumption? Assume the power plant efficiency as in part b) and Transmission and Distribution (T&D) loss of 10%. [5 points]

**ANS:**

“browner” region:

\[
\frac{12000kWh}{1-10\%} \times \frac{1.1kg}{kWh} \times \frac{ton}{1000kg} = 14.6ton \approx 15 ton
\]

“greener” region:

\[
\frac{12000kWh \times 0.5}{1-10\%} \times \frac{0.44kg}{kWh} \times \frac{ton}{1000kg} = 2.93ton \approx 2.9 ton
\]

d) The United States generated 1586 TWh of electricity from coal in 2013 (Source: EIA Electric Power Monthly). Assume that the average efficiency of coal-fired plants in the US is 33%. How much coal (in kilograms) was used to produce this amount of electricity? If we pile this amount of coal on a football field (area of 5500 m^2), what will be the height (km) of this pile? (No fancy cones, just assume the pile has rectangular sides that go straight up) Assume coal has a density of 2200 kg/m^3. [5 points]

**ANS:**

Electricity generation from 1.00 kg of coal: \[
\frac{29.3MJ}{kg} \times 33\% \times \frac{kWh}{3.6MJ} = 2.69kWh
\]

The amount of coal consumption: \[
1586 \times 10^9 kWh \times \frac{1.00kg}{2.69kWh} = 5.90 \times 10^{11} kg \approx 5.9 \times 10^{11} kg
\]

The height of the pile: \[
5.90 \times 10^{11} kg \times \frac{m^3}{2200kg} \times \frac{1}{5500 m^2} \times \frac{km}{1000m} = 48.7 km \approx 49 km
\]

Data source: EIA Electric Power Monthly Table 1.1.
e) You are also told that the total nameplate capacity of all coal-fired power plants in the United States is about 306 GW as of end of December 2013. What is the average capacity factor of coal power plants in 2013? [4 points]

ANS: $1586 \times 10^3 \text{GWh} \times \frac{1}{306 GW \times 8760 \text{hours}} = 0.5917 \approx 0.592$


f) [ER200/PP284 only] Our university just bought a gas combined heat and power plant (CHP), which can produce 12 GJ of heat per hour for steam generation and 2 MW of electricity at the same time. The sales engineer claimed that the Total System Efficiency can be 60-80%, which agreed with US EPA’s description. But some people were skeptical about this ultra-high efficiency compared with 33% efficiency from a coal-fired power plant. You researched about the definition of Total System Efficiency (TSE) and Effective Electric Efficiency (EEE) on the above EPA website and its related content, where a boiler efficiency of 0.80 is assumed. What are the TSE and the EEE for CHP with the following operation data? [5 points]

Fuel input: 0.56 metric ton of natural gas per hour

Electricity output: 2.0 MW

Heat output for steam generation: 12 GJ per hour

ANS: Converting the operation data to the GJ/hour unit:

Natural gas input: $\frac{0.56 \text{ton}}{\text{hour}} \times \frac{50.0 \text{GJ}}{\text{ton}} = 28.0 \text{ GJ/hour}$

Electricity output: $2.0 \text{ MW} \times \frac{3600 \text{ second}}{\text{hour}} \times \frac{\text{GJ}}{1000 \text{ MJP}} = 7.20 \text{ GJ/hour}$

Total System Efficiency: $\frac{\text{heat+electricity}}{\text{fuel input}} = \frac{12 \text{GJ/hour} + 7.2 \text{GJ/hour}}{28 \text{GJ/hour}} = 68.6\% \approx 69\%$

Effective Electric Efficiency: $\frac{\text{electricity}}{\text{fuel input} \times \text{boiler efficiency}} = \frac{7.2 \text{GJ/hour}}{28 \text{GJ/hour} - 12 \text{GJ/hour} \times \frac{1}{0.8}} = 55.4\% \approx 55\%$

(The method is defined here: http://www.epa.gov/chp/basic/methods.html)

g) [ER200/PP284 only] In the 2014 BP data, the $CO_2$ emission factor for coal was assumed to be 94.6 kg/GJ. And you found the following table for different types of coals in the IEA Energy Statistics Manual. Why is the Net Calorific Value (NCV) lower than the Gross Calorific Value (GCV)? Based on the values from the table, what type of coal is this BP’s value likely to be? [5 points]

<table>
<thead>
<tr>
<th>(kg/GJ)</th>
<th>Carbon content</th>
<th>Moisture content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anthracite</td>
<td>0.778 – 0.782</td>
<td>0.10 – 0.12</td>
</tr>
<tr>
<td>Coking coals</td>
<td>0.674 – 0.771</td>
<td>0.07 – 0.09</td>
</tr>
<tr>
<td>Other bituminous</td>
<td>0.590 – 0.657</td>
<td>0.13 – 0.18</td>
</tr>
</tbody>
</table>

ANS: The difference mainly comes from the energy used to heat up the moisture (water) in the fuel during combustion.

Assuming the carbon content is $Y$

$\frac{29.3 \text{MJ}}{\text{kg}} \times \frac{0.0946 \text{kg}}{\text{MJ}} = Y \times \frac{44}{12}$

$Y \times \frac{29.3 \text{MJ}}{\text{kg}} \times \frac{0.0946 \text{kg}}{\text{MJ}} \times \frac{12}{44} = 0.756 \approx 0.756$

It falls into the **coking coals** category.