Mining Power and Hydrocarbon Consciousness from the Monthly Electric Bill
A Classroom Project

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INTRODUCTORY PARAGRAPH (ABSTRACT)
(first 2 paragraphs of manuscript)

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We compiled the data (total kilowatt-hours (kWh) consumed, total cost in dollars, and number of people in the household) for each class and determined *per capita* averages for monthly and annual energy consumption in kWh and equivalent tons of coal as well as power load in watts. Data from several classes (70 electric bills total collected over several semesters) yield *per capita* averages:

- energy use rate = 476 kWh/month = 5.71 MWh/year = 2.9 tons of coal/year,
- power load = 661 W, and
- energy cost = $39/month (average price = 8.4 ¢/kWh).

The derived values provide a framework for discussions about personal and societal electric energy use and the consequent role of terrestrial hydrocarbons in sustaining such lifestyles. Interpretation and presentation of these data could be modified for audiences ranging from middle-school science classes to university environmental science seminars.

INTRODUCTION

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ELECTRIC ENERGY

Most electricity in the US is generated[1] by burning hydrocarbons such as coal or natural gas to create high-pressure steam which drives turbines attached to electric generators where, according to Faraday's Law of Induction, pulsing electric currents are induced in loops of wire forced to spin in magnetic fields. In countries such as France and Germany, and to a lesser extent the US, nuclear fission reactors provide the requisite heat for creating steam. Heat-driven electric generators have overall efficiencies[2] of only about 30-35 % , about half of the 64% theoretical efficiency (Second Law of Thermodynamics) of an ideal heat engine operating between the 540^{o}C and 20^{o}C temperature extremes typical of modern steam turbines. Thus electric generators transform three units of heat energy stored in hydrocarbons into about one unit of electric energy readily transmissible through networks[3] of wires across great distances to homes and industries. Burning hydrocarbons for heat, unfortunately, releases carbon dioxide (for example, burning coal[4a] releases approximately 1 kg CO_2 per kWh of electricity produced) and other toxic combustion byproducts[4b] into the atmosphere. Likewise, nuclear fission reactors used to produce heat also generate toxic radioactive byproducts **(4c)**, some with half-lives an order of magnitude greater than the age of human civilization.

A. CLASS SURVEY OF RESIDENTIAL ELECTRIC BILLS

Students and their families comprise a plausible sample of the larger US population of residential electricity consumers. Analysis of monthly electric bills from groups of students provides specific energy and power data for discussions and problems relating the joules (3.6×10^6 J = 1 kWh) and watts of simple DC/AC circuits to societal-scale projections of energy use in geographically immense circuits such as national power grids. Furthermore, collecting fresh consumer data from students themselves invests (and implicates) them in the results of the study.

Seventy students from various physics classes supplied monthly home electric bills (February-to-April range,1996-2004). While some students lived in apartments and reported their own consumption, most used bills from their parents' homes (generally in Texas). We took into account only the number of people actually living in each residence at the time of the bill. Large standard deviations (SD) for quantities reported below reflect the highly disparate electric lifestyles reflected in the data set; for instance, the *per capita* monthly energy consumption ranged by a factor of over 25 from 69 kWh to 1814 kWh.

Summing the total monthly energy used (in kWh) for the whole data set and dividing that sum by the total number of people served in all households yielded 476 kWh (SD = 336 kWh) for the average monthly *per capita* energy use (or 5.71MWh/year). Spreading this energy evenly over a month of hours yielded an average *per capita* continuous power load of 661 W (SD = 467 W) costing about $39/month (SD = $27/mo) or $1.30 per day for electricity whose average price was about 8.4 ¢/kWh (SD = 2.1 ¢/kWh). Our derived average *per capita* residential electric energy use (476 kWh/month) and electric energy use rate (661 W) correspond closely to 2003 statistics[5] for Texas of 458 kWh/month and 627 W, respectively; our derived average price of 8.4 ¢/kWh reflects the national US 2002 average residential price[6] of 8.5 ¢/kWh.

B. VISUALIZING ELECTRIC ENERGY USE

1. ENERGY = 476 kWh/person-month

One way to visualize each person's monthly consumption of 476 kWh of electric energy is to calculate the equivalent amount of energy in some other form: coal is an appropriate choice since over half[1] the electricity generated in the USA comes from burning coal. The heat energy content of coal depends on the type of coal[7] burned and ranges from about 2 kWh/lb (lignite) to 4 kWh/lb (anthracite); for this discussion we choose[8] 3 kWh/lb. Recall that the efficiency of burning coal to create steam for a turbo-generator is only about 30-35% (about one-third). Thus for every pound of coal (3 kWh of heat energy) burned to generate electric energy, two-thirds (2 kWh) of the heat energy is unavoidably wasted in the process so that only 1 kWh of electric energy is actually generated. Hence coal has a *de facto* "electric" energy density of about 1 kWh/lb while its heat-energy density is 3 kWh/lb; this a good example of the concept[9] of *transformity*.

Accordingly, the monthly *per capita* energy use of 476 kWh costs society 476 lbs of coal per month (or 2.86 tons of coal per person-year); thus, a standard railroad coal car hauling 100 tons of coal[10] would supply the annual electric energy needs of 35 people. On a longer time scale, the lifetime electricity habits of one of our average householders who lived for 70 years (Figure 2) would require the burning of two railcars (200 tons) of coal, a process releasing about 4.0×10^5 kg of CO_2 into the atmosphere.

2. POWER = 661 W/person

Our derived average *per capita* residential power load of 661 W quantifies the round-the-clock burden imposed on society and the environment by each person's electric lifestyle (hot water, cooling/heating, lights, electric and electronic tools and

novelties, etc.). This power value, perhaps the most significant finding for class discussions, can be visualized in various ways.

- Most simply, the typical householder of our survey represents an electric load approximately equivalent to seven 100 W light bulbs (**Figure 1**) shining (and heating) continuously.
- Next, thinking anthropocentrically (where English units rule) in terms of beasts of burden (one horsepower (HP) = 746 W), our power load of 661 W equals about 0.9 HP. Although horses are rarely used these days as draft animals, the image of a large domestic animal provides a meaningful power metaphor (and English metric) since for all history prior to the industrial revolution, the horse (or donkey, ox, buffalo or yak) was the primal beast of burden and only available power multiplier for human society. Hence we see (**Figure 1**) that servicing one person's 0.9 HP electric "needs" requires the power output of one horse struggling continuously at almost 100% efficiency. This single horse would actually need to be three horses because of the aforementioned inefficiency of generators; furthermore, in a compassionate world where each creature labored for only one-third of a day, we would need three teams of three horses. Thus each person's need for cheap and easy electric energy can be visualized as seven shining light bulbs requiring the equivalent work output of a stable of nine horses.
- Life on Earth's surface is organized into food webs powered by primary producers deriving their energy photosynthetically from the Sun. The solar intensity (energy/area-time) at the upper reaches of Earth's atmosphere is about 1400 W/m^2. The fraction[11] that reaches ground level depends on factors such as cloud cover, season, latitude and time of day. The value of 1000 W/m^2 is a reasonable estimate for midday solar intensity in temperate latitudes; hence each person's 661 W power load is equivalent to the incoming rate of free and available solar energy incident on 0.7 m^2 of Earth's surface. Assuming a highly-efficient process to turn sunlight to energy, then to first order, each person during peak daylight hours would only need about one square meter of direct sunlight to survive electrically. However, given that current-technology photovoltaic (PV) solar panels[11a,12] are only about 15% efficient, our 661 W person would instead require about 5 m^2 of solar panels to supply personal electric power.

C. THE HYDROCARBON FRAME OF REFERENCE

Since about 71 % of the electricity[1] produced in the US in 2003 originated from burning hydrocarbons (led by coal at 51% and natural gas at 16%), energy equivalences herein are referenced primarily to coal. US coal reserves[13] rank among the largest in the world and are estimated to last another 250 years, perhaps much longer than US oil reserves. With the US electricity market so closely coupled to domestic coal reserves, US electricity prices for the next few decades should rise more slowly than prices of materials derived from oil (gasoline, diesel fuel, home-heating oil, chemical fertilizers), given the increasingly heavy dependence of the US on oil imports. In 2004, for instance, 65% of oil used in the US was imported[14] from abroad, in some cases from regions often characterized by political unrest, oligarchic governments or the explosive presence of anti-modernist[15] cultural factions.

Energy stored in familiar hydrocarbons such as coal, oil and natural gas (primarily methane CH_4) is popularly thought to derive from pre-historic solar energy now stored in the geo-processed remains of ancient plants and animals; in this scenario, these biogenic hydrocarbons are described as fossil fuels. Alternate theories[16] propose abiogenic origins for terrestrial hydrocarbons whereby these materials were (and continue to be) formed by geophysical processes acting on deep crust and mantle sources of accreted primordial carbon compounds, primarily methane. These arguments are based in part on the established presence of methane on the Jovian planets and their moons[17] of our Solar System and the rich menu[18] of both simple and complex hydrocarbons distributed throughout interstellar space. In both scenarios, recently discovered[19] extensive and diverse colonies of subterranean bacteria (present in Earth's crust to depths of several kilometers**)** play important roles in modifying *in situ* the chemical composition of buried and sometimes migrating hydrocarbons.

Methane hydrate,[20] a less well-known terrestrial hydrocarbon, is a crystalline clathrate structure of water-ice incorporating CH_4 molecules existing in nature (at temperatures near 0^o C and pressures near 50 atmospheres) as massive and naturally occurring deposits in sub-seafloor sediments of continental margins and in arctic permafrost. Crystallization (hydrate form) and dissociation (free gas) cycles of terrestrial methane may be linked to cycles of global climate change[21] because methane is a very potent greenhouse gas,[22] more active than carbon dioxide by a factor of 21. Current known reserves of methane hydrates are estimated[20] to contain more energy than the sum of all other terrestrial hydrocarbon reserves, and widespread exploration and research programs are underway to find strategies and technologies for responsibly developing this huge energy resource.

Diverse and metabolically exotic chemosynthetic biocommunities are known to flourish on and under the seafloor[23] in areas where hydrocarbon seeps occur. This fact leads some researchers in the new field of astrobiology[24] to speculate that extraterrestrial life, if it exists anywhere, might be found as microscopic bacterial communities living (independent of photosynthesis) off the cold chemical energy of the hydrocarbons known to be widely distributed throughout the universe. Analogously, contemporary human society can be modeled as an intricate global meta-organism dependent as always (at the individual person level) on photosynthesis for food energy but now feeding collectively on accumulated hydrocarbons to satisfy growing appetites for electricity, heat, transportation and chemical fertilizers.

SUMMARY

Data derived from a collection of family electric bills provide quantitative starting points for analysis and discussions of electric energy use, environmental stewardship, and an introduction to the role of naturally-occurring hydrocarbons making possible and sustaining our energy-intensive social patterns. These discussions have immediacy and significance since they derive experientially[25] from basic data the students themselves collect. Personally, each student represents an incessant 7-light bulb living electric load **(Figure 1)** requiring the equivalent work output of at least one

horse; and societally, each student in one lifetime irreversibly consumes by fire the equivalent of 200 tons of nonrenewable coal **(Figure 2)**. The kilowatthour, heretofore just another abstract unit of energy, now can be visualized as equivalent to a pound of coal; and each modern person is seen to live a one-horsepower (or, to first order, a one-kilowatt) electric lifestyle. The hydrocarbon consumption process currently supporting this lifestyle, when scaled up by a factor of 300 million for the USA (or 6 billion for a hypothetical planetful of such people), releases exotic and toxic substances into the biosphere and implicates us as agents and participants in a novel global biogeochemistry experiment of uncertain outcome.

Classroom-based inquiry, rooted locally in basic practical physics and reaching outward through more extensive physical and social systems, is a strategy for presenting physics (perhaps even in *Physics First*[26] formats) to a wide audience not limited to science students.

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1
http://www.eia.doe.gov/cneaf/electricity/epm/epm_sum.html
(Electric Power Monthly August 2004 With Data for May 2004 – see p. 15, Table 1.1, "Net Generation by Energy Source")
http://www.eia.doe.gov/emeu/aer/txt/pbt0809.html
(Table 8.9 "Electricity End Use, 1949 – 2003")

2
Roger A. Hinrichs and Merlin Kleinbach, *Energy: Its Use and the Environment*, 3rd ed. (Brooks/Cole, Toronto, 2002), pp. 79-80.
http://www.eia.doe.gov/emeu/aer/append.html
(Table A6 Approximate Heat Rates for Electricity")

3
Clark W. Gellings and Kurt E. Yeager, "Transforming the Electric Infrastructure," *Physics Today* **57**, pp. 45-51 (December 2004).

4
CO2 release from burning coal & coal burning toxins & fission radwaste
Hinrichs, op. cit., a) p 296 ("Table 9.3 – Individual Carbon Dioxide Production");
b) p 256 ("Table 8.2 – Trace Elements in Coal");
c) p 466 ("Table 14.1 – Radioactive Wastes from Spent LWR Fuel")

5
http://www.eia.doe.gov/neic/historic/helectricity.htm (residential electric power consumption data for 2003 in file "sales_state.xls" under heading "By State" under heading "Consumption")

http://www.census.gov/popest/states/tables/NST-EST2004-01.pdf
census data for 2003 taken from "Annual Estimates of the Population for the United States and States, and for Puerto Rico: April 1, 2000 to July 1, 2004"

6
http://www.eia.doe.gov/neic/quickfacts/quickelectric.htm ("Electricity Quick Stats")

7
Hinrichs, op. cit., p 222 ("Table 7.3 - Ranks of Coal")

8
The regrettable but practical use of mixed SI and English units for discussing the energetics of coal is consistent with the cacophony of units used in the energy literature and industry. Furthermore, the student (and reader) may remember long after the class is over the equivalence of burning one pound of coal to get one kWh of electric energy.

9
Howard T. Odum, "Self-Organization, Transformity, and Information," *Science* **242**, pp. 1132-1139 (1988)

Howard T. Odum, *Ecological and General Systems: An Introduction to Systems Ecology,* revised ed. (University Press of Colorado, Boulder, 1994).

Transformity, the energy cost (in J/J) of converting some amount of lower quality energy (coal in this case) to smaller amounts of higher-quality energy (electricity), is a term used in systems-analysis discussions of energy flows in society. Converting three Joule-equivalents of coal to one Joule-equivalent of electricity is a process whose transformity is 3.

10
http://www.eia.doe.gov/kids/energy_fungames/energyant_trips/coalvisit.html

11
Richard Neville, *Solar Energy Conversion: The Solar Cell* (Elsevier, Amsterdam, 1995).

Aden B. Meinel and Marjorie P. Meinel, *Applied Solar Energy: An Introduction*, Addison Wesley, Reading, Massachusetts, 1976), pp. 39-115.

12
Barrett Hazeltine and Christopher Bull, *Appropriate Technology: Tools, Choices, and Implications* (Academic Press, San Diego, 1999), chapter 7.
http://www.solarbuzz.com/FastFactsUSA.htm
("Fast Solar Energy Facts – United States PV Market")

13
Paul B. Weisz, "Basic Choices and Constraints on Long-Term Energy Supplies," *Physics Today* **57**, pp. 47-52 (July 2004)

14
http://tonto.eia.doe.gov/dnav/pet/pet_sum_crdsnd_adc_mbbl_a.htm

15
Timur Kuran, "Why the Middle East is Economically Underdeveloped: Historical Mechanisms of Institutional Stagnation," *Journal of Economic Perspective* **18** , pp. 71-90 (Summer 2004).

16
P. N. Kropotkin, "Degassing of the Earth and the origin of hydrocarbons," *International Geology Review* **27**, pp. 1261-1275 (1985).

Thomas Gold, *The Deep Hot Biosphere* (Springer-Verlag New York, New York, 1999).

17
Tobias Owen, "Huygens rediscovers Titan," Nature 438, pp. 756-757 (8 December 2005). *http://www.nature.com/nature/journal/v438/n7069/full/438756a.html*

18
http://www.cv.nroa.edu/~awootten/allmols.html ("The 125 reported inter-stellar and circumstellar molecules. Updated 2004 Aug 24 by HAW.")

Pascale Ehrenfreund and Steven B. Charnley, "Organic Molecules in the Interstellar Medium, Comets, and Meteorites: A Voyage from Dark Clouds to the Early Earth," *Annual Review of Astronomy & Astrophysics* **38**, pp. 427-483 (2000).

19
James K. Fredrickson and Tullis C. Onstott, "Microbes Deep Inside the Earth," *Scientific American* **275**, pp. 42-47 (October 1996).

K. Pedersen, "Evidence for a Hydrogen-driven, Intra-terrestrial Biosphere in Deep Granitic Rock Aquifers", in C. R. Bell, M. Brylinsky and P. Johnson-Green (eds), *Microbial Biosystems: New Frontiers. Proceedings of the 8th International Symposium on Microbial Ecology*, (ISME-8, Halifax, Canada, 2000).

http://www.gmm.gu.se/groups/Pedersen/popDetail.php?ID-8
(Deep Biosphere Laboratory – Gøteborg, Sweden)

20
E. Dendy Sloan, Jr.. *Clathrate Hydrates of Natural Gases*, 2nd ed. (Marcel Decker, Inc., New York, 1998).
http://walrus.wr.usgs.gov/globalhydrate/index.html
("A Global Inventory of Natural Gas Hydrate Occurrence")
http://pubs.usgs.gov/factsheet/fs021-01
("Natural Gas Hydrates – Vast Resource, Uncertain Future")

21
James P. Kennett, Kevin Cannariato, Ingrid Hendy and Richard Behl, *Methane Hydrates in Quaternary Climate Change: The Clathrate Gun Hypothesis* (American Geophysical Union, Washington, DC, 2003).

Keith A. Kvenvolden, "Methane hydrate in the global organic carbon cycle," *Terra Nova* **14**, pp. 302-306 (2002). (note: crystallization/dissociation cycles of methane hydrate modeled by LRC-resonant circuit)

22
Hinrichs, op. cit., p 288 ("Table 9.1 – Greenhouse Gases")

23
I. A. MacDonald et al, "Asphalt Volcanism and Chemosynthetic Life in the Campeche Knolls, Gulf of Mexico," *Science* 204, pp. 999-1002 (14 May, 2004).

24
http://astrobiology.arc.nasa.gov
http://www.lyon.edu/projects/marsbugs/education.html
(undergraduate/graduate astrobiology programs)

25
David Kolb, *Experiential Learning: Experience as the Source of Learning and Development* Prentice Hall, Englewood Cliffs, NJ, 1984).

26
http://members.aol.com/physicsfirst/

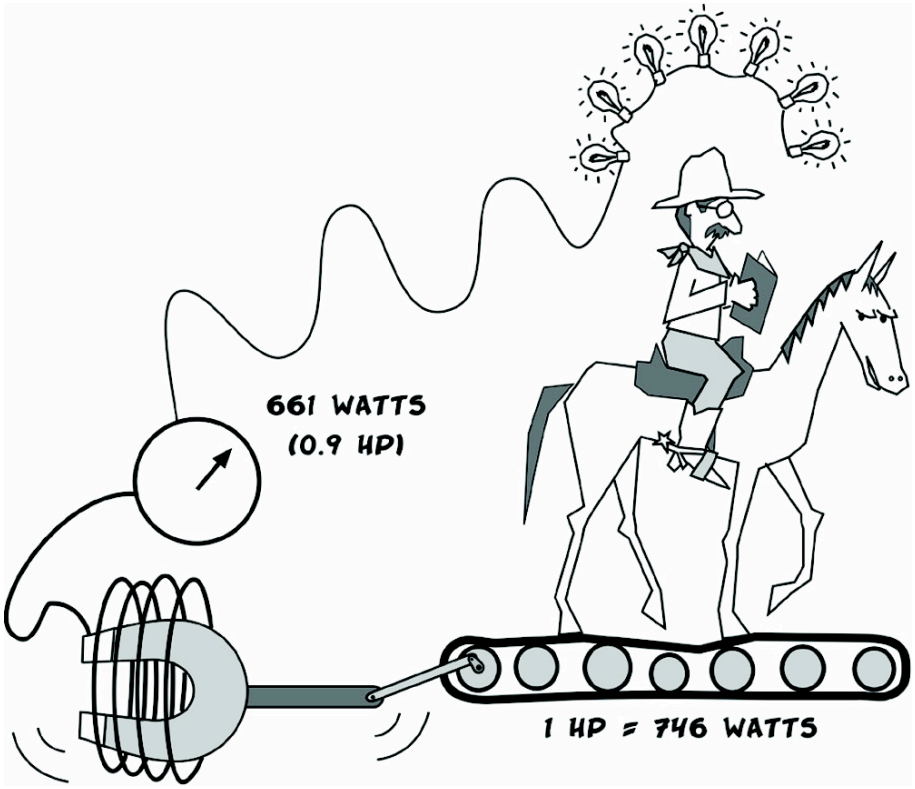


Figure 1
Our typical householder's incessant 661 W (= 0.9 HP = 7 light bulbs) electrical load requires a power source equivalent to one toiling horse.

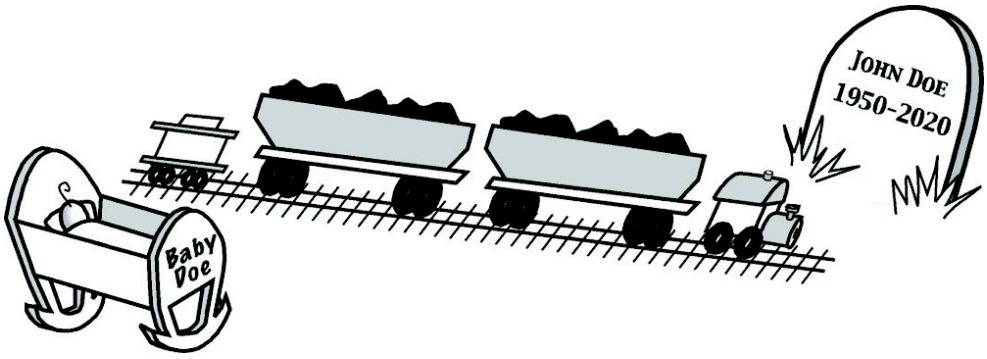


Figure 2
Over a 70-year lifetime, our typical householder's 661 W electrical load would, if powered by a coal-fired generator, necessitate the burning of 200 tons of coal (2 railroad cars) at the rate of one pound of coal burned per kWh of electric energy produced.