Energy: Past, Present, and Future

A Physicist's View

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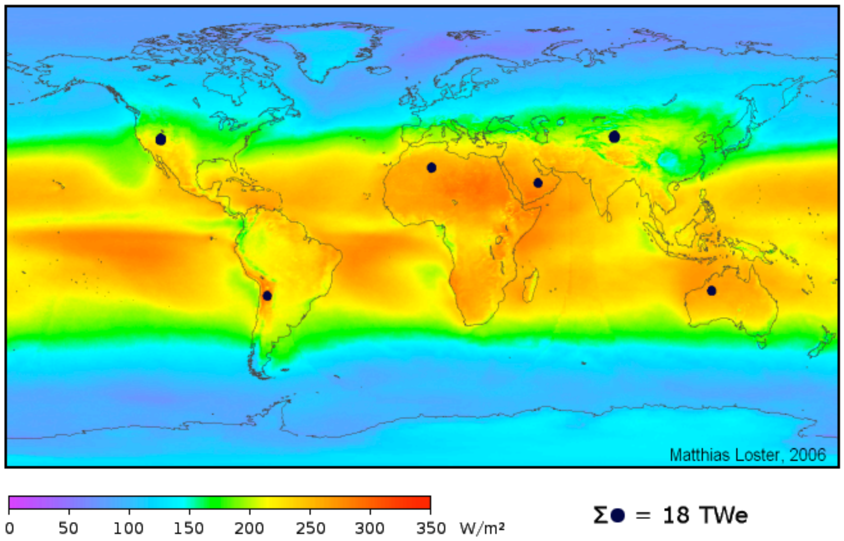
Sanity Check

- Earth is finite in size
  - pick your units
- Human population cannot grow forever
  - certainly not at levels measured in ~1% per year
- Energy sources within the earth are finite
  - fossil fuels are the earth's battery: batteries run out
- There are not an infinite number of elements/compounds
  - the periodic table fits legibly on one sheet of paper
- Low-entropy deposits of useful materials are finite
  - try extracting copper, gold, oil from your own backyard
- Imagination, however, seldom knows limits
  - do we lack the imagination to recognize limits?

Global Solar Potential

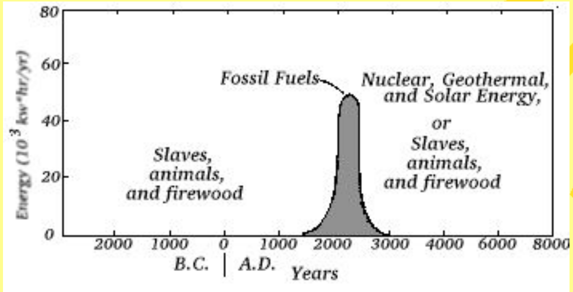


Assumes 8% conversion efficiency; Black dots represent area needed to cover ALL energy usage by humans (including all fossil fuels)

Physical implications of constant growth

- 2% growth per year in energy use, for example, doubles scale every 35 years
- But plenty of sunlight hits the land, so we're good for a while
  - With 15% efficient photovoltaic panels, we would cover all the land on earth in 320 years at a 2% per year growth rate
- But what if we had 100% efficiency, and covered all the earth?
  - We would reach the physical limit at 2% growth in 450 years
- Let's put our solar panels in space!
  - We would demand all the power the sun puts out in 1600 years (surrounding the sun in a sphere of panels!)
- But there are more stars in the galaxy
  - We would appropriate all 100 billion stars in the Milky Way galaxy in 2800 years
- Lessons:
  - exponentials are physically unrealistic over time
  - the last 200 year period is anomalous, and may not be the best model for anticipating our future trajectory

The Long View of Fossil Fuels



- We found the earth's battery
  - it took hundreds of millions of years to solar-charge the battery
  - we hooked up Las Vegas and watched it drain
- The last few hundred years have been unlike anything humans have ever experienced
  - we've ridden a crazy upward ride of growth (energy, economy, pop.)
  - is there a physical reason to expect this will continue?

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Have Energy; Will Gamble

In 50 years, will children look at this picture and ask: "what were you *thinking*?!"

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Industrial Age? Maybe *Energy* Age

- Coal enabled the steam engine,
  - first practical version introduced by James Watt in 1769
- One of the first uses of the steam engine was to pump water out of coal mines
  - so we could get more coal out of the ground
  - how shall we use it?
- Began an exponential process of energy consumption
- Finding oil in 1859 accelerated the process
- Fossil-fueled agriculture and food distribution led to population explosion
  - the "Green Revolution" of the 20th century is really a fossil-fuel revolution in how agriculture is practiced
    - fertilizers from natural gas feedstock
    - petroleum-fueled harvest and processing
    - petroleum-fueled global distribution of food

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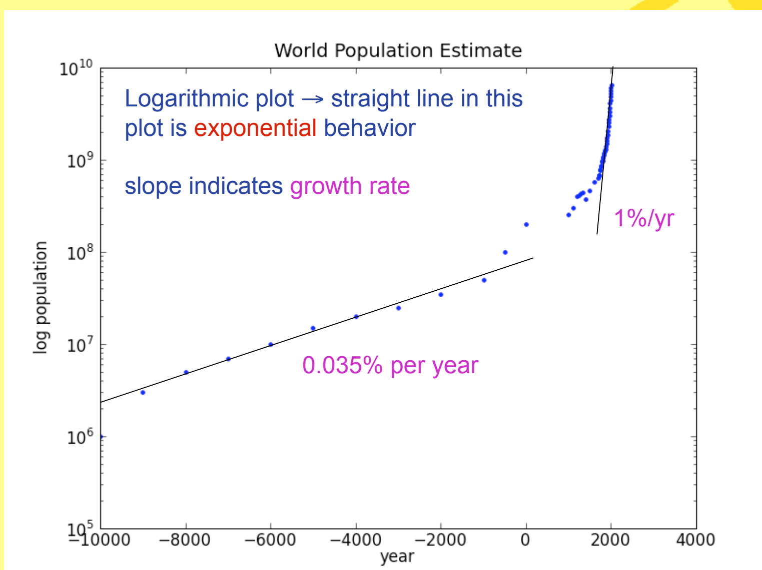
Did something change here?



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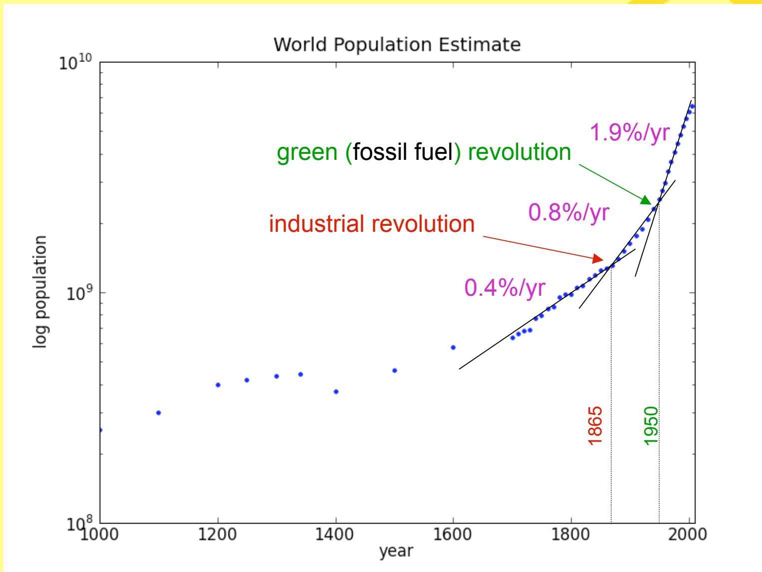
A closer look at recent trends…

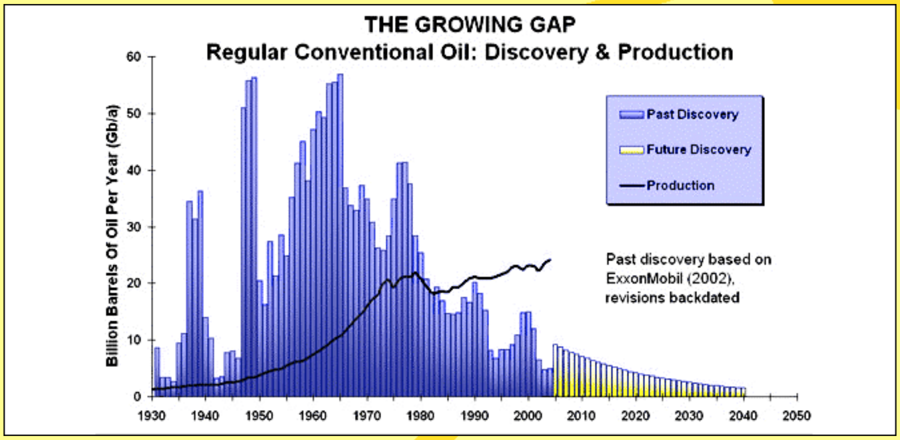


Coincidental timing, or cause-effect?

- We have a triple explosion on our hands:
  - using energy faster than ever
  - more people on the planet than ever
  - highest standard of living (hottest economy, most astounding technology) ever
- Which would you pick as the root cause, if these things are connected?

- If energy came *as a result* of the others, we would have heard:
  - Gee—all these people: we must find energy to power and feed them
  - Gee—our economy is on fire: we must find energy to support this level of enterprise
- In my view, I'll bet it was more like:
  - Gee—with all this energy resource, we can feed lots of (new) people and create amazing new technologies (let's go to the moon!)

Oil: A Story of a Finite Resource



- Discovery must lead production: can't pump what's not found
- Global discovery peaked in ~1960
  - still discovering oil, but < 10 billion barrels (bbls) per year, typically
- Production exceeded discovery in 1983
- Production *must* peak and then diminish—but when?

What perspective do we get?

Oil Industry Sets a Brisk Pace of New Discoveries

By JAD MOUAWAD

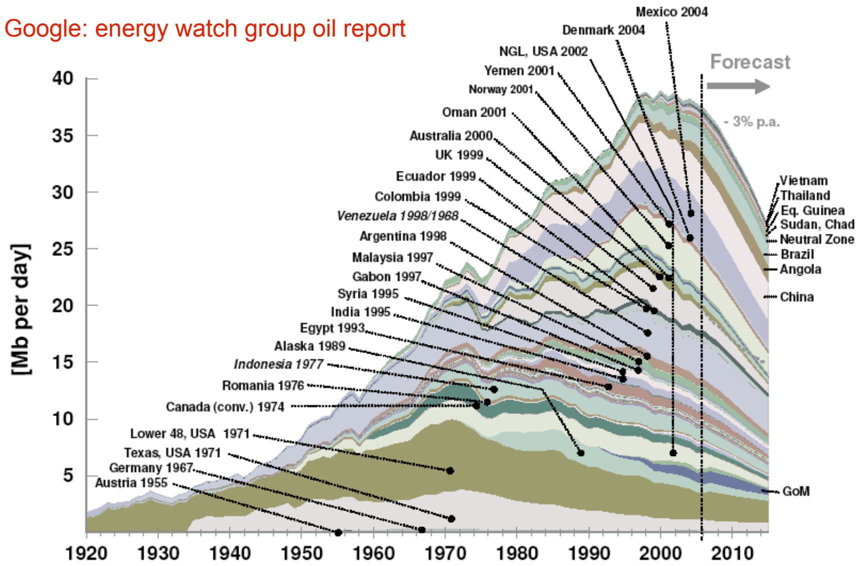
New oil discoveries have totaled about 10 billion barrels this year, on a pace to reach the highest level since 2000.

September 24, 2009 | BUSINESS | NEWS

- This recent headline in the New York Times was followed by a celebratory article extolling the virtues of market-driven discovery:
  - "…prices and the pace of technological improvement remain the principal factors governing oil production capacity"
- Late in the article, it is acknowledged that:
  - "Since the early 1980s, discoveries have failed to keep up with the global rate of oil consumption, which last year reached 31 billion barrels of oil."
- But immediately following:
  - "Reserve estimates typically rise over the life of a field, which can often be productive for decades, as companies find new ways of getting more oil out of the ground."
- If you need \$30k/yr to get by, but lately have earned \$7k/yr, do you pop the champagne bottle when you rake in \$10k one year?!

A look at the post-peak countries

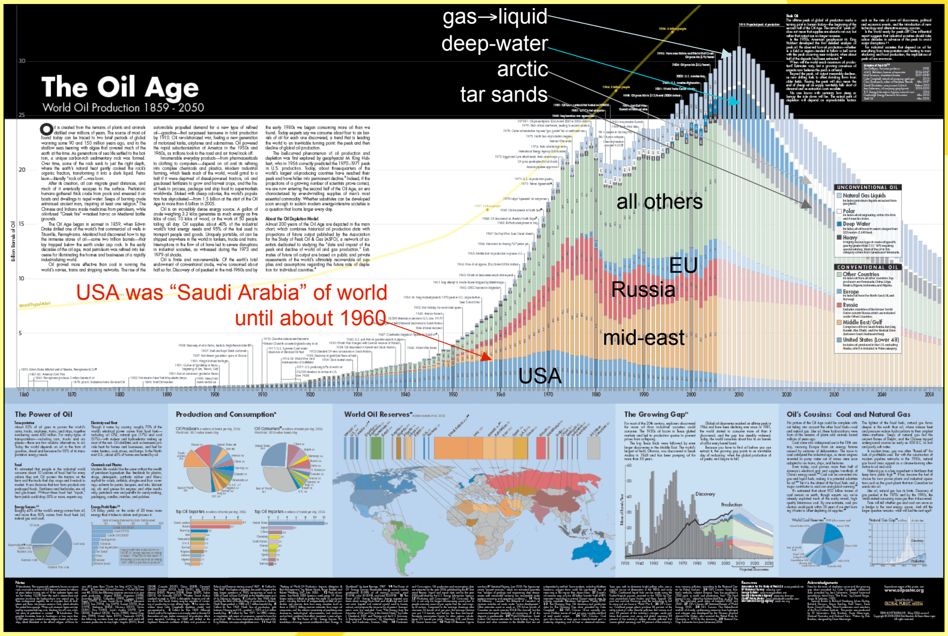
Google: energy watch group oil report



Ludwig-Bölkow-Systemtechnik GmbH, 2007
Source: IHS 2006; PEMEX, petrobras ; NPD, DTI, ENS(Dk), NEB, RRC, US-EIA, January 2007
Forecast: LBST estimate, 25 January 2007

Where do we stand on oil?

- 33 out of 48 major oil-producing countries are past their peak, and are in (probably permanent) decline
- The middle-east is the remaining “glittering prize”
- Even so, Saudi Arabia can’t push much harder
  - the 2008 price spike indicates that boosting production is not easy
- Overall, it is estimated that we have used about half (a trillion barrels) of the total conventional oil reserve
  - exactly where the peak would occur in a symmetric up/down curve
- Make no mistake; there is a lot more oil out there
  - a trillion barrels is a lot!
  - tar sands, etc. offer copious (non-conventional) resources
- But the rate at which we can extract and use the resource may be at or near its peak value



http://www.oilposter.org/

Why worry about peak oil?

- After all, oil is not the only fossil fuel
  - and there are other abundant resources besides conventional oil
- Oil is the lynchpin for transportation
  - and a global economy relies on global transportation
  - from what far reaches did the parts in your cell phone originate?
- Once conventional oil is in decline, demand will likely send the price shooting up
  - and new efforts to stem the decline (with non-conventional oil) will be unlikely to keep up with the relentless decrease of this massive-scale resource
    - a 3% per year decline in oil supply would require almost one new nuclear power plant per week of equivalent power replacement
- If a commodity as important to our economy as oil is in permanent decline, can we expect continued growth?
  - if not, what do interest rates, loans, banks even *mean*?

So what do we do?

- DON'T PANIC
- But we *must* take this seriously
  - our assumptions about "business as usual" are fragile, and should be examined
  - complacency presents too great a risk
- Examples of complacency:
  - we always solve our big problems: our scientists will save the day
  - fusion/geothermal/tidal/solar/etc. will save us in time
  - we find more oil all the time: no worries
  - growth is what we do: look at the past few hundred years
  - we'll be moving to Mars anyway

    or, in a related vein:
  - San Diego is always desirable: house prices won't go down
  - an event like the Great Depression can't happen in modern times: we're financially smarter now (imagine this statement mid-2008)
- As a physicist, I can't point to a principle that guarantees *any* of these things

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Okay, but still: what do we do?

- Modify our expectations about our future trajectory
  - what would a no-growth economy look like?
- Favor a long-term economic vision over short-term considerations
- Commit to reducing dependence on fossil fuels: phase them out
  - modify our behaviors to reduce our fossil footprint
- Support policies that promote renewable energy infrastructure
- Ask tough questions about "sustainability"
- Demand renewable energy from our utility providers

- Why should we do these things?
  - imagine someone presents evidence of a *possible* cliff ahead
  - do you ignore it and drive ahead full-speed?
  - do you slow down, start a turn, or both?
  - the risk is asymmetric: changing course costs little compared to the cost if the threat is real

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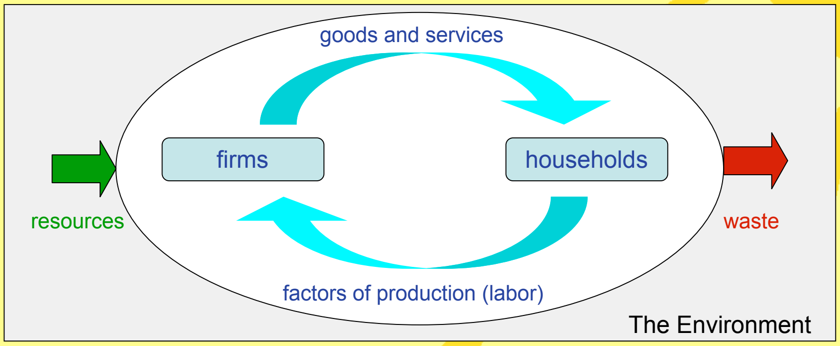
Simple view of the Economy



- Economists have historically been reluctant to draw a box around the model and label it “the environment”
  - this would beg the awkward questions:
    - how big is the economy relative to the environment?
    - what happens when we hit the boundaries?
    - is there a limit to growth?
    - what does a no-growth economy even mean?

Our Energy Options

- Human energy production/usage: 12 TW (Terawatt = 10^{12} W)
  - > 11 TW from solar-derived sources (nuclear, geothermal are only exceptions)
- Solar input onto the planet: 170,000 TW (120,000 TW retained)
- All photosynthetic activity: 40–90 TW (gets almost all bio-activity)
- Human metabolic activity: 0.6 TW (6 billion times 100 W)
- Continental wind energy rate: 50 TW (~5 TW practical limit)†
- Continental geothermal energy rate: 12 TW (diffuse, depletable)†
- Global hydroelectric energy rate: 4.6 TW (1.5 TW technically feas.)†
- Global tidal energy dissipation rate: 4 TW (far less is practical)

- Nuclear—while a practical short-term option—is not renewable, with a practical lifetime in decades unless breeder reactors allowed

† Information from Nate Lewis talk: nsl.caltech.edu/files/energy.ppt

A note about energy units

- 1 kWh is our standard commercial unit of energy
  - 1000 W for one hour; 1 W for 1000 hours, etc.
- Americans use 10,000 W each, continuously, in some form or another
  - so 10 kW for 24 hours is 240 kWh/day
  - usually only a small portion at home
- Comparisons:
  - 1 gallon of gasoline = 36.6 kWh of energy content
  - 1 Therm = 100,000 Btu = 29.3 kWh
  - heating 20 gallons of water (shower) 60 °F = 9,000 Btu = 2.6 kWh
  - 1kWh electricity produced from fossil fuel consumes 3 kWh of resource (due to typical efficiency of power plant of 30–40%

No Silver-Bullet

- The numbers tell us that no single solution (other than solar) is *capable* of replacing our 11 TW of fossil-fuel dependence
  - the number for bioactivity is larger than 11 TW, but year-in, year-out farming for our energy probably won't work
  - not to mention that we would have to commandeer virtually the whole planet's bio-system, oceans included
    - what would the poor critters of the earth eat?
- In fact, the scale of the problem is so immense, it is difficult for me to imagine pulling it off even in a combination of forms
- But let's not allow discouragement to stand in our way: let's take stock of what we can provide…

What can each source directly produce?

source	heat	electricity	liquid fuel
solar	YES	YES	
biomass	YES	YES	YES
wind		YES	
geothermal	YES	YES	
hydroelectric		YES	
tidal		YES	
nuclear	YES	YES	

What's that spell?

- Lots of ways to make electricity
  - which is good, because electricity is transportable and versatile
- A number of ways to make heat
  - which is good, because we do a lot of this
- Very few options for liquid fuel
  - and this is a problem: transportation will suffer

Addressing Transportation

- Airplanes need liquid fuel
  - the only source energy-dense enough to fly
  - biofuels likely most useful in this domain
- Cars really should be electric
  - then lots of available sources
  - batteries are the big holdup, and not guaranteed to improve in time
  - hybrid allows the occasional road trip
- Trains may come back into vogue
  - efficient; solid fuel (wood, coal) or huge batteries are options
- Centrally concentrated living
  - walk or bike to work
  - the American lifestyle pre-supposes cheap, abundant energy

To Change: First Quantify Consumption

- In order to make any changes, you must have good measurements to understand the impact & what to target
- Worthwhile learning how to read:
  - electricity meter (accumulated total *and* disk rate)
  - gas meter
  - water meter
  - see, e.g., http://en.wikipedia.org/wiki/Electricity_meter and similar pages
- Also there is a nice tool called the kill-A-Watt that lets you measure household devices
- Utility bills are also helpful for tracking longer-term performance

Assessment of my Energy Profile

- Looking at my bills April 2006–March 2007, I see that my household (2 people) used:
  - 3730 kWh of electricity in a year → 10.3 kWh/day
  - 330 Therms of natural gas in a year → 0.9 Therms/day = 26 kWh/day
  - 10 gallons of gasoline every 2 weeks → 26 kWh/day
- Total is 62 kWh/day = 2580 W
  - or 1300 W per person
  - 13% of 10,000 W American average
  - says most activity in commercial sector, not at home
- Worth noting that electricity comes from 35% efficient gas-turbine, so using ~3× the energy in gas feedstock
  - so 10.3 kWh/day translates to about 30 kWh/day from gas

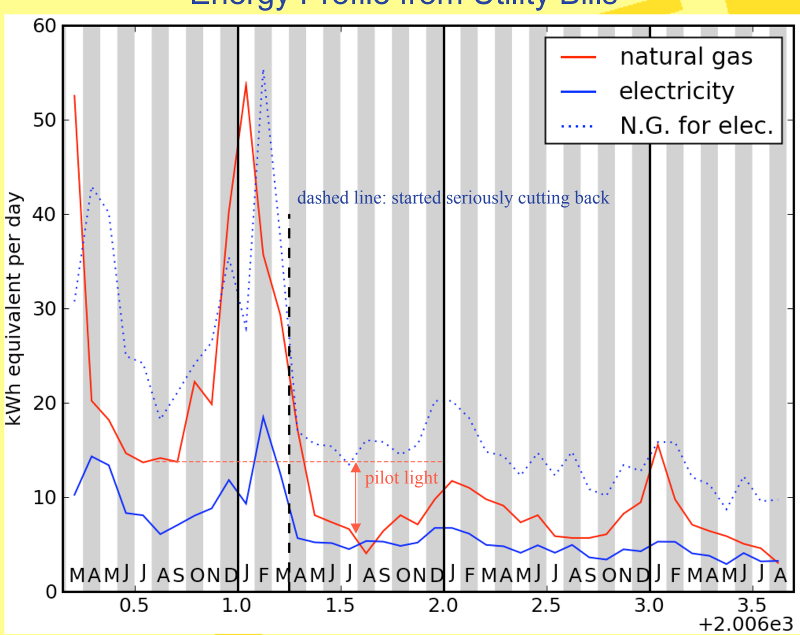
Average Americans

- 830 kWh electricity per month per household
  - about 300 kWh per person per month (10 kWh/day)
- 6×10^{12} ft^3 of natural gas use in residences per day
  - 480 kWh gas equivalent per month per person (16 kWh/day)
  - 1 Therm is 29.3 kWh, and is 102 ft^3 of gas
- 0.5 gallons gasoline per day per person
  - 560 kWh per month equivalent (18 kWh/day)
  - 1 gallon is 36.6 kWh equivalent
- Total power is 1340 kWh/month (44 kWh/day) = 1820 W
  - this is 18% of the average American's total of 10,000 W
  - so again, most is outside the home (out of sight, out of mind)

How much better can we do?

- In the year following my self-audit, my wife and I challenged ourselves to reduce our energy footprint
  - turned off furnace pilot light over summer (was responsible for 60% of our gas usage over the summer!)
  - never turned furnace/pilot back on
    - low power electric blanket helps!
  - shorter showers
    - lately: only on to get wet and rinse: soap up with water off!
  - line-dry clothes
  - all bulbs compact fluorescent
  - diligent about turning off unused lights
  - bike/walk around neighborhood (and bus to work)
  - install experimental (small) solar photovoltaic system (off-grid; battery-based) to run TV & living room, later fridge
- The solar experience taught us how precious the resources are
  - we're much more conscientious about *all* energy now

Energy Profile from Utility Bills



Big Reductions

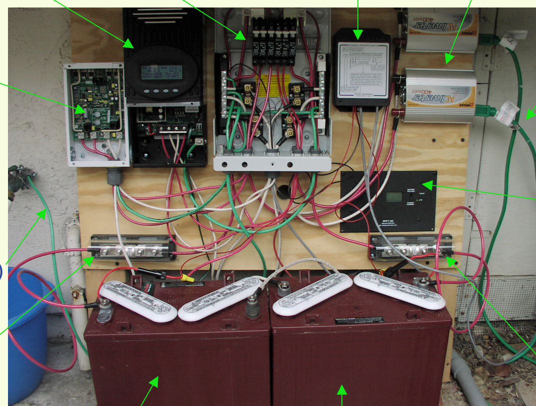
- Most substantial savings was gas (no furnace)
  - Went from 0.84 Therms/day to 0.28 Therms/day
    - equivalent to 25 kWh/day, down to 8 kWh/day
    - using 33% of what we used to!
- Line-drying clothes had largest electricity impact
  - some space-heater activity to compensate for no heat
  - Went from 10.5 kWh/day to 5.5 kWh/day
    - using 52% of what we used to
    - but this requires about three times this much in natural gas due to the inefficiency of generation, plus some transmission loss, so the real post-reduction usage is twice that of natural gas

A Modest, Stand-Alone System

- In 2007, I set up a small PV system to power my living room
- Used two different panel types, explored a number of charge controllers and configurations
- Built mounts to allow seasonal tilt adjustments
- Larger panel is 130 W poly-crystalline silicon at 16% efficiency
- Smaller is 64 W thin-film triple-junction at 8% efficiency
- Large panel handled TV, DVD/VCR (system A), smaller one powered lights (system B)

see article in Physics Today, July 2008

Dual System Components (covers removed)



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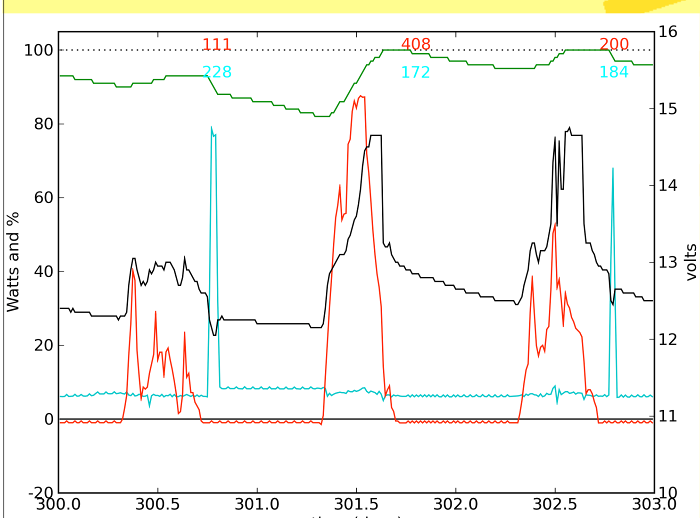
Three days of PV-TV monitoring



green: battery % full

black: battery voltage (right hand scale)

red: solar input, Watts

cyan: load usage; baseline for inverter, intermittent TV use

numbers at top are total solar yield (red) and total system usage (cyan) for that day, in Watt-hours

Home PV monitor for three late-October days in 2007: first very cloudy, second sunny; third cloudy

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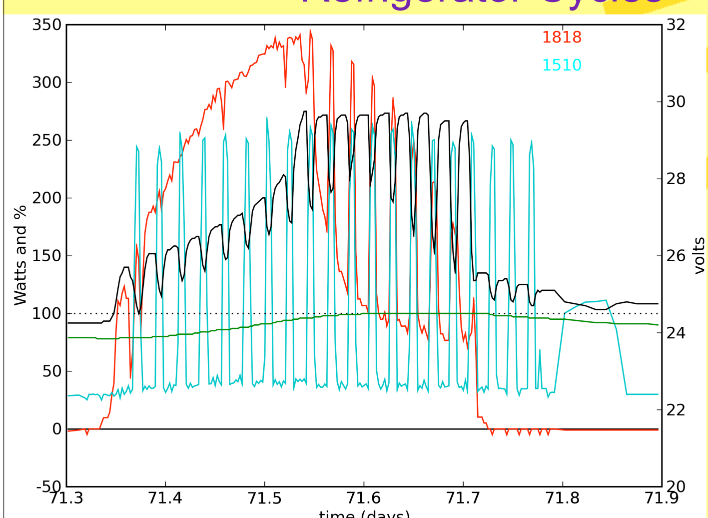
System Upgrades

- Over time, system has grown
- Now six 130 W panels
- Beefy inverter
- “smart” control to switch to grid power input when batteries low
- now running refrigerator (40% of electricity bill) and TV/entertainment most of the time off these four panels
- dreams for ongoing expansion

extensions on mounts allow tilts to 50°
portion shown here only gets 10° and 20°

Refrigerator Cycles



Briefly operated with 3 130 W panels…

Let’s tackle something more worthy, like the refrigerator…

Can see cyclic behavior as fridge turns on and off

Once battery reaches absorb stage voltage (~29.5 V), can relax current to battery (falling red envelope)

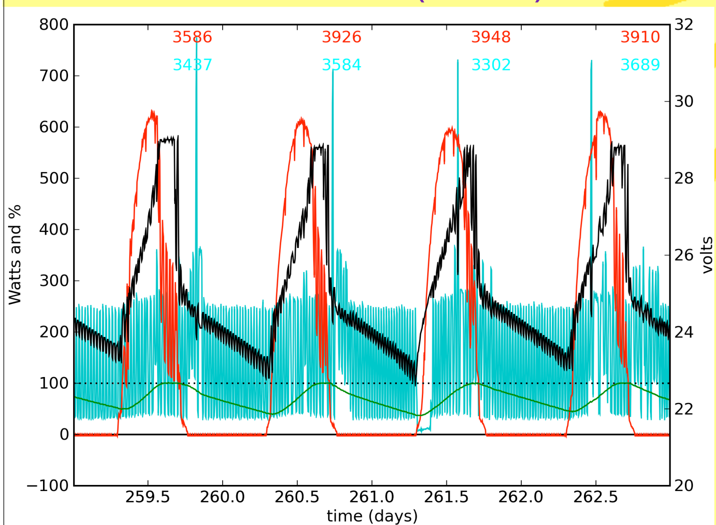
When fridge pops on, need full juice again

Some TV later in day

In this period, got 1818 W-h from sun, used 1510 W-h

Getting 1818 W-h from 340-W capacity → 5.3 hours equiv. full sun

Current (smart) scheme



Currently, smart inverter shuts off when battery gets low, using grid power to supply loads

Inverter comes back on when battery voltage hits a certain level

Note consistency of energy supplied (red numbers) and energy used (cyan numbers)

Infer 91% efficiency across four days (efficiency of sending solar juice to inverter, including battery)

Using solar for fridge almost 100% of time; otherwise grid

getting most out of system, without wasting solar potential

You Are What You Eat

- How much energy goes into producing our food?
- By some estimates, we spend 10 Calories of energy on every 1 Calorie delivered to the table
  - would not be possible when agriculture was powered by man and beast, or starvation would result
  - A 2000 Calorie diet is 2.3 kWh per day
  - Thus about 20 kWh per day in production (about 10% of the American energy footprint of about 240 kWh/day)
- Leveraging this down
  - compared to raising vegetable matter, meat takes more resources
    - after all, the animals eat plants, at some efficiency loss
  - beef is 7× amplification
  - pork is 3× amplification
  - poultry, fish is 1.5× amplification

Key Points

- The past few hundred years have seen an unprecedented availability of energy resources
- Our economic framework and way of life has been built on this energy foundation
- The future of conventional energy resources is jeopardized
- The future is not written, not guaranteed: we get to make it

Summary

- We can no longer take for granted a lifestyle afforded by cheap, abundant energy
- Our notion of growth must also change
- Psychology is no small part of the process of adapting to new realities
- On over-arching, quantitative analysis is critical
- On a personal level, measuring your footprint provides information and incentive to meet the reduction challenge
- Communication of the issues is vital: this problem will not fix itself

- Check out the fantastic book by David MacKay: free at www.withouthotair.com
- Also: http://storyofstuff.com by Annie Leonard

What Role Can Scientists/Academics Play?

- biology: algae, biofuels
- chemistry: batteries, PV processes, biofuels
- ecology: pricing resources, waste
- economics: drop the fantasy and give us steady state
- history: study overshoot, overreach
- physics: fusion?, PV technology, supercapacitors?
- psychology: understand the human propensity to live in fantasy
- sociology: designing a sustainable social structure