Energy on the Home Front

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Abstract. This article explores a variety of ways to measure, adjust, and augment home energy usage. Particular examples of using electricity and gas utility meters, power/energy meters for individual devices, whole-home energy monitoring, infrared cameras, and thermal measurements are discussed—leading to a factor-of-four reduction in home energy use in the case discussed. The net efficiency performance of a stand-alone photovoltaic system is also presented. Ideas for reducing one's energy/carbon footprint both within the home and in the larger community are quantitatively evaluated.

INTRODUCTION

It is clear that we cannot continue to rely on cheap fossil fuel energy for the indefinite future. The coming decades will see increased efforts to replace conventional energy sources with renewables—both as an effort to control carbon dioxide emissions and to mitigate economic disruptions caused by resource depletion. Many of the alternatives lack the reliability and convenience of our fossil mainstays. There do not appear to be any one-size-fits-all silver-bullet solutions to the energy challenge. Reliance on future technological breakthroughs (fusion, the ideal battery, a superconducting smart-grid, etc.) feels more precarious as time marches forward. After all, were we not all supposed to have jet packs by now?

Among the strategies discussed for meeting future challenges, one option with perhaps the largest potential impact is seldom discussed: choosing to use less. As concerned citizens of this world, we make choices all the time about how we might have less impact on world resources. We might recycle household waste, try to buy goods with less packaging, take our own bags to the grocery store, join a community-supported-agriculture cooperative, or any number of other behavioral changes. We might also (or instead) focus our attention on using less energy at home. This is the challenge I took up in 2007—made possible by a willing wife—and we have cut our domestic consumption of energy by about *a factor of four* in the process. If many of us were willing to change behavior on this scale, the enormity of our energy challenge would melt to a more obviously manageable beast. And even if few people adopt such behaviors, I am reassured to know how little it takes to meet my own needs, and that I am personally much less of a drain on the system.

In this article, I aim to provide the reader with tools, knowledge, and examples for accomplishing large reductions in energy usage. As a caveat, not all of the approaches I describe for our San Diego home will work for all people in all locations. On the other hand, we started from a comparatively slight energy profile and were able to trim this substantially. The theme of this article is more about *reduction* than *efficiency*. The latter is undoubtedly a useful tool in our arsenal, but gains in efficiency can sometimes lead to more profligate usage of energy. This phenomenon is known as Jevons' Paradox, or the Khazzoom-Brookes postulate.

TAKING STOCK

Real change must start with measurement. Without quantifying the scale of energy use, one has no baseline for improvement, and no context for where improvements can be most effective. A variety of inputs have guided my own exploration, as described below.

Utility Bills

Utility bills are a good place to start. The resolution is (typically) monthly, but good enough to establish a baseline. Because energy use and type tends to be seasonal, start by making a plot of electricity, gas, and any other inputs, such as heating oil. It is tremendously useful to use common units for the various inputs (I have tried without success to get my utility company to do this). Using the common unit of kWh, we list the conversions in Table 1.

TABLE 1. Home Energy Units.

Energy Source	Billing Unit	kWh
Electricity	1 kWh	1.0
Natural Gas	1 Therm	29.3
Gasoline	1 U.S. gallon	36.6
Heating Oil	1 U.S. gallon	40.6

For the purpose of assessing environmental impact, it is important to understand the local portfolio of energy sources used for electricity production, as this impacts the conversion efficiency and carbon footprint of the resource. For instance, a natural gas electricity plant---common in California—may deliver 0.35 kWh of electricity to my home for every 1 kWh of energy derived from natural gas.

The average American household (of which there are about 115 million) has a daily use of 30 kWh of electricity, and 35 kWh (1.2 Therms) of natural gas [1]. Our starting point was substantially lower. In the 12-month period preceding my energy “awakening,” our household of two used 3828 kWh of electricity (10.5 kWh/day) and 9000 kWh (307 Therms; 24.5 kWh/day) of natural gas. Given that the source of our electricity is dominated by natural gas turbines, the factor of three conversion/delivery efficiency puts the two sources roughly at parity in terms of energy use and CO_2 production.

Reading the Meters

Utility bills provide the bird's-eye view of a household's consumption habits. Some utilities also allow online monitoring of “smart” meter activity at hourly resolution—although often delayed by a day or more. Even given this welcome capability, neither form easily translates into action items for demand reduction. This is where metering can help. Digital meters are replacing analog meters in some parts of the country, but it is helpful to be able to read both types. The primary function of the meter is to measure cumulative usage for billing purposes. Thus the “odometer” aspect is the meter's main function. But for home assessment, the rate of usage is far more important—whether for electricity or natural gas. The odometer is often too crudely displayed to be of much use in determining instantaneous rate. For instance, the new “smart” electricity meter on our house only displays electricity usage in increments of 1 kWh—which is not very useful when daily consumption is knocked down to about 2 kWh per day. The biggest sin of our smart meter is the absence of an instantaneous power reading. Internally, it measures household current and multiplies (temporally) by voltage to get instantaneous power. But this information is not made available to the curious physicist.

Ignoring the odometer function of the meter, which is straightforward to figure out—even for the tricky alternating-direction analog gauges, I will describe how to extract useful rate information.

Analog Electricity Meter: Almost all analog electricity meters have a spinning disk whose average rate is proportional to power usage. A constant, usually called Kh, is typically printed on the faceplate of the meter, and is often 7.2 or some multiple thereof. This relates to the number of watt-hours (Wh) per turn of the meter. So if the spin period is T seconds, the power in Watts is $3600\times\mathrm{Kh}/T$. Be aware that the disk rate can vary by as much as a factor of two during one revolution even at constant input power. For accurate results, an integral number of rotations should be observed.

Digital Electricity Meter: The rotating disk is no longer available, and my digital meter refuses to provide a measure of instantaneous power. But it does have a “simulated” disk function, consisting of little blocks that appear and disappear in a way that mimics the left-to-right motion of the analog disk. After hours on the phone with my utility provider (during which time I explained the difference between kW and kWh several times), I learned that each time a block appears or disappears, one Wh of energy has been used. My meter cycles through six states of its disk symbols, so that one cycle represents 6 Wh. If this takes time, T, the power in Watts is $3600\times6/T$.

Natural Gas Meter: My analog gas meter has an odometer with a resolution of one-hundred cubic feet (hcf), which is 1.02 Therms. But it also has two dials for which full revolutions measure 0.5 cf and 2.0 cf. The dials have ten tick marks around the periphery, so that one may achieve 0.01 cf of resolution with a modest amount of interpolation. But since the gap between the fine scale and odometer dials is so large, meaningful monitoring must be frequent enough to ensure no dial wraps went unnoticed.

By studying the rate of the electricity meter, one can learn how much power particular devices consume, what a typical “on” state of a house is, and—very importantly—what the “off” state base load is for the house. By studying the natural gas meter, one can understand the constant rate of usage from pilot lights, and how much energy goes into a shower, for instance.

The Biggest Reduction

The single-biggest energy reduction in my household derived from monitoring the natural gas meter. I watched the 2 cf dial make a steady 0.72 revolutions per hour during a period when there were no demands for gas. Pilot lights were solely responsible for this consumption, amounting to 10 kWh/day, or almost half of our total natural gas usage. I turned off the furnace pilot light to learn that it was 70% of the problem. In fact, during summer months, the furnace pilot light used more gas than we used for all of our hot water! Needless to say, I left the pilot light off, as spring had arrived and the heating season was over. The big savings came the next year, when we planned to hold off on re-lighting the pilot light until it became unbearably cold in the house. That day never came. We tolerated temperatures that occasionally dipped to 13°C (55°F), but in San Diego, this is the worst we saw.

Admittedly, not everyone can tolerate these temperatures—and it took a few years before it seemed normal to us. But besides pointing out that humans did not evolve simultaneously with heating, ventilation, and air conditioning (HVAC), a key observation is that I don't care how warm my bookcase is; *I* want to be warm. And there are plenty of ways to maintain thermal comfort in a cool environment. Down slippers, blankets on the couch, and a 60 W (max) dual-control mattress pad go a long way. Heat the body, not the house.

The Kill-A-Watt®

A very handy device for taking stock of electricity demands is a unit known as the Kill-A-Watt®, which can be inserted between an outlet and the plug of a device to monitor instantaneous power at 1 W resolution (up to about 1800 W), accumulated energy at 0.01 kWh resolution, and elapsed time.[1] This is extremely useful for characterizing refrigerators, washing machines, computer and entertainment devices, etc. I have kept one on our efficient refrigerator for the last year, finding an average power consumption of 37 W. This device was crucial for deciding what devices I wanted to place on the solar circuit (described below), and has also been responsible for our unplugging or getting rid of devices that used far more energy than their function warranted. Because of the Kill-A-Watt, I know how much power each setting of the electric mattress pad consumes, what my laptop uses when asleep, charging, etc., and how much energy our always-on wireless internet access demands.

Knowledge is power. And knowledge *of* power is even better. For the investment, the Kill-A-Watt is bound to be worthwhile. To set the scale, 1 W of power over a year consumes 8.8 kWh of electricity. Depending on local cost of electricity, this might typically translate into about one dollar per year. If just 20 W of constant power drain is eliminated, the unit pays for itself in the first year. But I hesitate to make strictly financial judgments, as these often miss larger points.

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[1] This, and other commercial devices named in the text, does not represent an endorsement over competitive models. I simply report successful use of certain products, without having explored other—possibly superior—models.

My New Friend, TED®

Most friends cannot be bought. TED®, The Energy Detective, is an exception. TED is a whole-home electricity monitoring device, fitted into the main circuit-breaker box and providing 1 W resolution. My wife and I arrived at the house of our friends for Thanksgiving, bringing the just-purchased TED as an uninvited guest. While some of us (kids included) had great fun minimizing power output of the house, our hostess—expending substantial energy on meal preparation—was less enamored of the service interruptions. TED soon found refuge in our house, and despite my wife's initial attitude that the last thing we need is *another* energy monitoring device, within a few days she admitted that TED is "pretty cool."

TED provides an optional LCD unit that displays—among other options—instantaneous power. Finally I have access to the single-most important information pertaining to home usage without having to go outside and deal with the indirect (and not instant) information provided by the electricity meter. Now it is straightforward to measure appliances that the Kill-A-Watt could not (due to high power or integrated wiring). Logging features allow captures of activities at one-second resolution for a few hours, and several days at a time at one-minute resolution. It also tracks minimum, maximum, and cumulative usage across days, among other measures. Configuring a home's internet router appropriately allows remote access to TED's instantaneous and stored data.

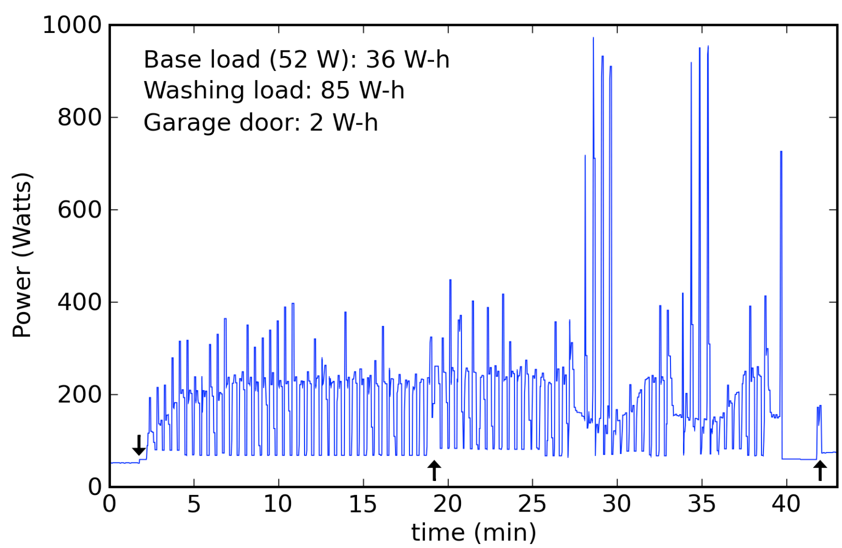

FIGURE 1. The energy cycle of a front-load washing machine, from TED, at one-second resolution. The down arrow is when the washing machine was plugged in (7 W phantom load), and the up arrows indicate times when the garage door was opened, then closed, each followed by a period when the garage door light remained on. Otherwise all activity is due to the washing machine's rotation-rest cycles and final spin cycles. Interestingly, 75% of the 6000 J energy associated with opening or closing the garage door is due to the compact fluorescent light bulb, operating at 15 W.

By the time TED arrived at our house, we had already trimmed our usage substantially. But even so, having a number constantly on display motivates further change. Within days, we trimmed our utility base load ("off-state" power) from 52 W to 36 W—mostly by recognizing that our HVAC system demanded 13 W to sit idle, even when the system is turned off. Figure 1 shows an example data capture from TED at one-second resolution, in this case highlighting the secret life of the washing machine.

Infrared Camera

Motivated by the fascinating article by Woolaway on infrared camera technologies in the first publication of the APS Sustainable Energy Conference in 2008 [2], I obtained a 120×120 format thermal infrared camera. While in my case, no single use could justify the expenditure, the range of discovered applications has made it a valued asset. In addition to learning about home energy issues, the camera is useful as an educational tool, to assist thermal engineering associated with my research, troubleshooting electronic component failure, and in general developing a solid intuition about the radiative world.

Within my home, the infrared camera has revealed a number of energy problems. It has exposed gaps in insulation and identified walls without insulation. It has helped to identify electronic devices that are consuming power unexpectedly. It has pinpointed the origin of drafts around windows and doors. It is also responsive to evaporative cooling that accompanies water leaks. The camera is therefore a great tool for evaluating a house's thermal state. But its expense seldom justifies its purchase for such an application in a single house. Figure 2 shows an example image from the infrared camera, in which an active dishwasher behind thin wood paneling reveals the path of the plumbing.

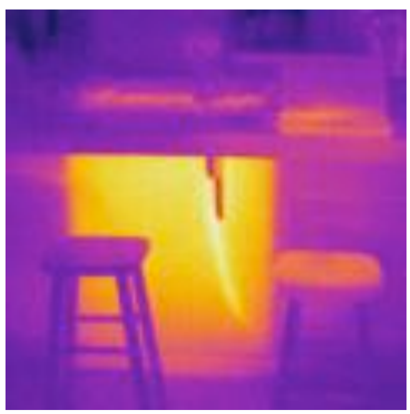

FIGURE 2. Example infrared view of a dishwasher in action. The dishwasher is situated within a counter-top "peninsula," so that this view is of the back side, covered by thin wood paneling. Note the hot water supply line, the warmed counter-top, the laptop on the counter at right, and that one of the two stools has recently been sat on. The temperature range in this image runs from about 22°C to 35°C.

ThermoChrons®

For assessing the thermal state of a house, it is hard to beat a time series of temperatures at key locations. But outfitting a home with a data acquisition system can be impractical. The iButton® Thermochron®, made by Maxim, makes the job easy. These are devices about the size of a stack of four nickels (17.4 mm diameter; 5.9 mm thick), containing an internal battery and no wires or ports. Communication is via the

1-Wire protocol, the device clicking into a USB-connected snap-ring socket for programming and readout. “Missions” can be set up to acquire temperatures on a sampling cadence from one second to hours, and can store 4096 records at 0.06°C resolution. An optional start-of-mission delay can also be set, and the device can either wrap or stop logging when the memory is full.

The most attractive aspect of the thermochron is that it can go anywhere it will fit, with no wires to complicate matters. They have metal exteriors, and therefore low emissivity. To couple effectively to the surrounding air, I hang them from string and use aluminum tape to provide a low-emissivity attachment. The hanging thermochrons provide yet another conversation-starter in our little house of data. Figure 3 provides an example of what can be learned from such information. For me, this will serve as a useful baseline if I make changes to insulation, roof albedo, ventilation, etc.

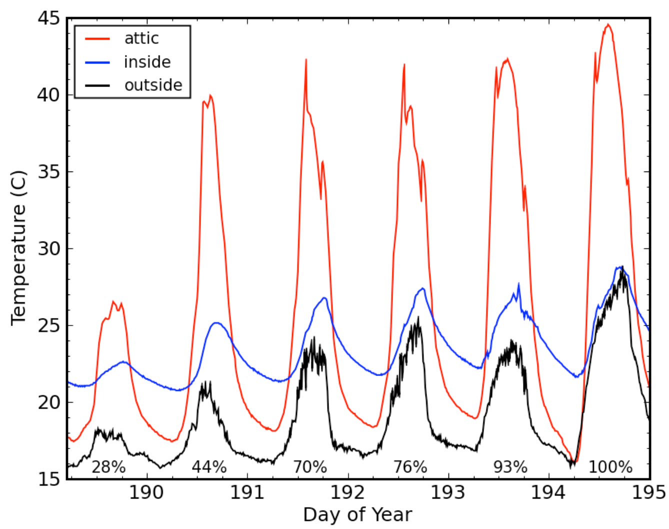

FIGURE 3. Part of a Thermochron campaign in July 2010, sampled at ten-minute intervals. The inside temperature (blue curve) is not air conditioned, although an attic fan comes on when the attic (red curve) temperature exceeds 42°C (then off at 33°C). The first day was completely overcast, and each day thereafter was progressively sunnier, until the last perfectly sunny day (photovoltaic yields for each day appear at bottom). Even days with no direct sun impose a thermal load on the roof. The attic fan appears to have only a few-degree impact. Most nights (and mornings) were accompanied by a marine layer, but the record indicates a clearing of the marine layer midway through the last night, as the roof radiated to space and turned sharply cooler before a clear sunrise.

DOMESTIC SOLAR ENERGY

As a physicist teaching courses on energy technologies, I felt woefully uneducated on the practical ins and outs of domestic energy production, and solar energy in particular. Because I was renting at the time, installing a grid-tie system—like almost all photovoltaic (PV) installations where utility power is available—was not a viable option. I embarked instead on the rewarding journey of building my own stand-alone system from commercial parts. I started very small, building two independent systems, each using one solar panel: a 64 W multi-junction thin-film panel, and a

130 W poly-crystalline silicon panel. The system is described in detail in the July 2008 issue of *Physics Today* [3].

The PV system has marched through a series of evolutionary steps since the publication of its description in 2008. The 64 W panel was set aside (now used to power a pump in a rainwater catchment system) and the system consolidated to a single one using a growing number of 130 W panels, a larger, smarter inverter, and more batteries. In the process, we moved to a different house and I wired a few dedicated breaker-protected AC circuits within the house for PV power distribution. The system now consists of 8 130 W panels; four 12 V, 150 Ah golf-cart batteries arranged in a 2×2 24 V configuration; a 3500 W inverter with the ability to switch in utility power when it senses low battery voltage; and internet-accessible monitoring.

The stand-alone PV system runs the refrigerator, entertainment console, cable modem and wireless router, two laptop computers, printer, and the attic fan. In all, we pulled 52% of our electricity in the last year from the PV system. The attic fan is a particularly good match, in that it tends to kick on right around the time the batteries reach full charge and begin refusing available energy. Plus, the attic fan is only needed on sunny days, when the batteries are likely to reach the full-charge state. Figure 4 shows a day in the life of the PV system.

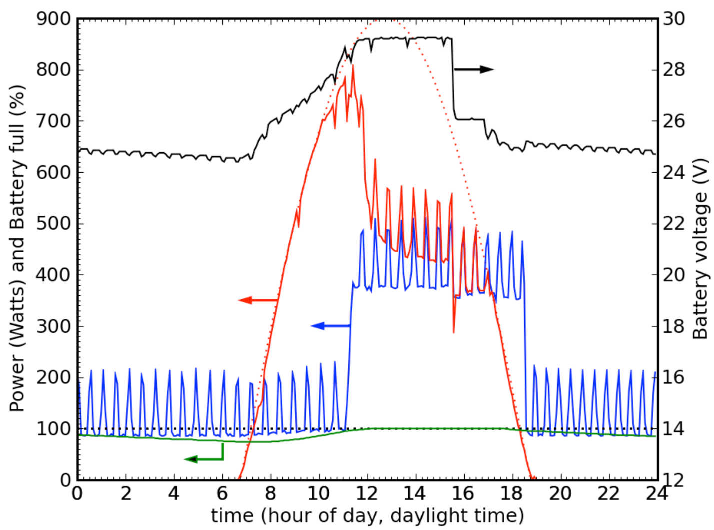

FIGURE 4. One day of PV generation in early May 2011, at five-minute resolution. The red curve is the solar input (the dotted line is a section of a cosine curve for comparison). The load curve (blue) is dominated by the cycling of the refrigerator, and the attic fan in the afternoon. The battery (black) achieved its "absorb" state voltage just before noon, after which the charge controller accepted a diminishing amount of the available sunlight. If not for the attic fan, far less solar energy would have been utilized. The green curve at bottom represents the state of charge of the battery.

Efficiency Report

Over the last year, the batteries in my PV system were powering their share of the house 92% of the time, switching to utility input during long periods of rain and clouds. The duty cycle could be substantially increased with more batteries. In the last year, the PV system received an average of 4.1 kWh/day and distributed 2.5 kWh/day to appliances within the house. The resultant 62% efficiency breaks down as shown in Table 2.

TABLE 2. PV System Efficiency.

Source	% of Input Energy	Comments
MPPT Charge Controller	4.8	In series with input from panel
Net Battery Loss	7.8	Not the same as battery energy efficiency
System Power	4.7	9 W for PV devices, monitors, communications
Inverter Base-Load	9.6	20 W to keep inverter on (92% of time, last year)
Inverter Inefficiency	11.2	88.5% efficient at converting DC to AC

The battery system constitutes a net 7.8% drain on the system, but since the battery is only a drain during the day when it charges, the net drain under-represents the battery energy efficiency. In my case, 53% of the energy delivered to appliances originated from the battery, while the remaining 47% came directly from the solar input while the battery charged. Given that roughly half the time is daytime, this balance makes sense. The actual energy efficiency of the battery bank was 84%—meaning that 84% of the energy delivered into the battery re-emerged in a useful form. This is different from charge efficiency, measured as amp-hours in versus out, which is 93% in my system. The difference is due to the difference in voltage during charge versus discharge states. The batteries characterized here are in their first year of operation, so that these numbers are at the high end of their lifetime performance.

An additional loss is incurred relative to a grid-tie system because potential solar input is turned aside when the batteries are fully charged. Compared to a friend's house with an excellently-exposed grid-tie system in the same neighborhood, my system soaked up 76% of the available 5.2 equivalent full-sun hours averaged over the past year. A properly designed stand-alone system needs some margin to deal with less-than-perfect weather, meaning that untapped solar potential on clear afternoons is inevitable. Devices like attic fans can partially fill this void. Given the ~90% inverter efficiency on a grid-tie system, and putting the numbers together, my stand-alone system delivers to appliances about 53% of the available energy that a grid-tie system would do.

The lesson is that a stand-alone system incurs a substantial efficiency hit compared to a grid-tie system. Moreover, the cost of periodically replacing batteries roughly offsets the cost-avoidance of the utility electricity. But I do not regret in the least the experience and independence my system has given me. I now know much more about the practical side of PV, and can understand better the challenges our nation will face if relying on large inputs of intermittent power, requiring storage. As I write this, the food in my mother's refrigerator/freezer is spoiling due to tornado/storm-induced power outages in Tennessee. I have peace of mind that this would not happen to me, and I may be very popular with neighbors if I offer to store some of their food in a crisis.

A Side Benefit of Solar

At least as important as the direct energy input from the PV array is the behavioral conditioning it has fostered. Building my own system—especially a stand-alone system—makes my energy very personal. I have worked to catch and store that energy, and I'm not about to waste it frivolously. I would never think of leaving the television or lights on when the batteries are losing charge. Standing in front of an open refrigerator door is a new kind of sin. The magic part is that this mentality carries over to parts of the house that are not on the PV distribution—and then beyond the boundaries of home. I consider this level of awareness to be a perk. Rather than take electricity for granted, I have come to value it on a more personal level.

REDUCTION TACTICS

Thus far, I have discussed ways to monitor energy consumption and identify power hogs, describing also a stand-alone photovoltaic system to offset utility electricity. A few examples of reduction have been offered along the way, but here I present a comprehensive list of the changes we have made to reduce our energy consumption. The net effect is that today we have a daily use of 5.0, 2.3, and 2.5 kWh in natural gas, utility electricity, and PV electricity, respectively, averaged over the past year.[2]

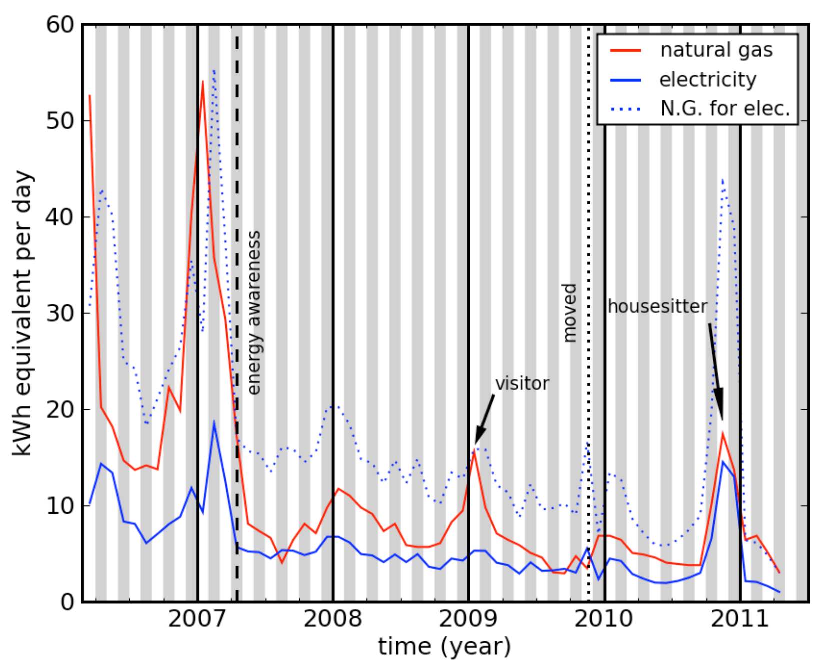

FIGURE 5. Usage of utility electricity and natural gas in my household across five years. The dashed vertical line indicates the moment at which I began paying attention to energy use. The dotted vertical line represents a move from a condominium to a house. The solid blue curve is electricity usage, and the dotted blue curve is the same thing multiplied by 3 to represent natural gas needed at the power plant to generate the electricity used. Note the difference in natural gas usage (red curve) between the summers of 2006 and 2007, due to the furnace pilot light! A visitor during January 2009 prompted us to resume heating the household temporarily, and a housesitter in the fall of 2010 produced another departure. Given the changes in awareness, household, and occupants during this time span, it becomes clear that the reduction is tied to *people* and *behaviors*, not the house itself

[2] An adjustment to the natural gas and utility usage was required to account for the presence of a housesitter during the past year, who, in a three-month period used 1043 kWh of electricity and 1250 kWh of gas. For these months, values were taken from the previous year.

Compared to our baseline performance in 2007–2008, we cut our gas usage by a factor of five, and our utility electricity usage by a factor of 4.5. Thus our domestic energy/carbon footprint (ignoring personal travel) was reduced by roughly a factor of five—counting the photovoltaic contribution as carbon-free. Actual electricity usage in the house—supplemented by PV—was reduced by a factor of 2.2, so that the total household energy went from 35 kWh/day to 9.8 kWh/day. Figure 5 illustrates our electricity and natural gas history through this transition.

What specific actions did we take to achieve this goal? Table 3 lists the various contributions, along with an estimate of the impact to average daily energy consumption.

TABLE 3. Household Energy Reduction Efforts.

Action	Source	Daily Saving (kWh)
Set Thermostat to 13°C (55°F)	Gas	15
Take less frequent showers	Gas	3
Take shorter showers, water off, mostly	Gas	2
Replace all incandescent bulbs with CFL	Elec.	1.5
Line dry clothes	Elec.	1
Be vigilant about turning unused devices off	Elec.	1
Swap refrigerator (75 W avg. → 37 W avg.)	Elec.	1
Disconnect large phantom loads	Elec.	0.5

Exporting Impact

Shaving demand at home is a direct and obvious way to reduce one's energy/carbon footprint. But consider that the total American energy diet consumes 3 TW continuously, amounting to 10 kW per person, on average. This totals 240 kWh/day per person and is far in excess of average household amounts. From before, we saw that the average American household uses 30 kWh of electricity and 35 kWh of natural gas per day. Assuming an average of three persons per household (300 million people in 115 households), and that every kWh of electricity delivered consumed 3 kWh in energy resources, the average American only expends about 42 kWh per day in domestic electricity and natural gas—only 17% of the total. In this light, working hard to shave domestic consumption may seem ineffective. But consider that:

- it is the sector over which we have the most direct control;
- the mentality of demand reduction at home propagates to external choices/behaviors;
- choices we make as consumers of domestic goods have an external impact.

So what other household decisions can have a big impact? Table 4 lists some possibilities (all of which are employed to some degree by me and my wife).

TABLE 4. Example Estimated External Reductions

Action	Estimated Daily Saving, averaged over year
Commute via public transportation	25 kWh per gallon of gas used in one round-trip
Decide against some air travel (even for work)	20 kWh per 10,000 miles avoided annually
Eat less meat	12 kWh vegetarian, 18 kWh vegan
Consolidate errands	5 kWh per gallon of gas avoided weekly
Refrain from buying luxury/unnecessary goods	2.5 kWh per $1000 avoided annually
Join a Community-Supported-Agriculture unit	2 kWh
Keep office lights off during the day	1 kWh

The numbers in Table 4 should not be taken as definitive, but rather suggestive. For this audience, it may be beneficial to illustrate the techniques employed to develop numbers for the table, so that readers can refine or apply similar quantitative analyses to suit personalized situations.

For automotive travel, we simply use the fact that each gallon of gas contains 36.6 kWh, and scale this to the frequency of the travel event. Conveniently, each yearly gallon used/saved corresponds to 0.1 kWh each day. Therefore, a commute occurring 250 days per year saves 25 kWh per day for each gallon that would be used for the round-trip commute. For air travel, a typical passenger jet gets 50 miles per gallon per passenger. Each 10,000 miles therefore consumes 200 gallons per passenger, so 20 kWh per day averaged over the year.

The impact of dietary choices on energy is a fascinating and rich topic. A 2002 study [4] concluded that agriculture accounts for 17% of fossil fuel use in the U.S. Since 85% of our individual 240 kWh/day net energy use derives from fossil fuels, we each expend 35 kWh/day on food. A 2100 kcal daily diet corresponds to 2.44 kWh/day, but overproduction and waste actually results in a per capita domestic food production (after subtracting exports) of about 3800 kcal daily, or 4.4 kWh/day. Immediately we see a factor of ten disparity in the amount of fossil fuel energy used compared to the energy content of the food that is produced/consumed. A study by Eshel and Martin in 2006 [5] evaluated the relative energy efficiencies of different dietary choices. The average American diet—consisting of 28% animal products (15% from meat, 13% from dairy and eggs)—consumes about twice as much fossil fuel energy to produce as does a vegetarian diet getting 15% of its calories from dairy and eggs. A vegan diet is better still (though perhaps not as easy), using about 20% of the fossil fuel energy that the average American diet uses in production. The energy efficiency of grains tends to be about ten times that of milk, chicken, and eggs, and about 40 times that of red meat and tuna [6]. But most of the energy is still expended on transport, refrigeration, and preparation. Modest assumptions lead me to guess that a vegetarian and vegan diet use 80% and 65% of these resources, respectively. The net effect is that a vegetarian diet in America uses about two-thirds the energy of the average diet, while a vegan diet may cut investment in food energy in half. Joining a CSA, and getting 500 kcal/day in vegetables might save something like 2000 kcal of fossil fuel energy per day, or about 2 kWh.

The estimated energy impact of consumer goods is very crude, and based on the estimate that 10% of an item's cost went into energy (mining, manufacture, distribution, etc.). This is in rough parity with our overall energy expenditure as a fraction of gross domestic product. Assuming an energy cost of \$0.1/kWh, \$1000 of purchased consumer goods in a year embodies about 1000 kWh, averaging to a little over 2.5 kWh per day. Buying used items is greatly facilitated by online tools, and is one of our primary tactics to relieve demand on the manufacture of new products.

Office lights are estimated to run at about 160 W (four 40 W fluorescent tubes), 8 hours per day for 250 days in the year.

Based on this table and the behavioral changes that I have adopted, I estimate a personal daily savings of approximately 60 kWh outside the home. This is about twice the impact that my wife and I have made on the household energy front.

THE NET EFFECT

Having reduced my household energy demand from 35 kWh/day to 7 kWh/day (not including the stand-alone PV contribution of 2.5 kWh/day), my personal saving is approximately 15 kWh/day on domestic energy—since these savings are shared by two people. By adopting a portfolio of the behavioral changes listed in Table 4, I estimate a personal reduction of 60 kWh/day. The combined effect is almost a third of the average American energy allocation of 240 kWh/day. It is rare to see efficiency gains of similar magnitude. To the extent that I was already a below-average energy consumer, the fractional gain may be even higher than stated, in my case.

Choices to reduce consumption can be difficult, and are indeed heretical to the growth-oriented narrative of our society. But the latter aspect is the key point. Only in the face of concern that growth is nearing physical limits does it make sense to modify our behaviors. To the extent that the limits are real, reduction may be our sharpest available tool. Voluntary reductions are far more palatable than mandatory reductions based on curtailed resource availability and associated unaffordability, and can also represent a fun challenge.

This article is intended to illustrate some examples for how reduction in energy demand might be accomplished, but should not be taken as a template to be copied. Each individual and situation will be different. A program of reduction is far more attractive if it is devised personally, and not handed down from some "authority."

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