America's New Calling

BY

Stephen R. Foster, J. Thomas Rogers, Robert S. Potter

Southwestern University
Georgetown, TX

Adviser:
Rick Denman

Abstract

The ongoing cell phone revolution warrants an examination of its energy impacts – past, present, and future. Thus, our model adheres to two requirements: it can evaluate energy use since 1990; and it is flexible enough to predict future energy needs.

Mathematically speaking, our model treats households as state machines and uses actual demographic data to guide state transitions. We produce national projections by simulating multiple households. Our bottom-up approach remains flexible, allowing us to: 1) model energy consumption for the current United States, 2) determine efficient phone adoption schemes in emerging nations, 3) assess the impact of wasteful practices, and 4) predict future energy needs.

We show that the exclusive adoption of landlines by an emerging nation would be more than twice as efficient as the exclusive adoption of cell phones. However, we also show that the elemination of certain wasteful practices can make cell phone adoption 175% more efficient at the national level. Furthermore, we give two forecasts of the current United States, revealing that a collaboration between cell phone users and manufacturers can result in savings of more than 3.9 billion Barrels of Oil Equivalent over the next 50 years.

Problem Background

In the year 1990, less than 3 percent of Americans owned cell phones [ITU]. Since then, a growing number of households have elected to ditch their landline in favor of acquiring cellular phones for each household member. Our task is to develop a model for analyzing how the cell phone revolution impacts electricity consumption at the national level.

Such a model ought be able to:

- Assess the energy cost of the cell phone revolution in America.
- Determine an efficient way of introducing phone service to an nation like America.
- Examine the effects of wasteful cell phone habits.
- Predict future energy needs of a nation (based on multiple growth scenarios.)

Assumptions

- The population of the United States is increasing at a rate of roughly 3.3 million people per year (according to the U.S. Census Bureau).
- The relatively stable energy needs of business landlines, government landlines, payphones, etc. have a negligible impact on energy consumption dynamics during the household transition from landlines to cell phones.
- No household member old enough to need phone service is ever without phone service.
- Citizens with more than one cell phone are rare enough to have a negligible energy impact.
- The energy consumption of the average cell phone remains constant.

We justify the last assumption on the grounds that future changes in cell phone energy requirements depend largely on changes in user habits and changes in manufacturing efficiency. Thus, they are difficult to predict. However, we drop this assumption in our final section.

Energy Consumption Model

Our approach involves three steps:

- We model households as state machines with various phones and appliances.
- We use demographic data to determine the probability of households changing state.
- By simulating multiple households, we extrapolate national energy impacts.

Households

The basic component of our model is the household. Each household has the following attributes:

- m : A number of members old enough to need a telephone.
- t : A number of landline telephones.
- c : A number of members with cellular phones.

The state of each household can be described in terms the above values. We will generate m from available demographic data and hold it constant.

A household can exist in one of four disjoint states at a time. Each state has two associated conditions.

- Initial State - When a household only uses landline telephones.
  - $t > 0$
  - $c = 0$
- Acquisition State - After a household acquires its first cell phone.
  - $t > 0$
  - $0 < c < \text{m}$
- Transition State - After all household members have their own cell phone but the landline is retained.
  - $t > 0$
  - $c = m$

- Final State - After the household abandons their landline telephones.
  - $t = 0$
  - $c = m$

These states are disjoint, but we do not assume that all states must be reached during the timeline of a household. We do assume that cell phones, once acquired, are never lost; and we assume that landlines, once dropped, are never readopted. Thus, a household will never reenter a state that it has left. Thus, a household will reach one or more of the above states in the order listed.

Suppose a household with three members ($m = 3$), one landline telephone ($t = 1$), and no cell phones yet ($c = 0$). The graph below shows the complete timeline of a hypothetical household with each of the four phases labeled.

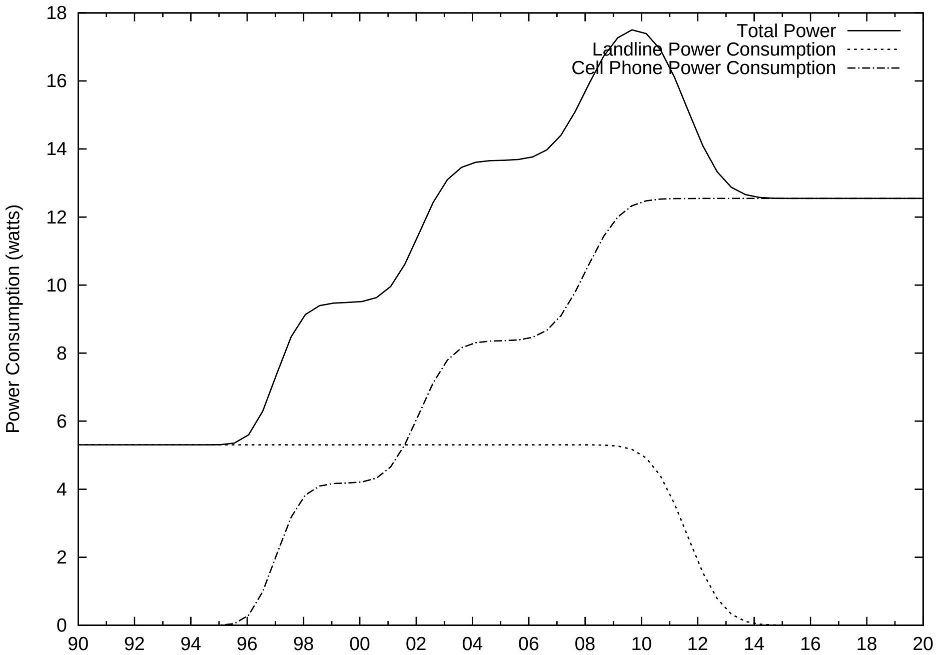

Figure 1.

Note that our model will generate household state transition probabilities from available demographic data. However, this process is simulation dependent; and we discuss it later, in the context of simulating the current United States.

Nations

Households are only part of the story. We model the national timeline during the country-wide transition from landlines to cell phones as a composition of multiple overlapping household timelines. Furthermore, the decisions that households make regarding when to acquire cell phones and when to abandon their landlines are dependent on the larger national context. For example, a household would be much more likely to acquire its second or third cell phone in 2008 than it would have been in 1990.

A hypothetical nation with only three households might have the following timeline composition:

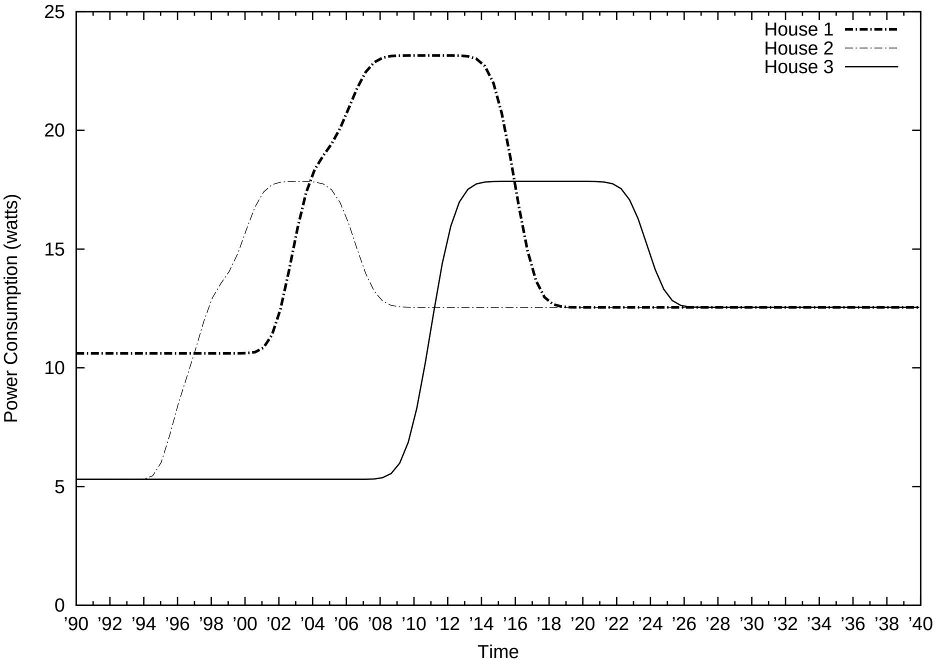

Figure 2.

The fact that the three household power usages converge is a result of there being 3 memebers in each of the three randomly selected houses monitored here. For every day, we aggregate the total rate of energy consumption for each household, generating a national timeline like so:

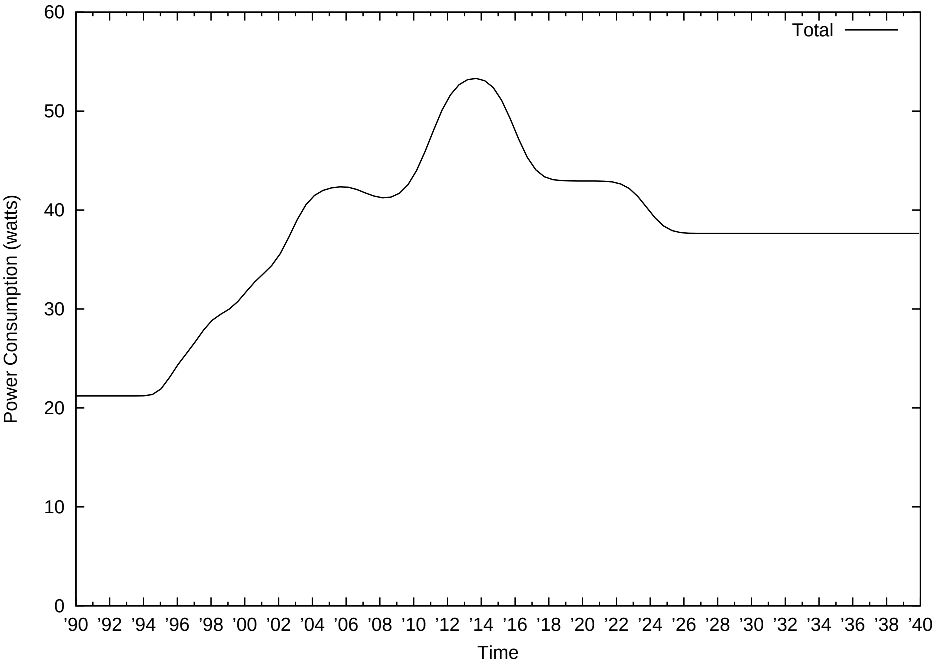

Figure 3.

We now proceed to construct such a timeline for the current United States.

The Current U.S.

Using Technological Data

In order to use our model in conjunction with relevant data, we have to calculate the following values:

- C_{wattage} : The average rate of energy consumption of a cell phone over its lifetime.
- L_{Wattage} : The average rate of energy consumption of a landline phone over its lifetime.

Note that we only deal with cordless landline phones because corded phones use minimal levels of energy and are ignored in the literature we have reviewed (Frey, Rosen, and Watts).

We derive C_{wattage} as follows:

$$C_{\text{wattage}} = \text{Charger}_{\text{wattage}} + \left(\frac{C_{\text{upfront}}\,(\text{joules})}{C_{\text{lifetime}}\,(\text{seconds})} \right) \tag{1}$$

With this formula, we incorporate the upfront energy cost in joules of manufacturing a cell phone (C_{upfront}) into the overall average wattage of a cell phone by dividing the upfront cost by the lifetime of a cell phone (C_{lifetime}) in seconds. We add to this the wattage of the average cell phone charger – which is what consumes energy during the use-phase of a cell phone's life cycle. (Note: The vast majority of cell phone energy consumption occurs in the manufacturing-phase and the use-phase [Frey], so we ignore the rest of a cell phone's life cycle.)

By analogy:

$$L_{\text{wattage}} = \text{Cordless}_{\text{wattage}} + \left(\frac{L_{\text{upfront}}\,(\text{joules})}{L_{\text{lifetime}}\,(\text{seconds})} \right) \tag{2}$$

The following table lists values obtained from research done by Frey et al..

C_{upfront}	=	148 MJ
C_{lifetime}	=	2 years
$\text{Charger}_{\text{wattage}}$	=	1.835 watts

Table 1.

Though there exist many different kinds of cordless phones, we choose to use the values for cordless phones with integrated answering machines, as determined by Rosen.

L_{upfront}	=	167 MJ
L_{lifetime}	=	3 years
$\text{Cordless}_{\text{wattage}}$	=	3.539 watts

Table 2.

Thus, our simulation uses the following values:

- $C_{\text{wattage}} = 4.182$ watts
- $L_{\text{wattage}} = 5.304$ watts

Using Demographic Data

We need demographic data to help guide the transition of household states over the course of a simulation. We could allow houses to decide randomly when and whether to adopt new cell phones as well as when and whether to drop their landline. However, we prefer to use actual penetration data to probabilistically weight household decisions.

Consider the household decision of whether to purchase a cell phone in month M. We use a three-step process to produce the cell phone acquisition probability function $a(M)$ employed in our simulation:

- Find historic data about the number of of cell phone owners over time.
- Interpolate between the data points.
- Define $a(M)$, the probability of a simulated household acquiring a cell phone in month M.

For step one, we used the following data obtained from the International Telecommunication Union. In step two, we use a linear interpolation between available data points to make a continuous function from 1990 (the start of our simulation) to 2009.

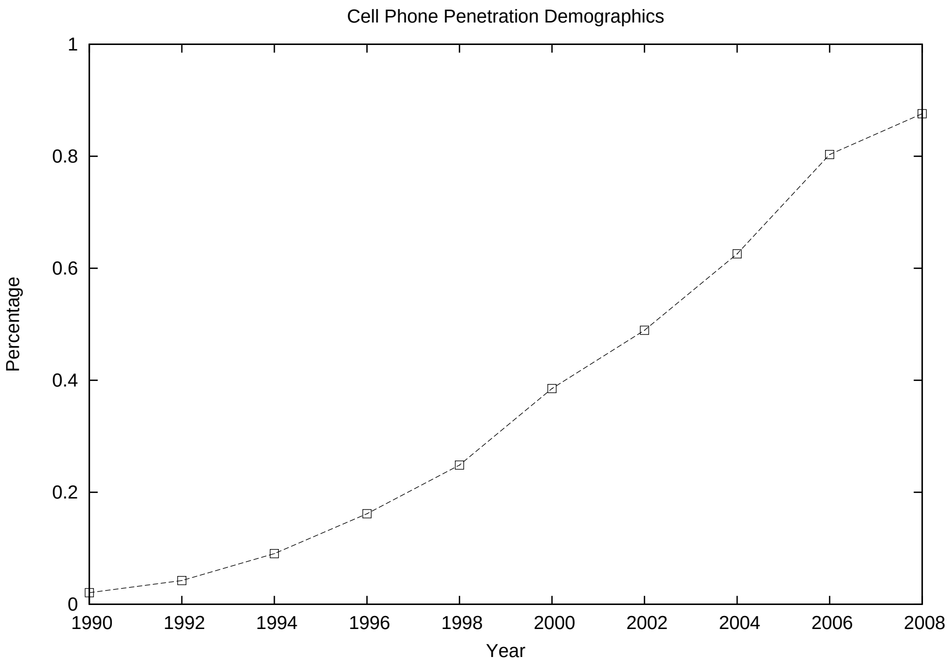

Figure 4.

Then, we use a linear regression to extrapolate the function between 2009 and 2040. Call this function f. Then, for step three,

$$a(M) = f(M) - \left(\frac{\displaystyle\sum_{H \in \text{Houses}} c(H, M)}{\displaystyle\sum_{H \in \text{Houses}} m(H, M)} \right) \tag{3}$$

Where $c(H, M)$ is the number of cell phones owned by members of simulated household H in month M; and $m(H, M)$ is the number of members in simulated household H in month M; and 'Houses' is the set of all households in the simulation. In essence, Equation 3 subtracts the current simulated cell phone penetration during month M from the approximated market penetration, $f(M)$, which is derived from available data.

Using $a(M)$, the households in our simulation make decisions that approximate historical data. As the second term in Equation 3 approaches the historical value returned by $f(M)$, the chances of a simulated household buying a cell phone decreases to zero.

We perform an almost identical process with historic landline ownership data in order to determine the probability of a household dropping their landline in month M. Because the process is the same, we omit it. Mnemonically, however: $a(M)$ shall be the probability of acquiring a cell phone; $d(M)$ shall be the probability of dropping a landline.

Simulating the Current U.S.

The historical demographic data will help guide our simulation, and the technological data will help us calculate the rate of energy consumption at any point during the simulation. With that said, we algorithmically generate household timelines like so:

```
While month M is before end date

  For every house H ∈ Houses do
    if H is in 'initial' or 'acquisition' state
      get a new cell phone with probability a(M)
    if H is in 'transition' state
      get rid of landline with probability d(M)
  End For

  Calculate power consumption using C_wattage, L_wattage, and current phone ownership.

  Let M = M + 1 month
end while
```

Here is the national timeline detailing the rate of energy consumption for the current United States over the past nineteen years.

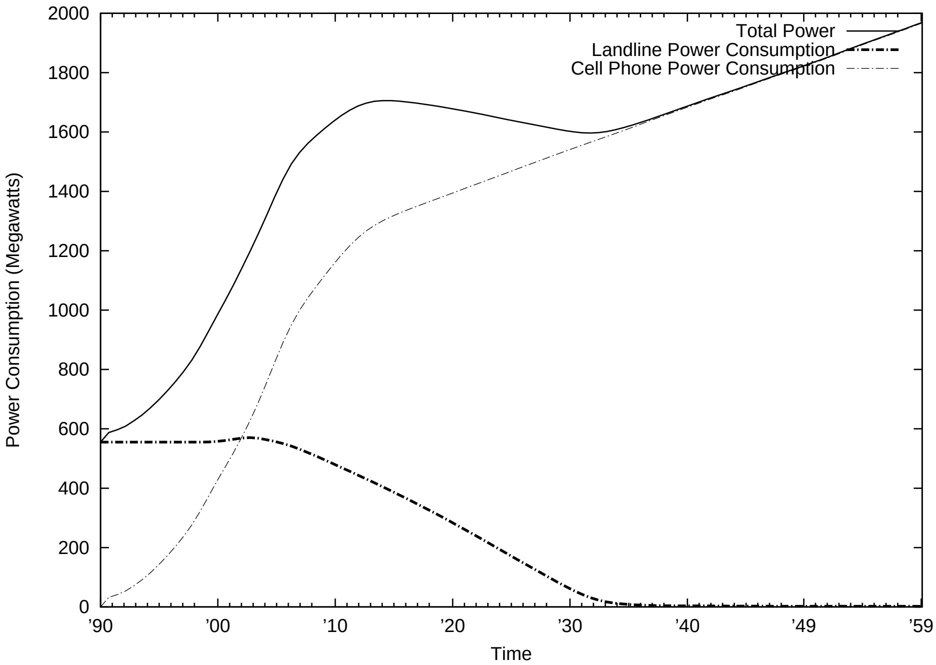

Figure 5.

Interesting features of this graph are:

- The steep energy consumption as Americans acquire cell phones yet retain their landlines.
- The drop after cell phone penetration slows and landlines are abandoned.
- The rising slope after households have dropped their landlines and the population grows.

At first, most households tend to be in an Acquisition State, having both landlines and an increasing number of cell phones. Next, households begin to progress to a Transition State, slowly dropping their landlines while retaining their cell phones – hence, the overall consumption drop. The final upward slope represents the steady state, in which population growth (and associated cell phone acquisition) is the only factor affecting energy consumption.

Optimal Telephone Adoption

Imagine an emerging nation without phone service but with an economic status roughly similar to the current United States. We now examine two hypothetical scenarios for introducing phone service to this nation:

- Cell phones Only
- Landlines Only

Because it took Russia roughly 6 years for cell phone penetration to go from 2 percent to 105 percent [ITU], we assume a similar timescale for introducing cell phones to our hypothetical nation. Furthermore, a country with the same economic status as the U.S. should be capable of making a similarly quick adoption of either cell phones or landline phones, even though landline phone infrastructure involves the extra complexity of laying cables.

Cell Phones Only

For our cell phone introduction plan, we assume that 0 percent of the population in 2009 has been given cell phones and that 100 percent of the population in 2015 has been given a cell phone. If we interpolate linearly between these two dates, we can derive the number of people that will be given a cell phone in any month during the 6 year period. If we assume that the rate at which cell phones consume energy remains roughly the same between 2009 and 2015, then we have all the information we need to run our simulation.

The only major change we make to our model is that the Initial State of a household now involves having no phones at all, and the Final State involves each household member owning a cell phone.

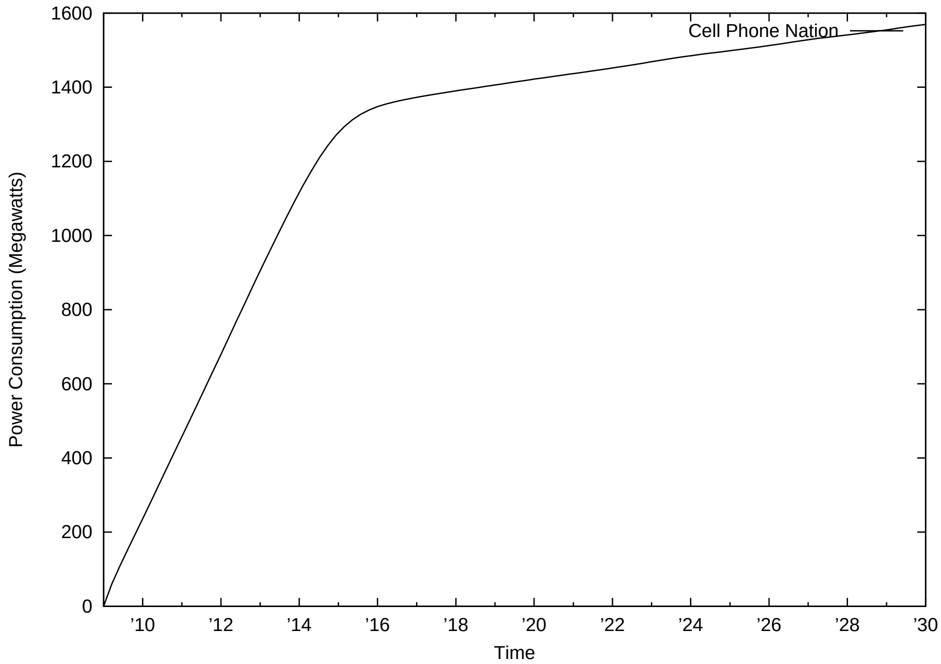

Figure 6.

The steep slope levels off when cell phone market penetration reaches 100 percent, and the only relevant factor after that is the population growth.

Landlines Only

Now we alter our model such that the Initial State of a household still involves having no phones, and the Final State involves having one landline. We take the previous graph and overlay a graph generated from a simulation that assumes the nation's households will adopt landlines instead of cell phones.

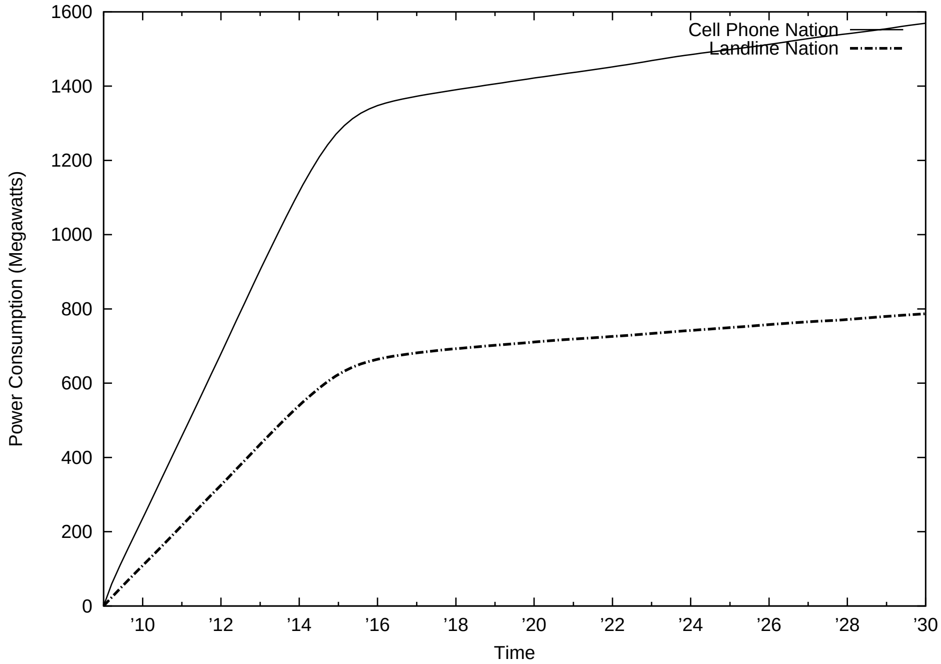

Figure 7.

Based solely on this graph, the Landlines Only plan seems optimal, since it requires less than half the power of the Cell Phones Only plan. However, we prefer to delay our recommendation. First, we examine a way to make cell phone adoption more energy efficient.

Wasteful Charging and "Vampire" Chargers

Although the above comparative analysis of the two plans shows Landlines Only to be a clear winner, we should take into account that the rate at which cell phones consume energy varies depending on the practices of cell phone users. Until now, we have assumed that the energy consumption of a cell phone is equal to the consumption of its charger – even though many people do not use their charger as conservatively as they could. We now relax this assumption and assess the total cost of certain wasteful practices by supposing that our hypothetical nation's citizens never

- charge a cell phone after it is finished charging.

- leave their charger plugged in when not charging it.

The value for C_{wattage} that we calculated earlier was based on Frey's assumption that cell phone chargers spend their lifetimes plugged in – mostly in standby (vampire) mode. We now derive a new value for C_{wattage} based on a different study by Roth and McKenney, which shows that the average cell phone only needs to spend a minimum 256 hours charging per year. In short, we make C_{wattage} dependent strictly on its minimum battery requirements and assume that users only charge their phones enough to keep them charged for the entire day. Roth also suggests that chargers require 3.7 watts when charging.

$$C'_{\text{wattage}} = \text{Battery}_{\text{wattage}} + \left(\frac{C_{\text{upfront}}\,(\text{joules})}{C_{\text{lifetime}}\,(\text{seconds})} \right) \tag{4}$$

$$\text{Battery}_{\text{wattage}} = \frac{\text{Time Spent Charging}}{\text{Lifetime}} \times \text{Wattage When Charging} \tag{5}$$

Thus, $\text{Battery}_{\text{wattage}} = \frac{256\,(\text{hours})}{8760\,(\text{hours})} \times 3.7$ watts $= 0.108$ watts. The second term in Equation 4 is the same as in Equation 1. So,

- $C'_{\text{wattage}} = 2.455$ watts.

Recall that our previous value was

- $C_{\text{wattage}} = 4.182$ watts.

We now show the effects of this new, lower energy expenditure on the simulation. Also pictured is our previous analysis of the phone adoption timeline in the hypothetical nation.

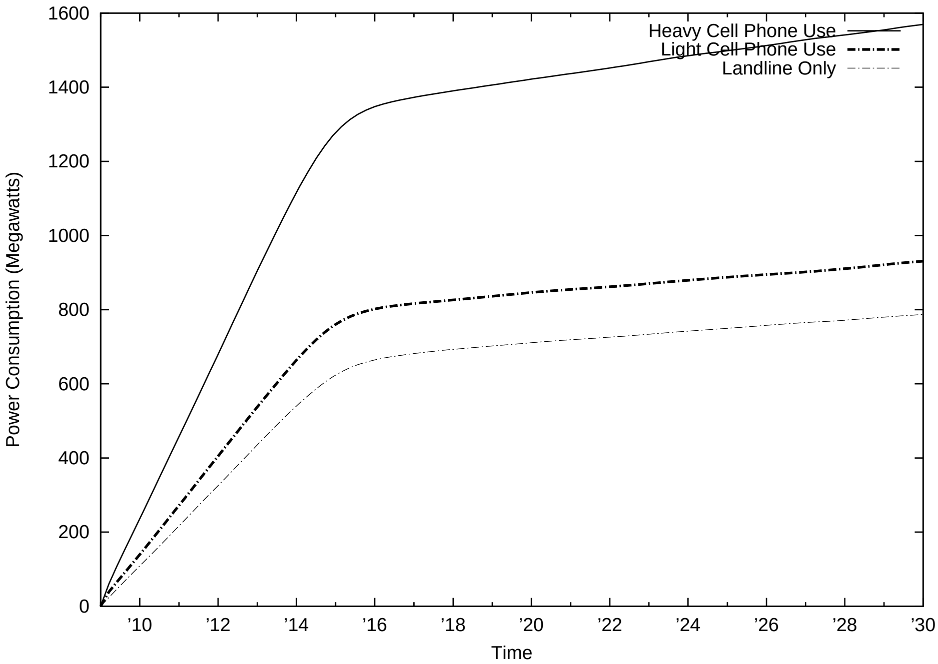

Figure 8.

The following graph shows the amount of energy wasted each month by vampire charging in Barrels of Oil Equivalent (BOE).

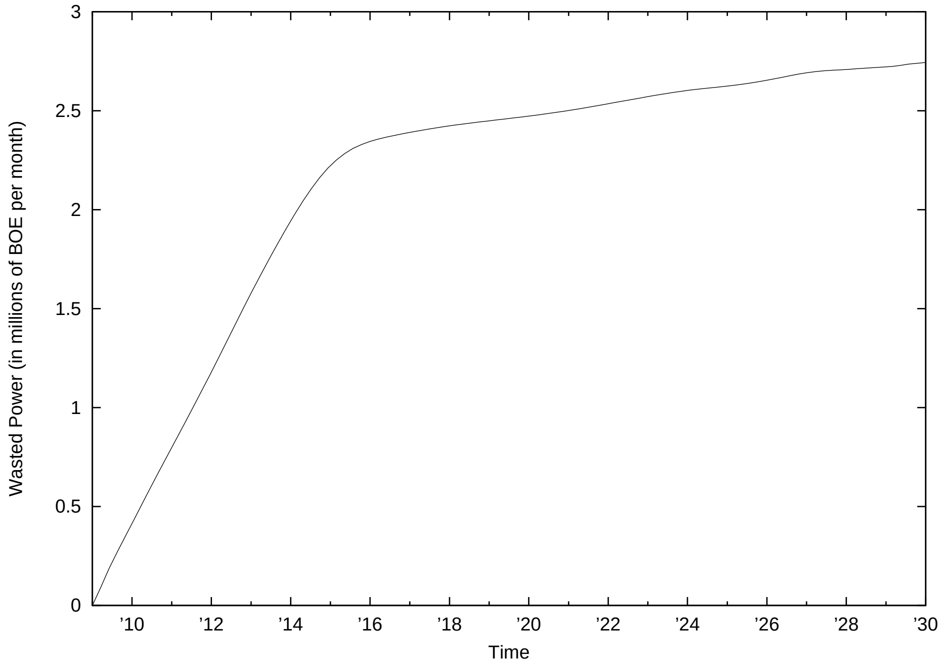

Figure 9.

By eliminating vampire charging, this power can be conserved, resulting in 175% more efficient energy consumption.

Other Household Appliances

Generalizing our previous analysis, we now assume that households do not simply use cell phones and/or landlines. They also each have the following common appliances:

- Zero or one computer (50 percent having a computer [census.gov 2]).
- Zero or one DVD player (84 percent having a DVD player [neilsenmedia.com]).
- Two or three televisions [neilsenmedia.com]

We selected these appliances because they are responsible for a significant amount of household energy consumption [Floyd]. We derive the "vampire" energy leakage from these appliances from various sources

Computer	2.63 watts	[Roth]
DVD Player	3.64 watts	[Roth]
Television	6.53 watts	[Floyd]

Table 3.

The graph of a single household might look like this, then:

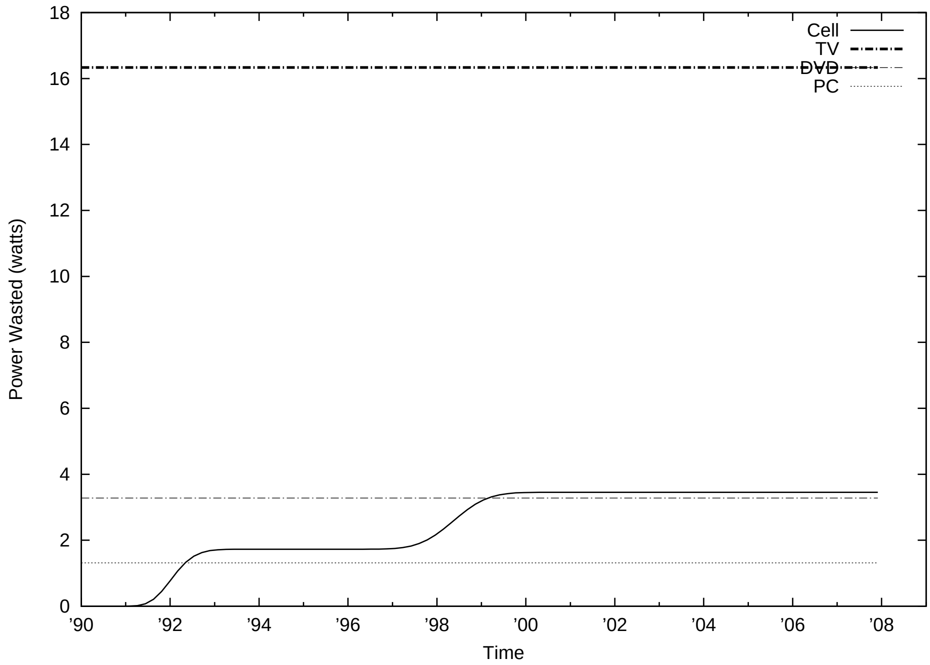

Figure 10.

We now graph our hypothetical nation's wasted power, interpreted in Barrels of Oil Equivalent.

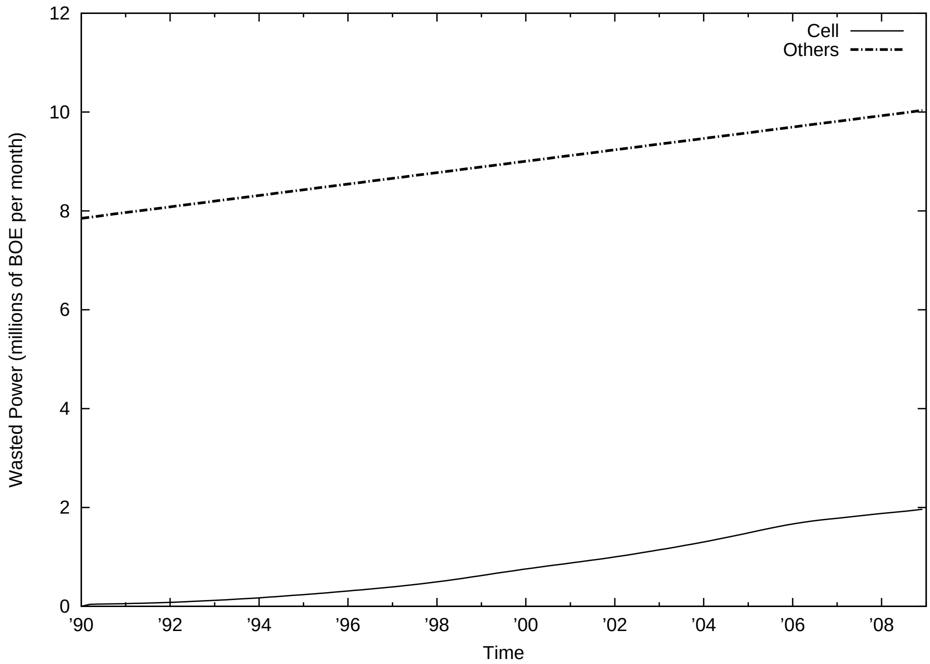

Figure 11.

Clearly, then, telephone-related energy loss is a significant contributor to the overall energy consumed by the U.S.. However, there exist electrical appliances that have a larger impact.

Predictions

Here we tie our previous work together into a predictive simulation that investigates the energy impact of the following eventualities:

- Cell phone efficiency stays the same.
- Cell phone efficiency decreases (i.e. with the introduction of smartphones.)
- People save 50 percent of energy currently lost to "vampire" charging.
- People do not stop "vampire" charging.

In all cases the population of the nation is assumed to grow at a rate of about 3 million people per year – a rate comparable to that of the current United States.

Optimistic Prediction

For our optimistic prediction, we assume that cell phone energy requirements continue to remain constant with each successive generation of cell phones. We also assume that the population manages to eliminate 50 percent of its energy consumption due to "vampire" charging.

Recall that our best case value for the use-phase energy consumption of a cell phone (i.e. no vampire charging) was:

$$\text{Battery}_{\text{wattage}} = 0.108 \text{ watts}$$

And our worst case scenario (i.e. a charger that is always plugged in) was:

$$\text{Charger}_{\text{wattage}} = 1.835 \text{ watts}$$

We now choose a use-phase value half-way between $\text{Charger}_{\text{wattage}}$ and $\text{Battery}_{\text{wattage}}$.

$$\text{Realistic}_{\text{wattage}} = 0.9715 \text{ watts}$$

As in Equations 1 and 4, we add this to the manufacturing phase energy cost to obtain an optimistic (but not too optimistic) average cell phone wattage. With this value, we graph the rate of energy consumption over the next 50 years.

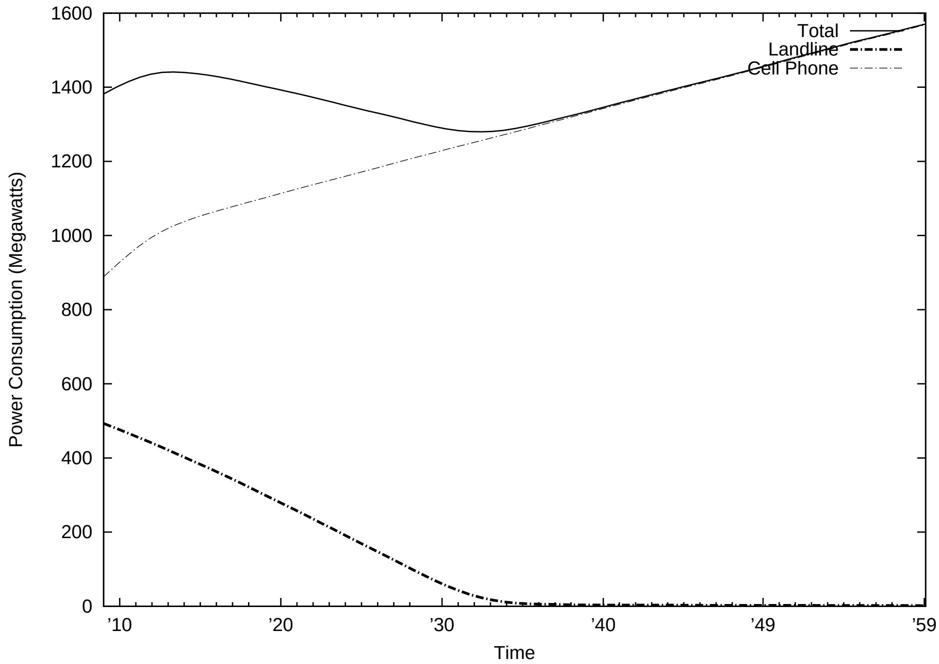

Figure 12.

As can be seen, landline telephone usage still contributes significantly to the total power consumption of the nation until the year 2030. The cell phone power consumption trend may not be meaningful until looked at alongside the pessimistic prediction.

Pessimistic Prediction

We assume here that cell phone energy requirements increase with each successive generation of cell phones at a rate comparable to the increase from regular cell phones to smartphones. In short, we are modeling the transition from landlines to cell phones to smartphones. We also assume that the population does not manage to avoid "vampire" energy loss.

Because smartphone technology exists in a state of relative infancy, technical information about it is scarce. Thus, we make an estimate of the average wattage of a smartphone based on the fact that for all tasks (emailing, text messaging, idling, etc.) a smartphone requires more than twice as much power than a regular cell phone [Mayo]. Endeavoring to be conservative, we assume that smartphone manufacturing costs are the same as cellphones, even though they are likely much higher. Thus, we borrow most values from Equation 1 to calculate average smartphone wattage:

$$S_{\text{wattage}} = 2 \times \text{Charger}_{\text{wattage}} + \left(\frac{C_{\text{upfront}}\,(\text{joules})}{C_{\text{lifetime}}\,(\text{seconds})} \right) \tag{6}$$

With $S_{\text{wattage}} = 6.017$ watts, and smartphones becoming widespread at around 2025, we are ready to make our comparison.

Comparison

The two predictive scenarios above are represented together in the graph below. Only the nation's total power consumption is graphed.

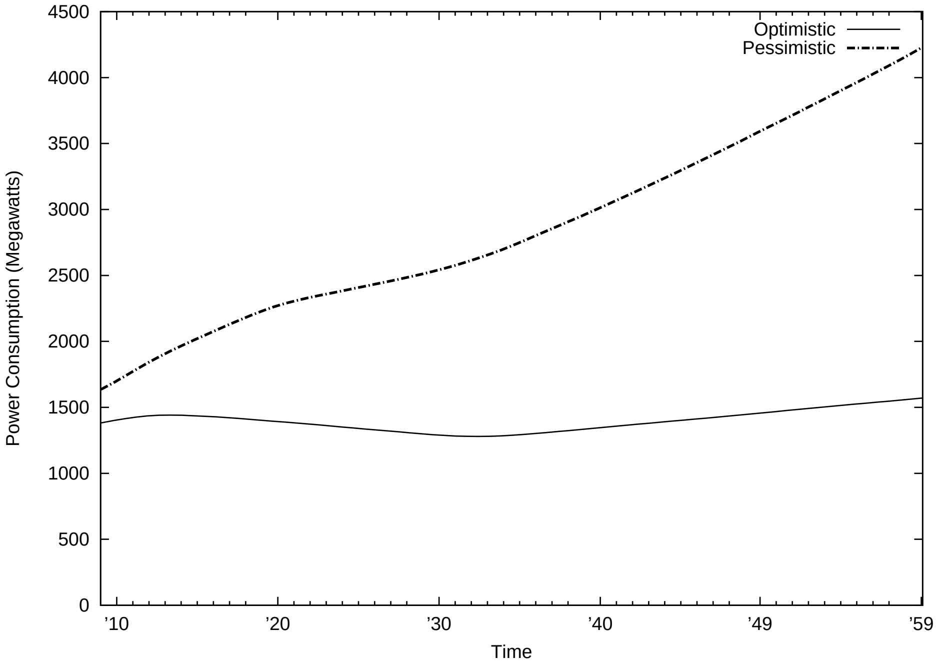

Figure 13.

It goes without saying that our model leads us to recommend the adoption of conservative practices (on the part of cell phone users) and research into greater phone efficiency (on the part of cell phone manufacturers). A 50% reduction in vampire phone chargine and a dedication to energy efficient phones, according to our simulation, would result in the conservation of 3.9 billion Barrels of Oil Equivalent over the next 50 years. And it is worth noting that even our pessimistic scenario is not as pessimistic as it could be, since we chose a deliberately low value for the energy cost of smartphones. And our optimistic scenario is not as optimistic as it could be, since we assumed only a 50 percent reduction in vampire energy losses.

Conclusion

Modeling the cell phone revolution can benefit from a bottom-up approach. The basic components of this approach are households undergoing a series of transitions such that each of their members acquires a cell phone and, eventually, the household abandons their landline.

For the emerging nation adopting a new telephone system, we found that landline adoption would be twice as efficient as cell phone adoption. However, if the nation enforces conservative cell phone energy use, the cell phone plan can be almost comparable to the landline plan.

Also, our model is capable of showing a vast divergence between an optimistic future scenario and a pessimistic one. This being the case, we must recommend a concerted energy conservation effort on the part of cell phone makers and cell phone consumers. Doing so would result in savings of over 3.9 billion Barrels of Oil Equivalent over the next 50 years.

Strengths & Weaknesses

Strengths

- **Uses Demographics**. Our model simulates the decisions of households based on historic data, making it a good model for assessing the energy consumed to-date.

- **Incorporates Manufacturing**. We incorporate the energy cost of a phone's manufacturing-phase into the phone's use-phase wattage, thereby increasing the simplicity of our model without ignoring the significant energy consumption during manufacturing.

- **Retains Flexibility**. Because our model is a bottom-up approach, various details at the household level can easily be incorporated into national simulations. We did this, for example, to assess the cost of "vampire" chargers and to assess the cost of non-telephonic appliances.

Weaknesses

- **Ignores Infrastructure.** We do not examine the energy cost of cellular infrastructure (towers, base stations, servers, etc.) as compared to the energy cost of landline infrastructure (i.e. telephone lines and switchboards.)

- **Extrapolates Naively**. Though we use demographic data to guide household decisions before 2009, we use simple regression techniques to forecast future demographic information. Using better forecasts would make predictions more accurate. A list of data we extrapolated are: cell phone energy-use changes, cell phone penetration dynamics, and landline abandonment rates.

- **Simplifies Households.** Our model doesn't examine all household member dynamics – i.e. members getting born, growing old enough to need cell phones, moving out, starting households of their own, etc.

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