ABSTRACT
Now more than ever there is a need for orchestrating the supply and demand-side of Utility-provided services such as Electricity, Gas, and Water. In real-time supply & demand side management, a variable price for service is sent from Utilities’ SUPPLY-SIDE via the Internet to the DEMAND-SIDE, such as to appliances in homes, to search for and encourage or discourage use and thus manage demand for Utility services. Demand is managed in aggregate across all users, not just at peak times, but rather throughout the day as capacity is needed or otherwise becomes available. There are three benefits: 1) traditional fossil-fuelled electrical capacity can operate less of the time and more efficiently, 2) renewable electrical capacity such as wind and solar power can be more efficiently put to immediate use right when it becomes available, and 3) additional means are available to protect Utilities’ transmission and distribution infrastructure. A critical requirement is that pricing changes often enough throughout the day so that budget-conscious and less fortunate consumers do not have to wait long for favourable pricing in order to cook a meal or otherwise get things done.

KEY WORDS
Networks, Electric, Utility, Supply and Demand Side Management

1. Introduction
Of the 1.7 billion homes in the world approximately 270 million or 16% currently have broadband Internet service. And some areas of the world are very highly penetrated by broadband. For example, in the United States nearly 60% of the homes have broadband and in Europe nearly 30%. These numbers are on the rise as evidenced by world-wide Cable Modem penetration growing from 21% from the third quarter of 2005 to the third quarter of 2006. Wide-area wireless penetration is growing even faster. There is no stopping this trend; much of our world, our laptops, PDAs and iPods are being hooked up to the Internet, and before long our home appliances will be on the ‘Net, too!

Broadband will provide a persistent ‘always on’ Internet Protocol (IP) connection between homes and Electric, Gas and Water Utilities. This persistent IP connection allows fluctuations on the SUPPLY-SIDE, for example from wind or solar power, to be accommodated on the DEMAND-SIDE by using thermal storage in hot water heaters and refrigerators as well as by deferring (or encouraging) discretionary loads such as dishwashers, clothes washers, clothes dryers, swimming pool pumps, etc. In short, a variable energy pricing signal will be continually broadcast in REAL-TIME through the Internet and in-home networks in search of smart appliances to encourage or discourage use (demand) in the home.

The ability to encourage or discourage use in the home will have a profound effect on utility generation and distribution. Imagine using weather forecasts, not just to decide when to bring a fossil-fuel generator off-line for maintenance, but to actually schedule energy usage during periods of high and low energy production from wind and sunshine. Imagine encouraging usage when the wind is blowing or the sun is shining. Conversely, imagine creating pent up demand and in so doing forestalling the spinning up and bringing online of ‘swing’ or peak generation facilities. And once such facilities are brought online, imagine being able to ramp up demand quickly so that the generator quickly approaches near its maximum output and in so doing operates at its greatest efficiency. Or imagine that a generator is kept at a constant output to reduce costly maintenance and rebuilding due to increased wear and tear during generator warm-up and cool-down. Lastly, imagine the real-time ability to protect and stabilize electric, gas and water distribution networks when transmission circuits or pipelines fail or become overloaded.

2. Supply and Demand
Examples in the remainder of this paper deal largely with electrical supply and demand, though similar opportunities exist for water & natural gas utilities, especially in transmission and distribution.
2.1 Supply-Side
Considering the SUPPLY-SIDE, generation of electricity is responsible for approximately 1/3 to 1/2 of primary energy consumption. For example, of all the energy consumed in New York State in 2005, 38% was used for the generation of electricity. Increasing efficiency of electrical generation will reduce overall fuel consumption, forestall building of new power plants, and have a positive impact on reducing greenhouse gases.

Exploring how energy is converted to generate electricity, Figure 1 shows typical United States Electrical Energy Production ‘Supply-Side’ Statistics.

![Pie chart showing energy sources in the US](image)

**Figure 1. Typical United States Electrical Energy Production ‘Supply-Side’ Statistics**

Notice the relatively small contribution of renewable energy in the United States shown in Figure 1. In contrast, wind power is responsible for nearly 30% of the total Danish demand for electricity and approximately 16% of Germany’s demand. To put this in perspective, wind power alone covers the aggregate demand of 1.4 million Danish homes, or in other words, the entire energy demand of western Denmark. The state of Texas also has significant wind power production and is the largest producer of wind energy in the United States.

Wind power production is expected to more than double in the next four years as shown in Figure 2.

![Bar chart showing world wind energy](image)

**Figure 2. World Wind Energy Total Installed Capacity (MW) and Prediction**

While efforts to foster increased production from renewable resources such as wind and solar are much needed and welcome, there is a growing problem of how to search for uses of (demands for) renewable energy right when it becomes available. As a result, countries such as Denmark have reached an upper limit and have begun or soon will limit production of renewable energy!

2.2 Demand-Side
The IP network will be used to communicate the availability (i.e., price) of SUPPLY-SIDE generation capacity so that the DEMAND-SIDE can utilize generation resources in the most fuel efficient and environmentally friendly ways.

To estimate the variable storage capacity of the DEMAND-SIDE, consider the various uses of energy in the home shown in Figure 3.

![Pie chart showing energy usage in US homes](image)

**Figure 3. Energy Usage in US Homes**

Some energy uses in the home such as lighting are required based on what users are doing, others are not. For example, encouraging or deferring water heating and refrigeration will have a significant positive impact on electrical demand without compromising the needs of users. And the ability will exist to schedule efficient generation for pre-cooling or pre-heating of living spaces, for example to cool millions of homes in southern climates before the occupants return on a summer evening, or heat homes in northern climates in anticipation of the workforce returning.

The methods presented here are hoped to be a significant extension to enhance prior work on load shifting and load curtailment. Much of the previous work has focused on shifting peak demand into the traditional diurnal valley so that a flatter demand curve results in lower requirements (and costs) for peak generation facilities. Such peak shifting is often achieved by creating a high pricing signal once a day during peak. In this peak-shifting scenario, every day at the same time peak pricing goes into effect which discourages usage. However, those users who can afford to pay peak pricing can choose to use as much as they want when they want, and may choose not to participate in load management at all.

While a more expensive price of energy might help curtail demand by users during peak, an extremely important
question is what is the impact on the less-fortunate and budget conscious users? A terrible negative effect of traditional peak pricing is that poor people simply cannot afford to use energy during peak. Waiting until 2:00 AM for the dishwasher to automatically start is a good thing, but would you like to wait until 2:00 AM when the price of energy is low enough to, say, cook dinner?

Extending prior work, the method proposed in this paper is to change the price of energy to encourage or discourage use many (many) times throughout the day, perhaps as many as 8 - 10 times, in predictable ways. The key is to vary pricing enough so that demand truly is responsive, while considering the needs and budgets of all consumers.

3. A Simple Supply and Demand Model

To illustrate efficient coordination between the SUPPLY-SIDE and DEMAND-SIDE, consider the simplified model of generation supply capacity shown in Figure 4 where each horizontal band is one or more ‘chunks’ of supply capacity.

Superimposing the simplified supply and demand models in Figure 6 illustrates how the supply side operates throughout the day in order to meet the aggregate energy demand across large serving areas.

Note that supply must always exceed demand—that there must always be spinning reserve generating capacity to meet unexpected demands and cover for generation or distribution failures.

The ‘stair steps’ in Figure 6 correspond to generators being brought on-line and off-line (i.e., starting up and shutting down) throughout the day as aggregate demand rises and falls.

4. Orchestrating Supply and Demand

The aggregate demand curve shown in Figures 5 and 6 has predictability—it rises and falls with smoothness throughout the day. It has Markovian-like behavior in that the next day’s demand is predictable; demand will be similar to the previous day, with exceptions due to weather (particularly temperature swings that affect heating and cooling demands), weekdays versus weekend days, holidays, etc.

However, when a real time pricing signal is sent in search of hot water heaters, refrigerators and other appliances in the home, aggregate demand can be much more controlled, yielding a stair-stepped DEMAND-SIDE characteristic that is forced to ‘follow’ (or accommodate) the stair-stepped SUPPLY-SIDE capacity as shown in Figure 7.
In Figure 7 the overall energy usage (i.e., the integral or area under the curve) is very similar to that shown Figure 6. While the pricing signal might or might not discourage overall usage in a 24 hour day, it definitely does discourage and encourage energy use at several times throughout the day. This is done to forestall bringing generating capacity online and then once brought online to move said capacity to its maximum output and efficiency as quickly as possible.

The duration of time that a facility might be forestalled in coming online might be from few to tens of minutes. The ability to delay the start of such a facility and then within minutes to bring it to near its maximum output has a significant fuel and environmental savings. Certainly some types of generators can come on-line and off-line more quickly than others, gas turbines being the most agile and perhaps nuclear plants being the least. And as previously stated there must be sufficient spinning reserve at all times.

4.1 Hot Water Storage

To estimate the energy storage capability of the DEMAND-SIDE, first consider the duty cycle of a residential Hot Water Heater shown in Figure 8.

Starting at the left side of Figure 8 there is a decline in water temperature from an upper limit of approximately 110° down to 95° over the period from near midnight to approximately 6:00 AM. The relatively constant slope of the temperature line over this period indicates that no water has been drawn from the tank. At 6:00 AM the water heater fires for a short duration to bring the output temperature back up from its lower limit, and fires again around 8:00 AM to accommodate the demand for hot water being drawn from the tank. Perhaps someone took a shower or did some laundry and/or dishes.

Zooming in on a six hour period suggests that the firing cycle (when hot water is not being drawn) is approximately 30 minutes in duration as shown in Figure 9.

Considering there are approximately 110 Million homes in the United States, roughly 11 million hot water heaters are firing around the clock, with even more expected to be firing before the morning rush hour and after the evening rush hour.

If 1/3 of the 11 million hot water heaters in the U.S. are electrically fired, then at least 3.7 million electric hot water heaters can be managed at any given point in time. Given that the typical electric hot water heater has a 4.5 kW demand when firing, the aggregate electrical demand of heating hot water is 16.5 GW (gigawatts) as indicated in Equation 1. This is a large amount of demand; representing approximately 22% of the 73.9 GW of worldwide electrical supply from wind power at the end of 2006.

$$\sum \text{WaterHeaters} \times 10\% \text{DutyCycle} \times 33\% \text{ElectricFired} \times 4.5kW$$

The storage Capacity of refrigerators is significant, especially in hot climates. For example, Florida's hot and humid climate challenges even the best refrigerators. Not surprisingly, refrigerators guzzle a lot of electricity in

**4.2 Refrigeration Energy Storage**

The storage Capacity of refrigerators is significant, especially in hot climates. For example, Florida's hot and humid climate challenges even the best refrigerators. Not surprisingly, refrigerators guzzle a lot of electricity in
Florida (on average about 200 Watts each). With roughly 7 million refrigerators in the state, the average demand of these units exceeds 1 GW. Over 25% of these refrigerators are old and inefficient—built before the advent of recent appliance efficiency standards. About 5% of them are replaced each year\textsuperscript{xi}.

The best estimate of the duty cycle for all properly working ‘Energy Star’ refrigerators is about 50\%\textsuperscript{xii}. Auto defrost models have a secondary duty cycle which amounts to about 10 minutes operation over a 18-36 hour period. This cycle draws a large amount of energy during that time, but compared to the compressor operation, impact on load is negligible.

Again, it is important to note that at almost any time, an expensive or inexpensive price of electricity could have been sufficient incentive for refrigerators to delay or accelerate compressor operation by 10 or more minutes without having a noticeable impact on food temperature or longevity.

If 7 million Florida refrigerators produce an average demand of 1 GW and northern-climate refrigerators use less energy, it is estimated that the 110 million refrigerators in the United States produce an average demand of \textasciitilde15GW, or nearly 20\% of the 73.9 GW worldwide electrical supply from wind power at the end of 2006.

Advancements in refrigerator technology will yield two-speed or variable-speed ‘always on’ compressors that will be managed similarly. Refrigerators will be encouraged to shift from low to high-speed, or vice versa, based on real-time energy prices.

5. Conclusion

The magnitude of demand that can be managed using real-time pricing is quantifiable and significant. Together, United States Residential Electric Hot Water Heaters and Refrigerators produce an average demand equivalent to approximately 40 – 45\% of the worldwide electrical supply from wind power at the end of 2006.

The opportunities to orchestrate supply and demand are very real. There are significant advantages in reducing burning of fossil-fuels, emissions of pollutants, and forestalling the building of new power plants. And there is the possibility that renewable resources such as Solar and Wind Power can search for and create demand in real-time and hence be used more extensively and efficiently.

Limitations to be overcome include the development of in-building energy controllers, Internet Protocol interfaces for appliances, and sensible appliance control algorithms to react appropriately to real-time pricing signals.

The examples provided were specific to electric utilities, though real-time control of demand will have benefit for the transmission and distribution infrastructures of electric, gas and water utilities.

Suggestions for Future Work

In time, the ‘search’ universe will be expanded well beyond utilities’ price signals that are sent out in search of smart appliances. In a much more all-encompassing way, the DEMAND-SIDE (of homes and businesses in the future) will be able to search the SUPPLY-SIDE for lowest cost/most efficient alternatives to meet heating, cooling and electric energy needs from such varied sources as distant utilities or a nearby cogeneration power plant in the basement, the neighborhood or the family’s hybrid car. The concept of the ‘networked home’ being ‘plugged into the car’ should be explored. If occupants or appliances in a home or business need, say, heat and electricity, the cheapest source may a local resource (e.g., a car), a utility resource, or a combination of local and distance resources.
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