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Valuing the Contribution of Energy Efficiency to Avoided Marginal Line Losses and Reserve Requirements

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Introduction

Utilities and their regulators have become familiar, comfortable, and sometimes enthusiastic about the energy savings that energy efficiency measures provide. These savings reduce fuel usage, reduce air pollution, and reduce consumer bills.

Energy efficiency measures also provide very valuable peak capacity benefits in the form of marginal reductions to line losses that are often overlooked in the program design and measure screening. On-peak energy efficiency can produce twice as much ratepayer value as the average value of the energy savings alone, once the generation, transmission, and distribution capacity, line loss, and reserves benefits are accounted for. Geographically or seasonally targeted measures can further increase value.

This paper is one of two that the Regulatory Assistance Project (RAP) is publishing on this topic; the second looks in a more detailed fashion at the transmission and distribution system benefits of energy efficiency.[2]

Principal Conclusions

The line losses avoided by energy efficiency measures are generally underestimated. Most analysts who consider line losses at all use the system-average line losses, not the marginal line losses that are actually avoided when energy efficiency measures are installed. Generally this is because average line losses are a measured and published figure, while determining marginal line losses requires more information and more detailed calculations.

Because losses grow exponentially with load, the marginal losses avoided are much greater than the average losses on a utility distribution system. As calculated in Figure 4, marginal line losses at the time of the system peak of 20% are entirely consistent with average line losses of 7% on a utility distribution system.

Because energy efficiency measures reduce loads at the customer premises, they also avoid the associated marginal line losses. As a result, the utility avoids the need for as much as 120% of the generating capacity needed to serve the avoided load.

1 This paper builds on work originally presented to the Northwest Power and Conservation Council's Regional Technical Forum (RTF); it has benefited greatly from the contribution of Charlie Grist of the Council staff and Adam Hadley, P.E., a consultant to the RTF. See: http://www.nwcouncil.org/energy/rtf/meetings/2008/09/Marginal%20Distribution%20System%20Losses%203.ppt http://www.nwcouncil.org/energy/rtf/meetings/2008/09/Marginal%20Distribution%20System%20Losses%20Illustration%20v.xls

2 *US Experience with Efficiency as a Transmission and Distribution System Resource,* Chris Neme, Regulatory Assistance Project, November 2011. http://www.raponline.org/docs/

Utilities maintain generating reserves so that when one generating unit goes out of service, customers continue to receive service. Because energy efficiency reliably reduces energy loads and avoids marginal line losses, thus achieving reliable reductions in loads to be served at the generation level, the utility avoids the need for expensive reserves to assure reliable service. When compounded with the avoided marginal line losses, energy efficiency measures can save about 1.4 times as much capacity at the generation level as is measured at the customer's meter. While the energy benefit of line loss avoidance by investment in energy efficiency is relatively well-understood, the capacity benefit is a separate and additional benefit that is seldom quantified by efficiency analysts.

Efficiency Has a Favorable Daily and Seasonal Resource Shape

Most electric utilities have loads that rise during the day and decline at night. They also have seasonal increases in the summer, winter, or both, compared with the spring and autumn seasons. This variation is caused by people waking up and turning on appliances, going to work and turning on lights and office equipment, and using air conditioners following the heat of the afternoon.

A typical utility will have an on-peak demand during the peak season that is twice as high as the average demand over the year. The ratio of average demand to peak demand is called the *system load factor,* and in this example, would be 50%. Figure 1 shows a typical utility daily load shape.

Because investments in energy efficiency reduce the very loads that cause the overall system load, they generally have about the same load shape as the loads themselves – rising at peak hours and declining at night. Therefore, efficiency measures generally contribute more to the reduction of peak demands than they do on average. They have a better "load shape" than baseload power plants, and the savings are consequently more valuable.

This load shape is not uniform from measure to measure. Some types of efficiency, such as Energy Star air conditioners, provide very large peak demand savings relative to the energy savings. Others, like more efficient street lights, may only reduce demand during shoulder or off-peak hours.

Analysis is required to determine the peak demand of various efficiency measures. This is measured by the typical *load factor* of the individual measure (ratio of average to peak demand reduction) and the *coincidence factor* of the measure (the portion of the demand reduction of the individual measure that will occur at the time of the system peak demand). Measures that provide most of their savings during the high-load hours are said to have a favorable load shape. All three of these measures are important to valuing the energy savings from efficiency measures.

The peaking capacity value of different measures varies by region of the country, depending both on climate and on whether the local utility system is summer-peaking or winter-peaking. A summer-peaking region, like Texas or Florida, will value the capacity benefits of air conditioning savings, but will derive much less capacity value from electric space-heating savings. Winter-peaking regions will have the opposite perspective. Utilities with dual peaks will generally assign a greater value to measures other than space conditioning (i.e., that reduce peak demand in both seasons) compared to regions with a strong peak demand in one season or the other.

Figure 1:

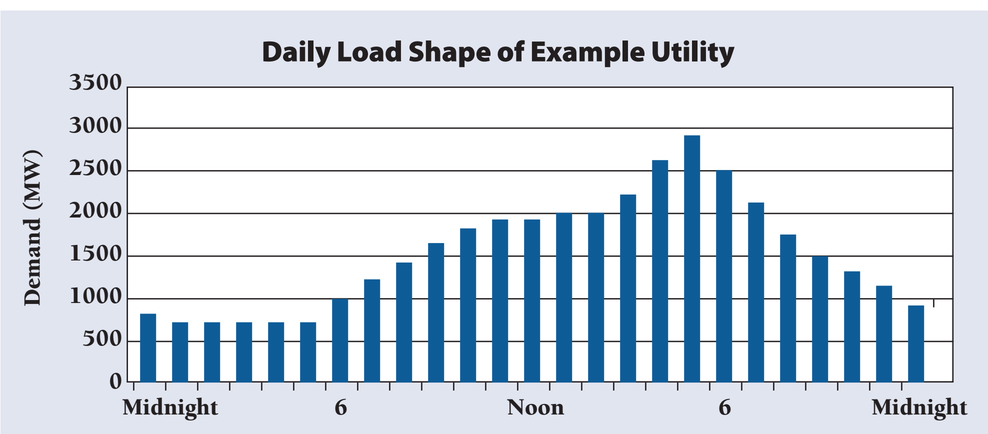


Figure 2 shows the relative on-peak summer and winter savings of some typical energy efficiency measures as evaluated in the Pacific Northwest, a winter-peaking region.

Figure 2

Ratio of Coincident Peak Savings to Average Annual Energy Savings [3]

Measure	Summer Peak	Winter Peak
Residential Lighting	0.90	1.37
Residential Water Heat	0.94	2.63
Residential Space Heat	0.28	4.00
Residential Air Conditioning	1.72	0.08
Residential Refrigerators	1.11	0.87
Commercial Lighting	2.17	2.00
Commercial Air Conditioning	2.86	0.08

As is evident in a winter-peaking region like the Pacific Northwest, investments in space heating conservation (floor, ceiling, and wall insulation) will provide very large peak demand benefits, whereas in summer-peaking regions, it is natural that air conditioning measures are most valuable. One of the more interesting findings of this particular analysis, however, was the relatively high winter-peak coincidence factor of residential water heating consumption.[4] This might be very different on a summer-peaking system.

Energy Efficiency Provides Significant Distribution and Transmission Loss Savings at the Time of Critical System Peak Demands

Because energy efficiency reduces loads at the customer premises, the utility does not have to supply these avoided demands with generating facilities. Generating facilities are often located at great distances from customers and require step-up transformers to get the power onto the transmission system, long transmission lines, transmission substations, step-down transformers to distribution voltages, distribution lines, and distribution line transformers.

Losses occur at each of these steps of the transmission and distribution system. Typical utility-wide average annual losses from generating plants to meters ranges from 6% to 11%, depending on the transmission distances, system density, distribution voltages, and the characteristics of transmission and distribution system components.[5]

Energy efficiency is often credited with avoiding these average losses when regulators and utilities value efficiency investments and set the program cost-effectiveness thresholds based on avoided cost. However, the losses on utility transmission and distribution systems are not uniform through the day and the year, and the peak capacity savings from energy efficiency are typically much greater than the average savings.

Line Losses on a Distribution System

Many utility conservation programs credit efficiency measures with line loss reduction, but most of these calculations are based on the *average* losses, not the *marginal* losses avoided by efficiency measures.

There are two types of losses on the transmission and distribution system. The first are *no-load* losses, or the losses that are incurred just to *energize* the system – to create a voltage available to serve a load. Nearly all of these occur in step-up and step-down transformers. The second are *resistive* losses, which are caused by friction released as heat as electrons move on increasingly crowded lines and transformers. Typically, about 25% of the average

3 Northwest Power and Conservation Council Regional Technical Forum, 2001; see: http://www.nwcouncil.org/energy/rtf/measures/support/procost/MC_AND_LOADSHAPE_6P.XLS

4 Water heat usage is concentrated in the early morning and early evening hours, when households are beginning and ending their day. System peaks typically occur when residential and commercial loads overlap – in the morning around 8 a.m. and the evening around 5 p.m.; therefore electric water heat usage is highly peak-coincident at least for a winter-peaking system. By contrast, while gas water heat usage occurs in the same hours, water heat is a very high load factor usage on gas systems, because in the natural gas industry, peak demand is measured on a daily basis, not an hourly (or sub-hourly) basis as is the standard for the electricity sector. Prior to the 1960s, timers were common on electric water heaters to keep them from contributing to peak demand; with the advent of smart grid resources, electric water heaters are now being looked to for demand response and to complement intermittent generation from wind.

5 Page 401a of the FERC Form 1 shows system losses and system retail sales, and generally fall in this range for vertically integrated utilities. Line losses attributable to wholesale sales and wholesale purchases are typically reported in part by the seller and in part by the buyer – and therefore the losses reported in the Form 1 may not reflect all losses attributable to retail sales by the reporting utility.

annual losses are no-load or core losses, and about 75% are resistive losses. Utility loss studies generally separate the core losses from the resistive losses.[6]

Losses increase significantly during peak periods. The mathematical formula for the resistive losses is I^2R, where “I” is the amperage (current) on any particular transformer or distribution line, and “R” is the resistance of the wires through which that current flows. While the “R” is generally constant through the year, since utilities use the same wires and transformers all year long, the “I” is directly a function of the demand that customers place on the utility. Thus, resistive losses increase with the square of the current, meaning losses increase as load increases.

Let’s start with a very simple calculation: the load (current times voltage) of a utility during the highest on-peak hours is two times the average load for the year, a system load factor of 50%. Because the voltage is constant, losses are a function of the square of the load, and that load is two times as high on-peak as the average, the total resistive losses are *four times* as great during the summer afternoon peak as they average over the year. It’s a bit more complicated than that, but this example gives a general idea.

Depending on the load shape of the utility (how sharp the “needle peak” is), the percentage of generation that is “lost” before it reaches loads are typically at least twice as high as the average annual losses on the system. During the highest critical peak hours (perhaps 5-25 hours per year) when the system is under stress, the losses may be four to six times as high as the average.

There are many tools available to utilities for line loss reduction, including voltage upgrades, reconductoring, and improved transformers. While these are valuable and may often be cost-effective, the focus of this paper is on the avoidable marginal losses as a result of load reductions from implementation of energy efficiency measures.

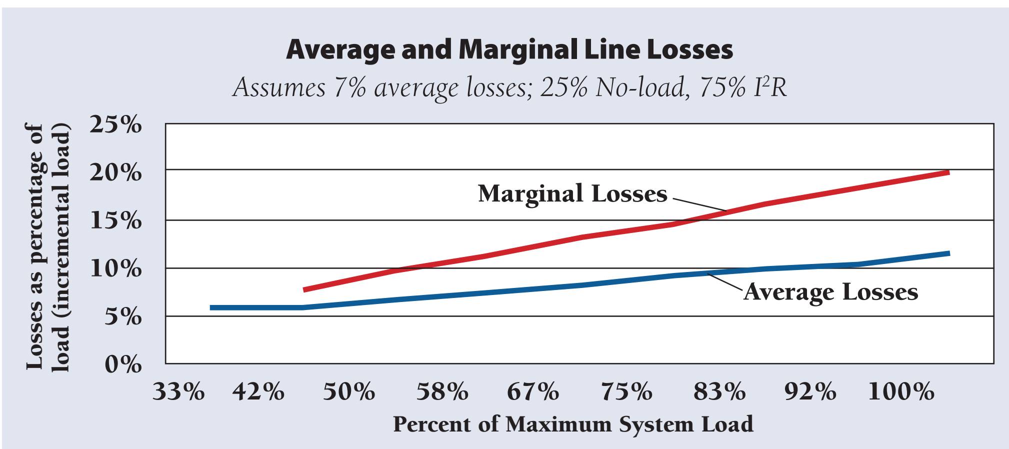
Marginal Losses Are Greater Than Average Losses

Important to valuing any investment is how much the *incremental* cost of the measure is, and what the incremental savings are.[7] Because the average losses increase with the square of the load, the marginal line losses at any point are significantly higher than the average losses at that same point on the load curve. It turns out that the incremental system losses during the peak hours are *much* greater than the average losses during these hours. As noted above, this is due to the total losses growing with the square (I^2R) of the load in response to linear growth in the loads, and the incremental losses (the change in losses with respect to the change in loads) are therefore more than exponential.

The graph below shows the average losses at various load levels for a hypothetical small utility with an average annual resistive loss of 7% on its system. It also shows the incremental losses sustained as load increased from the minimum level of about 100 megawatts to the system record peak demand of nearly 300 megawatts for this utility.

This utility’s average resistive losses on their distribution system are only about 7% over the course of the year. At their system extreme peak, the estimated total losses

Figure 3



6 In preparing this paper, the authors reviewed line loss studies for several utilities; they indicated no-load losses ranging from 18.5% to 30% of total annual losses. A mean figure of 25% is used for simplicity in illustrating the principle of marginal line loss calculation.

7` The most comprehensive and most commonly accepted cost-effectiveness test is the Total Resource Cost (TRC) test, which, when properly applied, measures both energy and non-energy benefits; but the principles in this analysis apply equally to the Program Administrator Cost (PAC) test used by some utilities and regulators to value energy efficiency investments.

Figure 4:

Calculation of Average and Marginal Line Losses

Load Level	No-Load Losses MW	Resistive Losses MW	Square of Load	Loss %	Total Loss MW	Incremental Load	Incremental Loss	Marginal Loss %
100	2.625	3.5	10,000	6.1%	6.1			
125	2.625	5.5	15,625	6.5%	8.1	25	2.0	8%
150	2.625	7.9	22,500	7.0%	10.5	25	2.4	10%
175	2.625	10.7	30,625	7.6%	13.3	25	2.8	11%
200	2.625	14.0	40,000	8.3%	16.6	25	3.3	13%
225	2.625	17.7	50,625	9.0%	20.3	25	3.7	15%
250	2.625	21.9	62,500	9.8%	24.5	25	4.2	17%
275	2.625	26.5	75,625	10.6%	29.1	25	4.6	18%
300	2.625	31.5	90,000	11.4%	34.1	25	5.0	20%

reached about *11%,* one and one-half times the average losses for the year. At that extreme peak, however, the *marginal* resistive losses – those that would be avoided if load had been a little bit lower if an efficiency measure were installed – were *20%.*

The graphic in Figure 3 is derived from the calculations above in Figure 4.

Few utilities or regulators have studied the marginal losses that can be avoided with incremental investment in efficiency measures that provide savings at the time of extreme peak demands. This type of analysis suggests a very significant benefit from measures that reduce peak demand, including energy efficiency, demand response, and use of emergency generators located at customer premises.

Mathematically, the formula I^2R reduces the marginal resistive loses to a calculation. At any point on the load duration curve, marginal resistive loses are two-times the average resistive losses at that same point on the load duration curve. During off-peak hours, when average resistive losses may be only 3%, the marginal losses are 6%. During the highest peak hours, when average resistive losses may be 10%, the marginal losses are 20%.

However, because part of the overall losses at every hour are (no-load) losses, the marginal losses are not two times the total losses – only two times the resistive losses. The no-load losses are not reduced by energy efficiency measures. A variety of utility loss studies indicate that 20%-30% of total losses are no-load losses, meaning that about 75% are resistive losses. Therefore this paper uses a rule of thumb that marginal losses are about 1.5 times average losses (it's actually a bit lower at low loads, and a bit higher at high loads where the no-load losses are a smaller part of total losses.)

This means that a conservation measure that saved 1 kilowatt at the time of the system peak measured at the customer's meter would save about 1.25 kilowatts measured at the generation level.[8] The critical peak-period marginal line-loss savings of energy efficiency therefore adds another 25% to the value of the load reduction itself, in determining the amount of generating capacity required to meet critical peak period demand. If the utility has 1.25 kW of generating capacity, and loses at the margin 20% of this capacity during the highest peak hours, it has 1 kW available to serve the load.

The hypothetical analysis may not be universally applicable, but the principles are universal: losses increase with the square of the demand, and incremental losses during the critical peak period are much larger than the average losses over the year.

Avoidable Transmission and Distribution Capacity Costs Are Significant

In addition to the avoided losses and the reduced need for generating capacity that can be achieved through

8 [1.25 – (.20 x 1.25) = 1.0]; If the utility must serve a 1 kW incremental load on-peak, it needs 1.25 kW of additional generating capacity to feed the transmission and distribution system.

energy efficiency investment at the distribution level, the peak load reduction from energy efficiency investment also reduces transmission and distribution capacity costs. Recognizing this value may be especially important for those jurisdictions that actually review T& D investments against targeted energy efficiency program opportunities.[9]

Transmission and distribution systems must be designed to carry extreme peak demands. The costs of oversizing systems for these demands are quite significant. In states where marginal cost of service studies are used to set rates, utilities regularly examine the cost of adding capacity to their transmission and distribution grids. The results of these studies vary widely, in part due to regional conditions and in part due to a lack of standardized methodologies.

The capital cost of augmenting transmission capacity is typically estimated at $200 to $1,000 per kilowatt, and the cost of augmenting distribution capacity ranges between $100 and $500 per kilowatt.[10] Annualized values (the average rate of return multiplied by the investment over the life of the investment) are about 10% of these figures, or $20 to $100 per kilowatt-year for transmission and $10 to $50 per kilowatt-year for distribution. There are also marginal operations and maintenance costs for transmission and distribution capacity, but these are modest in comparison to the capital costs.

In valuing energy efficiency investments, it is important to consider the avoided energy and capacity not only at the generation level, but also at the transmission and distribution levels. Inclusion of these values, particularly considering the marginal capacity benefits from incremental efficiency investments, can greatly increase the value of these measures, and therefore the level of financial assistance or incentives that utilities may offer to encourage implementation.

Another important benefit of increased energy efficiency at the distribution/customer level is the significant extension in useful life of distribution system components and the resulting deferral of capital expenditures for upgrade or replacement of electrical equipment, including conductors, transformers, etc. In effect, energy efficiency allows the system to absorb additional load growth without the need to upgrade system components as soon. This capital deferral translates more or less directly into avoided distribution-capital investment costs for capacity expansion. A prudent assumption is that the avoided capacity benefits are at least one-half of the utility's estimated marginal transmission and distribution capacity costs, based on their most recent cost-of-service analysis.[11]

Another benefit of reducing marginal losses is lower loss of service life due to a reduction in winding and insulation temperatures in distribution transformers, which are normally operated at up to 200% of their nameplate rating during peak load periods, a condition that causes accelerated aging of these components.

Efficiency Reduces System Generating Reserve Requirements

Utilities must provide *reserves* of generating facilities in order to ensure that service is not interrupted if (and when) generating units fail to operate as planned. Generating reserve requirements in the United States range from as low as 7% on hydro-rich utilities to as much as 25% for isolated small utilities in Alaska and Hawaii. Ten to fifteen percent is typical for large thermal-based systems.[12]

Efficiency investments reduce loads at the customer's meter, and, as we have seen, provide even larger reductions at the generation level during system peak periods when losses skyrocket and capacity/reserve requirements are greatest.

Since the reserve requirement is tied to the amount of generation required to serve load, efficiency reduces the reserve requirement not only by a percentage of the

9 Id footnote 2.

10 These wide ranges reflect the wide possible range of outcomes for distance, topography, real estate costs, and construction costs that may be incurred.

11 The capacity benefit may not be monetized immediately, due to temporary excess capacity; but over the life of a distribution circuit, eventually components will need to be replaced due to age or upsized due to growth. Using one-half of marginal cost implies that, on average, the capacity benefits will be realized within a half-lifetime of the circuit components.

12 The level of required reserves is a function of the size of the total system, the size of the largest single generating units, and the reliability of the various generating units. Because hydro units are generally relatively small and extremely reliable, utilities that rely on hydro for reserves have the lowest reserve requirements. Small island systems, like those in Hawaii, with a few relatively large generating units typically have the highest reserve requirements.

savings that customers enjoy, but also by a percentage of the incremental peak losses on the transmission and distribution system that reduce the utility's generation requirements. The reserve requirement is measured against the amount of generation needed – *including that needed to cover line losses.* Therefore, the avoided reserves resulting from efficiency investments are increased in value by the avoided marginal line losses.

The table below looks at the capacity savings during an off-peak period and an on-peak period for two hypothetical resources, one with a low coincidence factor relative to the system peak (efficient lighting), and one with a high coincidence factor, efficient air conditioning. The table shows that after considering the coincidence of different loads to the system peak, the marginal line losses, and the avoided reserve requirement, the capacity benefit of energy efficiency measures increases significantly from that measured at the customer's meter.

As is evident, the total capacity benefit of each of these measures is 1.44 times the capacity savings at the customer's meter, because of the value of the marginal line losses and avoided reserves during peak periods (line 8 divided by line 3). Thus the generation capital cost savings are significantly higher than if only average line losses were used and if the reserves benefits were not included.

Efficiency Is The Most Reliable Resource

Energy efficiency is the most reliable resource in which a utility can invest. Unlike any type of generating unit, efficiency investments are composed of hundreds or thousands of small, distributed units, each of which saves anywhere from a few watts (e.g., a compact fluorescent lamp) to a few kilowatts (e.g., a high-efficiency commercial air conditioning unit).

It has long been recognized that a utility network made up of a large number of small generating units provides a more reliable system simply because they will not all fail simultaneously. The same principle applies to energy efficiency investments, which are a large number of small energy-saving devices. But these go beyond this mathematical advantage in at least two ways:

First, the individual units (efficient light bulbs, refrigerators, and air conditioners) are, as a population, extremely reliable, far more so than any type of generating plant.[13] Energy Star windows, attic insulation, or variable speed drive in a commercial HVAC system are almost certainly not going to "fail" during a heat wave. Conversely, generating plants, transmission lines, and even distribution transformers are most susceptible to failure when under stress. Even the most reliable type of generating units (hydro turbines) have higher "forced outage rates" than energy savings devices.

Second, if one energy efficient unit does fail, such a "failure" often actually reduces electric demand (i.e., when a high-efficiency air conditioner breaks, the customer may be entirely without air conditioning – uncomfortable, but using less energy). The utility loses an "efficient" load, but nonetheless, the load goes down when the unit fails, generally reducing the load-related stress and threats to reliability on the system. When a generating plant or transmission line fails, it leaves the utility with the same load, and less ability to serve that load and with increased risk of a system outage affecting hundreds, thousands, or even millions of consumers.

Figure 5:

Peak Capacity Savings from Energy Efficiency Investments

Line		Lighting	Air Conditioning
1	kW Savings at Customer Meter	10	10
2	Coincidence Factor	0.25	0.75
3	kW Savings at Customer Meter at Peak (1 X 2)	2.5	7.5
4	Marginal Line Losses At Peak @ 20% (3 / (1 - 20%) -3)	0.625	1.875
5	kW Savings at Busbar (3 + 4)	3.125	9.375
6	Reserve Margin Requirement	15%	15%
7	Avoided Reserve Capacity (@ 15%)	0.47	1.41
8	kW Savings At Generation Level (5 + 7)	3.59	10.78

13 The most reliable peaking units have on-peak availability of about 95%, and forced outage rates of about 5%.

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How the Smart Grid Can Enhance the Application of Energy Efficiency Measures

At the time of the system peak demand, line losses are highest and marginal line losses may be 20% or higher. For this reason, actions that reduce load at the time of the system peak are extremely valuable. As utilities invest in smart grid assets and learn to deploy them, avoidance of expensive peak load related costs becomes more feasible. The application of smart grid technology will enhance the application of energy efficiency measures by:

- **Accurately measuring conditions on the distribution system before and after the application of load management tools, so that the value can be accurately known.**
  For the first time utilities will be able to accurately measure voltage, load, and reactive power at the distribution level down to individual customers. Data will be available to determine the level of losses occurring on a circuit and what control actions are needed. For example, the data will show when and how to optimally adjust circuit voltage level to reduce demand or save energy.
- **Providing the ability to control or shift demand at peak times**
  Customer load can be reduced or shifted by application of smart thermostats, pool pump controls, water heater controls, appliance controls, etc. This is most valuable during peak load events when the combination of energy savings and peak capacity savings is at its highest.
- **Providing the ability to utilize/control distributed generation (i.e. fuel cells, batteries, solar arrays, PHEV's etc.) as needed.**
  Customers may invest in distributed resources and energy storage to reduce their peak demand as measured by their electric meters, which typically measure non-coincident peak demand. With smart grid tools, the energy control center can interface with distributed generation to provide additional capacity at the utility's peak time or store renewable energy during off-peak periods, both of which benefit the system, but might not be apparent to the individual customer.

These types of control may enable the utility to avoid load during the needle peak hours – when marginal line losses may exceed 20%, and when generation reserves are stretched thin at a much lower cost than building additional generation, transmission, and distribution capacity. This will have a small effect on the value of energy conservation measures, such as those described here, which provide savings for thousands of hours per year. However, it may provide significant cost relief to the utility and its consumers in avoiding the cost of seldom-used capacity, thereby adding great value to the types of measures that provide savings concentrated at the time of the system peak demand.

The measures mentioned above are part of the emerging *demand response* capability of smart grid, which promises to provide a verifiable *virtual* reserve of reliable capacity directly equivalent to a *spinning reserve* but at a much lower cost.

Summary: The Avoided Line Losses and Avoided Reserves Benefits of Energy Efficiency Are Very Important

This paper has attempted to highlight two often-overlooked attributes of energy efficiency investments.

First, energy efficiency measures typically provide significant savings at the time of the system peak demand, and that time occurs when the line losses are highest. The avoided line losses can add as much as 20% to the capacity value measured at the customer meter.

Second, because they are reducing loads, including marginal line losses, energy efficiency measures also reduce the level of required generating reserves.

Each of these benefits increases the economic savings provided by energy efficiency investments. The compounding of a 20% marginal line loss savings and a 15% reserves savings can produce a 44% total generating capacity benefit, over and above the peak load reduction measured at the customer's meter.

For peak-oriented loads like air conditioning, the annual capacity cost of generation, transmission, and distribution *capacity* needed to assure reliable service can equal or exceed the cost of the *energy* used during the year.

Add it all together, and the total capacity value of energy efficiency investments in peak-oriented loads like space conditioning can be as valuable as the energy savings are.

Marginal line loss calculations and avoided reserve requirements should be an integral part of any evaluation of the benefits of energy efficiency measures.

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