

Energy Efficiency in the Power Grid



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ABB Inc.

The U.S. Department of Energy estimates that increasing energy efficiency could reduce national energy use by 10% or more in 2010, and as much as 20% in 2020, with net economic benefits for consumers and businesses as a result.

The concept of energy efficiency has moved in and out of favor with the public over the years, but recently has gained renewed broad-based support. The confluence of economic, environmental and geopolitical concerns around reducing America's exposure to disruptions in the supply of energy has moved efficiency to the fore. As a result, a number of initiatives are now underway to improve efficiency in a variety of areas, but much more can and should be done.

The US is not alone in these efforts. China presently has ten efficiency programs aimed at bringing the country's energy intensity—the amount of energy used per unit of GDP—in line with rivals such as the US and the European Union. The EU likewise has taken steps to improve energy efficiency in its member countries by 20% over the next fifteen years.

Efficiency is a simple concept which can perhaps best be summed up with the cliché, “doing more with less.” Perhaps the best-known efficiency program among American consumers is the Energy Star program that helps them to identify appliances like dishwashers and refrigerators that use less energy than other similar models. Indeed, the term “efficiency” is typically associated with how energy is consumed at the point of end use, but the concept of efficiency can also be applied to how energy is produced and distributed.

This paper will focus primarily on the electric power system, where most end-use applications outside of transportation and heating get their energy. We will first present a broadly inclusive definition of efficiency and then explore a variety of ways the grid can be made more efficient.

Generation

To gain an appreciation for the impact that improved efficiency can have, it is useful to examine the price we pay for inefficiency, and nowhere is this more apparent than in the generation of electric power. Typically, the process converts the latent energy in a fuel stock (coal, gas, uranium) into mechanical energy in a generator and ultimately electrical energy. However, other generation sources like wind and hydro power use the mechanical energy of moving masses of air or water to produce electric energy. Still other devices, such as fuel cells, use chemical reactions to generate electric energy. In all of these cases, though, some of the input energy is lost in the process.

The efficiency of generation varies widely with the technology used. In a traditional coal plant, for example, only about 30-35% of the energy in the coal ends up as electricity on the other end of the generator. So-called “supercritical” coal plants can reach efficiency levels in the mid-40's, and the latest coal technology,

known as integrated gasification combined cycle or IGCC, is capable of efficiency levels above 60%. The most efficient gas-fired generators achieve a similar level of efficiency.

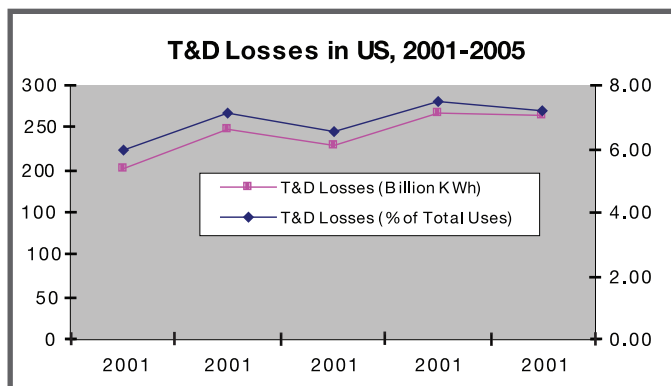
Obviously, though, even at 60% efficiency there is a tremendous amount of energy left behind in the generation process. That represents a higher cost of production for the generator, as well as a substantial waste of limited resources. There is, therefore, tremendous economic and ecological incentive to improve the efficiency of power generation so that more of the energy content of the input fuel is carried through to the output electricity. There are a variety of ways to improve generator efficiency, such as combustion optimization using modern control systems, but for the purposes of this paper we will focus on what happens after the generation process.

Transmission and Distribution

Once electric energy is generated, it must be moved to areas where it will be used. This is known as transmission—moving large amounts of power over sometimes very long distances—and is separate from distribution, which refers to the process of delivering electric energy from the high voltage transmission grid to specific locations such as a residential street or commercial park. Distribution is usually considered to encompass the substations and feeder lines that take power from the high voltage grid and progressively step down the voltage, eventually to the 120v level at which power enters our homes.

The transmission and distribution or “T&D” system, then, includes everything between a generation plant and an end-use site. Along the way, some of the energy supplied by the generator is lost due to the resistance of the wires and equipment that the electricity passes through. Most of this energy is converted to heat. Just how much energy is taken up as losses in the T&D system depends greatly on the physical characteristics of the system in question as well as how it is operated. Generally speaking, T&D losses between 6% and 8% are considered normal.

It is possible to calculate what this means in dollar terms by looking at the difference between the amount of electric energy generated and the amount actually sold at the retail level. According to data from the Energy Information Administration, net generation in the US came to over 3.9 billion megawatt hours (MWh) in 2005 while retail power sales during that year were about 3.6 billion MWh. T&D losses amounted to 239 million



Source: Energy Information Administration

MWh, or 6.1% of net generation. Multiplying that number by the national average retail price of electricity for 2005, we can estimate those losses came at a cost to the US economy of just under \$19.5 billion.

Congestion charges represent another significant cost of inefficiency in the T&D system, but are only partially determined by the physical characteristics of the grid. Congestion occurs when the scheduled or actual flows of electricity are restricted

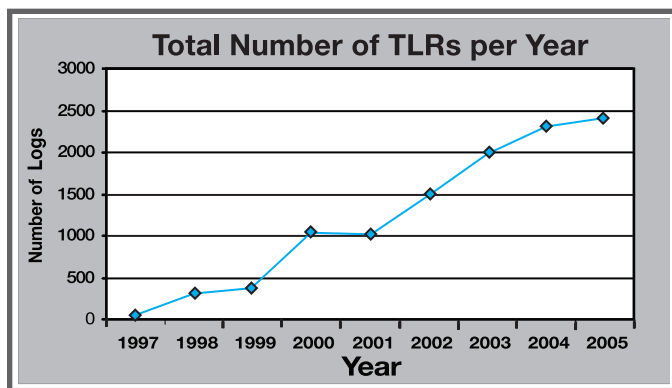
either by physical capacity constraints on a particular device or by operational safety constraints designed to preserve grid reliability. In order to meet demand, the system operator must find an alternative source of power that avoids the bottleneck. That alternative generator will be less economical, and therefore less efficient from a market perspective. A more robust T&D system, then, can provide a level, congestion-free playing field on which generators can compete.

Congestion is the result of a number of factors, notably a lack of adequate transmission investment and an increase in bulk power transactions in competitive energy markets. Recent figures on congestion at a national level are difficult to ascertain, however the experience of two of the nation's largest power markets will serve to illustrate the scope of the problem.

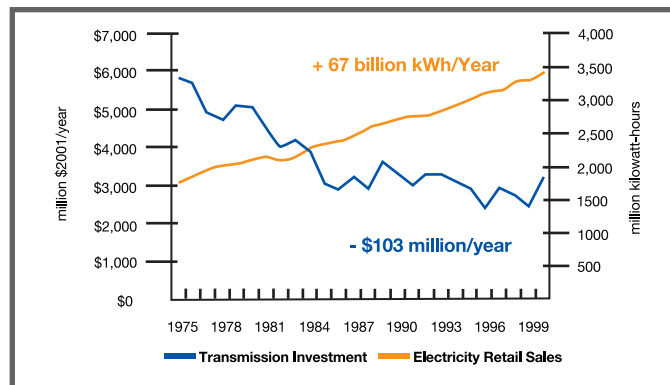
The California Independent System Operator reported congestion costs of \$1.1 billion in 2004, \$670 million in 2005, and \$476 million in 2006. It's worth noting that the ISO attributes much of the reduction in the '04-'05 period to critical expansions on the state's "Path 15" north-south transmission corridor. Similarly, the PJM

interconnection, which serves the largest territory of any regional transmission organization in the US, reported congestion costs of \$750 million in 2004, \$2 billion in 2005, and \$1.6 billion in 2006. PJM notes that since 2002, congestion costs have come in at 7-10% of annual total billings.

As these figures make clear, the cost of inefficiency in the T&D system is significant. However, the impact of congestion is not limited to the cost associated with dispatching less economical generation. Often the situation requires grid operators to curtail service to consumers in some areas to protect the integrity of the grid as a whole. These "transmission loading relief" actions (TLRs) have increased dramatically in recent years, up nearly 150% just in the 2001-2005 period.



Source: NERC



Transmission Investment vs. Retail Electricity Sales. Source: IEEE

Clearly too there is an inference to be drawn from these numbers about the relationship between efficiency in the T&D system and the reliability of that system. In every region of the US, for example, there are generation plants designated by the local grid operator as "reliability must-run" or RMR. These units are run regardless of their economic merit because their output is needed to maintain voltage levels. RMR units are often older, dirtier and less efficient than modern plants, due to the fact that they tend to be located

in urban areas where siting new plants is all but impossible. There are alternatives to RMR generators (i.e., FACTS devices, which are described in a later section), but our current reliance on them can be viewed as a byproduct of a less-than-optimal T&D system.

Demand-Side Energy Efficiency

The average person would likely point to energy consumption as the point where “efficiency” measures can be applied, and while our focus here is mainly on the supply side, it’s worth noting a few examples to illustrate the impact of demand-side efficiency efforts.

Most people are probably familiar with the Energy Star program mentioned earlier, or with the increasing popularity of compact fluorescent light bulbs that use a fraction of the electricity used in conventional bulbs to produce the same amount of light. But the single largest consumer of electric power is the industrial motor, which is used to run everything from assembly lines to compressors to the fans that blow air into the combustion chamber of a coal-fired generator.

It is estimated that fully 65% of industrial power is used in motors of various sizes, most of which run at full speed whenever they are turned on, even if they don’t need to. This is because the vast majority of industrial motors are controlled by drives that cannot alter the speed of the motor. Variable speed drives, also known as variable frequency drives, ramp the motor’s speed up or down to meet the requirements at a given moment in time. The resulting energy savings can be enormous. VSDs can reduce consumption by as much as 60%, which in energy-intensive facilities can equate to millions of dollars a year in energy costs.

What’s important to note here is the leverage that demand-side efficiency improvements can have when they a) greatly impact a small number of large energy consumers (e.g., VSDs), or b) have a more modest impact that is multiplied across many smaller energy consumers (compact fluorescent bulbs). Obviously, the former case is more easily realized than the latter, if only because there are relatively few people who need to be convinced of the value of the new approach. Consider, then, the potential of measures that enjoy the best of both worlds—a multiplicative effect combined with a small number of decision makers. That, in essence, is the main selling point for supply-side efficiency in the power system, and is where ABB has focused much of its technology and expertise. If a single utility implements a given technology across its entire system, thousands if not millions of customers come along for the ride.

Improving Efficiency in the T&D System

One example of efficiency measures aimed primarily at the utilities that operate the T&D system is an initiative underway at the US Department of Energy to implement new efficiency standards for distribution transformers. These are the grey cylinders you see perched atop utility poles in residential neighborhoods, and the metal-housed units placed on cement pads at ground level. There are over 40 million distribution transformers in service today in the US. They are among the most ubiquitous and the most standardized pieces of electrical equipment, and for that reason make a prime target for improvements that can then be propagated across large areas.

The proposed standards will have a relatively modest impact on the efficiency of a given transformer, around 4% over current models. However, when this incremental gain is multiplied across the thousands of units operated by even a small utility, the result is impressive. DoE expects to issue a final rule on the new standard later this year with implementation set for 2010.

There are other initiatives at the distribution level, but if we focus our attention on the measures that have the greatest potential for improving efficiency, we inevitably must look to transmission. There are numerous technologies that are already being applied to boost efficiency in transmission, and still more that have yet to reach full commercial implementation. In the following sections, we explore some of these technologies.

HVDC

Most of the transmission lines that make up the North American transmission grid are high-voltage alternating current (HVAC) lines. Direct current (DC) transmission offers great advantages over AC, however: 25% lower line losses, two to five times the capacity of an AC line at similar voltage, plus the ability to precisely control the flow of power. Historically, the relatively high cost of HVDC terminal stations relegated the technology to being used only in long-haul applications like the Pacific DC Intertie, which connects the vast hydro power resources of the Columbia River with the population centers of Southern California.

With the advent of a new type of HVDC, invented by ABB and dubbed HVDC Light®, the benefits of DC transmission are now being realized on much shorter distances. The Cross-Sound Cable connecting Long Island and Connecticut is one example of this technology.

FACTS Devices

A family of power electronics devices known as Flexible AC Transmission Systems, or FACTS, provides a variety of benefits for increasing transmission efficiency. Perhaps the most immediate is their ability to allow existing AC lines to be loaded more heavily without increasing the risk of disturbances on the system. Actual results vary with the characteristics of each installation, but industry experience has shown FACTS devices to enhance transmission capacity by 20-40%. FACTS devices stabilize voltage, and in so doing remove some of the operational safety constraints that prevent operators from loading a given line more heavily. In addition to the efficiency gains, these devices also deliver a clear reliability benefit.

Gas-Insulated Substations

Most substations occupy large areas of land to accommodate the design requirements of the given facility. However, each time power flows through a substation to step down the voltage, more energy is lost as the power flows through the transformers, switches and other equipment. The efficiency of the lower-voltage lines coming out of the substation is also markedly lower than their high-voltage counterparts. If power can be transmitted at higher voltage to a substation that is closer to where the energy will be consumed, significant efficiency improvements are possible.

Gas-insulated substations essentially take all of the equipment you would find in an outdoor substation and encapsulate it inside of a metal housing. The air inside is replaced with a special inert gas, which allows all of the components to be placed much closer together without the risk of a flashover. The result is that it is now possible to locate a substation in the basement of a building or other confined space so that the efficiency of high-voltage transmission can be exploited to the fullest extent.

Superconductors

Superconducting materials at or near liquid nitrogen temperatures have the ability to conduct electricity with near-zero resistance. So-called high temperature superconducting (HTS) cables now under development, which still require some refrigeration, can carry three to five times the power of conventional cables. The losses in HTS cables are also significantly lower than the losses in conventional lines, even when the refrigeration costs are included. A major vendor of superconducting conductors claims that the HTS cable losses are only half a percent (0.5%) of the transmitted power compared to 5-8% for traditional power cables. Superconducting materials can also be used to replace the copper windings of transformers to reduce losses by as much as 70% compared to current designs.

Wide Area Monitoring Systems

Much of the transmission system could feasibly be operated at a higher loading, were it not for reliability concerns. However, if operators were given the ability to monitor grid conditions more precisely and in real time, some of these constraints would be removed. One example relates to the simple fact that when transmission lines heat up, the metal becomes pliable and the lines sag, which can cause a short circuit if they come into contact with a tree or other grounding object. Wide area monitoring systems (WAMS) have many promising capabilities, one of which is line thermal monitoring. With this functionality, transmission operators could conceivably change the loading of transmission lines more freely by virtue of having a very clear understanding of how close a given line really is to its thermal limits.

Other Paths to Improved Efficiency

The technologies outlined above represent only a few of the many available options for improving energy efficiency in the T&D system. The Business Roundtable's Energy Task Force T&D working Group, which ABB chairs, recently published a list of efficiency-enhancing actions and technologies, some of which include:

- Distributed generation/Microgrids
- Underground distribution lines
- Intelligent grid design (smart grids via automation)
- Reduction of overall T&D transformer MVA
- Energy storage devices
- Three phase design for distribution
- Ground wire loss reduction techniques
- Higher transmission operating voltages
- Voltage optimization through reactive power compensation
- Asset replacement schedule optimization
- Distribution loss reduction via distribution automation
- Power factor improvement
- Load management (e.g., smart metering or price-sensitive load control)
- Power electronic transformers

These options vary in terms of expense and the changes they imply for equipment purchasing or operational practices. We list all of them here simply to illustrate the many ways in which greater energy efficiency in the power grid can be achieved.

Benefits of Improved Efficiency

The “business case” for energy efficiency is fairly straightforward: using less energy means paying less for energy. But a simple cost-benefit analysis might overlook some very important benefits that efficiency brings.

At this point, there is little doubt that regulation of carbon dioxide is coming, with the power sector as a primary target. While there are technologies both available and in development to mitigate CO₂ emissions from power plants, the fact remains that the easiest ton of CO₂ to remove from the atmosphere is the one that is not emitted in the first place. Greater energy efficiency in the T&D system means lower emissions in generation to deliver the same amount of consumed energy.

Fuel conservation and diversity is another strong selling point for efficiency, and here the benefits extend well beyond economic and even environmental considerations. Reducing US dependence on foreign fuel supplies—be they oil, natural gas or even coal—pays obvious dividends from a security standpoint, and the less we use, the less we have to buy.

Finally, within the context of the power system itself, it's important to recognize how interrelated energy efficiency is with grid reliability. In many areas of the US, transmission constraints have reached the point where they not only cost consumers billions of dollars in congestion charges, they threaten the integrity of the power system itself. Over the past twenty years, the situation has continued to deteriorate to the point where now the question of installing a new line is nearly moot in some locations. By the time it was completed, demand would long since have outstripped the ability of the local grid to meet it, so a short-term solution must be implemented in the interim.

FACTS devices offer a good example of how efficiency and reliability improvements often go hand in hand. Unlike siting and building a new transmission line, FACTS devices can be implemented quickly (less than a year from purchase to completion in some cases). They immediately boost the transmission capacity of the given line while also providing voltage support and bolstering the local grid's ability to withstand disturbances.

As the reliable supply of energy, especially electric energy, continues to grow in importance, the potential impact of energy efficiency cannot be overstated. With the array of technologies and methodologies now available, efficiency stands ready to play a much larger role in the energy equation.