Energy Efficiency Critical Targets

Mohammed Yedroudj
Dept. of Systems Engineering
Military Technological College
Muscat, Sultanate of Oman
Yedroudj.mohammed@mtc.edu.om

Sarim Al-Zubaidy
Military Technological College
Muscat, Sultanate of Oman
Sarim.alZubaidy@mtc.edu.om

***Abstract*— Despite the fossil fuel fired power generating plants being the major producers of greenhouse gases, it is clearly evident that renewable sources of energy are not going to replace them any time soon. There is a general consensus amongst scientists and governments that our climate is changing at an unprecedented rate, and it is argued that it is largely caused by greenhouse gas emissions from economic activity that is unlikely to be significantly scaled down through forums and protocols. Many studies indicate that a higher concentration of greenhouse gases in the atmosphere, particularly carbon dioxide, is the primary cause of global warming that is driving climate change. While awaiting for renewable energy to make further technological advances, improve its efficiency, and place itself as a cost effective contender to conventional power generation, energy efficiency and conservation are currently the least expensive alternative for power and process industry to meet a growing demand for cleaner energy. For all the renewable energy resources put together, renewable energy accounts for 19.1% of total electricity production, of which 85% is hydro-electricity. Energy efficiency and renewable energy should remain the twin pillars of sustainable energy policy [1]. In many countries, energy efficiency is also seen to have a national security benefit because it can be used to reduce the level of energy imports from foreign countries and may slow down the rate at which domestic energy resources are depleted.**

In this paper, we focus on the current state of the electrical system efficiency from generation to utilisation, and identify the critical areas where efficiency can be enhanced through current technology, design and operational practice.

***Index Terms*—Energy efficiency, greenhouse gases emissions, renewables, clean power, power plant, transmission & distribution, transformers, facts, sustainable buildings, smart grids, demand response.**

I. Introduction

Greenhouse gases (GHG) emissions are a by-product of population, economic activity in general and energy use in particular. Reducing economic activity to limit GHG emissions at a critical time when the world is on a slow recovery from the recent severe economic downturn is deemed to be a less likely alternative for developed and emerging economies alike. Instead, the drive is towards managing the by-products and the after-effects of economic activity as the lowest cost pathway through energy efficiency, clean power plants, low carbon electricity generation technologies, flue gas desulphurization (FGD or scrubbers), selective catalyst reduction (SCR) technology [11], carbon capture and storage strategies (CCS).

Amongst these, energy efficiency plays a vital role in limiting carbon emissions while reducing our dependency on fossil fuels and the impact on the environment. By increasing our energy productivity, or efficiency, we can do more with less. Energy efficiency is increasingly being seen as an integral part of national energy policy and action plans as a cost effective, readily available alternative energy resource. Improving energy efficiency will minimise energy wastage, cut costs for companies and consumers, reduce our reliance on fossil fuels and contribute to the overall economic competitiveness. Many countries have embarked [10] on efficiency programs aimed at bringing the country's energy intensity—the amount of energy used per unit currency of GDP—in line with the US and European Union. The EU likewise has taken steps to improve energy efficiency in its member countries by 20% over the next fifteen years.

We can reduce our energy consumption through better conservation measures and by using more efficient electrical appliances and equipment. Conserving electricity is analogous to turning off the water in the shower while shampooing; energy efficiently, however, is synonymous with the use of a better showerhead to use less for the same results.

II. Energy Efficiency

Energy efficiency [8] is the current buzz-word on the lips of many policymakers, industry, business executives and green citizens as energy cost and greenhouse gas emissions are going up instead of down, hitting record highs. The international Energy Agency defines something is more energy efficient if it delivers more services for the same or less energy input. Efficiency is the maximization of some desired output for the least amount of input. It is defined as the ratio of some output quantity to some input quantity, (η = output/input). The larger the ratio, the greater the efficiency.

The term "electrical energy efficiency" is not only associated with how energy is consumed at the user level, but the concept of efficiency can also be applied to how energy is produced and distributed. To date, the energy we use doesn't work hard enough for us. For example, more than 6%-11%, at least, of electrical energy produced is lost through transmission and distribution systems. There are also opportunities to make energy efficiency gains throughout the economy, such as improving the efficiency of electrical

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appliances (e.g. air-conditioning systems), developing electric vehicles and incentivizing companies to reduce their energy consumption through legally binding targets and regulation, and reducing heat loss from public sector buildings which account for more electricity usage than any other sector. No wonder, considering that we spend more than 90 per cent of our time in buildings. For example, the energy efficiency of a building is the extent to which the energy consumption per square metre of floor area of the building compares with established energy consumption benchmarks for that particular type of building under defined climatic conditions [7]. The typical benchmark is the median level of performance of all the buildings in a given category.

In a conventional steam power plant, the efficiency is simply the amount of electricity produced (output) divided by the fuel energy used (input) for the process. Different designs and fuels used produce different efficiencies with different GHG as a by-product. The highest efficiency achieved in producing electricity from a steam plant is in the order of 46% to 48% (with steam conditions at 300 bar / 600ºC-620ºC), and 50% to 55% net efficiency (with steam conditions at 350 bar /700°C-720°C) for a new boiler and recent turbine technology withstanding much higher temperatures available in mid-2010. For a gas fired power plant, the highest efficiency achieved so far, is in the order of 60%.

The European Union pledged in 2006 to cut its annual consumption of primary energy by 20% come 2020 through energy efficiency improvements that would yield an estimate of €1000/year/household. The initial lack of legally binding commitments by member states has put the program well off its targets projecting about 10% energy savings at best.
This has prompted a revision of the Energy Efficiency Action Plan to introduce some regulations such as the energy performance of buildings requiring an energy performance certificate, energy efficiency standards on household appliances (appliances, lighting, etc…) and transport such as limited CO_2 emissions on cars, and fuel efficiency labels on tyres.

III. Generation Efficiency Targets

Electrical energy is generated in bulk at power plants located miles away from cities and population centres. In order to reduce losses and conserve energy, power is transmitted at higher voltages over the national grid via power lines and cables to substations, which are closer to home. Voltages are then stepped down at customer's level to supply the low voltage loads as shown in the current system.

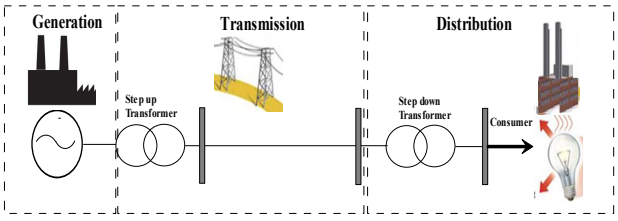


Figure 1. Conventional electrical system architecture

As much as two thirds of energy is wasted in the process of generating electricity and distributing it to the consumer. On average, 2-3% is lost in the transmission system at higher voltages due to corona and I^2R losses. While 5-6%, at best, is lost on the distribution system because they operate at lower voltages pushing up the I^2R losses. By far the generation is the least efficient where losses are within 45-65% depending on the power plant technology used. The question that comes to mind is whether there are any opportunities for improvement on efficiency over the three major stages of electrical energy depicted in Figure 1. It is worth noting that the current contribution of alternative energy to the world's overall energy consumption is no more than 6 to 7%.

A. Generation Efficiency

Efficiency losses in power generation, are the biggest issue facing the power industry today. Efficiency improvements can have broader impacts other than monetary gains for the plant operator. The overall measure of power plant efficiency comes from the heat rate (Btu/kWh); that is, the required thermal energy (in Btu's) to produce one kWh of electricity.

$$\eta_{th}(\%) = \frac{3412.75}{H_r} \times 100 \qquad (1)$$

By decreasing the heat rate, efficiency is improved and with it less fuel is consumed and less greenhouse gases are released. Increasing efficiency is believed by many to be the most effective strategy for reducing the impact on the environment from conventional power generation [3].

Typically, power plants operated near capacity will experience their most efficient heat rates. Plant cycling and low levels of operation will produce higher heat rates. Under competitive markets, it is expected that most plants that are dispatched will be operated at their most efficient levels [8].
There are cases where inefficiency is part of the operational strategies such as inappropriate power sharing between generators to minimize the cost. There are times when an operator is constrained to commit a particular generator, despite it being less economical, to meet demand requirements in some parts of the network and avoid a power congestion or a bottleneck. Congestion costs can be substantially high and adversely affects the efficiency of the grid. In 2005, the congestion costs amounted to $670 million as reported by the California Independent System Operator. In the next sections, we consider the major target areas where energy efficiency improvement can be implemented.

B. Power Plant Design

Plant designs based on natural gas or coal-fired power plants represent a trade-off between capital cost, efficiency, operational requirements, policy frameworks, price and security of supply. If efficiency is the goal, gas plants would come on top with heat rate of about 6000-6500 (Btu/kWh) leading to about 55% to 60% efficiency, while estimates for coal technology is 8000-11000 (Btu/kWh) with 37% to 44% efficiency.

Higher efficiency for new plants require higher pressure and temperature. This increases the cost of the plant as special

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alloy materials will be needed for the turbine and the boiler all at the expense of much higher capital cost. Technology improvements could assist by lowering the cost of these special alloy materials through discovery and better manufacturing processes.

C. Load Factor

In general, power plants operated close to their capacity will experience their most efficient heat rates. Plant cycling and low levels of operation for various reasons will produce higher heat rates, hence lower thermal efficiency. Under competitive markets, it is expected that most plants that are dispatched will be operated at their most efficient levels.

D. Ambient Conditions and Fuel Quality

Lower altitude, colder water and ambient air contribute to higher power plant efficiency, while at higher altitude, the low pressure affects the compression and expansion of gas/steam leading to turbine low power output.
Quality ranking fuels produce lower heat rates therefore leading to higher plant efficiency.

E. Environmental Emissions Control

Flue gas desulphurization (scrubber) and selective catalytic reduction (SCR), reduction of nitrogen oxide (NOx), and carbon dioxide (CO2), are increasingly on the up to comply with national and international greenhouse gas emission controls regulations. However, despite the obvious environmental benefits, such systems consume up to 2% of the overall energy generated and subsequently drop the overall efficiency of the plant. The efficiency loss of this parasitic load is for the right reasons to reduce greenhouse gases and preserve the environment in much the same way as good cholesterol is necessary to keep the human body healthy.

F. Cooling

The cooling water temperature as it enters the condenser has significant impact on the efficiency of steam plants. Higher temperature leads to an overall efficiency loss and vice-versa.

G. Upgrading of Existing Power Plants

Given that the average life span of a power plant is in the order of 40 years, it is more economical to opt for more efficient units when building a new power plant. Existing power plants may have been in operation for many years and therefore efficiency may have receded due to ageing of equipment, poor maintenance, running the system at incorrect operating parameters such as low pressure and temperature, unit controls not properly tuned, incorrect loading or off role operation where a system designed for base load is used for load following. Some plant design modifications can be undertaken to improve heat rates and in turn efficiency. In coal plants, an upgrade or refurbishment of turbine (e.g. nozzles), pulverisers, air heaters, burners, super heaters, condensers/heat exchangers, forced draft (FD) and induced draft (ID) fans can significantly restore efficiency close to new levels. The plant output may be reduced by as much as 2-8% due to FD/ID performance deficiencies. In extreme cases, a repowering option may be necessary, where the boiler is replaced by a combustion turbine (CT), or a new boiler.

H. Control and Instrumentation

Modern control techniques can provide better control of air, fuel and temperature during load tracking operations as well as during unit start up and shut down, resulting in lower stresses on boiler and turbine, improved pressure and temperature variations. Better control of FD and ID flow and pressure to match actual operating conditions can add significant improvement to the plant efficiency. For a combined cycle for instance, optimal control of inlet air temperature increases the mass flow rate and thereby increases the power output leading to higher efficiency of the cycle.

IV. Transmission and Distribution Efficiency Targets

Energy is often generated at power plants located away from the end-user site. Despite the fact that power is transmitted at extra high voltage the transmission and distribution (T&D) system power losses in advanced counties lie within the range of 6-11%. In some developing countries the T&D losses can reach a whopping 30% to 40%. The efficiency of a T&D system is related to power losses P_L incurred in the system. Efficiency can therefore be expressed as the ratio of the power available to the consumer P_O to the power injected into the grid P_{IN}. That is:

$$\eta(\%) = \frac{P_O}{P_{IN}} \times 100 = \frac{P_{IN} - P_L}{P_{IN}} \times 100 \qquad (2)$$

In monetary terms, suppose the yearly net energy generation in a certain country came to about 80.8 (TWh) or 80.8×10^6(MWh). At the lowest percentage loss estimate of 6%, the power transmission and distribution losses can reach 4848×10^6(kWh). At a rate of \$0.15/kWh, the yearly total losses amount to a conservative amount of \$727 millions.

Low efficiency as a result of higher losses can be attributed to technical reasons such as lines, cables and transformer losses, and nontechnical factors, namely pilferage, theft, and defective energy meters. Considering only the technical losses, T&D losses are largely due to transformer losses and the remainder is mainly due to cable and overhead line systems. Transmission transformers on high and extra high voltage are highly efficient (above 99.75%), while distribution transformers efficiency comes at 94-99%. Due to the shear number of distribution transformers, up to 2% of total power generated is estimated to be lost in distribution transformers, equivalent to nearly one-third of overall losses from the power system. Cables and overhead conductors amount to about 1% of total power generated. The following sections consider the critical targets for efficiency improvement and loss reduction in a transmission and distribution system, excluding end-user loads and appliances.

A. Power Transformers

To reduce core losses [5], [6], and in turn improve power transformers efficiency further, it is recommended to:

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*1) Select low core loss power transformers: r*esearch is still ongoing to shave a fraction of the iron core losses through better steel material, thinner lamination (0.1 micron or below), better steel cutting and manufacturing processes. Despite the very high efficiency of power transformers, there is still some further potential to obtain higher efficiency levels from improved material properties.

2) Use improved high permeability steel: grain oriented, laser treated (7mills lamina) and the new amorphous steel enabled the highest efficiency to be achieved with the least power loss [2] . In a study conducted [5] in Japan, it was estimated that 13 billion (kWh)/year, which amounts to about 1% of the nation's energy requirements, would be saved through replacing the existing 16 million distribution transformers with the amorphous type transformers.

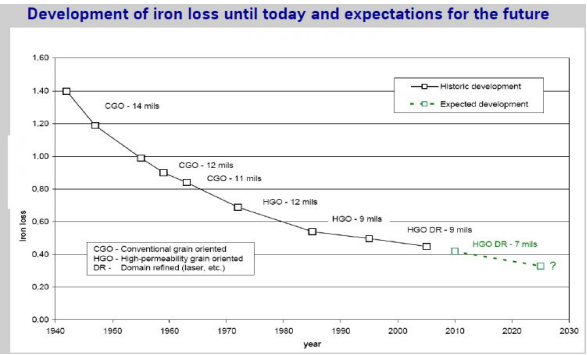


Figure 2. History of coatings on transformer core grain-oriented steel

3) Avoid transformers overvoltage: the core (iron) losses are highly dependent on the network voltage. A higher network voltage leads to higher core losses. For instance, 5% increase of the network voltage may cause 10-20% higher core losses, depending on the type of core material and the design of the transformer.

4) Avoid transformer loading: losses are relatively higher when transformers are lightly or heavily loaded. This means that there is considerable potential for energy saving with efficient transformers. Conductor losses slightly increase with the operating temperature of the transformer.

5) Act on poor power quality: Non-linear loads in the network will lead to harmonic current components in the transformer which add to losses. Transformer designs allows for some harmonic contents of the load current and harmonic effect is not taken into account, except in industrial or comparable installations with many distorting loads.

6) *Replace ageing transformers:* older transformers incur more losses and operate at lower efficiency.

B. FACTS Devices

The purpose of FACTS (Flexible AC Transmission Systems) devices is to control and maintain specific parameters of the electric power systems (typically reactive power and bus voltage) and provide a variety of benefits. Amongst such devices are:

1) Automatic Voltage Booster: the device boosts the voltage at its point of location in discrete steps. This, in turn, improves the voltage profile and reduces the losses in the section beyond its point of location towards the receiving end. A typical voltage booster has a total voltage boosts of 10% in four equal steps and the loss reduction is directly proportional to voltage boosts.

2) Capacitor Installations: capacitors connected across individual customers are traditionally used to boost the power factor. It is an effective method to reduce the amount of the current drawn from the supply while meeting the required kilowatt of the load, hence reducing the losses and aiding efficiency. This is generally achieved by connecting shunt capacitors across individual customers supply points.

3) SVC (Static VAR Compensators): are very high voltage devices that can dynamically control the utility's voltage at the point of common coupling. The role of a SVC is to keep the system voltage constant under all system operating conditions.

In general, a FACTS device's main benefit is its ability to increase line transmission capability, reduce system losses and therefore increase efficiency and reliability of the transmission grid. An inductive power system load (e.g. motor) requires reactive power for proper operation, which must be supplied by the source, increasing the current flow from the generator and through the lines, hence losses increase affecting system efficiency.

If reactive power is supplied near the load by a FACTS device, the line current is minimized, reducing power losses and improving efficiency. In addition to the efficiency gains, these devices also deliver a clear reliability benefit. Improving transmission capacity is also vital for the integration of renewable energy such as wind and solar which are often located far from the loads they must serve. For this reason, the cause of efficiency in the T&D system is in perfect alignment with the trend of expanding and integrating renewable energy generation and using FACTS improved grids to transport and distribute power.

C. Smart Grids and Demand Response

Smart grids are simply electricity networks with advanced communication technologies to monitor and manage the flow of energy from the source to meet the varying demand of the end-user. Smart grid technologies offer a more energy efficient and cost effective solution to the problem of aging grids, demand growth and grid integration of renewable resources. Smart grids advanced control technology can be precisely set to reduce losses, eliminate network overloading, and select the least cost power delivery plan to operate efficiently.

Of particular importance is the demand response enabled by smart grids whereby industrial or residential end-users alter consumption in response to price or other signals. Significant emphasis is being given to the impact of the demand side on improving efficiency through demand side management programs. Utilities are taking advantage of communication enabled smart grid meters and energy management systems to facilitate greater interaction and flow of information between the customer and the utility. This enables the consumer to take full advantage of the electricity market by responding to peak and off-peak price signals and consumption patterns.

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Smart grids deployment through communication enabled smart metering and energy management systems has promoted demand response approach to increase demand side participation and shift the focus from the generation response side to the end-user side. As such, optimised consumption of power is achieved through price incentives and timely usage. Demand response approach is a recent area of research to achieve further energy savings for the consumer and help utilities reach their energy efficiency targets.

D. Buildings Efficiency

Buildings consume about 40% of the world's energy and are responsible for nearly the same amount of emitted carbon [7], putting them higher than the transportation or industrial sectors. Technology exists to substantially reduce energy usage in buildings through demand response approaches. The best approach is to institutionalize energy management and conservation in all energy-consuming sectors, such as schools, commercial and industrial establishments. The "Better Buildings Initiative" adopted by many countries is the way forward to ensure commercial buildings use energy more efficiently. In modern buildings, heating and cooling are the most energy intensive activities, followed by electricity use for lighting, appliances and other services.

Efficiency should be an integral part of building design unless added in the course of a refurbishment. At the design stage, the use of appropriate construction material, selection of the most efficient equipment such as efficient boilers, pumps and chiller systems (e.g. VSDs, efficient motors), lighting system (e.g. compact and LED lights), adequate insulation and glazing (e.g. advanced electro-chromic windows which can be darkened or lightened electronically) would cut down substantially on the building running cost. A major efficiency boost would come from monitoring and measurement, energy audits and demand response schemes whereby energy consumption patterns are identified, building temperature, air circulation and lighting are kept at appropriate levels or modified accordingly to save energy for the consumer and reduce peak demand for the electricity. Buildings can be fitted with a range of energy-efficient technologies such as presence detection sensors and light sensing receptors that ensure less lighting is used near windows. Solar panels and mini wind turbines can be attached to the roofs and walls of buildings to generate electricity and become part of the smart grids that can sell electricity to the grid under light load and reduce usage at peak times.

V. Conclusions

With current power generation efficiency being in the range of 37 to 60 percent at best, there is a tremendous amount of energy wasted in the generation process and as such, there are ample economic and ecological incentives to improve the efficiency of conventional power generation. At the transmission and distribution level, where at least 6 to 11 percent of the electricity generated worldwide is lost, relentless technological efforts are being made to regain anything from the prevailing energy losses and subsequently achieve further efficiency gains through upgrading the ageing power grid transmission and distribution infrastructure, the use of more energy efficient equipment and enhanced grid voltage control. At the consumer level, efforts are concentrated on eco-features and sustainable building design, smart grids and more sustainable solutions that support demand response and energy management applications for homes and business buildings. Extensive research and development and many pilot projects are underway to achieve further efficiency gains in the distribution network with the help of smart technologies and the application of demand response techniques.

Invariably, there is a major role for renewable energy in the future as it develops into a cost effective alternative, with further improved efficiency and sustained investment. However, to date, improved efficiency, the proliferation of smart grids with demand response systems, upgraded building services, efficient equipment and appliances, can reduce peak demand and bring significant energy savings. Subsequently, this reduces our heavy reliance on fossil fuels for energy needs providing a sustainable present and a smoother transition to a cleaner, healthier, and more sustainable energy in the future.

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