The Role of Physics in Improving the Efficiency of Electricity Generation and Supply

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Acknowledgements

Executive summary

1: Introduction
   1.1: GHG emissions from electricity supply
   1.2: Reducing GHG emissions from electricity supply

2: Improving generating efficiency
   2.1: Improving power-plant efficiency
   2.2: Improving turbine design

3: Improving the transmission and distribution network
   3.1: Introduction
   3.2: Reducing power losses

4: Conclusions

Glossary

References
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Executive summary

There is an increasing acceptance that we need to accelerate our efforts to reduce emissions of greenhouse gases (GHGs) if we are to avoid significant climate change. The energy-supply sector is the largest source of GHG emissions globally, due mainly to carbon dioxide (CO₂) released from the combustion of fossil fuels for the production and supply of electricity, and in 2002 it accounted for a third of all GHG emissions. Developed industrial countries have historically emitted by far the greatest amounts of GHGs, but now demand for fossil fuels is increasing rapidly in newly industrialised countries, such as China. By 2004, China was producing 19% of the world’s fossil-fuel-based CO₂ emissions, almost half of which was a by-product of electricity and heat generation. Reducing emissions from the electricity-supply sector must therefore form a central plank of any climate-change strategy.¹

Approaches to reducing CO₂ emissions from electricity supply must cover both demand and supply. On the demand side, improvements in the efficiency of electricity use will be important. On the supply side, there are four broad ways in which the carbon intensity of electricity production can be reduced:

- by improving the efficiency of conventional fossil-fuelled plants, including the adoption of combined heat and power (CHP), where opportunities exist;
- by improving the efficiency of electricity transmission and distribution;
- by switching to lower-carbon fossil fuels, such as gas, and using low-carbon renewable energy and nuclear technologies;
- by using carbon capture and storage (CCS).

This report examines the contribution that physicists and physics-based research are making to improve the efficiency of conventional fossil-fuel-based electricity generation, to reduce energy losses from the transmission and distribution system, and to facilitate the integration of renewable-energy systems into the supply network. However, it does not discuss the efficient use of electricity.

In considering the contribution of both physics and physicists, it should be remembered that physics can be defined as “the science of the properties, other than chemical, of matter and energy”. Ideas and techniques from physics drive developments in a multitude of disciplines, including computing, electrical and mechanical engineering, materials science and electronics. Physicists can apply problem-solving techniques, and skills such as mathematical modelling, to a variety of situations.

Improving generating efficiency

In a conventional (i.e. electricity-only) coal-fired plant, combustion heat is used to produce superheated steam that drives a series of steam turbines, which in turn generate electricity. Such power plants have a generating efficiency for electricity of only about 35%. One of the key ways in which this efficiency can be improved is by increasing the temperature difference between steam entering and exiting the turbines, which increases the thermodynamic efficiency of the process. This has been achieved through the development of supercritical boilers, which have a generating efficiency for electricity of up to 45% and, more recently, ultrasupercritical boilers. Ongoing research aims to develop power plants that operate at even higher temperatures to raise the efficiency for electricity generation to more than 50%. Physicists are supporting such developments in a variety of ways, including developing materials suitable for use at such high temperatures.

It is important to note that the so-called waste heat from the thermal generation of electricity can become useful in CHP, as considered in the body of this report.

In both coal-fired and combined-cycle gas-turbine (CCGT) plants, the efficiency with which turbine blades extract energy from steam or hot gases is an important factor in the overall efficiency of the power plant. Sophisticated modelling of blade geometry in turbine design continues to deliver significant efficiency improvements by refining the shape and orientation of the blades.

Increasing the temperature that turbine blades can withstand allows the temperature difference between incoming exhaust gases and outgoing gases in the turbine to be increased, and thus increases the electricity-generation efficiency. The development of superalloys and thermal barrier coatings has enabled turbine blades to withstand even higher temperatures. Research to develop these materials and in particular to improve the strength of superalloys continues. Optical pyrometry, a technique that uses thermal (infrared) radiation to determine the temperature of turbine blades, has enabled improved efficiency through greater control of the turbine firing rate.

Transmission and distribution networks

About 7% of the power supplied to the UK grid is lost before delivery, mostly (80%) from the lower voltage distribution systems. These losses account for the emission of an additional 14 Mt CO₂ at power plants. Opportunities to improve the efficiency of the alternating current (AC) system by reducing resistance, however, are limited by practical and economic factors. Shortening transmission distances and increasing the

¹ Based on the most recently available figures from http://calt.wri.org.
cross-sectional area of wires in the current system would involve the widespread replacement of existing infrastructure, which would be costly and have its own associated inefficiencies. Instead, the focus of research in this area is on developing cables with reduced resistance and improved capacity for new applications.

High-temperature superconducting cables potentially offer a way of transmitting electricity with low losses, although there is an energy penalty from the cooling necessary for superconducting behaviour, meaning that the most suitable applications are likely to be long-distance transmission lines. There is a large amount of physics research in the development of new materials that exhibit superconductivity at higher temperatures so that less cooling is required, and also in developing a theoretical understanding of how high-temperature superconductivity arises. There is also considerable interest and research in using high-temperature superconductors to improve the efficiency of motors and transformers in the supply system, which could ultimately deliver significant CO₂ savings.

Finally, an increased penetration of distributed power generation, much of which is based on low-carbon technologies, such as microgeneration CHP and photovoltaic panels on domestic and commercial buildings, is likely to lead to increasingly higher fault current levels, and controlling these will be essential to maintaining the control and stability of the network. Fault current limiters based on high-temperature superconductors are being developed that instantaneously limit or reduce unanticipated electrical surges that occur on distribution and transmission networks.

Conclusions
The principles of physics underpin all aspects of electricity generation and supply, so physics research into technological improvements will play a vital role in reducing GHG emissions from the electricity sector. This report highlights significant developments in the areas of steam-generation efficiency and turbine design in thermal power plants; the efficiency of transmission and distribution networks; and the role of physicists in facilitating the integration of renewables and other distributed generation systems into the electricity network.
1: Introduction

There is now little doubt that the increase in global average temperatures observed since the mid-20th century is due to increasing atmospheric concentrations of GHGs.[1] Global atmospheric concentrations of certain GHGs – CO$_2$, methane (CH$_4$) and nitrous oxide (N$_2$O) – have increased markedly as a result of human activities since 1900 and now far exceed pre-industrial levels. Global emissions of GHGs increased by 70% between 1970 and 2004. Despite current climate-change mitigation policies and related sustainable-development practices, emissions are likely to grow over the next few decades, inducing further changes in the global climate system that will very likely be more significant than those observed during the 20th century.[1]

As a signatory to the Kyoto Protocol to the United Nations Framework Convention on Climate Change, the UK has committed itself to reducing its GHG emissions to 12.5% below 1990 levels by 2012. Global negotiations have already begun to develop a successor to the Kyoto Protocol, which will contain targets for post-2012, but the UK has also begun to consider future domestic targets. The 2007 Energy White Paper, “Meeting the energy challenge”[2] proposed more substantial reductions in the longer term – CO$_2$ emission reduction of 26–32% by 2020 and of 60% by 2050. These targets will be made legally binding in the Climate Change Bill.[3] The European Union (EU) is considering longer-term targets. It has already committed itself to reducing GHG emissions by 20% from 1990 levels by 2020, and by 30% if there is an international agreement committing other developed countries to comparable reductions and efforts from other “advanced developing countries”.[4]

The Stern Review for the UK government on the economics of climate change found that “If we do not act, the overall costs and risks of climate change will be equivalent to losing at least 5% of global GDP each year”, while “the costs of action [now]...can be limited to around 1% of global GDP each year.”[5] Although the costs are subject to uncertainty, many organisations, including those in industry, have called for an acceleration in the pace and scale of technological solutions to climate change.[6]

This report examines the supply of electricity and the contribution that physicists and physics-based research are making, through technological improvements, to reducing CO$_2$ emissions from the electricity sector. It looks both at how physicists are contributing to improving the efficiency of conventional fossil-fuel-based electricity generation, and at changes in the transmission and distribution system that may be necessary to allow the introduction of more low-carbon renewable-energy technologies.3

1.1: GHG emissions from electricity supply

The energy-supply sector is the largest source of GHG emissions globally, due mainly to CO$_2$ released from the combustion of fossil fuels for the public supply of electricity and heat. In 2002 it accounted for 45% of global CO$_2$ emissions or a third of all GHG emissions (figure 1.1). In the UK, public heat and electricity supply accounted for 185 Mt CO$_2$ or 33% of total CO$_2$ emissions in 2006, and in the US 2349 Mt CO$_2$ or 39% of total CO$_2$ emissions.[7]

While per capita emissions in rapidly industrialising countries are currently much lower than in, say, the UK and the US (figure 1.2), they have been growing rapidly (particularly in the case of China) and are forecast to continue to do so (figure 1.3). This will include significant growth in emissions from electricity generation because electricity demand, which has been sharply increasing, is forecast to continue rising substantially. By 2004, China was already producing 19% of the world’s fossil-fuel-based CO$_2$ emissions, almost half of which came from the generation of electricity and heat.[8]

Figure 1.1: Breakdown of global GHG emissions (35 865 Mt CO$_2$ equivalent) in 2002. Source: [8]

<table>
<thead>
<tr>
<th>GHG</th>
<th>Percentage</th>
</tr>
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<tbody>
<tr>
<td>CO$_2$</td>
<td>73%</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>17%</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>9%</td>
</tr>
<tr>
<td>HFC</td>
<td>1%</td>
</tr>
<tr>
<td>SF$_6$</td>
<td>0%</td>
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<tr>
<td>PFC</td>
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<tr>
<td>N$_2$O</td>
<td>9%</td>
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<td>CH$_4$</td>
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2 The UK has now committed to cutting GHG emissions by 80% of 1990 levels by 2050.
3 This report does not discuss the efficient use of electricity.
4 The majority of these emissions are associated with electricity generation because there is little public heat supply in these countries.
1.2: Reducing GHG emissions from electricity supply

Approaches to reducing CO₂ emissions from electricity supply must consider both demand and supply. The demand for electricity can be reduced by using more efficient appliances and devices, load management, and using less direct electrical heating. On the supply side there are four broad ways in which the carbon intensity of electricity production can be reduced:

- by improving the efficiency of conventional fossil-fuelled plants so that (a) more electricity is generated per unit of CO₂ produced and (b) more otherwise “waste” heat from the generation process is used via CHP technology;
- by improving the efficiency of electricity transmission and distribution;
- by using fossil fuels with greater heat production per unit of carbon, such as natural gas, and replacing fossil-fuelled plants with renewable-energy and nuclear power plants, which have very low GHG emissions;
- by using CCS, where CO₂ from fossil-fuel combustion in fossil-fuelled plants is captured and then transported to a suitable permanent storage site.

Section 2 of this report examines ways in which the efficiency of conventional electricity generation has been improved and further advances that may be made. Section 3 focuses on the contribution that physics and physicists might make to improving the efficiency of electricity transmission and distribution. It also looks closely at the changes in the transmission and distribution networks that may be necessary if there is to be large-scale adoption of distributed forms of low-carbon electricity generation (e.g. micro-CHP and some renewable-energy technologies), and renewable energy technologies sited in locations that are remote from the grid.
2: Improving generating efficiency

Ever since the first large-scale thermal power plants were built in the 1930s, the generating efficiency of new power plants has been progressively improved. Initially driven by the need to reduce the per unit cost of producing power, these developments are now important for decreasing the CO₂ emissions per unit of power generated. They generally result from design improvements to coal-fired plants, from CHP and, more recently, from the introduction of CCGT plants.

2.1: Improving power-plant efficiency

2.1.1: Coal-fired plants

In a conventional coal-fired plant, the heat produced is used to generate superheated steam (box 2.1), which drives a series of steam turbines to produce electricity. Such basic power plants typically have a generating efficiency (electrical energy output/heat energy input) of 36–38%. The overall efficiency of the power plant can be improved by utilising the waste heat (if there is a demand for it). CHP plants are discussed in section 2.1.3.

The generation efficiency of the power plant can be improved by increasing the temperature difference between steam entering and exiting the turbines, because this increases the thermodynamic efficiency of the process, allowing more “work” to be extracted from the steam. This is explained by the physics of the ideal Carnot cycle (box 2.2), where the efficiency of the cycle depends directly on the temperature difference between the hot reservoir (where heat enters the process) and the cold reservoir (where heat leaves the process).

In practice, an increased temperature difference between steam turbine entry and exhaust (achieved by raising the temperature of the former) has been accomplished by using supercritical boilers, which operate at pressures above the critical point of water. In physics, a critical point specifies the conditions (temperature and pressure) at which the difference between liquid and vapour states of matter ceases to exist (figure 2.1). For water, this arises at high temperature and pressure (374 °C and 22.1 MPa). Below the critical point, water density decreases as it is heated, while the pressure and density of the water vapour being formed increases. At the critical point the densities are equal. In contrast, above the critical point (in the supercritical range), water no longer gradually changes state from liquid to steam but instead decreases in density when heated because it has become a supercritical fluid.

The efficiency of the steam-generation process is improved by avoiding the phase change from liquid to vapour, where energy is required to break intermolecular bonds in the liquid. All of the heat added to the system can therefore contribute to raising the temperature and pressure of the fluid. Such power plants typically have an efficiency of 40–45%.

Further efficiency improvements can be gained by raising the temperature of the steam even further in an ultrasupercritical boiler. This operates using steam conditions even further above the critical point than supercritical plants and therefore achieves greater temperature differences across the turbine. To date, 24 ultrasupercritical plants have been built worldwide, and some industry stakeholders envisage that they will become the technology of choice for new coal-fired plants in the medium term.

However, some countries, notably the US, are far from convinced and favour other clean coal technologies, such as clean coal technologies (CCTs), which are discussed in section 2.1.4.

Figure 2.1: Critical point and phases of water.

Box 2.1: Superheating

Superheating is the process whereby a liquid is heated to a temperature higher than its standard boiling point at high pressure, preventing it from boiling. In power plants the steam generated by the boiler is superheated again, increasing its thermal energy and decreasing the likelihood that it will condense inside the turbine. Superheating increases the electricity-generation efficiency of a power plant.

Box 2.2: The Carnot cycle

The most efficient concept of a heat-engine cycle is the Carnot cycle. This consists of two isothermal processes (one corresponding to the heat-in process, the so-called “hot reservoir”, and the other corresponding to the heat-out process, the so-called “cold reservoir”) and two adiabatic processes. These conceptual processes would take infinite time at constant entropy without friction and, if possible, would therefore be reversible. However, the Carnot cycle is an ideal, since no real engine processes are reversible and hence all real physical processes involve some increase in entropy.

Generating efficiency is the energy of the electricity generated divided by the energy content (enthalpy) of the fuel combusted. It can be gross efficiency based on the amount of electricity generated or net (i.e. the amount of electricity exported from the power plant) after allowing for parasitic losses (i.e. electricity used by the power plant). It is also important to state whether it is based on the low or high calorific value of the fuel (i.e. whether water leaves the system as vapour or liquid). Values stated in this report are based on the low calorific value of the fuel (i.e. water exits as vapour), so the latent heat is not recovered.
2. Improving generating efficiency

such as integrated gasification combined cycle (IGCC) and pressurised fluidised-bed combustion. A recent report by the US Environmental Protection Agency [12] comparing IGCC with subcritical, supercritical and ultrasupercritical coal-fired plants found that, while the generating efficiencies of ultrasupercritical plants were similar to those of IGCC plants, emissions of air pollutants and volumes of solid waste generated from the IGCC plants were lower. Capital costs for the IGCC plants were estimated to be higher, but CO2 could be captured and sequestered at significantly lower cost, which would improve the relative economics under higher-carbon-price scenarios.

The efficiency of coal-fired steam-turbine generation can be improved further by pushing steam conditions significantly beyond the temperature and pressure of ultrasupercritical plants (600 °C, 30.5 MPa).[13] The EU-funded AD700 research programme aims to raise the net efficiency of coal-fired steam-turbine plants above 50% with a steam temperature of 700 °C and a pressure of 35–37.5 MPa (350–375 bar).[14] To date, the project has demonstrated that these efficiencies are technically achievable,[14] but the commercial feasibility of the technology will depend on developing materials that are suitable for use at such high temperatures, such as nickel-based alloys. One of the proposed applications for the nickel-based alloys is “double-shell” steam piping – a concept developed and patented by the energy services company Doosan Babcock Energy. The inner surface of the pipe that would be in contact with the steam is made from a thin, high-strength, highly temperature-resistant (but costly) nickel alloy, while the outer shell is made from cheaper steel.[14]

2.1.2: Gas-fired plants

In an open-cycle9 gas-fired turbine, the gas is burned

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7 These are average values, calculated using the typical generation efficiencies and the carbon emission factors given in Table 2.2. Formula: CO2 emission (g CO2/kWh) = 3.6 × carbon emission factor (t C/TJ)/typical generation efficiency.
8 Pressure of 30 MPa and dual-stage reheat.
9 “Open” means no recycling of materials or heat.
2: Improving generating efficiency

Parameter data for 2008

2: Improving generating efficiency

Box 2.3: The NuGas concept

In normal CCGT operation a secondary steam turbine is powered using steam produced by boiling water with the heat recovered from the hot exhaust gases from the gas turbine. In the NuGas cycle, however, the steam turbine in the CCGT plant is powered by steam taken from the nuclear steam cycle, which is then superheated using the exhaust heat from the CCGT (figure 2.3). This is thermodynamically more efficient and gives a greater electrical output from the steam turbine. While “borrowing” a proportion (typically 10–15%) of the steam from the nuclear steam cycle reduces the electrical output from the nuclear power plant, this is more than made up for by the increased output of the CCGT plant. The otherwise waste heat in the gas turbine exhaust gases below about 300 °C is recovered to heat the feedwater in the nuclear cycle, helping to improve the efficiency of the combined system.

For a CCGT plant capable of operating at a typical efficiency of 57%, use of the NuGas cycle should increase total plant electricity-generating efficiency to more than 63%, significantly higher than even the most ambitious forecasts for advanced gas-turbine-based developments (figure 2.4). Using a higher performance gas turbine would increase the NuGas efficiency further, since its advantage lies in the enhanced thermodynamic performance of the steam cycle within the CCGT.[15]

Figure 2.3 (top right): NuGas concept. Source: PB Power.

Figure 2.4 (bottom right): The generating efficiency of nuclear, coal and CCGT plants. Source: PB Power.

in a combustion chamber with compressed air and the resulting flue gases drive a turbine. A significant proportion (up to 50%) of the energy content of the fuel is contained in the hot exhaust gases, which are expelled to the atmosphere. Therefore, the efficiency of electricity generation can be improved dramatically by using the heat from these to produce steam (in a heat-recovery steam generator [HRSG]). This drives a secondary steam turbine, with around 70% of the generated electricity coming from the gas turbine and around 30% from the secondary steam turbine.[16] The overall efficiency of the CCGT plant can be improved even further (towards 90%) if it is operated as a CHP plant (figure 2.2), and the waste heat from the secondary steam turbine is recovered and used to supply a heat load.

Typical generating efficiencies and CO$_2$ emissions per unit of electricity (kWh) from the coal and gas technologies discussed above are shown in table 2.1. CCGT plants have lower CO$_2$ emissions (per kWh) than coal-fired plants, mainly because natural gas is a less carbon-intensive fuel than coal (i.e. it contains less carbon per unit of heat content), but also because of the higher generating efficiency of CCGT plants. The amount of CO$_2$ released when coal, gas and other fuels are burned is shown in table 2.2 (in terms of CO$_2$ per unit of energy released from the fuel, on a net calorific value [NCV] basis). The development since the early 1990s of CCGT plants by privately owned power companies in the UK has been responsible for a significant reduction in the carbon intensity of UK electricity generation and in CO$_2$ emissions from the electricity sector.

An interesting concept to raise the efficiency of CCGT plants further has been developed by the UK company PB Power. A CCGT plant is linked to the steam produced by a pressurised water reactor nuclear power plant to create a high-efficiency hybrid system called NuGas (box 2.3). This could also be used to increase the efficiency of nuclear power plants. The system typically
Section 2: Improving generating efficiency

### Box 2.4: Turbine blades

The blades in a gas or steam turbine are aerofoils. As the combustion gases or steam (the fluid) flows past them, it must travel more quickly above the aerofoil than below. According to the Bernoulli principle, the fluid that is travelling faster is at a lower pressure than the fluid below the blades, and this pressure difference across the blades causes a force on them (lift) perpendicular to the flow. The blades are oriented in such a way that a component of this force acts to rotate them, as in wind turbines (Figure 2.5).

The Bernoulli principle states that the pressure of a fluid decreases when its velocity increases (assuming that its gravitational potential remains the same and no energy enters the flow).

**Figure 2.5: The motion of fluid around an aerofoil and the resultant force. Source: Dirac Delta 2006 Science and Engineering Encyclopaedia.**

### Box 2.5: Fluid modelling to improve turbine design

Physics modelling is used to investigate the improved efficiency of turbine stators and rotors design. Figure 2.6 is a schematic of the fluid movement through turbine blades (from left to right). The colour corresponds to flow speed. The fluid speeds up through the first stator passageway, slows down through the rotors, where the passageway diverges, then speeds up even more through the second stage of different-shaped stators.

Experiments carried out in the 1980s showed that changing the relative circumferential position (corresponding to the vertical position of the blades in Figure 2.6) of neighbouring rows of blades could increase the efficiency of turbines and compressors by up to 2%.[19] This increase translates into around £3.5m additional annual profits or savings for a large coal-fired plant,10 and annual savings of around 50 kt CO₂.

The change of the relative circumferential position of neighbouring rows of blades is called “clocking”. This concept can be applied to stationary blades, which is known as vane-vane clocking, or to rotating blades, which is known as blade-blade clocking.

**Figure 2.6: Fluid flow through turbine blades. Source: Pittsburgh Supercomputing Center.**

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10 Based on the output of a 2 GWe coal-fired plant operating at a 66% load factor, within a vertically integrated company supplying electricity to industrial users at £60 per MWh.
2.2: Improving turbine design

In a power plant, the efficiency with which turbine blades extract energy (as work) from steam or other hot gases (box 2.4) is an important factor in the overall efficiency of power generation. There is thus a considerable amount of research into turbine design. For example, modelling the flow of fluids around the blades has been used to improve the shape and placement of the turbine blades (box 2.5), leading to increases in power-plant efficiency of the order of 0.5%. This increase is large by rotating-machinery standards, where even an extra 0.3% is considered significant. Such an improvement in efficiency could result in around £3.5m additional annual profits or savings for a large coal-fired plant\(^1\) and annual savings of around 50 kt CO\(_2\). Increasing the temperature that turbine blades can withstand allows a greater temperature difference between incoming exhaust gases and outgoing gases in the turbine, and thus increases the electricity-generation efficiency. Over recent decades there has been a significant amount of physics-based research into materials that will allow turbine blades to operate at higher temperatures. Techniques that have been developed include manufacturing the blades from specially designed superalloys and making use of thermal barrier coatings (TBCs).

Superalloys are metallic alloys that often exhibit excellent resistance to creep and oxidation (and therefore maintain their strength and shape for longer). Creep in the blade can result in it making contact with the casing and then failing, so the use of superalloys prevents the deformation and failure of blades.\(^{22}\) Thermal barrier coatings consist of two layers: the outermost thermal barrier, which is made of a ceramic and thus has a very low thermal conductivity; and a bond coat that serves the dual purpose of providing oxidation resistance and helping the outer coating to adhere to the turbine blade. Despite being less than 1 mm thick, TBCs enable a temperature difference of 100–300 °C\(^{23}\) between the working fluid and the metal surface of the turbine blade, allowing an increase in gas temperature of up to 110 °C and a corresponding increase in temperature across the turbine. In many instances superalloys and TBCs are used in tandem. Research being carried out at Queen Mary, University of London to understand and improve the strength of superalloys is described in box 2.6.
Box 2.7: Optical pyrometry

Traditional operating methods in fossil-fuelled plants rely on indirectly measured and calculated parameters to define maintenance schedules and control gas-turbine operation. By continuously and accurately monitoring the temperature of individual blades in the high-temperature section of a gas turbine, optical pyrometry offers a major leap forward in the control and operation of gas turbines. Using this information it is possible to refine predictions of blade life, detect abnormal blade conditions and assess the effect of abnormal operation. With this real-time data the operator can improve gas-turbine efficiency by up to 1% and reduce maintenance costs by optimising maintenance scheduling.[24]

Power utility companies and gas-turbine manufacturers are seeing many benefits from these measurements. These include improved efficiency through turbine firing-rate control, improved maintenance procedures from the development of blade-life management programmes and the prevention of blade failure by detecting blocked cooling channels in blades.

Optical pyrometry makes use of thermal radiation. This is the electromagnetic radiation emitted by an object as a result of, and corresponding to, its temperature.[25] At the turbine-blade operating temperature range, optical pyrometry detects infrared radiation from the blades, which is then compared with a known (calibrated) reference to determine the temperature of the blade (figure 2.9). The data obtained from the optical pyrometry measurements are output in the form of a temperature trace, such as that shown in figure 2.10.

Figure 2.9 (above): Optical pyrometer penetration in a gas turbine. Source: Amory and Hovan.

Figure 2.10 (left): Optical pyrometric trace of a turbine, highlighting the hot blade (number 14). Source: LAND Instruments International.

Physics-based research has also led to the improved control of gas turbines. The design of optical pyrometry instruments for the continuous monitoring of the temperature of turbine blades has allowed improvements in operating efficiency of up to 1% (box 2.7).
3: Improving the transmission and distribution network

3.1: Introduction

Historically in the UK, electricity has been generated in large centralised power plants and then transmitted as AC at high voltage to areas of demand, before being stepped down to a lower voltage for distribution to consumers (figure 3.1 and box 3.1). This transmission and distribution system was designed for one-way power flow from the power plant to the consumer and it uses passive distribution networks that have very little built-in intelligence. [26] However, many low-carbon generating options, which the UK will need to encourage if it is to reduce CO2 emissions from electricity supply, place different requirements on the network. Large wind- or wave-power schemes, which need to feed into the high-voltage transmission network, may be located in remote locations far from areas of demand and in some cases far from the transmission grid. Microgeneration sources would need to feed into the low-voltage distribution network (figure 3.2). In addition, certain renewable sources generate intermittently and their large-scale application would require greater use of intelligent networks.

Transmission of power by direct current (DC) has advantages and disadvantages. One disadvantage is that voltage transmission is more complex, demanding powerful electronic components. A major advantage is that more power can be transferred per unit cross-section of cable and there are no inductive losses.

Box 3.1: The UK electricity grid

The electricity generated at the centralised power plant is AC at relatively low voltage (~400 V). Power losses decrease with increasing voltage (for a given power transmission), so the voltage is stepped up (increased) using a transformer before being transmitted to the areas of demand using the high-voltage (typically 400 kV and 275 kV) [27] transmission network. The UK network consists predominantly of 7240 km (4500 miles) of overhead line and 660 km (410 miles) of underground cable [27] for AC power. The only DC cables are on interconnectors.

Substations contain transformers to “step down”, or reduce, the voltage for safe distribution on lower lines in the distribution network, before stepping down again through further transformers to 33 kV, then 11 kV and finally to 240 V in the local network for supply to small-scale consumers. Larger industrial users may be supplied directly from the distribution network.

Microgeneration technologies, such as micro-CHP or photovoltaic panels in domestic and commercial settings, will need to be able to export surplus power into the low-voltage distribution network. This means that the network must be able to deal with reverse power flows. This will require more active management of the network, additional monitoring and control equipment.
3. Improving the transmission and distribution network

and, if there is widespread deployment, strengthening of the local and distribution networks.

This part of the report examines some areas in which physics-based research and physicists can contribute to the reduction of losses in the current distribution system, developments in DC transmission technology, enabling the integration of distributed forms of low-carbon electricity generation and the integration of large-scale renewables into the transmission system.

3.2: Reducing power losses

In 2006, power losses from the UK grid are estimated to have been 29,000 GWh or about 7.1% of electricity supplied to the grid. The majority (80%) of these occurred in the lower-voltage distribution networks; the high-voltage transmission system accounted for only 20% of power losses. At a generating cost of £40/MWh, this represents financial losses of about £1 billion per year or, with the current fuel mixture, approximately 14 million tonnes of CO₂.

3.2.1: Reducing resistive losses

Resistive power losses in the transmission and distribution networks are proportional to the resistance of the power lines, which depends on the length, cross-sectional area and material used for the cable. Potential options for reducing these resistive losses are:

- Shortening existing power line routes is rarely cost-effective, but in the future the use of embedded generation and microgeneration will reduce the distance over which power must be transported.
- Increasing the cross-sectional area of transmission and distribution lines is not cost-effective for the current network due to extra material costs, the cost of replacing cables and the potential requirements to strengthen towers to support extra cable weight.
- The development of new materials is an area where physicists are working to reduce resistance and increase capacity. The majority of power lines are at present made of strands of aluminium alloy, reinforced with steel strands for strength (aluminium conductor steel-reinforced cable). Changing the arrangement of individual strands and the overall shape of the cable can also help to reduce power losses.
- Using DC transmission (section 3.2.2).

Induced power losses occur in cables with a metal sheath around them due to the induction of an alternating magnetic field in and around the sheath. Similarly, inductive losses occur in the pipe of pipe-type cables. These losses do not occur in DC lines.

3.2.2: High-voltage DC lines

For renewable-energy options such as wind, wave and tidal power, the location of the power plant is determined by the availability of the physical resource and may be far from the locations where the power will be used. For example, in the UK there is substantial wind resource in remote parts of Scotland, far from areas of high power demand in southern and eastern England, and much of the marine resource is off the north-west coast of England. More broadly, China and India have large reserves of hydropower located in sparsely populated regions, up to 2000 km away from where power is generated.

Figure 3.2: An electricity system with distributed generation from small-scale power plants. Source: [16]
needed. The potential use of the large solar resource in north Africa and the Middle East, for instance through the use of concentrated solar power, similarly depends on transmitting the power to centres of population in the region, and potentially to Europe.

One option for the bulk transmission of power from remote sites is the use of high-voltage DC (HVDC) power lines, which have lower power losses than conventional AC transmission systems. This is particularly true for long, undersea cables, which have a high capacitance. In these, current required to charge and discharge the capacitance of the cable causes additional power losses\(^1\) in AC systems.

Another advantage of HVDC systems is that they take up less physical space. That is because for a given power rating the constant voltage in a DC line is lower than the peak voltage in an AC line, where there is a varying current. The voltage determines the insulation thickness and conductor spacing required, with higher voltages needing greater spacing, so an HVDC system can be more compact. Furthermore, DC lines require two cables rather than three. This means that HVDC systems can be used where space is limited. In addition, for long-distance transmission lines, the land corridor needed is less than that for an equivalent AC system.

While the cost of the HVDC line itself may be cheaper (using two cables rather than three), the additional equipment required for high-voltage rectification and inversion in HVDC systems is costly. Over long distances, however, some of these additional costs are offset by savings in operating costs from the reduced power losses, making HVDC more attractive.

HVDC systems have been installed in a number of places across the world (table 3.1 and figure 3.2), transmitting power across distances of up to 1000 km at voltages of as much as 600 kV. To increase the distance over which it is economic to carry the power (e.g. 2000–3000 km), it is proposed to move to ultra-HVDC, at 800 kV. This has been made possible by research in a number of areas:\[^{28}\]

- the development of new materials (plastics) suitable for use as insulators at a higher voltage in an outdoor environment;
- refined measuring techniques using advanced laser technology to determine the characteristics of insulating materials and systems;
- advanced control systems.

### Table 3.1: Details of HVDC systems across the world

<table>
<thead>
<tr>
<th></th>
<th>Year</th>
<th>kV</th>
<th>MW</th>
<th>km</th>
</tr>
</thead>
<tbody>
<tr>
<td>India – Rihand power plant to Dehli</td>
<td>1990</td>
<td>500</td>
<td>1500</td>
<td>814</td>
</tr>
<tr>
<td>Brazil – Itaipu hydropower plant to San Paulo</td>
<td>1987</td>
<td>600</td>
<td>6300</td>
<td>800</td>
</tr>
<tr>
<td>Phillipines – Leyte geothermal power plant to Manila</td>
<td>1998</td>
<td>350</td>
<td>440</td>
<td>451</td>
</tr>
<tr>
<td>Australia – Tasmania to mainland – underwater cable</td>
<td>2006</td>
<td>600</td>
<td>290</td>
<td></td>
</tr>
<tr>
<td>China – Three Gorges hydropower plant to Shanghai</td>
<td>2006</td>
<td>500</td>
<td>3000</td>
<td>1060</td>
</tr>
</tbody>
</table>

As well as contributing to such research, physicists are making important contributions to the development of components for HVDC voltage-converter technologies. For example, silicon-based thyristor valves, which have a low operating temperature, have been superseded by the development of thyristor valves based on silicon carbide ceramics. These operate at much higher junction temperatures and current density. Also, advanced computer-aided design tools have enabled three-dimensional field calculations to improve the design of transformers.

#### 3.2.3: Use of superconductors

High-temperature superconductors (HTS; box 3.2) are virtually resistance free and are being widely researched and developed for many applications, including use in power transmission, motors, transformers, magnetic energy storage and fault current limiters.

#### 3.2.4: Transmission and distribution

The use of virtually lossless conduction provided by superconductors in electricity distribution could theoretically significantly increase transmission efficiency, as well as provide the ability to carry greater current densities than conventional aluminium alloy lines of the same size. However, there are a number of technical challenges that need to be overcome before the technology is applied in practice.

First, while superconducting materials in the laboratory conduct electricity with virtually no resistive losses,\(^{12}\) in practice, superconducting transmission cables have losses due to imperfections in several
3: Improving the transmission and distribution network

Box 3.2: High-temperature superconductors
Superconductivity is a quantum mechanical effect that occurs in certain materials when they are cooled below a certain, material-dependent critical temperature. Below this temperature the normal resistance to electrical conductivity is absent and therefore the material can conduct electricity without loss. The first superconductive behaviour was observed in mercury in 1911. However, it was not until 1986, when HTSs were discovered by physicists K Alexander Müller and J Georg Bednorz, that there became the possibility of wide-scale practical applications. Before this it was thought that materials had to be cooled to below 30 K to allow superconductivity. This could only be done with the use of liquid helium, which is both expensive and difficult to use. The discovery by physicists of HTSs with critical temperatures above 77 K allows the much cheaper liquid nitrogen to be used as a coolant, opening up many more potential applications. The most common HTSs are a family of superconducting ceramic materials (cuprates) largely containing copper oxide planes.

The question of how superconductivity arises in HTSs is one of the major unsolved problems of theoretical condensed-matter physics and is a topic of intense experimental and theoretical research.

Box 3.3: Bixby Road substation, 2006
In 2006, 200 m of underground HTS cable was installed in American Electric Power’s Bixby substation. The facility provides electricity to around 20,000 residential, commercial and light industrial customers in Ohio, US. The cable is rated at 13.2 kV, 3.0 kA. It is predicted that the cable will lose only 0.5% of the electricity that it distributes, compared with an average 5–8% loss by traditional power transmission and distribution cables.

Despite these problems there is still considerable interest in the use of superconducting cables and there have been trials around the world (box 3.3). Power companies are also interested in the higher capacity and power density offered by superconducting cables, which would mean that smaller rights of way are required for transmission lines, substations can be smaller and more power can be delivered to areas where space for transmission cables is limited. These benefits would be greater for superconducting cables than for HVDC cables.

3.2.5: Transformers and motors
HTSs are also being developed for use in transformers and electric motors, where it is predicted that losses could be cut by about 50%. Transformers and motors use a large proportion of all electricity generated (30% in the US), so this could deliver significant savings. A group of Finnish scientists estimated that if all existing power-plant generators, transformers and electric motors in the EU were replaced with HTS devices, and the reduction in electricity demand was released as reduced generation at coal-fired plants, CO₂ emissions from electricity generation would be reduced by between 27 and 53 Mt CO₂, or 0.6–1.3% of EU GHG emissions in 2005.

3.2.6: Fault current limiters
When an unplanned event, such as lightning or downed power lines, occurs, a large surge of power can be sent through the grid, resulting in a fault, irrespective of the method of electricity generation on the network. A fault is any abnormal situation in an electrical system in which the electrical current may flow through the intended part(s) at an abnormal level (or not at all), and this can result in a partial or total local failure in the functioning of an electric system. Serious faults can generate surge currents of more than 100 times the normal operating current. These faults can therefore result in damage to expensive grid-connected equipment. An increase in dense urban power systems and the growth in penetration of distributed power generation are both leading to rising high fault current levels.

A superconducting fault current limiter (SCFCL) is a device that uses superconductors to limit or reduce instantaneously any unanticipated electrical surges that may occur on distribution and transmission networks. SCFCLs are therefore more effective in limiting fault currents than conventional devices. They have negligible impedance under normal conditions and limit the current quickly and effectively and automatically recover when the current returns to normal. At present SCFCLs are not commercially available, but there are numerous projects worldwide to develop prototypes and R&D has reached a state where the first commercial installations at distribution voltage levels are viable in the near future.
4: Conclusions

The principles of physics underpin all aspects of electricity generation and supply, so physics research into technological improvements will play a vital role in tackling GHG emissions reduction from the electricity sector. This report highlights significant developments in the areas of steam-generation efficiency and turbine design in thermal power plants; the efficiency of transmissions and distribution networks; and their role in facilitating the integration of renewables and other distributed generation systems into the electricity network.

For example, in power generation, supercritical and ultrasupercritical steam-turbine plants have increased their efficiency to around 45%. Research into new high-temperature materials supports the future development of a second generation of ultrasupercritical steam-turbine plants, increasing efficiencies even further. Innovative concepts such as NuGas may also play a future role after the more conventional measures have been accomplished.

In turbine design the sophisticated modelling of blade geometry continues to deliver efficiency improvements, as does the development of superalloys and thermal barrier coatings, which makes higher operating temperatures possible. Optical pyrometry has enabled improved efficiency through turbine firing rate control. Furthermore, physics supports methods to reduce losses in the transmission and distribution networks. In the future, ultra-HVDC lines may be used more widely to reduce losses, as well as to improve long-distance international power exchanges.
Glossary

**Alloy** A compound made up of two or more metallic elements.

**Alternating current (AC)** An electrical current in which magnitude and direction vary cyclically with a sinusoidal characteristic.

**Bernoulli principle** Simplified as “The pressure of a fluid decreases when its speed increases.”

**Clocking** The change of the relative circumferential position on a turbine of neighbouring rows of blades/aerofoils to increase the efficiency of the turbine.

**Combined-cycle gas turbine (CCGT)** A type of power plant where the high-temperature gas-turbine exhaust gases are used to generate more electricity using a steam turbine.

**Combined heat and power (CHP)** A type of power plant where the otherwise waste heat produced by the power-generation process is used for district heating or industrial processes.

**Creep** The tendency of a material to stretch or extend gradually when a constant load is applied over a prolonged period of time.

**Current** A flow of electricity.

**Direct current (DC)** A current that flows continuously in the same direction.

**Distributed generation** Generation that is located close to the point of demand and feeds electricity into the distribution network rather than into the transmission network.

**Distribution network** The network of power lines, cables and substations that takes electricity from the transmission network and transports it to the end user.

**Ion** A charged atom, created when a neutral atom loses or gains an electron.

**Heat engine** A device for converting heat into work by virtue of a temperature difference.[32]

**Kyoto Protocol** The international agreement under the United Nations Framework Convention on Climate Change (UNFCCC) that set legally binding CO₂ emissions reduction targets for its signatory countries.

**Resistance (electrical)** The extent to which a conductor inhibits the flow of current.

**Renewable energy** Energy obtained from flows of energy in the natural environment, such as sunshine and wind (may also include energy from ongoing sources of waste, e.g. landfill gas).

**Strain** The extension of a material subject to a force, per unit of its original length.

**Superalloys** Alloys that are tolerant to high temperature and resistant to creep and oxidation.

**Supercritical** Steam conditions above the critical point (22.1 MPa).

**Superlattice** A material made up of alternating layers of several substances.[33]

**Transformer** A piece of equipment used to increase (step up) or decrease (step down) the voltage on the transmission or distribution network.

**Transmission network** The network of high-voltage (>~130 kV) power lines, cables and substations that transports electricity from where it is generated to local distribution networks.

**Ultrasupercritical** Steam conditions above 580 °C and 27 MPa.[34]
References


[5] Stern N 2006 The Stern Review on the Economics of Climate Change HM Treasury and the Cabinet Office. www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/sternreview_index.cfm


[17] Imperial College of Science, Technology and Medicine Centre for Environmental Technology in partnership with Parliamentary Office of Science and Technology 2001 The Nature of UK Electricity Transmission and Distribution Networks in an Intermittent Renewable and Embedded Electricity Generation Future


[20] www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6VM5-4B9HX0-30&_user=10&_rdoc=1&_fmt=&_orig=search&_sort=d&view=c&acct=C0000502211&version=1&_urlVersion=0&userid=10&md5=35a1d4c9eb8a8a8f13c0677eb6d1efd


[34] World Coal Institute. www.worldcoal.org/pages/content/index.asp?PageID=421
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