SYSTEMS TO SUPPORT DECISIONS ON ELECTRIC POWER GENERATION

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Summary

The steam cycle—the manner in which most electric power is generated—is inherently an inefficient process. With current technology, less than 40% of the thermal energy available can be converted to electricity. In addition, the present practice of building large central station power plants concentrates the pollutants at the power plant site. Any conscious move toward or away from the use of electricity requires weighing the advantages of electric power at the end-user point against the disadvantages of

producing it.

1. Introduction

Energy in the form of electricity has certain distinct advantages. Electricity is clean, efficient, and versatile at the end-user point and it can be produced from all the energy resources. Electric power can perform almost any task and is essential in some tasks. These virtues, however, can come at a cost in efficiency for some applications. Environmental control technologies can be used on large plants, and environmental pollutants are readily monitored at a central-station power plant. However, the release of large amounts of pollutants in one place has a concentrated effect of the environmental impacts.

2. Electricity Production Systems

2.1. Fossil Fuel Power Plants

The use of fossil fuels to generate heat and power dominates the global energy market. For example, 40% of EU and 45% of world electricity supply is currently derived from coal (Figure 1).

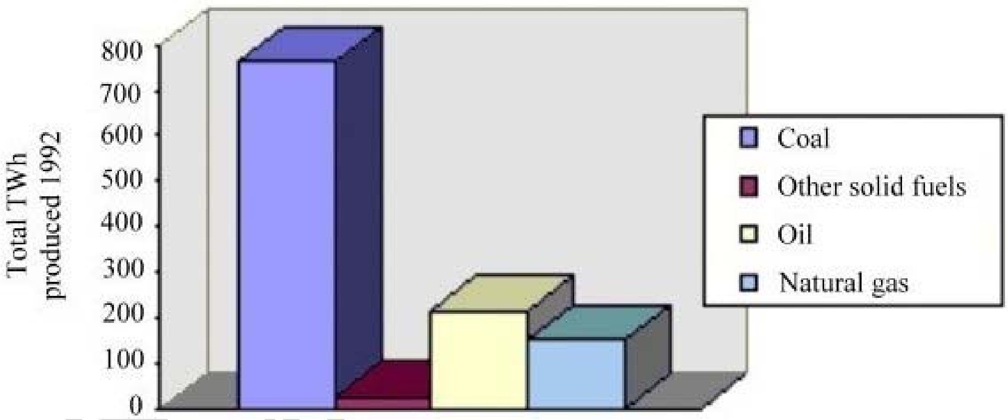

Figure 1. EU electricity production from fossil fuels by fuel type.

This reliance will continue for the foreseeable future, as the construction of new nuclear power plants will be very limited in many countries and the fact that fossil fuels are cheap, plentiful, diverse and, particularly in the case of coal, secure in supply. All these factors combined ensure that rising worldwide energy demand, fueled by economic growth, will be met mainly by the use of fossil fuels. This is particularly so in developing countries, which often have substantial indigenous reserves of coal.

In parallel with this continuing reliance on fossil fuels, the harmful environmental effects of emissions from fossil fuel use are causing growing concern. These emissions include CO_2, NO_x, SO_x and particulates, and have a range of negative international and local impacts in terms of global warming, acid rain and of course human health. In many developing countries however, mitigating these impacts is not as high a priority as is currently the case in the industrialized world.

This is because the overriding objective of those countries' energy policies is to ensure the cost-effective generation of sufficient heat and power to meet increasing demand for economic growth. Large multinational companies, almost exclusively supply fossil-fired heat and power generating technologies with European-based firms maintaining a competitive and, in many areas, leading position. The fact that national heat and power markets are equipped with different technologies is mainly due to the variations in environmental legislation and economic conditions in individual countries. There are many heat and power generation concepts. Many of these can produce heat (in the form of steam or hot water) or power e.g. the use of the Rankine steam cycle, or both (in CHP applications).

This section does not attempt to cover all possible technologies or technology combinations. It focuses on those that dominate the provision of large-scale centralized heat and/or power production from fossil fuels, whether it is coal, oil or gas. These advanced heat and power generation concepts have two central aims: to improve the fuel conversion efficiency of the process and to reduce emissions, whilst maintaining high availability and low operating costs. It should be noted that improving efficiency itself has a positive environmental effect by reducing the amount of raw material that has to be used for the same net energy output; small improvements in efficiency can lead to substantial environmental benefits. The technologies described here can either be used in new applications, or can be used to refurbish and improve the operation (efficiency, emissions, availability or cost) of existing plants. The technologies are described in six modules:

1. Pulverized fuel (PF) combustion
2. Atmospheric fluidized bed combustion (AFBC)
3. Combined cycle power generation (CCGT)
   - natural-gas-fired combined cycles (NGCCs)
   - natural-gas-fired turbines integrated with existing plant (NGICC)
   - integrated gasification combined cycles (IGCCs)
4. Pressurized fluidized bed combustion (PFBC)
5. Pressurized pulverized combustion (PPC)
6. Fuel cells for stationary applications

Each module describes the technology and the energy conversion cycle in which the technology is conventionally used. There are component technologies that have overlaps between two modules (e.g. hot-gas cleaning technologies are needed for both IGCC and PFBC electricity generation applications); these are covered in the most appropriate modules.

Many of the technologies described in this section can be used for the conversion of a wide range of fuels, including renewable energy feedstocks such as biomass and wastes. Increasingly, interest is being shown in the use of technology that can offer fuel flexibility, to enable operators to use a wide range of fuels, and to use fuels in combination co-firing. The status of commercial development of the key heat and power technologies varies. Only PF combustion (well established and reliable), AFBC and NGCCs are currently fully commercially available, although many of the other technologies are approaching commercial viability.

2.1.1. Pulverized Fuel Combustion

Most of the electricity produced from coal is generated in conventional power stations based on subcritical PF combustion. PF combustion involves grinding coal into fine particles and injecting it with air, into the lower part of a combustion chamber (Figure 2). The particles burn in suspension, and release heat. Most PF combustion is used for power generation. The heat released by the burning of coal is transferred to water tubes in the combustion chamber walls. This generates high pressure and temperature steam, which is fed into a turbine-generator for the production of electricity.

Combustor size and steam temperatures and pressures have gradually increased since the technology first emerged in the early 1900s. Modern commercial subcritical plants, that operate at steam pressures of around 180 bar and temperatures of about 570 °C, can achieve generation efficiencies of ~39%, while the more sophisticated supercritical units rely on higher steam pressures (around 240 bar) to raise efficiency levels to 44%. The most recent technological advance is the ultra-supercritical plant. Designed for steam pressures of up to 275 bar and temperatures up to 590 ºC, it is expected to achieve generation efficiencies of up to 47%.

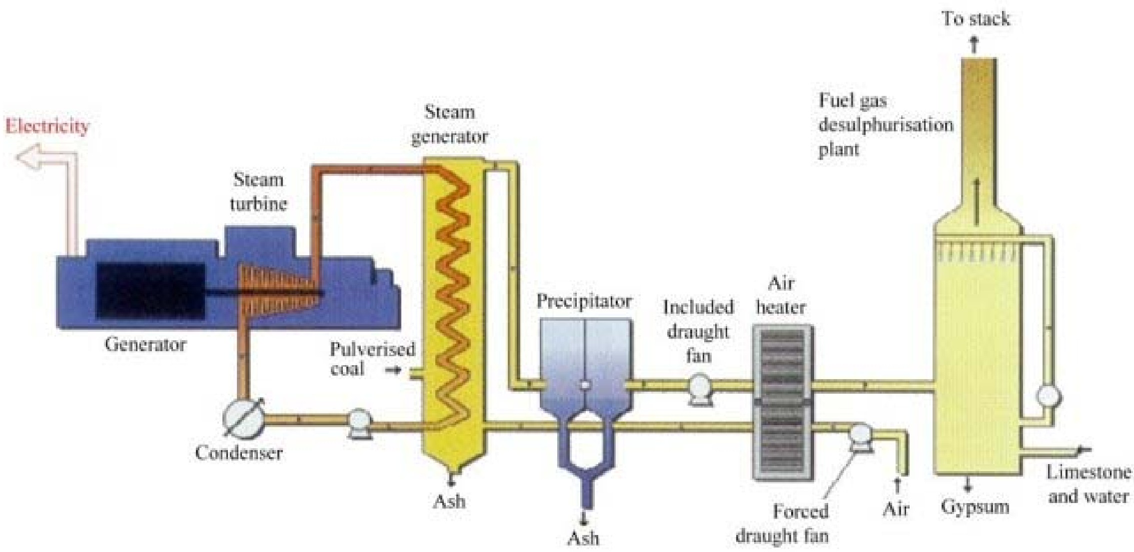

Figure 2. Typical Coal-Fired Power Station with Flue-Gas Desulfurization.

2.1.2. Atmospheric Fluidized Bed Combustion

The term “fluidized bed” reflects the status of particulate matter kept in free motion by an upward flowing fluid (gas or liquid). The status of any particle-fluid system is limited by two benchmarks: the minimum fluidization velocity and the entrainment velocity. When a system is operating between these two benchmarks it is known as a bubbling fluidized bed or bubbling AFBC. The fluidized particles are a mixture of sand particles and coarse fuel ash. Ash granules can be removed from the fluidized bed by “bottom” type extraction or by entrainment with the flue gas once the ash particles have been sufficiently reduced in size by the eroding action of the fluidized sand. Solid fuels can be fed into the combustor under the fluidized bed, but “over-bed” feeding is possible and is usually specified when liquid fuel is used (Figure 3).

The combustion heat is recovered via in-bed heat exchangers and adapted standard boiler equipment. Fly ash (and coarse ash) can be recycled for deep combustion with the help of the fuel feeding system. The air required for fluidization and combustion is fed via an air distributor that is commonly a nozzle tray whose design is classified by the manufacturer. There is a section above the bed known as the freeboard whose diameter is much larger than the bed diameter. The reduced air velocity in this region ensures that solid particles entrained in the gas flow return to the bed by gravity. Additional air for post-combustion of gaseous fuel components, known as secondary air, is often introduced into the freeboard region to ensure complete burnout of the fuel. When a fluidized bed combustion system is designed to operate above the entrainment velocity it is known as a circulating fluidized bed, or circulating AFBC. A high duty cyclone is used to separate flue gas from the entrained particles that are continuously recycled to the bottom of the fluidized bed. The recycled particles often pass through “sand coolers” before passing into the bed and the heat recovered is used to augment steam raising. For this reason circulating AFBCs can usually dispense with in-bed heat exchangers which can suffer erosion and eventual failure. The circulatory nature of this system means that the fluidized bed combustor is in the form of a tall column that affects the shape and height of buildings and enclosures. Fluidized beds can be integrated with steam raising boilers, which enables them to be used for power generation (Figure 4). Atmospheric fluidized bed combustors (AFBC) have been applied in industrial heating, industrial and utility power generation and CHP applications in various parts of the world. AFBC uses a continuous stream of air to create turbulence in a mixed “bed” of inert material and coarse fuel ash particles. The velocity of the gas stream ensures that the particles remain suspended and move about freely. In this state they behave like a fluid—in other words, the bed becomes “fluidized.” In a bubbling AFBC the bed retains a defined surface level.

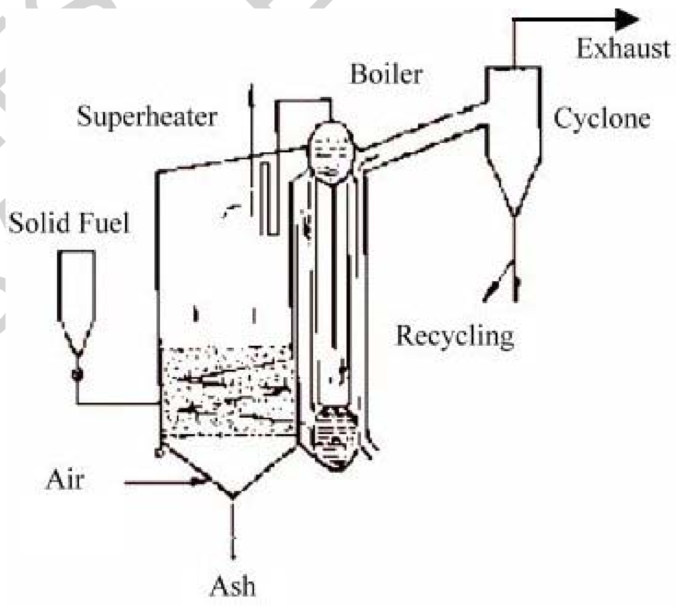

Figure 3. Fluidized bed.

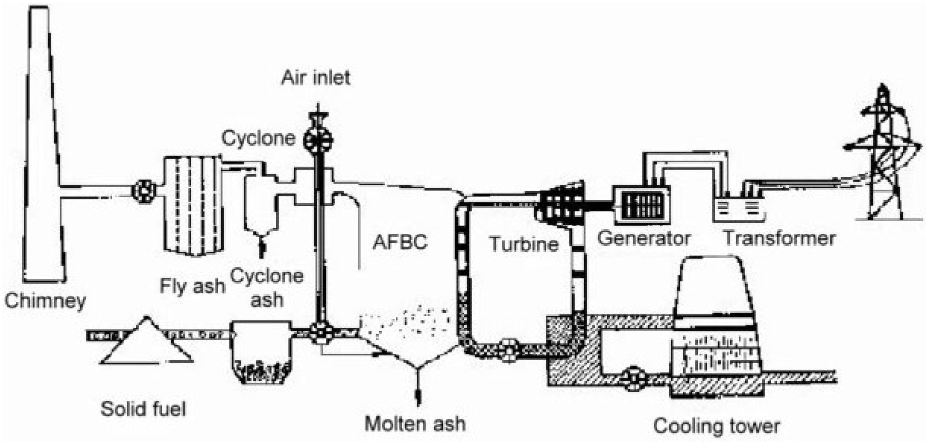

Figure 4. Flow sheet of AFBC power station.

In the circulating version (Figure 5) higher gas velocities create a turbulent cloud of solids throughout the combustor. The lighter portion escapes from the top of the combustion vessel, entrained in the flue gas, but is then captured in a heavy-duty cyclone and recirculated back to the bed. When fuel is added to a hot fluidized bed, the constant mixing encourages rapid heat transfer and complete combustion. The heat generated is recovered by in-bed heat exchangers and other boiler equipment, and is used to generate steam for industrial or power plant use. Low combustion temperatures limit emissions of NO_x, while adding calcium-based sorbents with the fuel removes SO_2 from the flue gas stream.

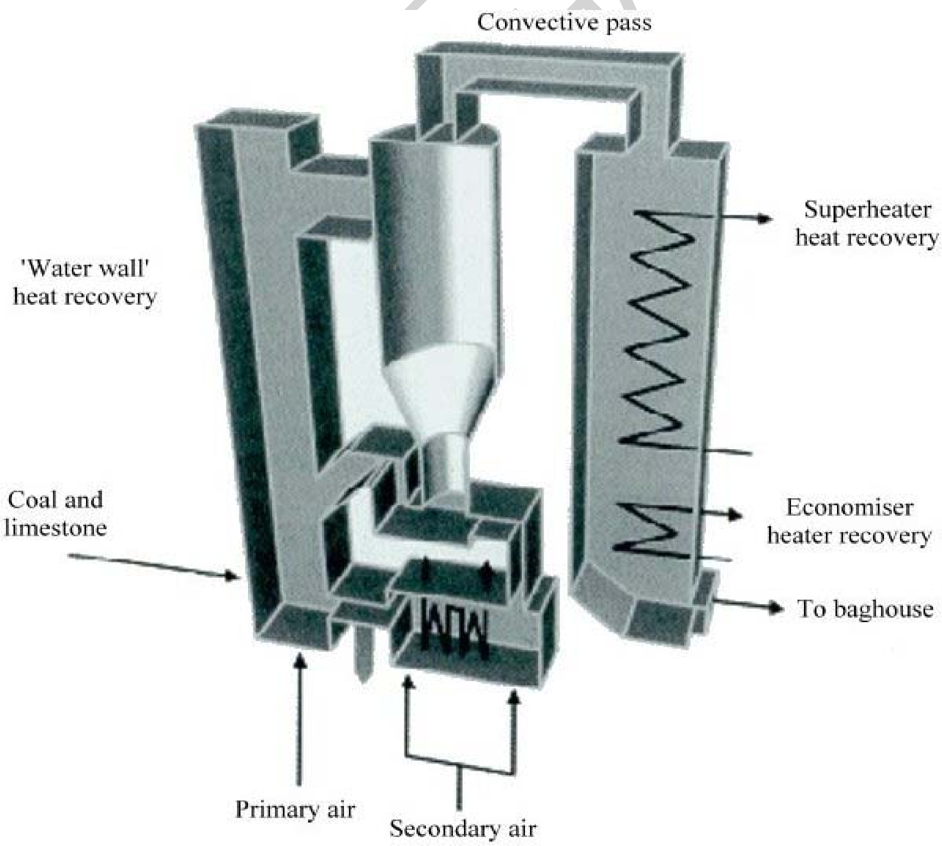

Figure 5. Heat transfer in circulating fluidized bed combustion.

2.1.3. Combined Cycled Power Generation

The gas turbine (Brayton) cycle is one of the most efficient cycles for the conversion of gas fuels to mechanical power or electricity. The use of distillate liquid fuels, usually diesel, is also common where the cost of a gas pipeline cannot be justified. Gas turbines have long been used in simple cycle mode for peak lopping in the power generation industry, where natural gas or distillate liquid fuels have been used, and where their ability to start and shut down on demand is essential. Gas turbines have also been used in simple cycle mode for base load mechanical power and electricity generation in the oil and gas industries, where natural gas and process gases have been used as fuel. Gas fuels give reduced maintenance costs compared with liquid fuels, but the cost of natural gas supply pipelines is generally only justified for base load operation. More recently, as simple cycle efficiencies have improved and as natural gas prices have fallen, gas turbines have been more widely adopted for base load power generation. This is the case especially in combined cycle mode, where waste heat is recovered in waste heat boilers, and the steam used to produce additional electricity (Figure 6).

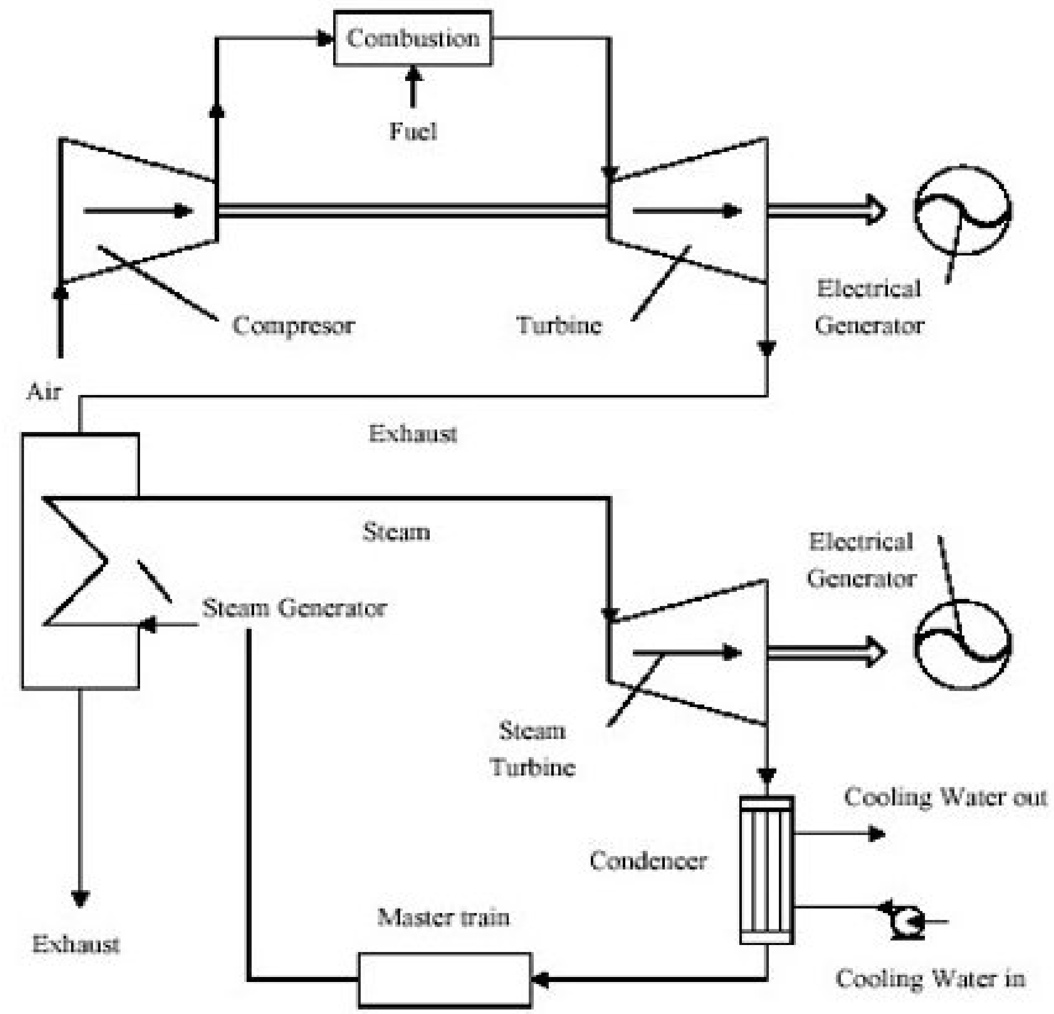

Figure 6. Combined cycle power plant.

The efficiency of operation of gas turbines depends on the operating mode. In full load operation they give the highest efficiency. Efficiency deteriorates rapidly with declining power output. Today's base load efficiency for natural gas-fired turbines is in the range of 36% (LHV) for large-scale turbines (169–200+ MW_e) to 25% or less (1 MWe range). The efficiency is related to the firing temperature in the combustion chamber and the turbine entry temperature. The larger turbines generally feature higher temperatures as market opportunities, and pressures, are more influential at these scales. Development is underway for still higher temperatures (1369 °C and higher). To reach this, new materials (blades) and cooling techniques are needed, as are measures to suppress NO_x formation. Firing coal-derived gas (from coal gasification, IGCC) requires design changes to cater for differing gas properties, combustion characteristics, and mass flow compared to natural gas.

2.1.3.1. Natural Gas Fired Combined Cycles (NGCCs)

It is possible to build a power station where a natural gas-fired gas turbine (GT) is used to generate electricity, and the waste heat from the GT is used to raise steam to generate additional electricity via a steam turbine. This system is known as a natural gas combined cycle (NGCC). The basic principle of the NGCC is simple: burning gas in a gas turbine (GT) produces not only power—which can be converted to electric power by a coupled generator—but also fairly hot exhaust gases.

Routing these gases through a water-cooled heat exchanger produces steam, which can be turned into electric power with a coupled steam turbine and generator. This setup of GT, waste-heat boiler, steam turbine and generator(s) is called a combined cycle. This type of power plant is being installed in increasing numbers round the world where there is access to substantial quantities of natural gas. This type of power plant produces high power outputs at high efficiencies and with low emissions. It is also possible to use the steam from the boiler for heating purposes so such power plants can operate to deliver electricity alone or in combined heat and power (CHP) mode.

Efficiencies are very wide ranging depending on the layout and size of the installation and vary from about 40% (now considered poor) to about 56% (LHV) for large new natural gas-fired stations. For efficient firing of coal-derived gas this type of cycle is used; the combination is called Integrated Coal Gasification Combined Cycle (IGCC). Developments needed for this type of energy conversion is only for the GTs. Both waste heat boilers and steam turbines are in common use and well-developed, without specific needs/possibilities for further improvement.

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Biographical Sketch

Christopher J. Koroneos: studied Chemical Engineering in Columbia University where he also earned his Doctorate. His research interests are in the areas of environmental engineering, energy engineering, process engineering, environmental process synthesis, and life cycle analysis.

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