THERMAL POWER PLANTS

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Contents

Summary

Large-scale power production requires the use of heat in a thermodynamic cycle to produce mechanical work, which in turn can generate electrical energy. Substantial quantities of fuel are hence required to sustain the production of heat. Fuel may be combustible, as in the case of fossil fuels such as coal and oil, or fissionable, as in the case of nuclear fuels such as uranium. All fuels produce waste products, which must be discharged, dumped, or stored. Such products range from innocuous water vapor to hazardous nuclear waste.

Not all the energy in the fuel can be converted into work. Some of the heat produced must be rejected to the environment. This requires a suitable interface with the environment. As far as possible, large bodies of water are used, with the water being pumped through the power plant heat rejection system as a coolant. This is usually not an environmental issue but does have an effect on the siting of a power plant.

Generally the siting of a power plant, except for a nuclear plant, depends first, on the ease of delivery of fuel, second, on the access to water for cooling, and third, on the distance of transmission of power to the consumer. Naturally power plants should be located as near to the electrical power demand centers as possible.

Electricity cannot be stored in any significant quantities and must be generated as required. This puts demanding operating requirements on power plants, which must have a high degree of reliability. A further unique aspect of power plants is the huge capital investment, and hence the long financing period required. This makes power utilities rather conservative in their approach to new technologies. On the other hand, development of power plants has reached a plateau so that current technology is not readily dated.

Future prospects in the power generating field are likely to be in the areas of fuel selection and environmental control to reduce emissions, small-scale power production by private companies taking advantage of the benefits of combined cycles and co-generation, and life extension of existing plants to minimize financial investment in new plants. Large-scale power production by multi-unit central generating stations including nuclear plants will nevertheless always be a necessity simply to meet the overall demand for electric power.

1. Technology Development

1.1. Introduction

The technology of power plants has developed in much the same way as that of other technologies. Generally certain factors promote or inhibit development in a particular direction. The concepts or knowledge may exist but implementation may be impractical, impossible, or uneconomical until other associated technologies become available. On the other hand, the need to implement a desired process may be inhibited by lack of knowledge until new research has been carried out. Thus, in the development of a technology, research and generation of new knowledge go hand in hand with the desire and need to implement advanced technological developments.

Economics is a major driving force in the development of a technology. There is a major advantage in developing a technology that will provide a cheaper product than was previously possible. Need is also a major factor and, in times of war, severe need has produced the fastest development in technology.

There are three phases in the development of most technologies. The first is the initial discovery of the concept or the creation of new knowledge. This is followed by rapid development or implementation of the ideas or techniques. The final phase is a refinement of the process, or improvement in the efficiency, to obtain a well-established and economical technology. The large-scale production of electrical power from thermal plants has gone through these phases over the past century and is currently a well-established technology. Nevertheless, there are aspects of power production that are still in the early and middle stages of development and can be considered as being emerging technologies.

1.2. Discovery

Considering that thermal power plants are a combination of a heat source, a thermodynamic cycle, and an electrical generator, there are three major technologies.

The production of heat as a technology goes back to historical times when heat was used to fashion various ceramic and metallic implements. The concept of a thermodynamic cycle to produce work came much later with the production of steam and its use in a vacuum cylinder to create a force. It was only after the discovery of the nature of electricity and, in particular, the development of the light bulb, that a demand for the production of electricity arose. Naturally there were many basic concepts to be established. Electrical generators powered by suitable machines as well as methods of electricity distribution were required. Once this technology had been founded there was tremendous scope for its development as many associated technologies were already in an advanced developmental stage.

1.3. Development

Once electricity had been recognized as a viable source of energy for both light and power, the conversion from gas lighting to electric lighting and from steam power to electric power took place rapidly. The distribution of electricity for lighting was simpler and easier than the distribution of gas. Conversions of driven machinery had to take account of the economics, as the total power consumption was significant. Efficiency also played a part as, in an industrial plant for example, the conversion of mechanical energy to electrical energy, its distribution to individual motors, and the conversion of electrical energy back to mechanical energy had to be competitive with the direct transmission of mechanical power via a rather complicated system of overhead line shafts and belts.

Following the Industrial Revolution, when first hydro power and then steam power were developed as sources of driving power for industry, the concepts of producing and distributing mechanical power and of using a thermodynamic cycle to generate mechanical power had been established and were viable. This had great benefits for the electric power industry as reciprocating steam engines and newly developed steam turbines could be readily adapted to drive electrical generators.

A further factor in the development of electric power production was economy of scale. Because the distribution of electricity was much simpler than that of mechanical energy, it meant that one central generating station could supply electric power to several surrounding industries. Since it is cheaper to build and operate a single large plant rather than several small ones of the same capacity, the central generating station had significant economic benefits compared with separate mechanical power sources in individual industries.

With the advent of central generating stations operating independently of industry with electricity as their only product, the question of efficiency arose. Obviously there was an economic incentive to produce and sell more electricity for a given quantity of purchased fuel. Production could be enhanced by judicious operation but ultimately only improved by increased efficiency of conversion. This depended upon the thermodynamic cycle efficiency, which is limited in turn by the high and low temperatures in the system.

Overall, the development of thermal power plants was rapid in the early part of the twentieth century due to the availability of related technologies and the convenience and economy of using electric power from a central generating station.

1.4. Refinement

In the latter part of the twentieth century the technology of thermal generating stations has been refined in various ways. By the middle of the century developments in economy of scale, and in thermodynamic efficiency, had created thermal plants with overall efficiencies in excess of 30 percent. The cost of electricity had been reduced substantially making it a suitable source of power for almost any application.

Since then, thermodynamic efficiencies have increased to over 40 percent. Economies of scale have resulted in single unit size increases of about ten-fold to give units with capacities above 1,000 MW. This has been accomplished not by major changes in the technology but by small refinements to the thermodynamic cycle as well as to the steam-generating unit, the turbine, and electrical generator. Such changes have involved the adoption of higher temperatures and pressures, as well as the reheat of partially expanded steam and the elimination or reduction of many minor heat and friction losses.

Currently both fossil fuel fired and nuclear reactor thermal power plants operate at efficiencies close to the theoretical maximum. They produce electric power reliably and at low cost compared with other forms of mechanical energy. In fact in many regions the cost of electricity is comparable with the cost of other forms of heating energy. This is remarkable as, taking account of the thermodynamic conversion efficiency, only part of the original energy is still available for use.

2. Resource Development

2.1. Resources for Heat Generation

Thermal power plants require for fuel any substance that can be used to generate heat. Thus any carboniferous or hydrocarbon fuel (commonly known as fossil fuels) may be used, as well as various nuclear fuels. Naturally economics will indicate which is the most suitable for a particular application. Whatever fuel is used it must be extracted from its source, refined to an acceptable level of purity, and processed into a combustible or fissionable product.

Over the years, the type of fuel used to generate steam for the production of both mechanical and (later) electrical power has changed. Originally wood was the obvious source of fuel as it was readily available, easily harvested, and conveniently burned. The properties of coal were known long before it was used as a fuel but it was considered to produce such offensive products that, at one time, in England, the penalty for using it was death. This was an effective method of pollution control in historical times when most of the countryside surrounding villages was in a pristine condition.

The Industrial Revolution brought with it high demands for fuel. Forests were rapidly denuded and coal with its offensive products was available in high-density deposits not far beneath the surface of the earth. Associated with the Industrial Revolution are visions of dozens of smoke stacks belching forth black plumes of smoke which, when mixed with fog in certain atmospheric conditions, produced the notorious smogs in England.

Somewhat later, oil was discovered in the United States and initially was considered somewhat of a novelty and freak of nature. Once its properties became known, and it was found that it actually consisted of a mixture of various hydrocarbon liquids that could be separated, demand for it increased rapidly. Crude oil proved to be an ideal source of lubricating oil and illuminating oil and rapidly displaced the natural products previously used. It was also a source of light hydrocarbon fuels, which were ideal for motor vehicles. The heavy residue became available as a fuel oil for large-scale combustion in power plants.

More recently, in the search for further reserves of oil, natural gas has been found in extensive quantities. As a fuel for combustion it is almost ideal in that it is clean burning and ash free. It also requires the minimum of preparation prior to combustion and does not produce noxious products as do coal and fuel oil.

Nuclear fuel is markedly different in that it is a nuclear reaction rather than a chemical reaction that produces the heat. The only nuclear reaction currently able to produce heat on a continuous and controlled basis is that of fission of certain heavy elements. Of the four fissile materials only one is found in suitable quantities in nature. This is Uranium-235, which makes up only 0.7 percent of natural uranium. When an atom of this material fissions surplus energy is released and certain radioactive fission products are produced from the resulting atomic fragments.

Extraction, refinement, and processing of nuclear fuel prior to its use in a power plant are much more sophisticated than the equivalent processes for fossil fuels. However, due to the extremely high-energy release per unit mass of nuclear fuel compared with that of chemical fuels, it is considerably cheaper per unit heat output than most fossil fuels.

2.2. Use of Resources

As resources are developed and then replaced with other resources, either because of the decline of the original resource or because of the attractiveness of the new resource, they exhibit a certain pattern of growth and decline over a period of time. For a single resource that is sufficiently attractive to be in high demand this pattern is a bell shaped curve. Figure 1 shows typical curves (not based on factual information) for different resources. Initially the growth in demand is slow due to its novelty and lack of extraction technology, as well as limited application. Once its attributes become known and associated technologies well developed, the growth in demand becomes rapid giving a steeply rising curve. Eventually, easily recovered resources become scarce, costs increase, and the rate of usage declines, slowing the growth rate. A peak in the curve is reached when the costs of the development of new resources become so high that the availability of the resource is limited. Beyond this point increasing costs and reduced availability makes the resource less attractive, and growth declines slowly.

Once the resource availability reaches a point when new usage of the resource collapses, there is a rapid decline in its use until a relatively low level of usage is reached. Beyond that point there is a slow decline due to the continued demand for specialized use of the resource even if it is difficult to extract and costly to obtain.

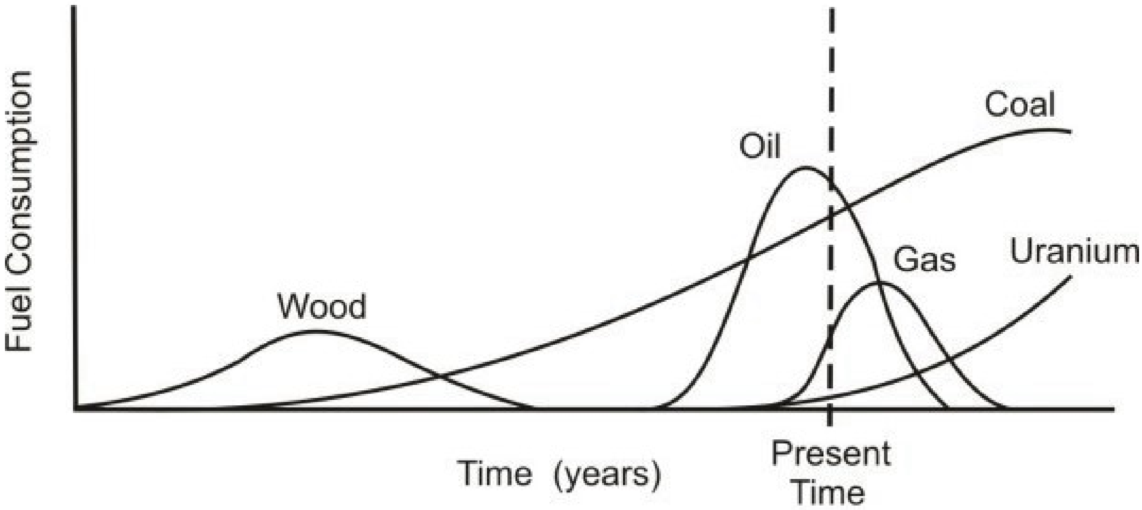

Figure 1. Typical demand curves for natural resources

The bell shaped curve is characteristic of many natural resources where use is driven mainly by availability and cost. Oil is a good example, with extraction and use well documented. Furthermore, knowledge of untapped reserves allows for some prediction of future usage. A high demand during the early part of the twentieth century produced a rapid growth in production and usage. Near the top of the curve however, when limits in availability became apparent, uncertainty of supply led to reduced usage and increased costs. This was highlighted by the oil crisis in the 1970s. Since then, the growth has slowly reached a peak and began a slow decline. It would be expected that as existing resources are gradually depleted the decline would eventually become rapid.

Transition from growth to decline is not necessarily associated with markedly rising costs, as would be expected with a valuable resource that suddenly cannot meet the demand. Before the peak much of the resource may be used just because of its convenience, and adaptation can be made to use an alternative resource instead. Also the resource may have been used wastefully when in plentiful supply, and more careful use of the resource can reduce the demand substantially while still producing the same end result. This has been the case with oil and the pattern of its production and demand, as well as the costs of extraction and end product, makes an interesting study. Efficiency of usage has generally increased and profits of the producers probably declined over this period. Political influences, though strong, have merely caused blips on the curve. Other resources such as wood have followed a similar pattern but with a much lower peak and a much longer period of usage. The decline in the use of wood for heating purposes in European countries was rapid due to denudation of the forests and availability of coal.

The growth in the use of coal has been steady and not nearly as dramatic as that of oil. This is because coal is not nearly as convenient to use as oil, and the use of coal is generally confined to fixed installations as opposed to use in vehicles such as trains and ships. The use of coal is also associated with some degree of pollution. To minimize this, combustion equipment has become more sophisticated and more expensive. Nevertheless, reserves of coal currently available indicate that the use of coal will continue to increase steadily and that a peak in its use is still a long way off.

The use of nuclear fuel resources is still in a period of slow growth. It was anticipated that growth in the usage of this resource would be more rapid, and at one stage there was some concern that supplies would not be able to match the demand. This did not happen, and a general slowdown of the world economy slowed the demand for electrical power. Nevertheless, nuclear fuel is ideally suited for use in large-scale electrical power production and no doubt its growth in this field will continue to increase, and will likely dominate, once coal has reached its peak and begun to decline.

3. Environmental Effects

3.1. General

The utilization of any natural resource has some effect, usually detrimental, on the environment. On a large enough scale the effect may be sufficient to change the local ecology. Similarly the processing of the natural resource, and its use to produce an end product, has an effect on the environment by way of the waste products generated. Usually these are also detrimental but there are some examples of beneficial effects.

Overall, the adverse effects on the environment have to be weighed against the benefits to society. The cost of alleviating the adverse effects has to be factored in as well. A further factor is the ultimate cost and environmental effect of not using a particular technology, but employing a more damaging technology instead. In the field of power generation alternatives do exist. Some may be less damaging to the environment than others but the overall effect of the production of a given quantity of electricity should always be assessed when making a comparison.

The scale of the operation is important when considering the effect on the environment. If one considers the installation of a small electric power generating plant with a capacity of say 10 MW and compares a few different technologies, it is found that certain local effects are negligible. If a coal fired plant was installed, the amount of ash produced would accumulate slowly and that small fraction discharged up the stack would be dispersed over a wide enough area for there to be no detrimental effect. If a hydro plant were installed, it would not require major civil works and there would be little effect on the river ecology. If wind plant were installed, about a dozen windmills would be required on the top of a hill, again with little effect on the environment. If however the capacity were increased to say 1,000 MW, typical of a modern electrical generating unit, the effect on the immediate environment would be dramatic. The coal-fired plant would produce enormous quantities of ash requiring a special disposal area, and sophisticated technology would be required to minimize the discharge of fly ash from the stack. The hydro plant would require a major dam and a large area inundated with water to provide an adequate storage volume. The wind plant would require some thousand windmills spread over the countryside, possibly utilizing valuable land. With large-scale power production there are thus more constraints than when considering small-scale applications.

It may appear then that there are advantages in small-scale applications. There are two factors to consider however. The first is economy of scale. It is cheaper to build a single large unit than many small units of the same total capacity. The other factor is the amount of effluent produced. Many small units together produce the same amount of waste, such as ash, as a single unit of the same total capacity. The quantity of waste therefore is cumulative and ultimately many small, individually innocuous effects become damaging to the environment.

For these reasons then it is common practice in industrialized countries to conduct environmental assessment reviews prior to the installation of any new power generating equipment, and to monitor the operation of existing plants to ensure that their discharges to the environment do not exceed certain specified limits.

3.2. Ash Production

Solid fossil fuels such as coal produce significant amounts of ash when burned. The ash content of typical coals is generally around 10 percent but varies widely from less than 5 percent to more than 25 percent and even up to 40 percent. Generally when burned in suspension as pulverized fuel some 80 percent of the ash is carried out of the furnace with the flue gas while the remaining 20 percent falls into a hopper below the furnace. Unless suitably cleaned, the flue gases would be highly polluting with the fine fly ash being dispersed into the atmosphere. A typical electrostatic precipitator capable of removing 95 percent of particulate matter from the flue gas leaves a reasonably clean plume of flue gas. With a tall stack and good atmospheric dispersion this may be adequate. Power plants in more sensitive areas, where the surrounding area is used for habitation or agriculture, may require more stringent controls over particulate emission so as to produce a virtually non-visible plume of exhaust gas.

The amount of ash collected naturally depends upon the ash content of the particular fuel used. Most ash is generally inert after some initial reaction with water and can be readily disposed of in a suitable dump or landfill. Coarse ash from the furnace bottom can be dumped without treatment, but fly ash from the gas path requires damping with water and compacting in a landfill, or slurrying with water and settling in a slime dam. Of concern though is the possible draining of leachate into the local groundwater or surface water systems. This is usually acidic and may contain some undesirable elements. The design and location of an ash dump or landfill site has therefore to be given some consideration and be subject to periodic monitoring. Good sites can ultimately be restored and replanted with vegetation.

Heavy fuel oil has a very much lower ash content than coal but provision still has to be made for clean up of the flue gas to prevent excessive particulate emission. This ash can be handled in a similar manner as that from coal but, since there is less inert material, the concentration of undesirable elements, particularly heavy metals, is much greater. Appropriate precautions must be taken to avoid these being dispersed into the

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Biographical Sketch

Robin Chaplin obtained a B.Sc. and M.Sc. in mechanical engineering from the University of Cape Town. Between these two periods of study he spent two years gaining experience in the operation and maintenance of coal fired power plants in South Africa. He subsequently spent a further year gaining experience on research and prototype nuclear reactors in South Africa and the United Kingdom, and obtained an M.Sc. in nuclear engineering from Imperial College, London University. On returning and taking up a position in the head office of Eskom he spent some twelve years there, initially in project management and then as head of steam turbine specialists. During this period he was involved with the construction of the Ruacana Hydro Power Station in Namibia and Koeberg Nuclear Power Station in South Africa, being responsible for the underground mechanical equipment and civil structures and for the mechanical balance-of-plant equipment at the respective plants. Continuing his interests in power plant modeling and simulation, he obtained a Ph.D. in mechanical engineering from Queen's University in Canada. He was subsequently appointed as Chair in Power Plant Engineering at the University of New Brunswick, where he teaches thermodynamics and fluid mechanics and specialized courses in nuclear and power plant engineering in the Department of Chemical Engineering. An important function is involvement in the plant operator and shift supervisor training programs at Point Lepreau Nuclear Generating Station. This includes the development of material and teaching of courses in both nuclear and non-nuclear aspects of the program.