Introduction

At present, we utilize only two major sources of energy — fossil fuel and nuclear fission energy. (Hydroelectric and tidal energy sources complement these two, but only in a very restricted way.)

Both fossil fuels and fission energy have significant and, in some cases, severe limitations — finite reserves, environmental pollution, biological hazards, safety. These limitations will become more apparent as the demand for electrical power and other forms of energy increases with the growth in population and the increasing degree of industrialization.

There appear to be two, so-far untapped sources of energy that may make significant contributions to our future energy requirements — solar energy and nuclear fusion energy.

Before discussing these two sources of energy it is appropriate to mention an energy conversion device which may enable cleaner and more efficient utilization of our fossil fuels, both in small and large scale conversion processes.

The Fuel Cell

In the fuel cell, chemical energy is converted directly into electrical energy by a process which is essentially the reverse of electrolysis. In the simplest cell the fuel, hydrogen, is combined with the oxidizer to form water and energy. The reactions occur at two electrodes placed in contact with an electrolyte (for example aqueous potassium hydroxide) which provides hydroxyl ions and water for the reactions. The electrical energy is released by electrons flowing in the external circuit:

Anode: \( \text{H}_2 + 2\text{OH}^- \rightarrow 2\text{H}_2\text{O} + 2e^- \)

Cathode: \( \frac{1}{2}\text{O}_2 + \text{H}_2\text{O} + 2e^- \rightarrow 2\text{OH}^- \)

Overall reaction: \( \text{H}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{H}_2\text{O} + \text{energy} \)

The first fuel cell was operated in 1839 by Sir William Grove, but it was not until 1959, when F T Bacon solved the problem of providing good contact between gas and liquid at the electrode, that a practical design was achieved. The most spectacular application of fuel cells has been as power plants for the Apollo spacecraft.

The fuel cell has a number of advantages over other conversion devices, the most significant being its high efficiency (~60%) and the low level of environmental
pollution. It is particularly well-suited to the requirements of small power plants in remote areas or in confined areas (where pollution is a problem). It is possible that
the fuel cell could replace the internal combustion engine as a power plant for motor vehicles; several experimental vehicles are already in existence. A major
disadvantage of present fuel cells for this application is the high fuel cost.

More recently, considerable interest has been shown in the possibility of utilizing a solid dielectric, such as zirconia at $1000^\circ C$, to enable a large number of
cells to be stacked to produce power in the 100 MW range. Such a scheme, using
natural gas as fuel, is currently under study at BHP's Shortland laboratories.

**Solar Energy**

Solar energy is undoubtedly a most attractive possibility as a major contributor to our energy requirements. The solar flux at sea level is approximately
0.8 kW m$^{-2}$ for the middle six to eight hours of the day. If we assume 20%
efficiency in converting this flux to electrical power and average over the whole day,
we have an average power generating capacity of 50 W m$^{-2}$. Australia's average
electric power consumption in 1970 was $5.7 \times 10^6$ kW. A power station running
on solar energy would require a collecting area of only 50 square miles to provide
this power — a tiny fraction of our land area.

There are two general approaches to the problem of converting solar energy
into electrical power. One uses a photoconducting surface, such as the silicon-boron
cell developed by Bell Telephones to convert the energy directly into a DC current.
Such a device has a theoretical efficiency of 24% and a currently achieved efficiency
of ~15%. Energy storage and the cost of producing the photoconducting surface
appear to be two major obstacles to be overcome before such a system could be
used on a large scale.

In the second approach, heat exchangers are used to heat a working fluid from
which the energy is extracted. Until recently, most schemes using this approach
had incorporated rather low temperatures for the working fluid with resulting low
overall conversion efficiencies. Recently, Meinel and others (working at the
University of Arizona) have proposed a complete 1000 MW plant in which they
hope to achieve a working fluid temperature of $1000^\circ F$ and an overall conversion
efficiency of 30%.

In their proposal, a liquid metal loop (probably NaK) transfers heat from the
collecting surface to a molten salt loop which incorporates a 50 million litre thermal
storage tank, enabling operation overnight and perhaps for periods of one or two
cloudy days. A heat exchanger transfers the stored energy to a high pressure steam
loop ($1000^\circ F$ at 1,200 psi). The total area of the station would be approximately
15 km$^2$.

Essential to the success of this proposal is the utilization for the solar flux
collecting surface of selective surfaces which absorb strongly in the visible (where
most of the solar flux is concentrated) but radiate only weakly in the infrared, thus
minimizing the radiative losses from the relatively cool collecting surface.
surfaces satisfying these requirements, usually with a multi-layer arrangement, are already available. Recent advances in the technology of laying down such surfaces have reduced their cost by about a factor of three over the last few years to about one dollar per square metre.

Clearly, there are many technological problems to be solved before the large scale use of solar energy becomes a reality; but the prospects look sufficiently encouraging to ensure that a major research effort on the problem will be mounted within the next few decades.

Nuclear Fusion Energy

Solar energy comes from the release of nuclear energy in the fusion of hydrogen nuclei to form helium (in two, rather complex chains of reactions). This reaction is much too slow to be of use in a fusion reactor. Instead, one must use the heavy isotopes of hydrogen — deuterium (D) and tritium (T). The relevant nuclear reactions are

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\begin{align*}
D + D & \rightarrow \text{He}^3 + n + 3.2 \text{ MeV} \\
T + p & \rightarrow \text{He}^4 + n + 4.0 \text{ MeV} \\
D + T & \rightarrow \text{He}^4 + n + 17.6 \text{ MeV}.
\end{align*}
\]

The higher energy released in the D–T reaction makes a 50/50 mixture of deuterium and tritium the most favourable one for a fusion reactor. For the reaction to proceed, energies of 10–20 keV must be achieved (to overcome the electrostatic repulsion of the two nuclei). Even at these energies most of the collisions simply result in a scattering — only a very small fraction of the collisions result in a nuclear reaction. There are therefore two basic requirements that must be met before we can hope to extract useful energy from the fusion reaction. First, we must heat the fuel to a very high temperature so as to achieve the desired kinetic energies (~100 × 10^6 K for the D–T reaction). Second, we must confine the particles for a sufficiently long time to enable us to extract more energy from the nuclear reactions than the energy used (and lost) in heating and containing the fuel. (For the D–T reaction we require a density-confinement time product of 10^{14} \text{ cm}^{-3} \text{ sec}, say, 10^{14} \text{ particles per cm}^{-3} \text{ contained for ~1 sec}.)

At these high temperatures the gas will be a plasma — a form of matter which unfortunately exhibits a wide variety of instabilities which make it difficult to confine for the times required. Various confinement schemes have been proposed and tried, it appears certain that specially-shaped magnetic fields of about 100 kilogauss will provide the best solution to the problem.

Progress towards achieving the required 'thermonuclear' conditions has been steady over the past twenty years. For some time, in the late 50's and most of the 60's, there appeared to be an almost insuperable barrier to achieving reasonably long confinement times. However, in 1969 Russian workers broke through this barrier...
in an experimental device, the TOKAMAK. Their very encouraging results have now been duplicated in several western laboratories.

If the TOKAMAK performance can be extended to machines of much larger size we will indeed be very close to achieving the required thermonuclear conditions. The problem is currently being attacked in two ways. First, we need to know very much more about the behaviour of this potential fuel — plasma. (We don’t yet know why the TOKAMAK works.) This will be achieved through the work of research laboratories throughout the world, where work is being done on plasma physics. Second, we must investigate, empirically, whether the TOKAMAK machine can be scaled up to a much larger size. Larger versions are currently being designed, or constructed, in Russia and the USA. Other countries, for example the UK, France, Germany, Japan, are also involved in substantial machine-oriented programmes. It seems likely that by the mid or late 70’s we will know whether the TOKAMAK is a good basis for the design of a fusion reactor power station.

The TOKAMAK results and the general level of progress in plasma physics have been sufficiently encouraging to prompt detailed discussion of the engineering design of a fusion reactor power station. (The first International Conference on Nuclear Fusion Reactors was held at Culham, England in September, 1969) Most designs envisage the use of the deuterium-tritium mixture. In this system about 80% of the energy is released as 14 MeV neutrons which have to be slowed down and, through a system of heat exchangers, used to generate steam. In addition, tritium must be bred in the reactor and recovered for use as fuel. The fusion reactor power station thus consists of three basic components: the reactor, the heat exchanger and tritium breeder, and a conventional steam-driven generator. Most of the major engineering features and problems are now clear.

The reactor vacuum vessel, which will be about 3 m minor radius, must be constructed of a material with high tolerance to energetic neutron bombardment — niobium is a likely choice. Surrounding the vacuum vessel will be a lithium (or lithium salt) blanket which will act as a heat exchanger and as the tritium-breeder (through neutron-induced reactions). Outside this blanket will be a shield of borated water and then superconducting magnet coils to produce the confining field of 80–100 kilogauss. The heat exchanger will probably be in two stages — lithium to potassium (or NaK) and potassium to water. Typically, the station will be large — perhaps 5000 MW(e) — with capital cost comparable to the fast breeder reactor station.

The fusion reactor ranks, with solar energy, as a major and most attractive energy source of the future. It will be competitive in cost with the fast breeder reactors, its fuel reserves (deuterium from the ocean) are enormous, it produces no particulate pollution and little radioactive waste, it is safe and could be sited quite close to large population centres. Its development still requires the continuation of the basic plasma physics research programme and a much-enlarged engineering and materials science research programme. Undoubtedly we shall see this occur during the next ten to twenty years.
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