Cambridge University Press
978-0-521-85107-7 - Plasma Physics and Fusion Energy
Jeffrey P. Freidberg
Excerpt
More information

Part I

Fusion power

Cambridge University Press
978-0-521-85107-7 - Plasma Physics and Fusion Energy
Jeffrey P. Freidberg
Excerpt
More information

1

Fusion and world energy

1.1 Introduction

It has been well known for many years that standard of living is directly proportional to energy consumption. Energy is essential for producing food, heating and lighting homes, operating industrial facilities, providing public and private transportation, enabling communication, etc. In general a good quality of life requires substantial energy consumption at a reasonable price.

Despite this recognition, much of the world is in a difficult energy situation at present and the problems are likely to get worse before they get better. Put simply there is a steadily increasing demand for new energy production, more than can be met in an economically feasible and environmentally friendly manner within the existing portfolio of options. Some of this demand arises from increased usage in the industrialized areas of the world such as in North America, Western Europe, and Japan. There are also major increases in demand from rapidly industrializing countries such as China and India. Virtually all projections of future energy consumption conclude that by the year 2100, world energy demand will at the very least be double present world usage.

A crucial issue driving the supply problem concerns the environment. In particular, there is continually increasing evidence that greenhouse gases are starting to have an observable negative impact on the environment. In the absence of the greenhouse problem the energy supply situation could be significantly alleviated by increasing the use of coal, of which there are substantial reserves. However, if the production of greenhouse gases is to be reduced in the future there are limits to how much energy can be generated from the primary fossil fuels: coal, natural gas, and oil. A further complication is that, as has been well documented, the known reserves of natural gas and oil will be exhausted in decades. The position taken here is that the greenhouse effect is indeed a real issue for the environment. Consequently, in the discussion below, it is assumed that new energy production will be subject to the constraint of reducing greenhouse gas emissions.

To help better understand the issues of increasing supply while decreasing emissions, a short description is presented of each of the major existing energy options. As might be expected each option has both advantages and disadvantages so there is no obvious single

Cambridge University Press
978-0-521-85107-7 - Plasma Physics and Fusion Energy
Jeffrey P. Freidberg
Excerpt
More information

path to the future. Still, once the problems are identified it then becomes easier to evaluate new proposed energy sources.

This is where fusion enters the picture. Its potential role in energy production is put in context by comparisons with the other existing energy options. The comparisons show that fusion has many attractive features in terms of safety, fuel reserves, and minimal damage to the environment. Equally important, fusion should provide large quantities of electricity in an uninterrupted and reliable manner, thereby becoming a major contributor to the world's energy supply. These major benefits have fueled the dreams of fusion researchers for over half a century. However, fusion also has disadvantages, the primary ones being associated with overcoming the very difficult scientific and engineering challenges that are inherent in the fusion process. The world's fusion research program is finding solutions to these problems one by one. The final challenge will be to integrate these solutions into an economically competitive power plant that will allow fusion to fulfill its role in world energy production.

The remainder of this chapter contains comparative descriptions of the various existing energy options and a more detailed discussion of how fusion might fit into the future energy mix.

1.2 The existing energy options

1.2.1 Background

The primary natural resources used to produce energy fall into three main categories: fossil fuels, nuclear fuels, and sunlight, which is the driver for most renewables. In general these resources can be used either directly towards some desired end purpose or indirectly to produce electricity which can then be utilized in a multitude of ways. The direct uses include heating for homes, commercial buildings, and industrial facilities and as fuel for transportation. Electricity is used in manufacturing and construction, as well as home, commercial, and industrial lighting and cooling.

One issue applicable to all sources of energy is efficiency of utilization, which directly impacts fuel reserves and/or cost. Clearly high efficiency is desirable and in practical terms this translates into conservation methods. Logically, conservation should be used to the maximal extent possible to help solve the energy problem.

As a simple overview of the current world energy situation consider the end uses of energy. In the year 2001 industrialized countries such as the USA apportioned about 60% of their energy to direct applications and 40% to the production of electricity. See Fig. 1.1.

Electricity is singled out because of its high versatility and the fact that this is the main area where fusion can make a contribution. A detailed breakdown of the relative fuel consumption used to generate electricity in the USA for the year 2001 is illustrated in Fig. 1.2. Observe that fossil fuels are the dominant contributor, providing about 70% of the electricity with 51% generated by coal. Nuclear, gas, and hydroelectric generation also made substantial contributions while wind, solar, and other renewable sources had very little impact (i.e. 0.4%).

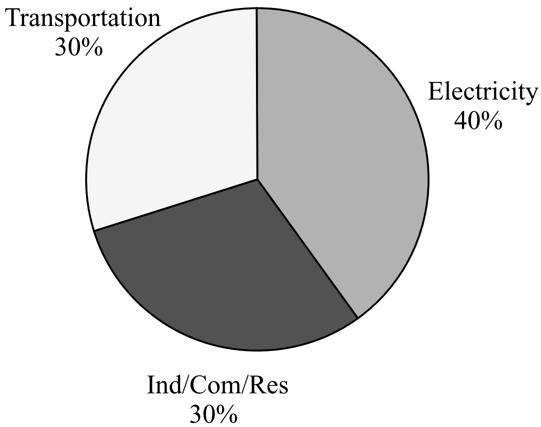

Figure 1.1 Apportionment of energy in the USA in 2001 (Annual Energy Review, 2001 Energy Information Administration, US Department of Energy).

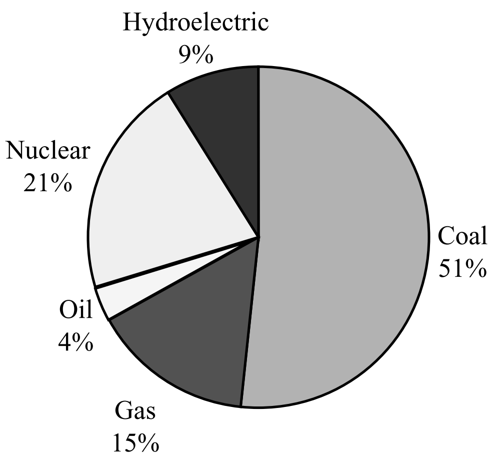

Figure 1.2 Breakdown of fuel consumption to generate electricity in the USA in 2001 (Annual Energy Review, 2001, Energy Information Administration, US Department of Energy).

What are the conclusions from these facts? First, most of the world's energy, including electricity, is derived from fossil fuels. Second, all fossil fuels produce greenhouse gases. Third, if greenhouse emissions are to be reduced in the future, even though energy demand is increasing, new energy capacity will have to be met by a combination of nuclear, hydroelectric, renewable (e.g. wind, solar, geothermal) sources, and conservation. Fourth, some major direct energy usages, such as heating by fossil fuels, could be replaced by electricity, although at an increased cost because of lower efficiency. Fifth, transportation is a special problem because of the need for a mobile fuel. As discussed shortly electricity may be

Table 1.1. *Estimate of energy reserves for various primary fuels. These are very approximate and should be viewed as guidelines. The total usage assumes that the source is used to supply the entire world's energy at a rate of 500 Quads per year (slightly higher than the 2001 rate). The self-usage assumes that each source is used to supply energy at its own individual 2001 usage rate. Also 1 Quad ≈ 10^{18} joules.*

Resource	Energy reserves (Quads)	Total usage (y)	Self-usage (y)
Coal	10^5	200	900
Oil	10^4	20	60
Natural gas	10^4	20	100
U235 (standard)	10^4	20	300
U238, Th232 (breeder)	10^7	20 000	
Fusion (D–T)	10^7	20 000	
Fusion (D–D)	10^{12}	2×10^9	

able to help here through the production of synthetic fuels, ethanol, or hydrogen, which ultimately may be used to replace gasoline and diesel fuel.

To summarize, increasing electricity production in an economic and environmentally friendly way is a vital step in addressing the world's energy problems now and in the future. Fusion is one new energy source that has the potential to accomplish this mission. It is, however, a long term solution (i.e., 30–100 years). In the interim, fossil fuels will remain the primary natural resources producing the world's electricity.

With this as background, one is now in a position to describe in more detail the various existing energy options, particularly with respect to electricity, in order to put fusion in a proper context.

1.2.2 Coal

Coal is the main fossil fuel used to generate electricity (51% in the USA). One major advantage of coal is that there are substantial reserves in many countries capable of supplying the world with electricity at the current usage rate for hundreds of years. See Table 1.1 for a list of approximate reserves of various types of fuel. If fuel availability was the only energy issue, coal would be the solution for the foreseeable future. However, when environmental concerns are considered, coal becomes less desirable.

Coal provides continuous, non-stop electricity by means of large, remotely located power plants. This vital non-stop property is known as "base load" electricity. For reference, note that a large power plant typically produces 1 GW of power, capable of supporting a city with a population of about 250 000 people. Two other important advantages of coal are that it is a well-developed technology and that it is among the lowest-cost producers of electricity.

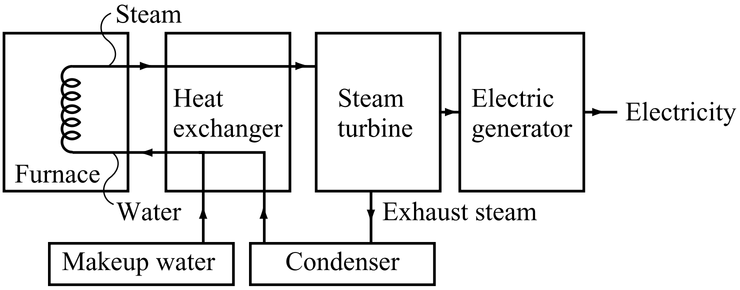

Figure 1.3 Schematic diagram of a fossil fuel power plant.

To help visualize how much coal is required to produce electricity, consider the city of Boston which has a population of about 600 000 people, and whose total rate of electrical energy consumption corresponds to 2.4 GW. The volume of coal required to provide continuous power at this level for one year would completely fill one 70 000 fan football stadium.

Consider next the efficiency of converting coal to electricity. Burning any fossil fuel (i.e., coal, natural gas, or oil) is a chemical process whose main output is heat. As shown in Fig. 1.3, a heat exchanger converts water to steam which then drives a steam turbine connected to an electric generator, thereby producing electricity. The laws of thermodynamics imply that for reasonable operating temperatures, the maximum overall efficiency for converting heat to electricity is about 35–40%. More heat is lost out of the smokestack than is converted to electricity. This unpleasant consequence is unavoidable and occurs whenever a steam cycle is used to produce electricity, as it is for coal and nuclear systems.

The main disadvantage of fossil fuel combustion is environmental in nature. Burning any fossil fuels leads to the unavoidable generation of carbon dioxide (CO_2) which is largely responsible for the greenhouse effect. This is a serious disadvantage when considering increased usage of fossil fuels for new electricity generation.

There are also several coal-specific environmental disadvantages. Because of impurities, when coal is burned it also releases fly ash (largely calcium carbonate), sulfur dioxide, nitrous oxide, and oxides of mercury, all of which are harmful to health. These emissions can be reduced, although not completely eliminated, by electrostatic precipitators and scrubbers. However, this increases the cost of electricity.

Interestingly, there are also small amounts of radioactive isotopes contained in natural coal that are released into the atmosphere upon burning. Although the fractional amounts are small, the quantities of coal are large and more radiation is actually released by a coal power plant than by a nuclear power plant. Even so, the level of radioactivity is believed to be sufficiently small not be a concern.

In summary, one can see that coal has both advantages (fuel reserves and cost) and disadvantages (greenhouse gases and emissions). Because of its advantages, and because there are no obviously superior alternatives, coal will remain a major contributor to electricity production for many years to come.

1.2.3 Natural gas

Natural gas is a fossil fuel that consists mainly of methane (CH_4). It is widely used to heat homes, commercial buildings, and industrial plants, as well as to produce electricity. About 15% of the electricity produced in the USA is derived from natural gas. The amount of liquefied natural gas required to power Boston for one year is comparable in volume to that of coal. With respect to coal, natural gas has both advantages and disadvantages.

Consider the advantages. First natural gas burns more cleanly than coal. There are far fewer emissions and the amount of CO_2 released during combustion is smaller. Second, natural gas plants can be built in smaller units, on the order of 100 MW. This leads to a more rapid construction time and a smaller initial investment, both desirable financial incentives. Third, natural gas powered plants can be operated in a "combined cycle" mode. Here, thermodynamic steam and gas cycles are combined, leading to an increased overall conversion efficiency of gas to electricity of 50–60%. Lastly, many would agree that natural gas, when available, is the most desirable way to heat homes and industrial facilities in terms of convenience and cost.

There are also several disadvantages. First, the amount of CO_2 produced per megawatt hour of electricity, while less than for coal, is still very large, as it must be for any fossil fuel. Thus, contributions to the greenhouse effect are considerable. Second, the reserves of natural gas are much less than those of coal. Current estimates are for less than 100 years at the present rate of usage. See Table 1.1. Also, most of the known reserves do not lie within the boundaries of the industrialized nations where the majority of the gas is consumed. Third, high demand coupled with production limits and relatively scarce reserves have led to high and unstable fuel costs. Fourth, it is more difficult and more expensive to transport and store natural gas than coal or oil because of the need for pipelines and high-pressure liquid storage tanks. Fifth, since natural gas is such an ideal fuel for heating, many feel that its use to produce electricity is a poor allocation of a valuable natural resource. The incentive for this poor allocation is largely motivated by short-term economics and energy deregulation with too little thought given to long-term consequences.

To summarize, the use of natural gas to produce electricity has advantages (cleanest burning of any fossil fuel and low short-term cost) and disadvantages (greenhouse gases, limited reserves, and poor allocation of resources). Overall, short-term financial incentives dominate the tradeoffs and will likely lead to the continued use of natural gas for electricity production.

1.2.4 Oil

Oil is the last of the fossil fuels to be discussed. It is an excellent fuel for transportation because of its portability and its large energy content. It is also the fuel of choice for heating when natural gas is not available. A large amount (i.e., 35%) of the energy used in the world is derived from oil, with much of it devoted to transportation usage. It is rarely used to directly produce electricity.

As a measure of energy content note that a 1 gallon milk container filled with gasoline is capable of moving a typical automobile 25 miles, indeed an impressive feat. Furthermore the total weight of a fully loaded 15 gallon fuel tank is only about 120 pounds, a negligible fraction of the total weight of the automobile. A full tank can therefore efficiently move an automobile about 375 miles, again, a truly impressive feat.

The second issue of interest is the cost of gasoline. It is surprisingly inexpensive compared to many other common liquids. In the USA the untaxed price per gallon of gasoline is still less than that of bottled water. Gasoline would appear to be a bargain, even at present higher prices.

Nevertheless, there are disadvantages to the use of gasoline for transportation. First, since gasoline is a fossil fuel it produces a large amount of greenhouse gases, comparable in total magnitude to that of coal. Second, crude oil is only readily available in a few areas of the world. One major source is the Middle East, which is fraught with political instability. Third, the reserves of oil are much less than those of coal, on the order of several decades at present usage rates. The competition for oil from the developing countries will likely increase in the future raising costs and perhaps limiting supplies.

Are there ways to decrease the world's dependency on oil? There are possibilities, but they are not easy. Consuming less oil by using hybrid vehicles could make an important contribution and may be accepted by the public even though it raises the initial cost of an automobile. Consuming less oil by driving smaller automobiles with improved fuel efficiency could also make a large contribution, although many may be reluctant to follow this path, viewing it as a lowering of one's standard of living.

A different approach is based on the fact that gasoline can be produced from coal tars and oil shale, of which there are large reserves. The end product is known as "synfuel," but at present the process is not economical. Also since synfuel is a form of fossil fuel, the production of greenhouse gases still remains an important environmental problem.

Another approach is to use non-petroleum fuels produced by bio-conversion. One method currently in limited use is the conversion of corn to ethanol, a type of alcohol. Although ethanol is a plausibly efficient replacement for gasoline, the economics of production are not. Large amounts of land are required and considerable energy must be expended to produce the ethanol, comparable to and sometimes exceeding the energy content of the final fuel itself.

There has also been considerable interest and publicity in developing the technology of using hydrogen in conjunction with fuel cells to produce a fully electric car, thus completely replacing the need for gasoline. Hydrogen has the advantages of: (1) a large reserve of primary fuel (e.g. water), (2) a high conversion efficiency from fuel to electric power, and (3) most importantly the end product of the process is harmless water vapor rather than CO_2. This may be the ultimate transportation solution but there are two quite difficult challenges to overcome.

First hydrogen itself is not a primary fuel. It must be produced separately, for instance by electrolysis, and this requires substantial energy. If the energy for the electrolysis of water is derived from fossil fuels much of the gain in reduced CO_2 emissions is canceled. Second, the energy content of hydrogen at atmospheric pressure, including its higher conversion efficiency, is still much lower than that of gasoline, by a factor of about 1200. Therefore, to increase the energy content of hydrogen fuel to a value comparable to gasoline, the hydrogen must be compressed to the very high pressure of 1200 atm. This poses a very difficult fuel tank design problem for on-board storage of hydrogen. Another option is to store the hydrogen in liquid form, but this requires a costly on-board cryogenic system. A third option is to develop room-temperature compounds that are capable of storing and rapidly cycling large quantities of hydrogen. The development of such compounds is a topic of current research, but success is still a long way into the future. One sees that the on-board storage of high-density hydrogen presents a difficult technological challenge.

The conclusions from this discussion are as follows. There is no simple, short-term, attractive alternative to gasoline for transportation. Synthetic fuel, ethanol, and hydrogen are possible long-term solutions, but each has a mixture of unfavorable economic, energy balance, and environmental problems. Providing the energy to produce hydrogen or ethanol by CO_2-free electricity (e.g. by nuclear power) would be a big help but would not solve the other problems. In the short term the best strategy may be to increase the use of hybrid vehicles and to evolve towards smaller, more fuel efficient automobiles.

1.2.5 Nuclear power

The primary use of nuclear power is the large-scale generation of base load electricity by the fissioning (i.e., splitting) of the uranium isotope U^{235}. At present there is still public concern about the use of nuclear power. However, a more careful analysis shows that this form of energy is considerably more desirable than is currently perceived and will likely be one of the main practical solutions for the future production of CO_2 free electricity.

There are several comparisons with fossil fuel plants that show why nuclear power has received so much attention as a source of electricity. The first involves the energy content of the fuel. A nuclear reaction produces on the order of one million times more energy per elementary particle than a fossil fuel chemical reaction. The implication is that much less nuclear fuel is required to produce a given amount of energy. Specifically, the total volume of nuclear fuel rods needed to power Boston for one year would just about fit in the back of a pickup truck. This should be compared to the football stadium required for fossil fuels.

A second point of comparison is environmental impact. Nuclear power plants produce neither CO_2 nor other harmful emissions. This is a major environmental advantage.

Another issue is safety. Despite public concern, the actual safety record of nuclear power is nothing less than phenomenal. No single nuclear worker or civilian has ever lost his or her life because of a radiation accident in a nuclear power plant built in the Western world. The worst accident in a USA plant occurred at Three Mile Island. This was a financial disaster for the power company but only a negligible amount of radiation was released to the environment. The reason is that Western nuclear power plants are designed with many overlapping layers of safety to provide "defense in depth" culminating with a huge, steel reinforced containment vessel around the reactor to protect the public in case of a "worst" accident. The large loss of life and wide environmental damage resulting from the Chernobyl accident occurred because there was no containment vessel around the reactor. Such a design would never be licensed to operate as a nuclear power plant in the West. Overall, safety is always a major concern in the design and operation of nuclear power plants, but the record shows that for Western power plants the problems are well under control.

Consider next the issue of fuel reserves. This is a complex issue. In the simplest view one can assume that U^{235} is the basic fuel and once most of it has been consumed in the reactor, the resulting "spent fuel" rods are buried in a permanent, non-retrievable repository. In this scenario there is enough U^{235} to provide electricity at the present rate for several hundred years. On the other hand the spent fuel rods contain substantial amounts of plutonium which can be chemically extracted and then used as a new nuclear fuel. In fact, it is possible to use the resulting plutonium in such a way that it actually breeds more plutonium than is being consumed. The use of such "breeder" reactors extends the reserves of nuclear fuels to many thousands of years. Breeders are more expensive than conventional nuclear plants and are not currently used because of the ready availability of low cost U^{235}. However, in the long term breeders may be one of the energy sources of choice.

Nuclear waste and how to dispose of it is another important issue. Here too there are subtleties. One point is that many of the radioactive fission byproducts have reasonably short half-lives, on the order of 30 years or less. They need to be stored for about a century during which time they self-destruct by radioactive decay into a harmless form, an ideal end result. It is the long-lived, multi-thousand year wastes that receive much public attention and scrutiny. Several possible solutions have received serious consideration. The waste can be dissolved in glass (i.e., vitrification) and permanently stored. The fuel can be chemically reprocessed for re-use in regular or breeder reactors, thereby transforming much of the long-lived waste into useful electricity. Third, there are techniques that, while currently expensive, transmute long-lived, non-fissioning radioactive waste byproducts into harmless elements. Also, a critical point is that the total volume of nuclear waste is very small. The total nuclear "rubbish" resulting from powering Boston for one year would fill up only a small fraction of a pickup truck. The conclusion is that there are a variety of technological solutions to the waste disposal problem. The main problems are more political than technological.

The last issue of importance is nuclear proliferation, which concerns the possibility that unstable governments or terrorist groups would gain access to nuclear weapons. At first glance one might conclude that reducing the use of nuclear power would obviously reduce the risks of proliferation. This is an incorrect conclusion. The key technical point to recognize is that the spent fuel from a reactor cannot be directly utilized to make a weapon because of the low concentration of fissionable material. Nevertheless, spent fuel is often reprocessed to make new fuel for use in nuclear reactors thereby increasing the fuel reserves as previously discussed. However, one intermediate step in reprocessing is the production of nearly pure plutonium, which at this point could be diverted for use as weapons. A major component of an effective non-proliferation plan should thus involve the detection and prevention of the diversion of plutonium for weapons use by unstable