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FUSION ENERGY IN INDIA'S LONG-TERM ENERGY FUTURE

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ABSTRACT

World population is still increasing, driving a demand for more energy and, in the developing countries, for more energy per capita to raise the standard of living. India is a clear example of this situation, with a population projected to rise from one billion today to 1.6 billion in 2050 and to 1.8 billion in 2100. Studies suggest that if energy is used efficiently, a decent standard of living in a temperate climate could be achieved with about one tonne of oil equivalent (toe) of energy per capita per year. For this level to be met, India's energy consumption would have to rise from the present 500 Mtoe/a to about 1,800 Mtoe/a in 2100. If energy efficiency gains are low then much more energy would be needed to achieve a decent standard of living.

In this paper an analysis is made of the potential contribution of indigenous energy sources (fossil and renewables , excluding solar energy) to meeting this need. It is shown that, with the present understanding of indigenous resources, even with an average efficiency improvement of 2.5 by 2100, and 20% energy imports, there could be a gap developing between demand and supply in the latter half of this century. Present options available to fill the gap are increased energy imports, fission, and solar energies. Fusion energy is discussed as a potential complementary energy source to meet India's needs. It has potential advantages with regard to environmental impact and the ready availability of fuel. This possibility raises interesting questions about how India might best work in the international fusion R&D program to position itself for the deployment of fusion energy.

1. INTRODUCTION

1.1 Population

World energy demand is projected to increase substantially over the 21st century because of the increasing population and because of the need to raise the standard of living in much of the world.

There have been many projections of future world energy use. An illustrative range of estimates is shown in Figure 1. The unit of energy is a million tonnes of oil equivalent (Mtoe = 4.2 x 10^{16} Joules). The range shown encompasses from about 1.5 times the late 1990's level (assuming a relatively low demand and huge improvements in efficiency of energy use) to 5 times that level (assuming larger growth in demand and less efficiency improvements). Assuming that there will also be a need to minimize emissions, it can be expected that there will be a need for a broad portfolio of energy options to meet the varying demands of different areas of the world. In this context, fusion energy is an interesting prospect.

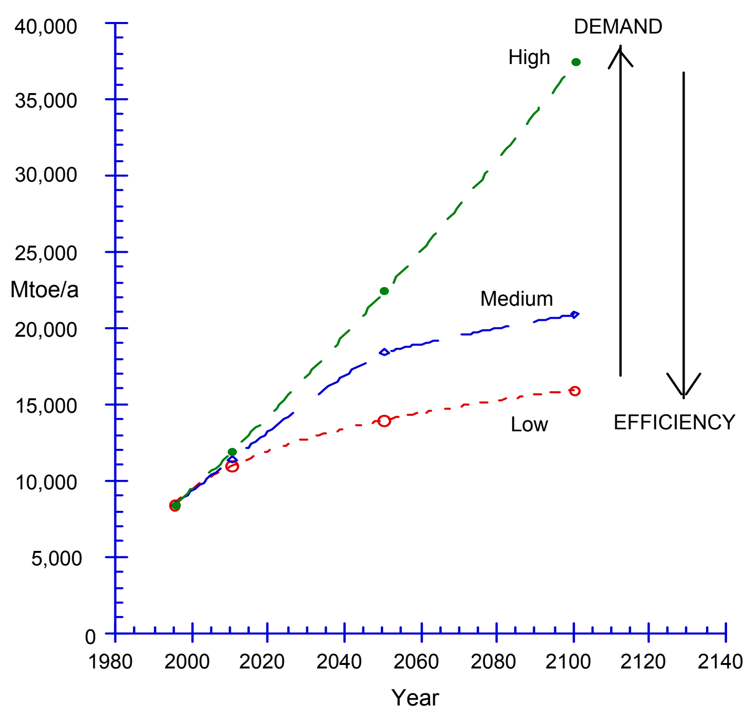


Figure 1—Illustrative projections of world energy demand for the 21st century (Bent, Orr, and Baker, 45).

1.2 Fusion Energy

Fusion energy is a potentially useful complement to other energy sources in meeting increasing energy demands in an environmentally satisfactory way. Along with "solar" energy (biomass, solar, wave, and wind) and, to a lesser extent geothermal energy, it is the only other effectively infinite and massive source of energy on earth. It has advantages with regard to safety, waste disposal, and proliferation issues that would make its deployment advantageous in some situations (Barabaschi).

Although a number of fuel cycles are possible, the most likely one to be exploited first uses deuterium and tritium (produced by neutron irradiation of lithium). Lithium occurs in substantial quantities and might be extracted from seawater. A pure deuterium cycle, while more difficult to realize, might also be possible. Deuterium, which occurs naturally as one part in 6,500 of all hydrogen, is effectively limitless. Put another way, the potential fusion energy in the deuterium in one gallon of water is 300 times the energy in a gallon of gasoline.

The developed world (mainly) has made and continues to make large investments in fusion energy research and development—more than 1 billion dollars per year. The development path for fusion energy is such that it might be possible to have fusion ready for deployment by the middle of the 21st century (FESAC). It is interesting to consider where its availability might be most important at that time. The simplest answer is in countries that are projected to lack adequate indigenous energy resources; Japan comes to mind. However, many such countries, in which populations are not projected to be increasing in 2050, will have found a solution to their problems before that time. A second question then arises for such countries as to why they would replace part of their existing energy solution with fusion energy. One answer is that they would do it to help reduce greenhouse gas emissions.

India is also an interesting possibility for fusion deployment because its population is projected to be increasing through 2050, and the energy demand will probably still be increasing. India has large resources of fossil fuel that, on present understanding, could provide a large part of the needs in the next decades. However, it appears that these resources could provide only a moderate part of its likely needs in the latter part of this century. Therefore, fusion energy, which is studied in India, could be part of the solution to replace fossil energy (Kaw). It is the issue of potential energy needs and supplies over the next century in India, and a potential role for fusion energy, that is the topic of this report.

2. INDIAN POPULATION GROWTH AND ENERGY DEMAND

2.1 Historical Demographic Trends for India: To 1996

2.1.1 Fertility Rate, Death Rate, And Population Growth

It appears that there is a need for a greater annual energy use per capita to change a society from the developing phase to the developed phase. In the developing phase, it is commonplace for parents to have far more than the two children required to sustain the population, often to improve the chance that the parents will be looked after in their old age. Consequently, the population grows, leading to higher energy demand. As societies become more affluent, and particularly when the women are wage earners, smaller families become the norm. In this situation, energy may be used to raise the standard of living rather than just deal with the burgeoning population. In fact, energy itself may be viewed as an important facilitator in this transition, because its availability influences educational opportunities, the standard of living, health, and job opportunities. One cannot prove a cause and effect between per capita energy use and fertility rates (population growth rates), but historical trends for the developing countries have followed such a course (see Appendix A).

These points may be derived in part from data in United Nations Demographic and Statistical Yearbooks, which provide information on fertility (average number of children born per woman), crude death rate, life expectancy at birth, population, population growth rate, and per capita energy use.

Life expectancy at birth in India has risen from 22.6/23.3 years (male/female) in the period 1901 to 1911, to 39.9/38 years from 1950 to 1955, and to 60.3/60.6 from 1990 to 1995. The crude death rate per thousand people per year has declined from around 15 in the mid-1970's to around 9 in the mid-1990's. During the period 1951 to 1990-1995, the fertility rate dropped from 6.0 to 3.4. The population growth rate has decreased only a modest amount in recent decades, even though the fertility rate had dropped significantly, because of the decreasing death rate.

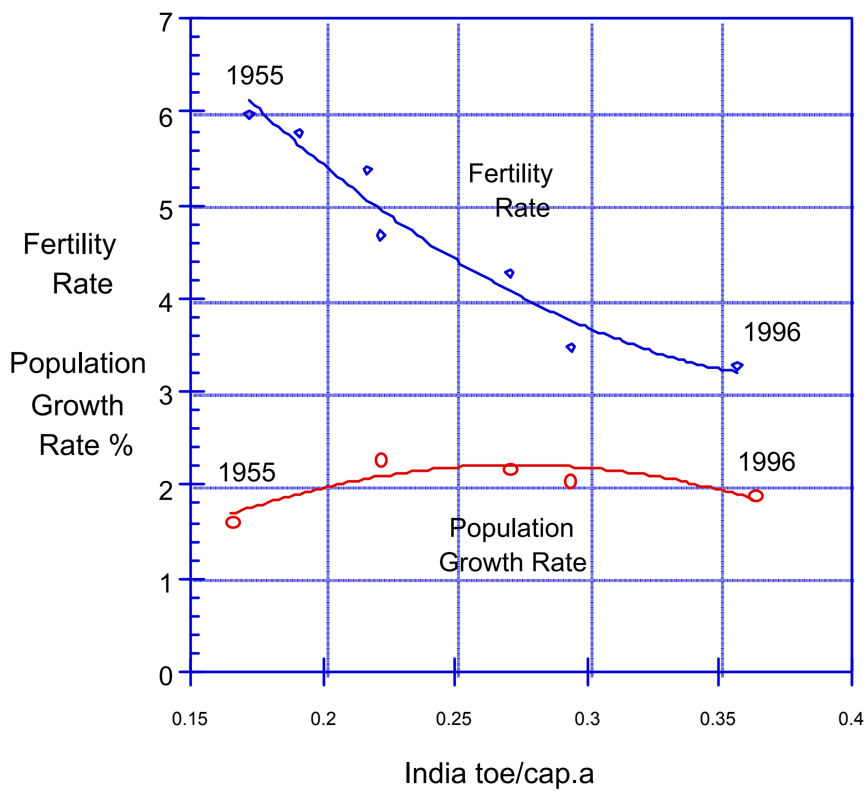
Both the birth rate (fertility) and the death rate have decreased in India since the 1950's. However, the difference between the birth rate and death rate only began to drop recently, leading to the low rate of change in the population growth rate seen in Figure 2. Note that, fertility and growth rate are only roughly proportional when the death rate is constant!

A simple formula (Sheffield 1998) that fits historical data for population growth rate (G) versus annual per capita energy use (E), is:

$$G = (E_c - E)/(1.6\ E^{0.38})\ \% \qquad (1)$$

Where energy (E_c, E) is measured in tonnes of oil equivalent per capita per annum (toe/cap.a.), and E_c is the per capita annual energy use at which the population growth rate would be zero e.g., 2.5 toe/cap.a with the efficiency of today's energy use.

Figure 2—Fertility rate (the average number of children born to a woman) and population growth rate (the annual percentage increase in population) are plotted versus total annual primary energy per capita from 1955 to 1996. The death rate declines throughout the period (United Nations Yearbooks).



The approximation in using an average energy per capita hides the effects of a distribution of energy per capita with rich, middle class, and poor populations. Nevertheless, if the distribution function for energy use remains roughly constant, it seems reasonable to extrapolate past trends, following the general world trend for the effects of increasing energy per capita on population growth rates. If, in fact, the distribution changes, it may be accounted for by varying the parameter E_c, which may be viewed as a measure of social change (Sheffield 1998)

2.1.2 Energy Use

The United Nations Demographic and Statistical Yearbooks and the International Energy Agency's World Energy Outlooks give information on India's energy use. The UN publications list commercial energy use after 1972, while the IEA gives both "commercial" and biomass energy use, so there is the issue of deciding how to assign the biomass energy. The IEA data for three separate years over a 24-year period in India shows an average use of 0.17 toe/cap.a of biomass energy.

One complication is that some information is quoted in coal equivalent energy and some in oil equivalent energy. The UN uses the factor 0.7 to equate coal energy to oil energy. This factor is consistent with the World Energy Council's use of 29.3 GJ/tonne for good quality coal and 42 GJ/tonne for oil. However, when working with actual tonnes of Indian coal, it is important to remember that Indian bituminous coal is of poor quality, typically 16.05 GJ/tonne, and its lignite only 4.6-10.1 MJ/kg (WEC 1995). On average, given the mix of mainly bituminous coal recoverable reserves, 1 tonne of Indian coal has an energy value of about 0.37 tonnes of oil.

The various figures for annual per capita energy use are given in Table 1. The UN only uses the words commercial energy after 1972, and at this date there is a significant change in the trend of the energy quoted. Whether this is because they have re-calibrated the energy value of the coal used or have ceased to include some biomass energy is unclear. Biomass energy is added to commercial energy in the table, but only half the nominal amount of biomass energy is used in this paper for prior use because it was used inefficiently. For the future, a more effective use of biomass is expected to make it more comparable with commercial energy, e.g., using modern stoves and gasifiers, and its full energy is used in the analyses below.

Table 1—Estimate of annual per capita energy use in India (UN 1955 to present, IEA 1995, and WEC 1995 and 1998)

Year	UN (toe/cap.a) Comm. After 72.	IEA (toe/cpa.a) Commercial	IEA (toe/cap.a) Biomass	Total assumed (toe/cap.a)
1955	(0.080)			0.165
1961	(0.105)			0.190
1966	(0.122)			0.207
1972	(0.131)			0.216
1973	0.117	0.117	0.162	0.198
1980	0.136			0.221
1985	0.185			0.270
1990	0.223	0.221	0.144	0.293
1995	0.271			0.356
1997		0.277	0.200	0.377

2.2 India: Future Population and Potential Energy Needs

If the population growth/energy trends discussed above continue, they will have important consequences for countries such as India that have large populations (one billion of today's six billion people in the world), low per capita energy use (0.4 toe/cap.a.), and relatively large population growth rates (2% per annum). If this growth rate were to continue, India's population would be two billion by 2035, and four billion by 2070! In fact, the World Bank (Bos) projects a stabilization of the population of India around 2100 at about 1.8 billion people. Some more recent estimates from the United Nations (WEC 1995 and 1998) project a slightly smaller growth rate, with a population in 2050 of 1.572 billion as opposed to the World Bank's projection of 1.623 billion. Note that the World Bank projected population is still increasing a little after 2100! On the other hand, Gupta uses 1.753 billion people as an estimate for 2050. The World Bank's projection for India's population is shown in Table 2.

Table 2—Projected population of India (Bos), population growth rate and annual per capita energy use calculated using equation 1, without (E_c = 2.5) and with energy efficiency improvements included (E_c drops to 1.25 by 2100), i.e., a factor of 2 improvement.

Year	Population (millions)	Growth Rate G (%)	E (toe/cap.a)			Total Energy No Eff.Imp. Mtoe/a	Tot. Energy. Eff. Imp. 2x by 2100. Mtoe/a
			No Eff. Imp. E_c = 2.5	Eff. Imp. 2.0x E_c	Eff. Imp. 2.0x E		
1990	845	2.13	0.31	2.5	0.31	260	260
1995	934	1.84	0.41	2.5	0.41	380	380
2000	1,016	1.61	0.51	2.5	0.51	520	520
2005	1,095	1.41	0.62	2.42	0.58	680	640
2010	1,170	1.25	0.73	2.33	0.64	860	750
2015	1,238	1.11	0.84	2.25	0.70	1,040	870
2020	1,304	1.00	0.94	2.18	0.75	1,230	980
2025	1,370	0.89	1.06	2.11	0.80	1,450	1,100
2030	1,432	0.79	1.16	2.03	0.84	1,660	1,200
2035	1,488	0.705	1.26	1.96	0.88	1,870	1,310
2050	1,623	0.49	1.57	1.77	0.98	2,550	1,590
2075	1,755	0.215	2.05	1.49	1.13	3,630	2,000
2100	1,813	0	2.50	1.25	1.25	4,530	2,270

A good fit to the population (P) is obtained with the formula below, which treats population growth as zero after 2100:

$$P = 1016 + 16.31Y - 0.0834Y^2, \text{ where Y is zero in 2000 and } Y \leq 100 \qquad (2)$$

If historic trends for per capita energy use continue there are implications for energy needs. Therefore, the population growth rate and related annual per capita and total energy use, calculated using Formula 1, are also shown in the table. The annual energy required at 2.5 toe/cap.a. would be 4,533 Mtoe in 2100. For perspective, note that today's world energy use is about 10,000 Mtoe/a.

Achieving such a level would represent quite a challenge. Fortunately, energy efficiency improvements can be expected. On the assumption that it is the useful energy that counts in regard to population growth rates, not that wasted, some of the energy needs should be met by reducing waste. As a second example, the case is considered in which the critical energy (E_c) drops steadily to 1.25 toe/cap.a, by 2100 owing to an annual efficiency improvement of 0.696%. This corresponds to an overall efficiency improvement of a factor of 2 over the period 2000 to 2100 (i.e., a combination of all the different improvements in the various sectors of energy use). See Sheffield (1997) for a U.S. example. **Note that, following this first analysis, it is assumed that an efficiency improvement of 2.5 over the period 2000 to 2100 might be needed.**

The two cases are assumed to roughly bracket the possible future energy demand in India for this period. In fact, given the challenge of meeting the higher demands, we will only look at the more efficient cases. Interestingly, some projections for Indian energy demand (Tata Energy and Resources Institute) suggest a rate of increase of energy of 3.8%-4.3% a year up to 2020. Assuming the starting figure of 520 Mtoe/a in 2000, this would lead to 1,100-1,210

Mtoe/a in 2020 (comparable to the Table 2 estimated need of 980-1,230 Mtoe/a), calculated with Equation 1, from the expected population growth rate G and effective value of E_c. The primary scenario of Gupta projects 935 Mtoe/a in 2020 and 2,435 Mtoe/a in 2050, close to the case in Table 2 with no efficiency improvements.

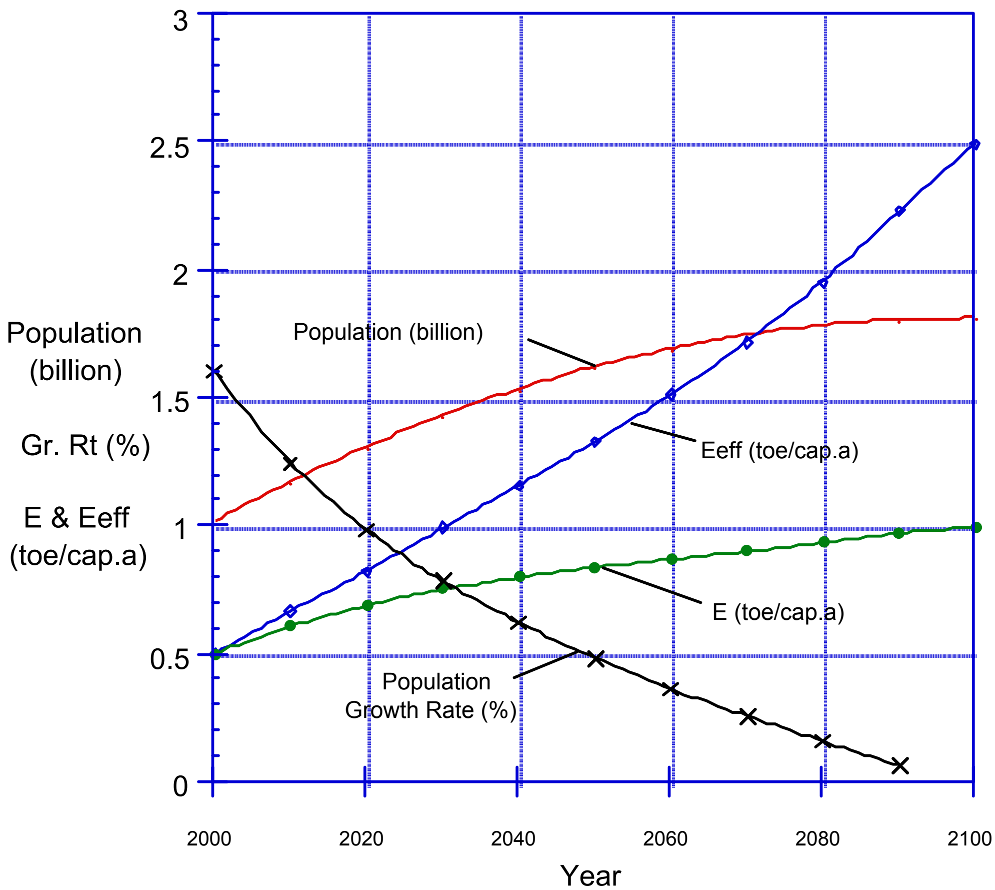
Note that while the energy demand is estimated using Equation 1, a similar answer comes from simply assuming that there is a minimum annual per capita energy use to achieve a respectable standard of living, above the poverty level, in an efficient society (see below).

Could the demand be even lower, while meeting the societal needs? Yes, but it would require more dramatic social changes and efficiency improvements. Goldemberg and Johanssen suggest that around one toe/cap.a of energy, used efficiently, is the minimum energy needed for a respectable standard of living in a temperate climate. In some sense, the use of even lower per capita energy numbers would beg the question of how to provide "enough" energy. In this paper, we also consider per capita energy use of around one toe/cap.a., with much improved efficiency as a reasonable goal. This level of one toe/cap.a would have a useful energy, in today's terms, of around 2.5 toe/cap.a, if an efficiency improvement of 2.5x were realized.

The integrated energy use from 2000 through 2100 is 254,000 Mtoe for the case of no efficiency improvements, and 153,000 Mtoe with efficiency improvements. Note also that in the efficient case the energy use in India in 2100 is comparable with that in the United States today.

Parameters for a third case with a 2.5x improvement in efficiency for the period 2000-2100 are plotted in Figure 3. Note the high level of the effective value of per capita energy use, because with efficiency improvements the amount of useful energy increases with a lowering of actual total energy expenditures. For this example, the integrated energy demand from 2000-2100 is 130,000 Mtoe.

Figure 3—Population, population growth rate, and per capita energy use for the case of 2.5x efficiency improvement in the period 2000-2100.



3. FUTURE ENERGY SUPPLY IN INDIA

In this section, an analysis is made of future energy options for India. It is assumed that a high priority will be given to using indigenous resources. The analysis shows that, with the present understanding of Indian energy resources, the possible demand, discussed above, will be hard to meet in the latter part of the 21st century. In the first half of this century, coal and a growing use of renewable energies and fission energy, coupled with continually improving efficiency and increased imports, should be able to meet the need. In the latter half of the century, even greater efficiency will be required coupled with much more fission and solar energy, and fusion energy, when available. Of course, if it turns out that fossil resources are much greater than calculated today (an example is given) it will be possible to reduce the rate of demand for fission and solar energies in the near-term. Alternatively, shortfalls might be met by increasing imports further!

The approach to meeting the energy demand is discussed in a series of steps, designed to indicate the potential contributions of the various energy sources and efficiency improvement.

3.1 Resources

The resources presently supplying significant amounts of energy (> 1Mtoe/a) are coal, gas, oil, biomass, hydropower, and nuclear fission. The use of solar power and wind power, while low today, is increasing. Other renewable sources are presently at a very low level.

The analysis presented in Table 2 and Figure 3., indicates that energy demand might be:

- 1,590 Mtoe in 2050, and 2,270 Mtoe in 2100 for a 2x efficiency improvement, and
- 1,370 Mtoe in 2050 and 1810 Mtoe/a in 2100 for a 2.5x efficiency improvement.

The IEA's estimate of energy use in 1997 was 461 Mtoe.

This energy was provided predominantly by coal (153 Mtoe), oil and petroleum products (88 Mtoe), gas (18 Mtoe), biomass (193 Mtoe), hydropower (6.5 Mtoe), and nuclear (2.5 Mtoe).

The historical annual rate of increase in energy from the IEA's numbers in Table 1 (1973-1997) was 2.25%. Achieving the energy levels projected in the Table 2 would require 2.1% pa from 1997 to 2050, and then 0.6% pa from 2050 to 2100.

In 1997, most of the fossil fuel used was produced domestically. Imports, mainly oil, were about 50 Mtoe.

It can be expected that fossil fuels, along with biomass energy, will continue to be the major sources of energy in the next decades. However, if the energy demand rises as projected above, it does not appear to be possible for indigenous fossil resources to meet the increased demands through this century. How fossil fuels might be used and how other resources can bridge the gap is discussed below.

3.1.1 Key points about possible energy demand and supply

Before getting into a detailed discussion of India's indigenous energy resources, we will discuss some simple examples of possible integrated indigenous energy demand and potential supplies. In Figures 4 and 5 there are some examples of integrated energy demand for the periods 2000-2050 and 2000-2100. These include the two examples in Table 2 plus the case in Figure 4, which have an efficiency improvement of 2.5 times in the period 2000 to 2100. In addition, for each case, three levels of energy imports are considered—10%, 15%, and 20 %.

Figure 4—Example of possible integrated indigenous energy demand for the period 2000-2050.

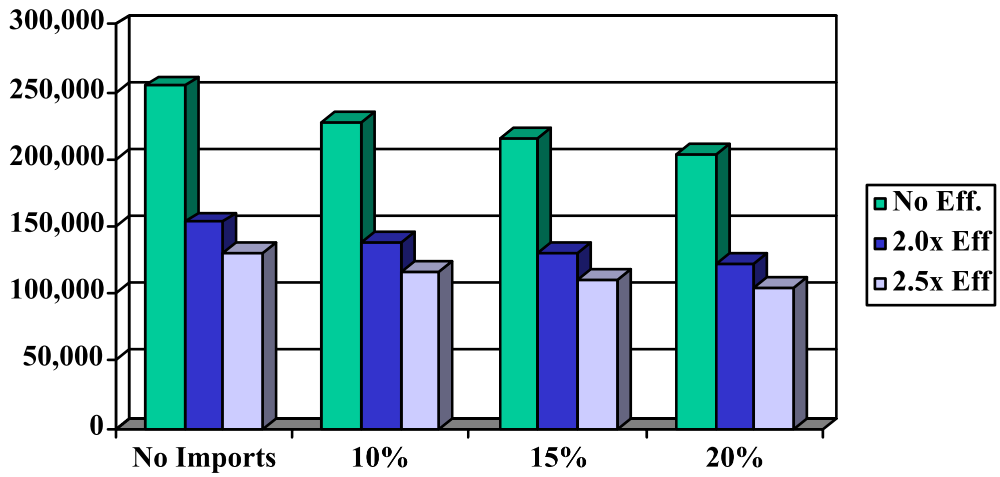
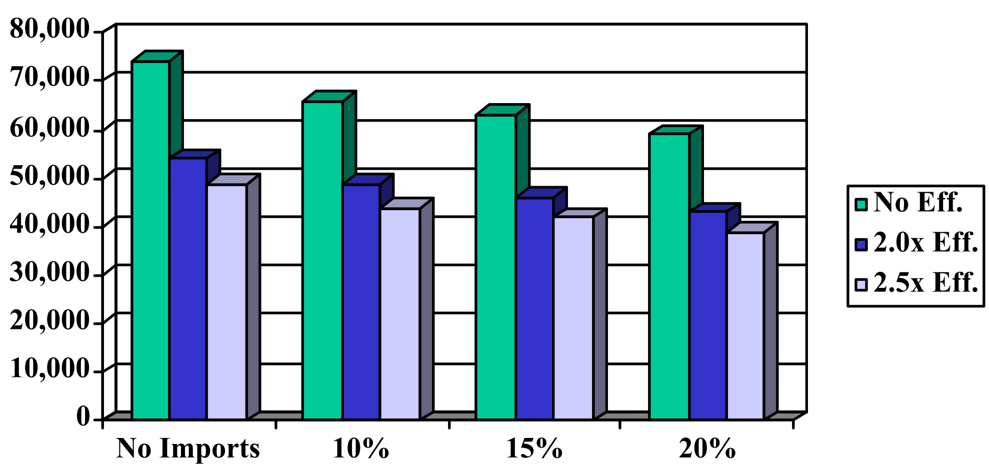


Figure 5—Example of possible integrated indigenous energy demand for the periods 2000-2100.



In the next sections, there is a more detailed discussion of indigenous energy supplies. The bottom line is that estimated fossil resources, including coal bed methane (but not methane hydrates) are about 49,000 Mtoe. As can be seen from Figures 4 and 5 these resources might be able to meet demands up to 2050 but are far short of projected energy demands up through 2100.

Additional indigenous energy resources include renewable energies. Leaving aside solar energy for the present, these resources include biomass, hydropower, wind power, geothermal power, and tidal and wave power. It is estimated that the total energy available, if these resources were extensively exploited, could provide about 350 Mtoe/a. (With the exception of biomass, these resources are treated as worth twice the electrical energy they produce because they are replacing coal, assumed to be converted to electricity with 50% efficiency.)

A simple case is considered in Table 3, where it is assumed that these renewable energies are available at 350 Mtoe/a from 2000, and all of the fossil fuel is used. The year in which the fossil fuel is consumed is calculated. An additional case is considered in which it is assumed that there is 25% more coal.

Table 3—Year at which all fossil fuel would be consumed assuming the availability of 350 Mtoe/a of renewable energies of (except solar energy).

	Year of depletion of fossil fuels		
Case	**No Efficiency Imp.**	**2.0x Efficiency Imp.**	**2.5x Efficiency Imp.**
No Imports	2047	2060	2066
10% Imported Energy	2050	2065	2071
15% Imports	2052	2068	2076
20% Imports	2054	2071	2080

Having 25% more coal would delay depletion, relative to the 2.5x case by 7 to 10 years.

The bottom line of these simple estimates is twofold:

- It is unlikely that fossil fuel would be depleted in a way that led to a cliff in indigenous energy production. Therefore, it seems prudent to assume a typical bell-shaped rise and fall of indigenous fossil consumption, as experienced in similar situations. This implies a decreasing production of fossil fuel around 2050.
- Given the above assumption, other indigenous sources of energy will be needed, starting now. The level of efficiency improvements and energy imports encompassed in the table are already ambitious!

The other indigenous resources are solar and nuclear. In the latter case, given that the potential energy deficit widens after the peak in indigenous fossil production (probably around 2050), a potential energy source might be fusion energy. These points are elaborated on below.

3.1.2 Electricity production

The past trend towards an increasing fraction of electrical energy use is expected to continue. The increase may even accelerate if electricity-producing energy sources, such as hydropower, nuclear, solar electric, wind, and wave and tide are used to replace fossil fuels. The question arises as to how to treat electrical energy—as a primary energy source or as a replacement value for fossil energy. The IEA allows for waste heat in describing the level of nuclear energy, but for hydropower uses only the electrical energy. The major part of electricity today is produced from coal, at around 30% average efficiency. On the assumption that alternatives to fossil energy are replacing fossil energy, their equivalent thermal energy will be used. However, the fossil electricity production efficiency is increasing steadily and the waste energy is decreasing. Therefore, allowing for future improvement, an effective efficiency of 50% will be assumed post-2010. The improvements in the efficiency of electricity end-use and co-generation heat use are accounted for in a blanket improvement in energy efficiency assumed for this study.

3.1.3 Use of depletable resources

An important issue regarding the use of depletable resources is what to do when the annual use is rising to a level at which their complete depletion will come in the period of interest. This is certainly the case for the estimated reserves of conventional oil and gas. One approach is to use an exponentially decreasing amount of the resources each year from the peak production level (Bartlett). Let R be the present the size of the resource at peak production, and let r(t) be the annual production of the resource, then in future years $r(t) = r(0)e^{-kt}$ and the total amount of the resource extracted in the future will be $R \geq E = r(0) \int_0^{\infty} e^{-kt} dt = r(0)/k$. Setting E=R, gives the decay constant $k_0 = r(0)/R$ for which all the resource will be exhausted. The half-life for resource exhaustion will be $T_{1/2} = \ln 2/(r(0)/R)$.

3.1.4 Coal

The World Energy Council's 1995 Survey of Energy Resources list gives total in-place Indian bituminous coal resources as 197,000 Mt (megatonnes of coal), and estimates additional resources of 86,000 Mt. The equivalent numbers for lignite are 26,000 Mt and 4,000 Mt respectively. Of these resources, recoverable amounts are estimated as 68,000 Mt + 43,000 Mt for bituminous coal and 2,000 Mt and 4,000 Mt for lignite. Giving a total of 117,000 Mt in 1995.

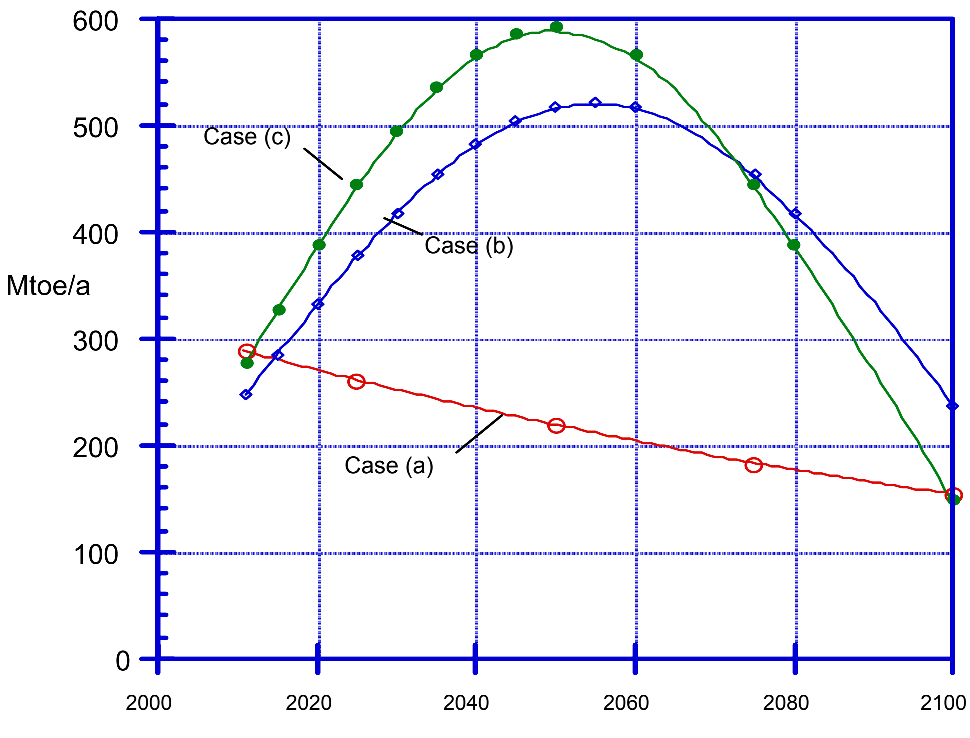
Using the average equivalent oil energy for the Indian quality coal, discussed above (0.37 toe/tonne of coal), and this mix bituminous and lignite mix yields 43,300 Mtoe. If this were used at the projected 2050 total energy demand rate above of 1,590 Mtoe/a, it would be gone in 27 years. Even if all of the coal reserves were recoverable, they would only last 73 years. Therefore, it seems improbable that coal can meet more than a moderate part of the projected demand over this century.

Actual coal production was 263 Mt in 1993 and 308 Mt in 1996. Articles in the WEC's Global Energy, First Magazine 2001, project a demand of 562 Mt (208 Mtoe) in 2007 and

775 Mt (287 Mtoe) in 2011. The average annual growth rate projected from 2001 to 2011 is about 6%, consistent with historical trends. If this occurs, the integrated consumption from 1997 through 2011 would be 7,600 Mt. If the 2011 level were then sustained through 2050, the integrated consumption would be 37,800 Mt. This would leave 79,200 Mt, or 1,580 Mt/a (586 Mtoe/a) for the next 50 years. This level is substantially less than the projected demand, even for the 2x efficient energy case, in which total energy use rises from 1,590 Mtoe/a in 2050 to 2,270 Mtoe/a in 2100.

Three cases, illustrating the potential use of the coal, are shown in figure 6.

Figure 6—Illustrative cases of Indian use of coal resources.



Case (a): Coal use after 2011 declines exponentially following the formula above with nk_0 = r(0)/R = 775/ 109,400 = 0.0071, and $T_{1/2}$ = 98 years.

Case (b): Coal use follows a $sine^2$ kind of usage from 1970 through depletion in 2140 i.e., peak production in the period around 2055. Allowing for coal use before 1996, the total amount available would be about 120,000 Mt rather than the 117,000 quoted above. With this simple formula, the relatively small usage before around 1970 is ignored, and there is a 6% a year rise in production through 2011 consistent with Goldemberg and Johansson. In 2055, production would equal 1,411 Mt/a, (522 Mtoe/a) and the amount of coal remaining would be 60,000 Mt (22,200 Mtoe).

Case(c): Similar, but depletes the coal more rapidly, starting in 1975 with peak production around 2050 and depletion in 2125. In 2050, production would be 1,600 Mt/a, (592 Mtoe/a) and the amount of coal remaining would be 60,000 Mt (22,200 Mtoe). This is the case we will use in the initial assessment of meeting India's estimated energy demand.

A fourth case (d) will be considered below to allow for there being more fossil energy available than presently estimated, e.g., methane hydrates. As an example, 25% more coal is used. This extra coal is used as a surrogate for there being more extractable fossil fuels in general.

Note, in general, that the actual decline of coal may be slightly less owing to some of the demand being met by imports. Imports in 1997 were 4% of consumption.

For comparison, Gupta projects indigenous coal use of 354 Mtoe/a in 2020 and 563 Mtoe/a in 2050, moreover he uses explicit percentages of fossil fuel imports.

3.1.5 Oil

The WEC 1995 lists recoverable reserves as 1,011 Mtoe in 1993. Production was 27 Mtoe/a in 1993, and 33 Mtoe/a in 1996. If this rate of production continues, let alone increases, the oil will be gone in 31 years. Even if further oil were discovered, boosting reserves by, say, a factor of 4 would not alter the fact that indigenous oil is not likely to be a major contributor over this century. Clearly, imported oil will continue to play a major role. We will assume that oil use continues at the 1996 level through 2011, and then decreases exponentially with $k_0 = 33/396 = 0.0833$ and $T_{1/2} = 8$ years.

There have been discussions about building oil and gas pipelines to India from the Middle East and Central Asia for facilitating their supply. Of course, there remain a number of political problems in accomplishing such a goal. Nevertheless, such pipelines would be important if India were to increase its fossil imports substantially, as discussed below.

3.1.6 Gas

The situation for conventional natural gas is similar. Note 1000 m^3 = 0.857 toe. The WEC 1995 lists recoverable reserves as 686 x 10^9 m^3, with an additional estimated amount of 735 x 10^9 m^3. Production was 20.4 x 10^9 m^3 in 1993 and 22.9 x 10^9 m^3 (19.6 Mtoe) in 1996. At the 1996 rate, the gas will last 62 years, but it is still a relatively small contribution compared to the total energy demand. Production is projected to increase. Nevertheless, we will assume that gas production continues at the 1996 level through 2011 and then decreases exponentially, with $k_0 = 22.9/1013 = 0.0266$ and $T_{1/2} = 31$ years.

Interestingly, there are unconventional sources of gas such as coal bed methane and methane hydrates (off the coast of India). The former source might amount to a few to 10% of the unused coal energy. Exploitation of methane hydrates is under investigation.

3.1.7 Biomass energy

Biomass energy from trees and agricultural residues has always provided a large part of India's energy needs, as shown in Table 1 above, amounting to about 200 Mtoe in 1997. Unfortunately, the use of this biomass has led to soil erosion and deforestation. Sustaining or increasing such a level of use will require much improved practices, including the use of higher yield biomass. In the 1992 UN study, the RIGES (Johansson, Kelley, Reddy, and Williams) analysis of renewable energies suggested that it might be possible to produce up to 560 Mtoe/a of biomass energy annually in all of South and East Asia by 2050. Allowing that at this time the population of India might be about a half of that in the region, and assuming a uniform production per capita would suggest a possible increase from about 200 Mtoe/a in 1997 to 280 Mtoe/a by 2050.

3.1.8 Hydropower

The 1998 WEC report lists a present capacity of 21.3 GWe of hydropower, and actual generation in 1996 as 69,070 GWh of electricity (7.9 GWe average power). A further 28 GWe is planned. The technically exploitable potential capacity is estimated as 84 GWe, which at an assumed 40% load factor would imply an output capability of 294 TWh per year (33.6 GWe average output) or 25 Mtoe of electricity per year. The hydropower can displace fossil fuels in producing electricity. Assuming 50% efficiency for fossil energy conversion to electricity, the lower estimate for hydropower capability would be equivalent to 50 Mtoe per year of fossil energy replaced.

3.1.9 Fission

Net generation of nuclear electricity in 1996 was 7.4 TWh (0.84 GWe average, and 1.6 Mtoe/a fossil fuel equivalent) from 1.7 GWe capacity (WEC 1998). More recently, in 2001/2002 the installed capacity of 2.72 GWe achieved an average load factor of 85%, or 3.5 Mtoe/a fossil fuel replacement (Nuclear News 2002). By 2010, the capacity is expected to be 6.7 GWe, about a 9% per year growth rate. If the Indian nuclear plant capacity factor stayed at 85%, a level typical of mature nuclear systems, the annual energy production would be 8.6 Mtoe/a (coal energy equivalent).

As an example of future trends, consider the case in which 2 GWe is added per year from 2010 until 2050 (see the discussion in 5.2). The capacity would rise to 86 GWe in 2050. The fossil fuel replacement value (50% efficiency fossil fuel to electricity) would be 103 Mtoe/a in 2050.

Such levels of nuclear generation are large. Today's world nuclear generating capacity is around 400 GWe. However, in relation to total population, it is relatively much less than in a number of countries, e.g., in France there is about 1 GWe per million people. Therefore, this kind of goal should be achievable.

The Indian plans for fission energy development are focused on the use of thorium rather than uranium because India has substantial thorium resources. Because thorium is a fertile material rather than a fissile material, its use will require breeder reactors. India has a program to develop the capability to exploit its thorium (Nuclear News 2001).

3.1.10 Solar power

At the end of 1996, the installed capacity was 28 MWp, with an annual generation of 0.04 TWh (WEC 1998). Total PV capacity is projected to reach 150 MWp (megaWatt peak) by the end of 2002. The Indian Renewable Energy Development Agency estimates a theoretical potential of 5 x 10^{15} kWh/year of solar thermal energy (WEC 1998), or **429,000 Mtoe/a** thermal, an average of 180 W/m^2 average over India's land area of 3,166, 830 km^2. How much of this energy could be used is uncertain. Obviously, cost will be an issue. Today, the cheapest photovoltaic modules cost a few dollars a peak watt, and if 0.1% to 1% of the country were covered in PV cells, the cost would be huge. Nevertheless, human-made structures cover 0.1% of the area of many countries, therefore such coverage is a possibility, particularly when the unit costs of solar collectors are reduced. If 0.1% of the land were covered with solar collectors, they would collect 430 Mtoe/a of thermal energy. If this were converted to electricity at 20% efficiency, it would generate 86 Mtoe/a of electricity. In terms of replacing coal, used at 50% efficiency, it would be worth 172 Mtoe/a.

An obvious issue for electricity production is that the present world level of photovoltaic cell production is only a 300 MWp per year. To reach the multi-gigawatt level will require a sustained high growth rate of solar cell production to meet the needs of India and other countries. Therefore, in the early years, much of the solar energy example use of solar energy might be thermal rather than electric. A mixture of thermal use and electricity production could well be equivalent to a similar level of energy use because of inefficiencies in the use of the direct thermal energy.

We will assume for a first example (see 5.2) that solar energy use in India is built up to a level of one-third of fission energy; 34 Mtoe/a (fossil equivalent) by 2050; 27 GWe or 135 GWp (if it were all electricity).

3.1.11 Wind power

The potential for wind power in India is estimated to be about 45 Gwe (Bakshi and Jagadeesh). Assuming an availability of 30%, this would amount to about 10 Mtoe/a of electricity or, in terms of fossil fuel replacement, about 20 Mtoe/a.

3.1.12 Other renewable energy sources

The 1998 WEC report lists studies of tidal power for the Bay of Kachch, potential for 1.6 TWh /a (0.11 Mtoe/a), and for the Gulf of Khambhat a potential of 10-15 TWh (0.7-1.0 Mtoe/a). There is also a small program on wave power.

Geothermal power is an important further possible energy source. However, typically, on the continents, the average power is only about 0.06 W/m^2, which is much lower than solar power. Therefore, it is less likely to be a massive source of energy, unless there are extensive hot spots.

3.1.13 Intermittent sources and hydrogen production

Intermittence is a particular problem for solar and wind power, since neither is available for more than 25 to 50% of the time. From the point of view of an electricity grid, estimates are that typically 10 to 25 % of the electricity source may be intermittent, depending on the strength of the grid. Further, because the sources of intermittent energy will not be uniformly distributed, their fraction of local power will vary. For these reasons, both storage systems and sources of continuous power, such as coal, fission and fusion, will be important contributors.

Hydrogen, as an energy carrier, is of particular interest because it may be produced from a variety of energy resources, and it can be used as fuel in buildings, industry, and transportation. It can be used also for energy storage. Today, most hydrogen is produced from natural gas and/or in the oil refining process. In the future, a far greater amount can be expected to come from biomass and from the electrolysis or thermal processing of water because:

- Production of hydrogen is an attractive option for intermittent electric sources: to save and store peak production; and to lessen the size of the local grid, which will not have to be sized for peak electricity production.
- For continuous power sources with low fuel costs, such as fission and fusion, it is a good option for the use of off-peak power, because with their relatively high capital costs it pays to operate such plants continuously at full power. As shown in a recent paper on large fusion power plants, it would also allow such base-load plants to load-follow (Sheffield 2001).

For all of the reasons above it appears likely that the potential Indian energy deficit, projected in the analysis above for the latter part of this century, will be met by some combination of increased imports, fission and solar energy, and that fusion energy could be a useful complementary source. Further, it may be expected that some of these indigenous sources will produce hydrogen as a complement to electricity.

4. SUMMARY OF POTENTIAL INDIAN ENERGY SOURCES UP TO 2050

4.1 Indigenous Resources Summary

Possible indigenous sources of energy for use in India are summarized in Table 4. The numbers used are those discussed in Section 3, with the assumption that the maximum use of biomass energy, wind power, and hydropower will be reached by 2050.

Table 4—Example of possible Indian use of indigenous fossil and renewable energy sources and imports in 2050 (ex fission energy, solar energy, and imported energy)

Energy Source	2050 annual use Mtoe/a	Comments
Coal	592	Case (c), shown in Figure 3.
Oil	1	
Gas (a)	8	Coal bed methane (estimated as 10% of coal resources) and methane hydrates are additional resources.
Biomass	~280	
Hydropower	50	Fossil fuel replacement value.
Wind	20	Fossil fuel replacement value.
Other Renew.	~2	Excluding solar energy.
Total Supply	953	
Demand	1590	Improved efficiency case **2x** by 2100.
Deficit (a)	**637**	

(a) The estimated deficit in this period might be eliminated by even greater efficiency improvements, the use of fission and solar energies, and imports that are more substantial.

The potential contributions of these various sources of energy are shown in Figure 7. The trend of an increasing energy deficit after 2050 reflects the example use of fossil energy. A lower rate of coal use, up to 2050, would simply give a larger deficit earlier on, and a more rapid use of coal would lead to an even more abrupt increase in the deficit later. If this understanding of demand and potential supply is correct, the deficit will have to be filled by some combination of imports of energy, fission energy, solar energy, and greater efficiency improvements. Obviously, if there were more fossil fuel, it could be used to delay the need for alternative energy sources. Looking ahead to the second half of the century, where further increases in energy demand are expected, it appears that fusion energy could play a valuable role, when developed.

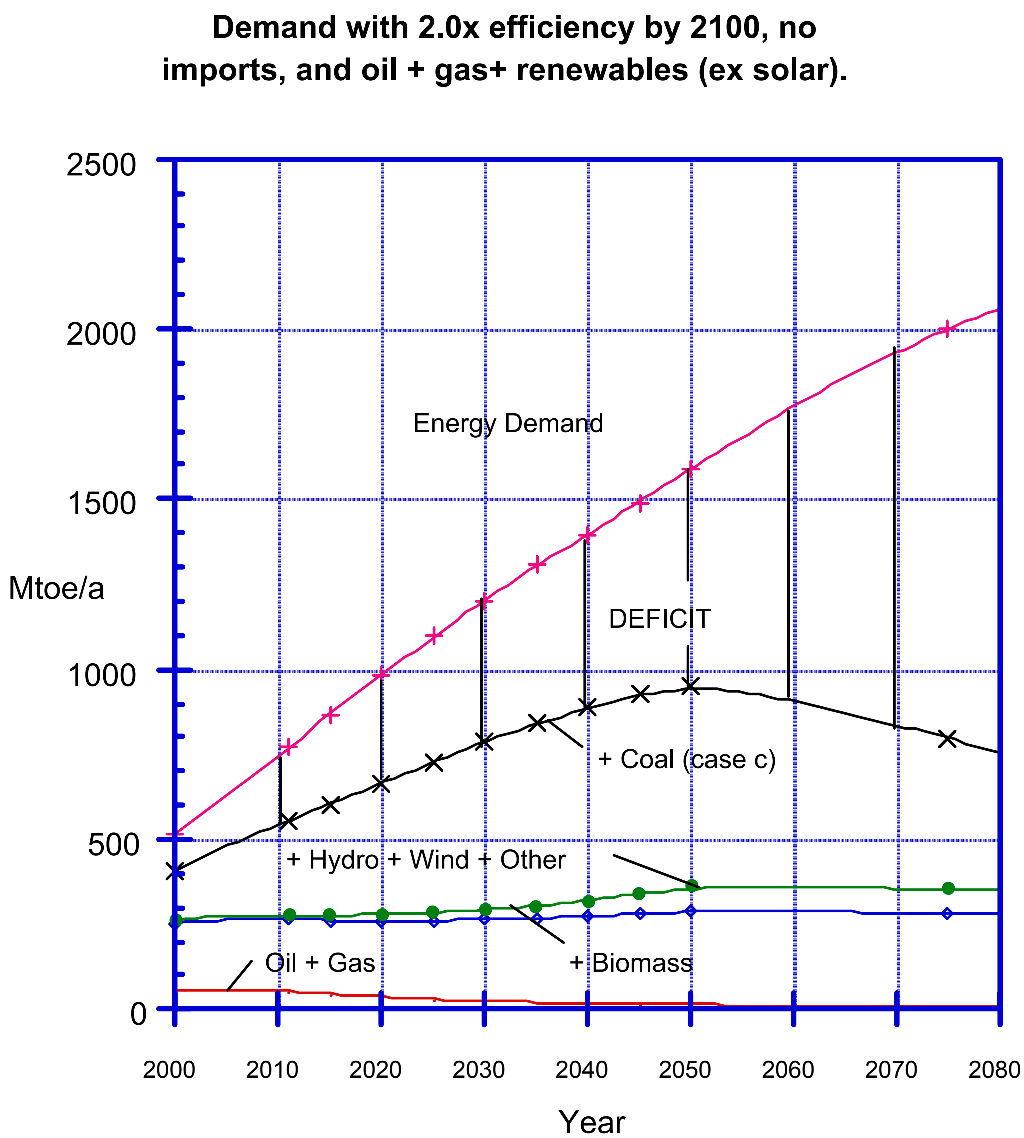


Figure 7—Illustrative example of supply and demand for energy in India, using indigenous resources of fossil energy (coal, case c), biomass energy, hydropower, wind power, tide and wave power. Efficiency improvement is 0.696% per year, or a factor of 2.0 between 2000 and 2100. The energy sources are added to meet the demand.

4.2 Cost of the Alternative Energy Sources

Clearly, the cost of energy will be a major factor in determining which of the potential energy options would be chosen. Today, solar thermal heating is economic in many places, notably those with high fuel costs such as Barbados. In 1998, the cost of solar electricity was estimated as about 15-30 c/kWh, but the price was decreasing and it was estimated that it would drop below 10 c/kWh within the next decade (The Solar Letter). The reason for the decrease was a reduction in the capital cost of solar modules from a low cost of around 4 $/peak Watt to the range $1-1.5/peak Watt. The cost of electricity from fission is around 4-5 c/kWh in regions, such as France, where a mature nuclear industry has been developed.

Another important factor will be whether the sources are indigenous, putting them under Indian control, or have to be imported. In 1997, imports were about 11 % of total energy use. As seen in Figure 5, there may be a need to increase imports but presumably the level will be bounded by cost and by internal security considerations. For this exercise, we consider the cases where energy imports rise to 15% or 20% of total usage. Interestingly, Gupta increases imports of fossil fuels in his baseline scenario to 35% in 2020 and 69% by 2050, rather than expanding the use of fission and renewable energies.

Deficit met by oil imports—If the deficit energy of 637 Mtoe/a, shown in Table 5, were met with imported oil at $25/barrel in 2000$ (typical of prices today), it would cost about $120 billion a year to import the deficit energy. Further, there would be the issue of the availability (cost) of fossil fuels to import in 2050, given the world's rate of use of lower cost resources.

Deficit met with nuclear energy—Of course, if the energy were produced by nuclear it would involve a huge capital investment in addition to an annual operating cost. Assuming that electricity is worth twice the energy in the primary power that created it, 637 Mtoe is equivalent to 424 GWe operated continuously, or about 530 GWe of nuclear power at 80% capacity factor.

For nuclear power at $2,000/kW installed (Delene, *et. al.*), the capital cost would be ≤ $1100 billion. Note that costs for some advanced plants are projected to be less! The operating costs for such a nuclear system would be about $31 billion per year (see Delene, *et. al.*).

Deficit met with solar energy—If the deficit energy were all met with solar electricity, at an average of 180W/m^2 of solar thermal power and an electrical conversion efficiency of 20%, the solar system would cover about $1.2x10^4$ km^2, or about 0.4% of the area of India (allowing for a factor of two gain for coal replacement). This area would be reduced if the solar power were placed more in areas of highest isolation.

The capital cost of the solar modules, assuming a future price of 1$/Wp, would be about $900 billion, assuming that the peak power was about twice the average power. The operating costs for solar should be less per GWe than for fission.

The bottom line of this simple analysis is that the deficit energy could be available through some combination of imports, nuclear, and solar energy. It seems unlikely that

it would be provided by only one source. In any circumstance, it will involve large amounts of funding.

Deficit reduced by greater energy efficiency—Greater efficiency improvements would alleviate the problem of energy supply, but their cost would have to be balanced against that of providing the energy.

At the assumed rate of efficiency improvement of 0.696% per year (2x improvement over 100 years), the improvement by 2050 is 1.41x, i.e., only 1/1.41 of the energy of the no improvement case is required to perform the same functions. Hence E_c = 1.77 toe/cap.a.

At a rate of 0.921 per year (2.5x over 100 years), the gain by 2050 is 1.58x and the demand of 1590 Mtoe/a drops to 1363 Mtoe/a, using formula 1 with E_c = 1.58 toe/cap.a.

Note that a factor of 4x improvement is at the limit of what some efficiency aficionados claim is possible. However, such a gain would require the very best approaches be used in all new energy-using elements and in rebuilding or refurbishing the existing infrastructure. It seems prudent to consider the cautious position that efficiency improvements will be substantial but not at the limit of what might be achieved in an ideal situation. In the spirit of sharing the contributions to meeting the energy demand, we use an efficiency improvement of 2.5x for the energy scenarios that follow. With such an improvement in efficiency, the deficit becomes 410 Mtoe/a. An example case with 15% and 20% imported energy is shown in Figure 8.

The deficit energy of 410 Mtoe/a might be provided by building up by 2050 to say, 15% to 20% imports (204 Mtoe/a to 273 Mtoe/a), plus fission energy of 103 Mtoe/a coal equivalent (86 GWe at 80% availability), and a third as much solar energy, 34 Mtoe/a. Annual costs for imports, if oil were at \$25/barrel, would be about \$37b/a to \$49b/a. Capital costs for nuclear and solar, respectively, would be about \$170b and \$55b. Assuming an annual payback of 0.1x the capital investment for 20 years, the annual paybacks would be \$17b/a and \$6b/a, some of which would be paid off before 2050. The operating costs would be \$5b/a for the nuclear plants and somewhat less for the solar systems. In total, the annual payments would be in the range \$65b/a to \$77b/a. With the estimated population of 1.623 billion, the cost per person would be \$40 to \$47 per person per year. This example is illustrated in Figure 9.

Increased fossil fuel availability—Figure 10 gives an example in which there is 25% more coal available. This, coupled with 15% to 20% of imported energy and the 2.5x efficiency improvement, would eliminate the deficit up to 2050 without the need for more fission or solar energy.

Figure 8—Illustrative example of supply and demand for energy in India, using indigenous resources of fossil energy (coal, case c), biomass energy, hydropower, wind power, tide and wave power. Efficiency improvement is 0.921% per year, or a factor of 2.5 between 2000 and 2100. The energy sources are added to meet the demand.

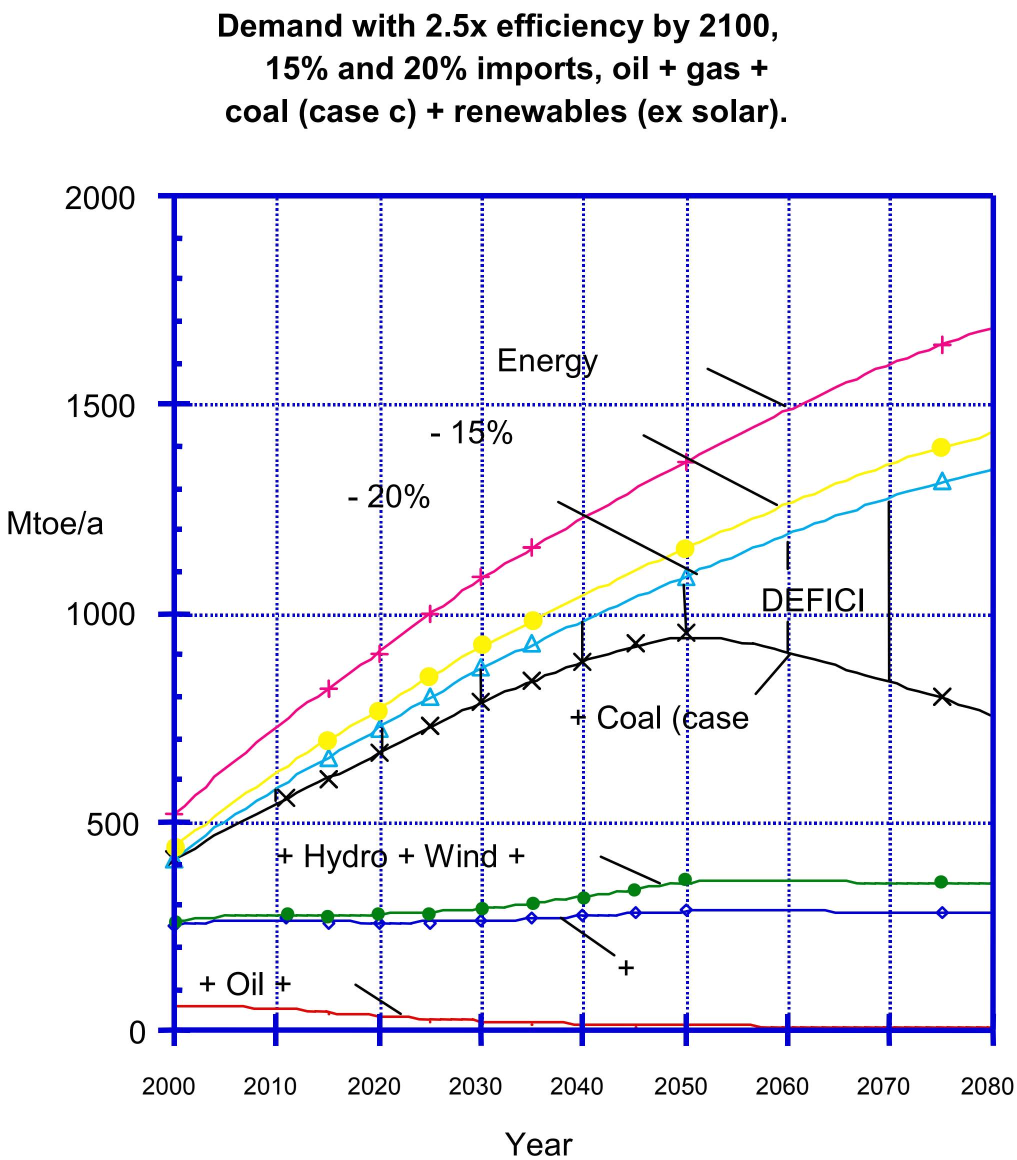


Figure 9—Illustrative example of supply and demand for energy in India, using indigenous resources of fossil energy (boosted coal, case c), biomass energy, hydropower, wind power, tide and wave power. Efficiency improvement is 0.921% per year, or a factor of 2.5 between 2000 and 2100. The energy sources are added to meet the demand. Imports are in the range of 15% to 20%.

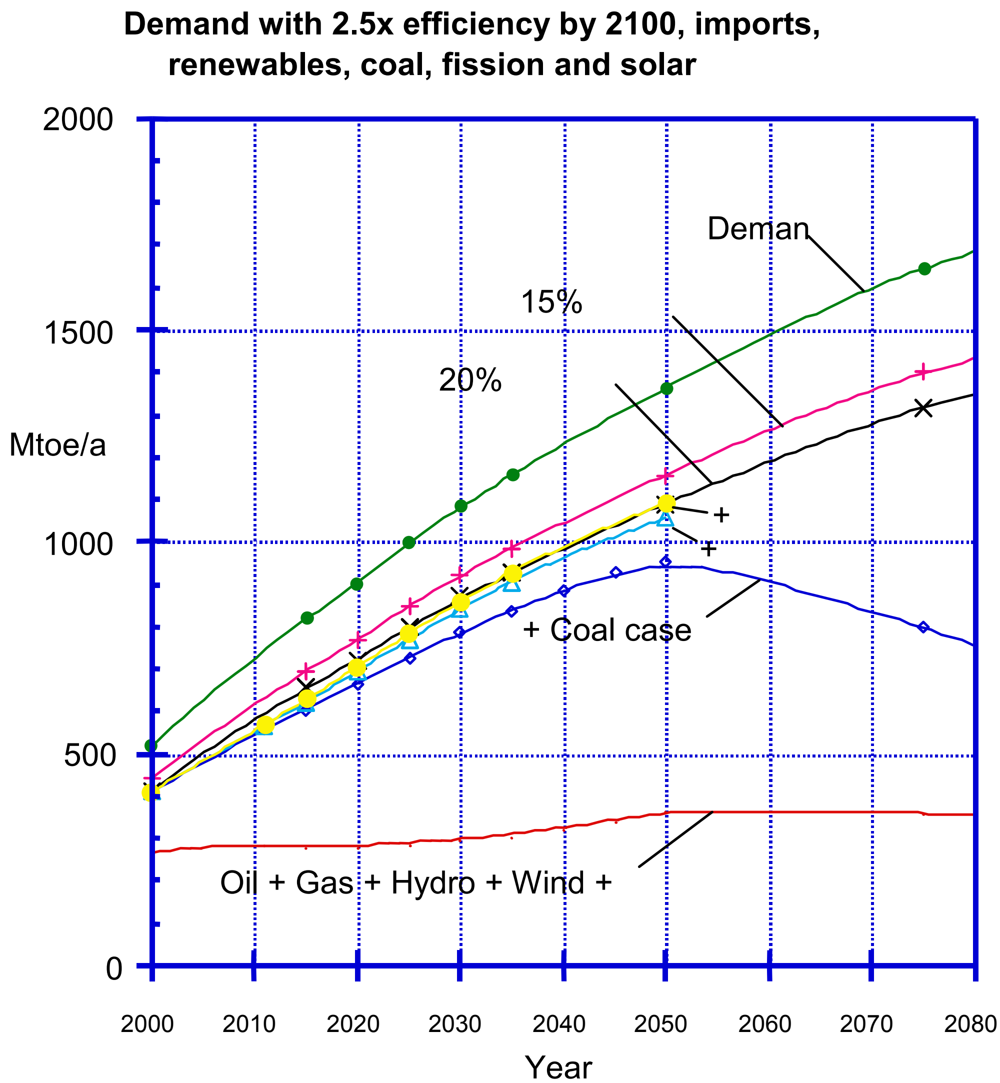
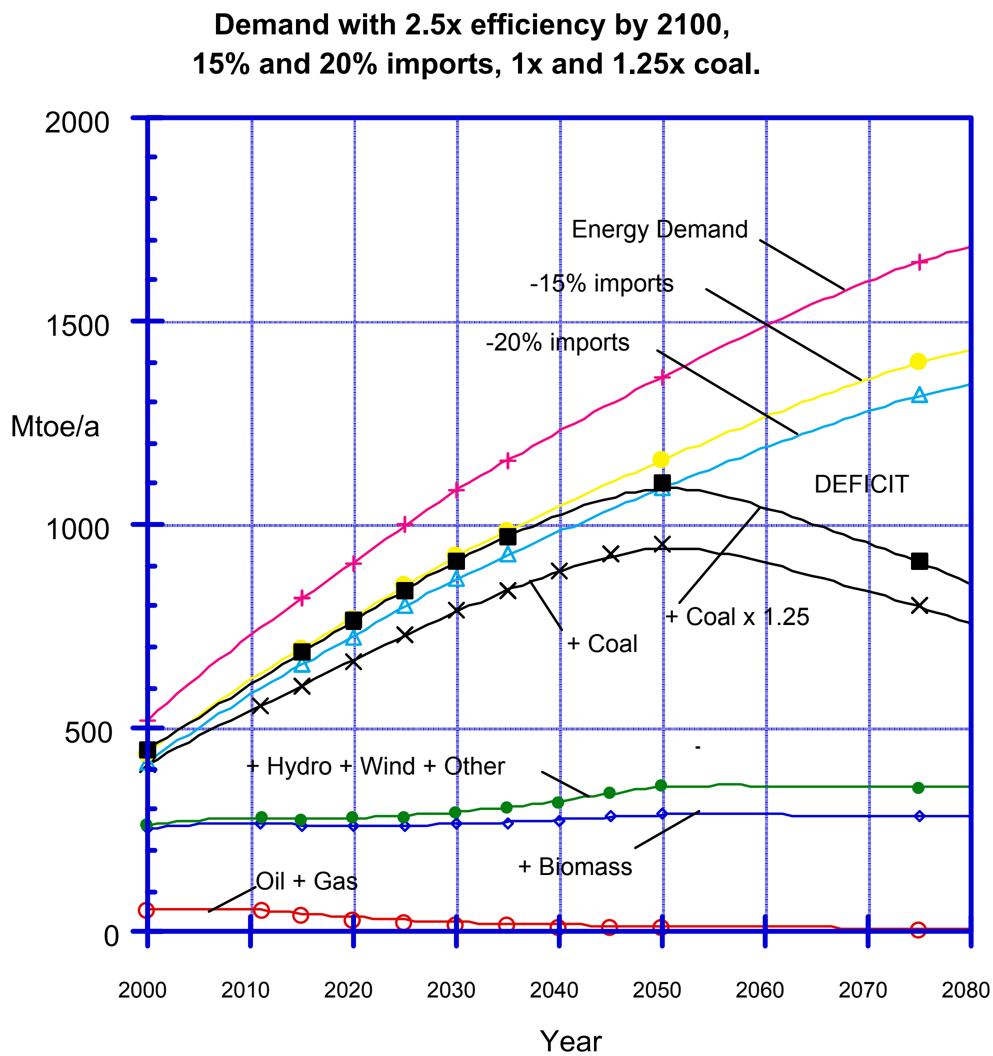


Figure 10—Illustrative example of supply and demand for energy in India, using indigenous resources of fossil energy (boosted coal, cases c and d), biomass energy, hydropower, wind power, tide and wave power. Efficiency improvement is 0.921% per year, or a factor of 2.5 between 2000 and 2100. The energy sources are added to meet the demand. Imports are in the range of 15% to 20%.



4.3 Conclusions for Meeting Energy Demands for 2000 to 2050

The examples given above illustrate the kinds of options available for meeting possible energy demands in the period 2000 to 2050. They are:

- Greatly improved efficiency of energy use, approaching 1% per year.
- Substantial imports, possibly in the range of 15% to 20% of demand.
- Use of a large percentage of fossil energy resources (about 50%).
- Use of close to the maximum estimated resources of the following renewable energies: biomass, hydropower, wind power, and others.
- A large increase in the use of fission and solar energies.

A key point is that, unless it is possible to dramatically reduce the assumed energy demand, or increase the efficiency of energy use even faster, it will be necessary to use 50% of the indigenous fossil resources. Consequently, with an energy demand still growing and decreasing annual use of indigenous fossil resources, there will be an increasing energy deficit after about 2050.

Even if fossil resources turned out to be 25% greater, they would only delay the problem about 20 years. Alternatively, the fossil fuels could be used for a longer period at a lower level than the example, see Figure 4. However, this would require some combination of an even faster build up of fission and solar, more imports and greater efficiency before 2050.

One obvious question is: "What would happen if energy supply were less than projected?" Well, if there is some connection between per capita energy use and population growth, the population might grow even faster, making a solution with zero population growth harder to realize.

It is in this post-2050 period that the possible use of fusion energy is interesting.

5. PROSPECTS FOR FUSION ENERGY

5.1 Development of Fusion Energy

Fusion power is a potentially useful complement to fission power and has advantages with regard to safety, waste disposal, and proliferation issues that would make its deployment advantageous in some situations (Barabaschi). Fusion fuel cycles are mentioned in Section 2. When a deuterium fuel cycle is realized, this energy source is in effect infinite. It is estimated that there are over ten million million tonnes (10^{13} tonnes) of deuterium in water. The energy equivalent, if all the deuterium and the byproducts of its fusion were fused, approaches a million million gigatonnes (10^{21} gigatonnes) of oil equivalent energy. Present world energy use is only about 10 gigatonnes of oil equivalent per year and may rise to 20 to 30 Gtoe/a. Therefore, deuterium-based fusion energy has the potential to supply the world for well over a billion years!

Other fusion interactions involving helium-3, lithium, and boron offer the possibility of much lower neutron production, but are more speculative—helium-3 because of the question of its availability on earth; and lithium and boron because of the higher temperatures required for releasing net energy.

While the development of economic electricity from fusion energy is a very challenging task, substantial progress has been made in recent years in both magnetic and inertial fusion research, in showing that energetic fusion products behave as expected and in demonstrating some of the key technologies. These successes have led to support of the design and R&D studies for the International Thermonuclear Experimental Reactor (ITER) in magnetic fusion and the U.S. National Ignition Facility (NIF) in inertial fusion (under construction). The construction of ITER is awaiting a decision of the international partners—the European Community, Japan, and Russia. Assuming the operation of NIF and ITER or similar facilities and an aggressive program on improvements to fusion devices, nuclear technologies, and materials, it would be possible to develop fusion energy so that commercial power plants might be operating about the middle of the present century.

Build-up rates for fusion power plants may be constrained by the time to replace the energy used in constructing them and in producing the fuel (small). Estimates for some representative fusion plants indicate that the energy payback time might be up to 1.5 years. Thus to get net energy from fusion requires a plant capacity doubling time of longer than this! Similarly, there is a constraint on doubling time imposed by the tritium build-up rates to support new plants (assuming that the deuterium-tritium cycle is used). Consideration of these factors suggests that a construction rate with a doubling period of 5 years or so should be possible (Perry). Following the demonstration of fusion energy in a limited number of countries, a systematic deployment of fusion power is anticipated. It may be expected that in many cases, because of their technological complexity and waste disposal issues, fusion and fission plants will be built and operated by international consortia, allowing their deployment in countries which do not have in-house all the skills needed.

5.2 Estimated Costs of Fusion-Generated Electricity

Numerous studies have been made of fusion power plants, designed to operate in the 1 GWe range. The focus on the 1 GWe range is because such a plant size is more commonplace and at smaller sizes it is harder to meet the physics, technology, and engineering requirements. Such studies have identified the conditions under which such power plants might be competitive with other sources of electricity in the future. In simple terms, competitiveness may be defined as production of electricity at around 5 c/kWh in today's dollars. The studies clarify: what physics performance will be required for creating and sustaining the hundred million degree fusing plasmas; what the technology and materials needs will be; and what reliability and capacity factor (availability) will be needed.

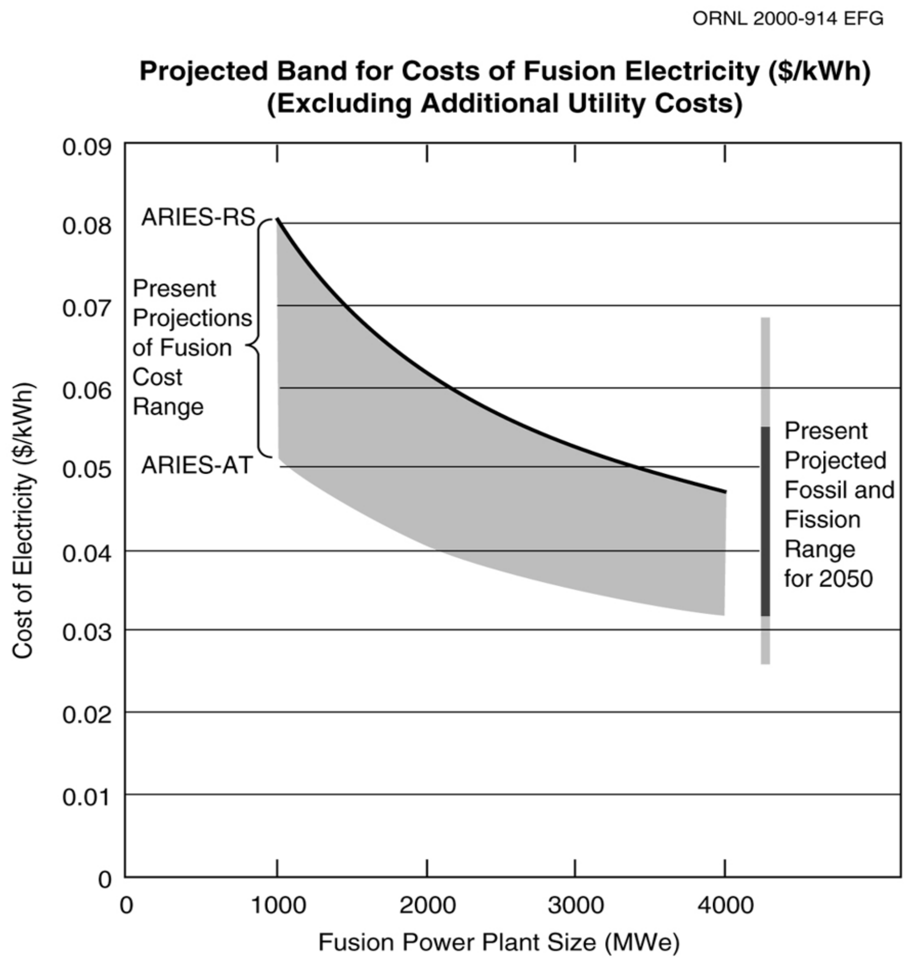
Studies of fusion power plants using magnetic or inertial confinement have also shown an economy of scale. (See, for example, the ARIES studies of Miller, *et al.* in 1996 and 2000 [ARIES-RS and ARIES-AT, respectively]; Dolan; Galambos, *et al.;* Hender*, et al.;* Sheffield *et al.* (1986); and Zuckerman, *et al*.) At a size larger than 1 GWe, not only should the cost of electricity (COE) be less, but it should also be easier to accommodate the volume needed for plasma cleaning systems and the access needed for cooling and maintenance.

The use of fusion energy to generate products other than electricity has also been considered, and hydrogen production is an attractive opportunity (Kulcinski, Logan, Waganer, *et al.*, and Sheffield *et al.* 2001). The concept of a "hydrogen economy" is of great interest, e.g., Johansson, *et al.*, Socolow, and Williams. It should offer a cleaner and healthier environment for future generations.

In this paper we will consider such larger power plants because, as shown in Figure 11, they offer the possibility of lower than 5 c/kWh electricity, or may be viewed as providing a margin for accommodating unforeseen costs while achieving around 5c/kWh. In addition, we will consider co-production of hydrogen. This is advantageous because it allows more flexibility in plant operation, including the possibility of load following for what might otherwise be a base-load plant.

Economy of scale studies for both magnetic and inertial fusion power plants show the cost of electricity decreasing with increasing electrical capacity, approximately as $(P_e/P_{eo})^{-0.35}$ in the range of interest. Consequently, while a typical 1,000 MWe fusion plant might produce electricity at 5 to 9 c/kWh, a 4,000 MWe plant might produce at 3.2 to 5 c/kWh. The ARIES-RS power plant, based on the tokamak concept, was completed in 1996. The ARIES Systems Code projected the performance and cost of the ARIES-RS plant up to the 4 GWe size. It should be noted that no optimization for the larger size was accomplished—the plants were merely scaled up with a constant wall load constraint. To assess other possible improvements, the ARIES group has since commenced a new design and evaluation effort of an advanced tokamak reactor, the ARIES-AT (Miller, *et al.* 2000). It has a more efficient plasma, with higher greater plasma shaping to yield higher plasma pressures for a given magnetic field (higher beta values). A new, higher temperature tritium breeding blanket design has been incorporated that yields much higher thermal conversion efficiency. Efforts were made to significantly lower the capital cost of the power core components. It was also anticipated that the plant availability could be raised to help lower the average cost of electricity. The combined effects of these improvements enable the advanced tokamak's cost of electricity to be lower than the RS's. The range of cost of electricity from both plants is shown in Figure 11 (Sheffield *et al.* 2001).

Figure 11—Projected range of costs for ARIES-RS and ARIES-AT, by plant size, excluding additional utility costs to accommodate the larger power plants (Sheffield *et al.* 2001).



5.3 Scenarios with Deployment of Fusion Energy

For the purposes of this analysis it will be assumed that there are advantages in having fewer, larger, fusion power plants and the reference case will use 3GWe plants with 80% capacity factor, with a third of the power being used to produce hydrogen by electrolysis (Nuclear News 2001). Each power plant would provide energy equivalent to 3.6 Mtoe/a, allowing that fusion energy is replacing coal energy used at 50% efficiency. The co-production of hydrogen for very large power plants offers two advantages. The reduction in power connected to the grid reduces the extra cost of strengthening the grid to handle such a large single contributor. Co-production also allows some load following for a plant that otherwise would be run at constant (maximum) electrical power. The fusion program is assumed to start with 1 plant operating in 2050, continue with a second in 2055, 2 more in 2060, 4 more in 2065, and then 8 more each 5 years until 2100. By 2100 there would be 64 plants producing 3GWe each, a total of 192 GWe, or 230 Mtoe/a (coal plant replacement value).

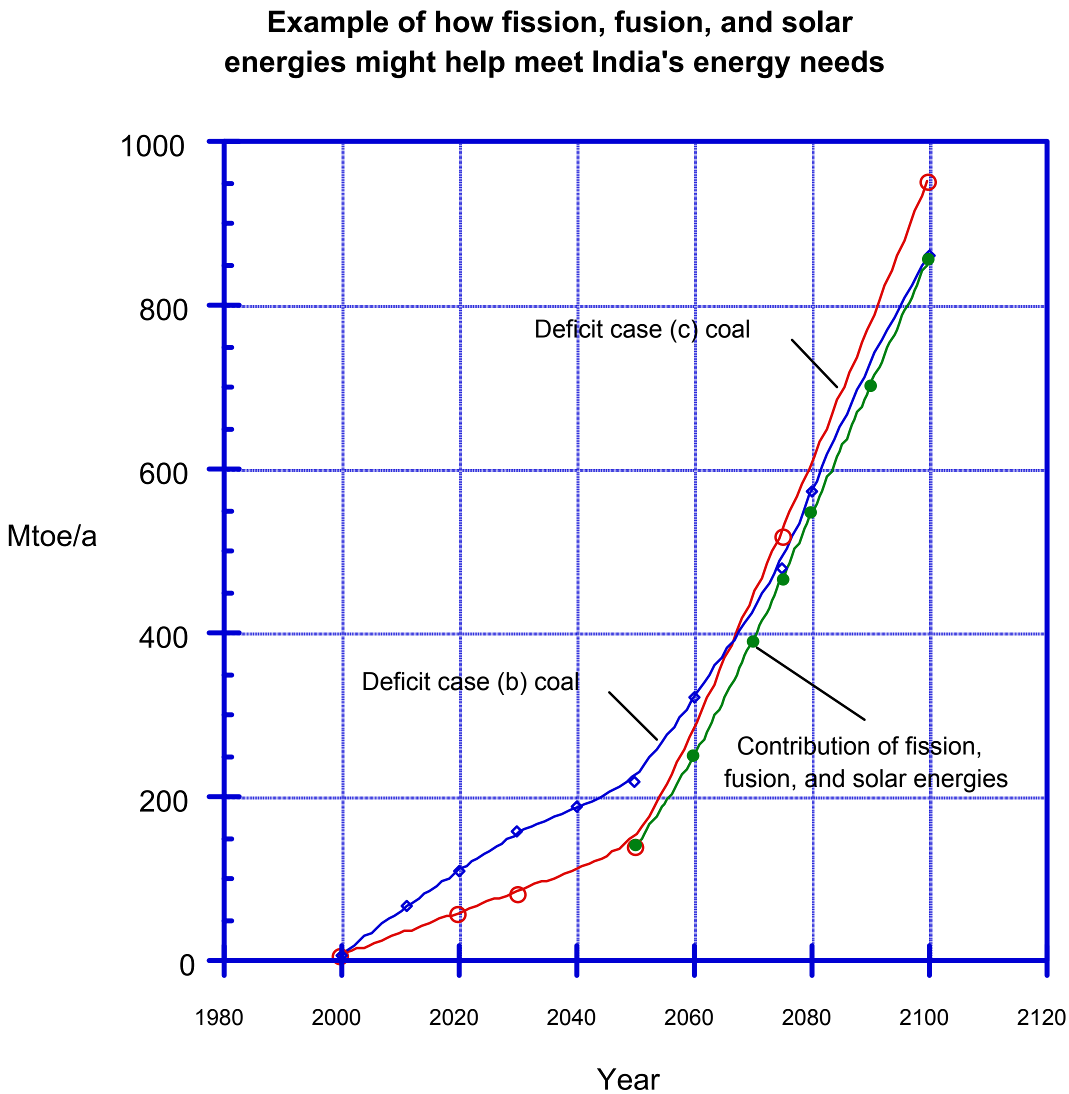
An example scenario for the build up of fission, fusion , and solar energies is shown in Table 5, with an assumed increase from 2050 to 2100 in fission capacity of 4 GWe/a (4.8 Mtoe/a), and an increase in solar energy use of 5 Mtoe/a. Such a level of contribution from the three energy sources is needed to meet the projected deficit for the case of 20% imports and cases (b) and (c) (Figure 7) for coal use. The match to the projected deficit is illustrated in Figure 12.

Table 5—Example scenario for the build up of fission, fusion, and solar energies in India in the period 2050 to 2100.

Year	Fission Mtoe/a	Fusion Mtoe/a	Solar Mtoe/a	Total Mtoe/a
2050	103	3	34	140
2055	127	7	59	193
2060	151	14	84	249
2065	175	29	109	363
2070	199	58	134	391
2075	223	86	159	466
2080	247	115	184	546
2085	271	144	209	624
2090	295	173	234	707
2095	319	202	259	780
2100	343	230	284	857

Clearly, within these scenarios there is ample opportunity for fusion energy to play a role. As mentioned above, the deployment of fusion will require two things: the development of a viable fusion energy source; and its competitiveness in the market at that time. This latter topic will be the subject of a separate study.

Figure 12—Example showing how a combination of fission, fusion, and solar energies might be used to complement other renewable energies, substantial energy imports in the face of declining indigenous fossil production, and meet India's growing energy needs in the period 2050 to 2100.



6. POSSIBLE PATH FOR INDIA IN FUSION

I return now to the question of what India might do to enhance the possibility of adopting the fusion option around the middle of this century. This could be an important topic for a workshop, but in the meantime, I present a few thoughts.

The estimated cost for the realization of fusion energy is many 10's of billions of dollars. It seems unlikely that India would be prepared to make such an investment in the near-term, because there are other opportunities such as fission (which is already economic) and solar (which is progressing towards being economic when used on a massive scale). However, fusion energy does have potential advantages with regard to being an unlimited source of energy and having attractive environmental features. Therefore, in the long-term, it could be an attractive energy option. Given that there is a large world R&D effort on fusion, it seems logical that India should continue to participate as a partner with the major players (EEC, Japan, Russia, USA) in order to keep abreast of development. A modest role in ITER would provide enormous benefits with regard to having a hands-on knowledge of magnetic fusion realities. A role in the international inertial fusion would probably be harder to obtain because of its connection to the defense side of fusion.

In the longer term, as fusion approaches commercialization, a crucial question will be how the developed countries will act. If fusion energy is massively deployed in developed countries, then presumably a large industrial base will develop, the cost will come down and a performance database will be established relatively rapidly. A question for India will be how to obtain a role in the industrial side, to lower costs of deployment in India. If the developed countries do not embrace fusion energy rapidly, then India may have to form a consortium with other countries in the same boat to provide the industrial base needed for fusion energy deployment.

7. SUMMARY

The analysis above of India's projected population growth and the potential energy demand to achieve a decent standard of living for its people suggests that annual energy consumption will have to triple from 2000 to 2050 and approach quadrupling by 2100. This is on the assumption that a decent standard of living might be achieved in a temperate climate with only 1 toe/cap.a of energy, if the energy were used very efficiently. In examples efficiency improvement of 2 to 2.5 times were considered. With a 2.5 x efficiency improvement, 1 toe in today's usage would be equivalent in terms of useful work to 2.5 toe in the future.

A second analysis shows that, with the present understanding of indigenous energy resources (fossil and renewables [excluding solar energy]), it would be hard to meet the demand in the latter part of this century, even with 20% energy imports. Today and in the next decades, it is expected that indigenous coal resources will meet much of the demand. The primary problem is the relatively limited amount of coal available compared to a half-century to a century of high demand for it.

Options to fill the gap, in addition to more imported energy, include much increased fission and solar energy usage. Fusion energy is an important potential complementary energy source because it might be available in the latter half of this century and it has readily available fuel and environmental advantages.

Fusion energy is being developed internationally and a series of question arise as to what more India could do be involved in the world program and develop the in-house capabilities to be able to capitalize on fusion when it is developed.

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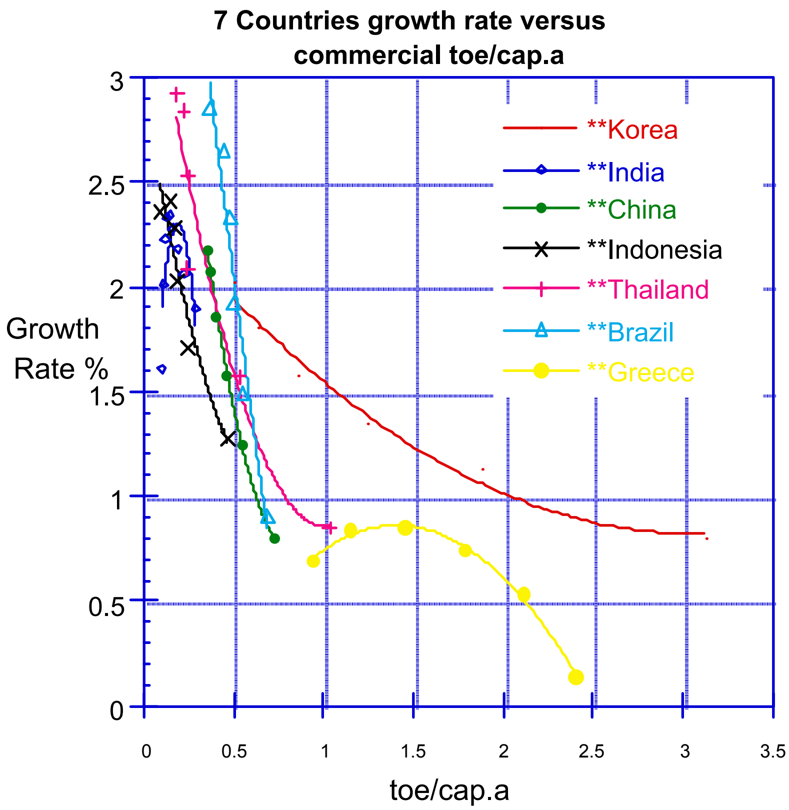
APPENDIX A—WORLD POPULATION GROWTH RATE AND PER CAPITA ENERGY USE

A simple formula that fits historical data for population growth rate (G) versus annual per capita energy use (E) is:

$$G = (E_C - E)/(1.6\ E^{0.38})\ \% \qquad (A.1)$$

Where energy (E_C, E) is measured in tonnes of oil equivalent per capita per annum (toe/cap.a.) (see FESAC).

Figure A.1—Changing population growth rate for seven countries as the annual commercial energy per capita is increased 1970 to 1996 (India 1955 to 1996).



E_c is the critical annual energy per capita at which the population growth rate becomes zero. This quantity has typically been in the range of 2 to 3 toe/cap.a, as shown by extrapolating the mean of the curves in Figure 3 to the x-axis. It may be viewed as reflecting cultural differences between countries, i.e., do social or religious customs, or politics dictate a preference for large or small families?

REFERENCES

Bakshi, R. and A. Jagadeesh. 1999. "Wind power--one of India's great resources." Renewable Energy World 57, Vol. 2, No. 3. London: James and James.

Barabaschi, S (chair). 1996. Fusion Programme Evaluation. Euratom Report 17521. Brussells, Belgium: European Commission DG-XII

Bartlett, A. A. 1986. "Sustained Availability: A management problem for nonrenewable resources." American Journal Physics 54, 398.

Bent, R., L. Orr, and R. Baker, eds. 2002. Energy: Science, Policy, and the Pursuit of Sustainability. Island Press, 45.

Bos, E., My T. Vu, E. Massiah, and R .A. Bulatao. 1994. World Population Projections: 1994-95 Edition. Baltimore and London: The Johns Hopkins University Press (for the World Bank).

Delene, J. G., with J. Sheffield, K. A. Williams, R. L. Reid, and S. Hadley. 1999. "An Assessment of the Economics of Future Electric Power Generation Options and the Implications for Fusion." Oak Ridge, TN: Oak Ridge National Laboratory, Report ORNL/TM-1999-243-R1.

Dolan,T. J. 1993. "Fusion Power Economy of Scale." Fusion Technology 24, 1, 97.

FESAC (Fusion Energy Science Advisory Committee). 2003. "Fusion Development Path." Available online at www.ofes.fusion.doe.gov.

Fusion Science and Technology. July 1, 2001.

Galambos, J., L. W. Perkins, S. Haney, J. Mandrekas. 1995. "Commercial Tokamak Reactor Potential with Advanced Tokamak Operation." Nuclear Fusion, 35, 5, 551.

Goldemberg, J. and T. B. Johansson, eds. 1995. "Energy As An Instrument for Socio-Economic Development." New York: United Nations Development Programme.

Gupta, S. 2000. "Long-term Carbon Emissions, Fossil Fuel Substitution and Greenhouse Gas Mitigation Studies for India." India's Energy: Essays on Sustainable Development (P. Audinet, P. R.Shukla, and F. Grare, eds.). New Dehli, India.

Hender, T., et al. 1996. Proceedings of the Twelfth Meeting on the Technology of Fusion Energy, ANS, Fusion Technology 30, 1605.

ITER Technical Basis. 2002. ITER EDA Documentation Series No.24. Vienna: International Atomic Energy Agency.

International Energy Agency. 1995. World Energy Outlook 1995 Edition. Paris, France: OECD Publications.

Johansson, T. B., R. H. Williams, H. Ishanti, J. A. Edmunds. 1996."Options for Reducing CO2 from the Energy Supply Sector." Energy Policy 24 10-11, 985.

Johansson, T. B., H. Kelley, A. K. N. Reddy, and R. H. Williams. 1993. "Renewable Fuels and Electricity for a Growing World Economy: Defining and Achieving the Potential" in Renewable Energy: Sources for Fuels and Electricity. Washington: Island Press, 1-71.

Kaw, P.K. 1992. "Fusion Power, Who Needs It?" Artsimovich Memorial Lecture, 14th IAEA Conference on Plasma Physics and Controlled Fusion, Wurzberg, Germany.

Kulcinski, G. L. 1996. "Near Term Commercial Opportunities from Long Range Fusion Research." Proceedings of the Twelfth Meeting on the Technology Of Fusion Energy, Reno, Nevada, June 1996, in Fusion Technology 30, 411.

Logan, G. 1993. Poster paper 4-PC-10. 15th IEEE/NPSS Symposium on Fusion Engineering, Hyannis, Massachusetts, October 11-15, 1993.

Miller, R. L., et al. 2000. "Systems Context of the ARIES-AT Conceptual." Fusion Power Plant, Proceedings of the 14th ANS Topical Meeting. Park City, UT: October 2000.

Miller, R. L., and the ARIES Team. 1996. "Fusion Power Plant Economics." Proceedings of the Twelfth Topical Meeting on the Technology of Fusion Energy. ANS (December 1996), and Fusion Technology 30, 3, part 2B, 1959.

NIF (National Ignition Facility). 1994. "Conceptual Design Report." Livermore, CA: Lawrence Livermore National Laboratory, UCRL-PROP-117093.

Nuclear News 2002. ANS. July, p. 54.

Nuclear News 2001. ANS. June, p 61.

Perry , A. M. 1984. Private communication. Oak Ridge, TN: Oak Ridge National Laboratory.

Sheffield, J., W. Brown, G. Garrett, J. Hilley, D. McCloud, J. Ogden, T. Shields, and L. Waganer. 2001. "A Study of Options for the Deployment of Large Fusion Power Plants."

Sheffield, J. 1998. "Population Growth and the Role of Energy Use Per Capita." Journal of Technological Forecasting and Social Change 59, 55-87.

Sheffield, J. (coordinator). 1997. Introduction to Energy Technology R&D: What Could Make a Difference? Vol. 2, part 1, End-Use Technology. Oak Ridge, TN: Oak Ridge National Laboratory, ORNL-6921/V2/P1.

Sheffield, J., R. Dory, S. Cohn, J. Delene, L. Parsly, D. Ashby, W. Reierson. 1986. "Cost assessment of a generic magnetic fusion reactor." Fusion Technology 9, 2, 199.

Socolow, Robert, ed. 1997. Fuels Decarbonization and Carbon Sequestration: Report of the Workshop. Princeton University, PU/CEES Report No. 302.

Solar Letter. 1998. November 6, 383.

Tata Energy and Resources Institute. 2001. teri Globe, News Letter of the Tata Energy and Resources Institute 4, page 4, March 2001.

United Nations. Population Division, Department of Economic and Social Affairs. 2001. World Population Prospects: The 2000 Revision. New York: United Nations Publications, Draft ESA/P/WP.165, 28.

United Nations. Demographic and Statistical Yearbooks, 1955 to present. New York: United Nations publications.

Waganer, L. and the ARIES Team. 1997. "Assessments of Markets and Customers for Fusion Applications." 17th IEEE/NPSS Symposium on Fusion Engineering, San Diego, CA: October 6-9, 1997, and updates.

Williams, R. H. 1996. "Innovative Strategies for Achieving Deep Reductions in GHG Emissions for the Energy Sector in the 21st Century." Presented at Exxon Research and Engineering, Annandale, New Jersey, April, 1996.

WEC (World Energy Council). 2001. Global Energy, First Magazine.

WEC (World Energy Council). 1995 and 1998 Survey of Energy Resources.

Zuckerman, D. *et al.* 1988. "An Induction Linac Driven Heavy-Ion Fusion Systems Model." *Fusion Technology* 13, 217.