World population and energy demand growth: the potential role of fusion energy in an efficient world

John Sheffield

Phil. Trans. R. Soc. Lond. A 1999 **357**, 377-395
doi: 10.1098/rsta.1999.0333

World population and energy demand growth: the potential role of fusion energy in an efficient world

By John Sheffield

Energy Technology Programs, Oak Ridge National Laboratory and the Joint Institute for Energy and the Environment, University of Tennessee, PO Box 2009, TN 37831, USA

The fertility rate for women and the related population growth rate for numerous developing (transitional) countries show a downward trend with increasing annual per capita energy use. On the assumption that such trends will continue, estimates are made for some simple cases of the energy demands required to stabilize the world's population in the period 2100–2150.

An assessment is made of how these energy demands might be met, capitalizing as much as possible on the indigenous energy resources for each of the ten major regions of the world: North America, Latin America, Europe OECD, Former Soviet Union and Central and Eastern Europe, China, Pacific OECD, East Asia, South Asia, Africa, and the Middle East. Consideration is also given to the potential need to limit carbon emissions because of global-warming concerns.

The study highlights the crucial nature of energy-efficiency improvements and the need to use all energy sources if the world is to find a sustainable future with a much improved standard of living in the developing world. While, globally, there are huge resources of fossil fuels, they are unevenly distributed and some of the areas experiencing major population growth are not well endowed with them. Even allowing for the substantial deployment of renewable energies (biomass, geothermal, hydro-, tide, wave and wind power), if fossil-fuel use is restricted or has limited availability, there will be a need in a number of regions (e.g. South Asia) for substantial amounts of nuclear and solar energy to meet their long-term needs.

The deployment of more fission power can build upon the existing successes. The availability of fusion power will depend upon the pace of the development program and, in principle, fusion-power deployment might start around the middle of the 21st century. Example scenarios of possible contributions of the various energy sources are described, to illustrate the potential roles for fission and fusion power.

Keywords: annual energy per capita; population growth; energy demand; mass efficiency; nuclear fusion

1. Introduction

The fertility rate for women in countries across the world, at any particular time, shows a downward trend with increasing annual per capita commercial energy consumption (Goldemberg & Johansson 1995). An analysis of United Nations data (United Nations Statistical Yearbooks 1965, 1975, 1977, 1987, 1994) for the past

Phil. Trans. R. Soc. Lond. A (1999) **357**, 377–395

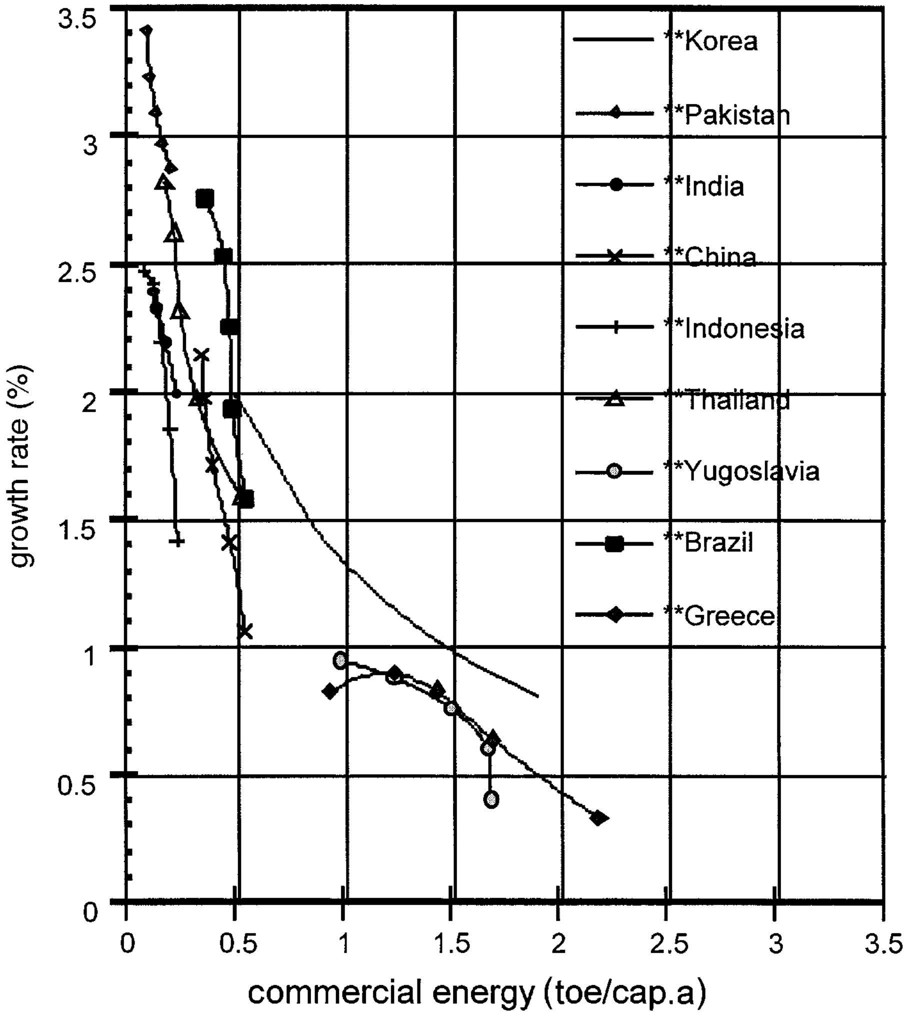

Figure 1. Population growth rate versus annual energy per capita for the period 1965–1992 (taken from Sheffield (1998)).

30 years shows that the related population growth has a similar and dynamic dependence on annual per capita energy-consumption rate for most of the world's transitional countries (Sheffield 1998). Thus, it appears that per capita energy use is a useful surrogate measure of the many factors that can influence population growth rate: emancipation of women, standard of living, education, etc. (Cohen 1995). The transitional countries are those whose population growth rates were decreasing, during this period, towards the zero or very low growth rates of the developed countries, e.g. Brazil, China, Greece, India, Indonesia, Korea, Malaysia, Mexico, Pakistan, Thailand, Yugoslavia (see figure 1). The curves are a best fit to averaged UN data. Similar trends can also be seen for smaller countries, e.g. in the Caribbean, Barbados, Cuba, Guadeloupe, and Martinique (Sheffield 1999). Related studies have been made by Gouse *et al.* (1995). It is emphasized by Cohen (1995) that there is no demonstrated

unambiguous connection of diminishing growth rate to standard of living and related factors such as energy use.

While there are differences in growth rates (G), for different countries, at a fixed per capita energy value, there is a trend for each country that is captured by the simple formula,

$$G(\%) = (E_c - E)/(1.6 \times E^{0.38}), \quad \text{for } E = E_c,$$

where E is the annual commercial per capita energy use in tonnes of oil equivalent per year ($\textsc{toe}\,\mathrm{yr}^{-1}$), and E_c ($\textsc{toe}\,\mathrm{yr}^{-1}$), the value of energy at which the growth rate becomes zero, is assumed to depend upon 'cultural' factors (Sheffield 1998).

If this trend continues, the transition of the world to the low growth rate and stable population (*ca.* 10–12 billion by 2100–50) projected by the World Bank (Bos *et al*. 1994) and other organizations, will require a substantial increase in per capita energy use for the developing world. On the assumption that it is the useful energy that counts, not that which is wasted, energy-efficiency improvements will be crucial to meeting the world's energy needs. Therefore, an effective energy, $E_e = hE$, is defined, in which h is the efficiency improvement over that in the year 2000, e.g. if $h = 1.25$, 1 $\textsc{toe}\,\mathrm{yr}^{-1}$ of energy in 2020 is as useful as 1.25 $\textsc{toe}\,\mathrm{yr}^{-1}$ was in 2000;

$$G(\%) = (E_{ce} - E_e)/(1.6 \times E_e^{0.38}), \quad \text{for } E_e = E_{ce}.$$

2. Energy-demand projections

There are numerous options for meeting world energy demands up to 2050, by which time energy-demand is projected to be in the range of double today's use: 18 000 ± 4000 Mtoe yr^{-1}. Conventional oil and gas resources are large and there are abundant coal and unconventional fossil resources to meet such a demand (such as methane hydrates). However, reductions in fossil-fuel use may occur as a response to climate-change concerns or due to a local depletion of resources; but it is only after about 2030–50 that emissions from fossil fuel would have to be restricted substantially to limit climate-change effects (Wigley *et al*. 1996). Two options are available to limit emissions: a reduction in fossil-fuel use and sequestration of carbon. The use of other energy sources, nuclear and renewable energy, can also expand to meet the increasing energy demand. Different countries have different opportunities and capabilities for the use of the various energy sources. Therefore, in this period, it seems likely that there will generally be

(1) an increase in the efficiency of energy use to minimize energy demand;

(2) an increasing use of other energy resources to complement fossil energy use; and

(3) an increase in carbon sequestration.

A move to use hydrogen as a mobile fuel is possible because (1) it can facilitate the use of fossil fuels with sequestration of carbon; and (2) because its production from intermittent electricity sources, such as solar and wind power, and from steady sources of energy, such as nuclear power, can increase their usefulness. The development of improved fuel cells makes hydrogen an attractive fuel for both static and mobile applications.

After about 2050, it is predicted that energy demand will continue to increase, even with further efficiency improvements, to around 27 000 ± 11 000 MTOE yr^{-1} by the year 2100. At this level of energy use, it is expected that conventional sources of oil and gas will have been depleted, there will be an increasing number of countries without significant fossil resources and, in the fossil area, demand for coal and unconventional fossil resources will be increased. If global warming concerns remain an issue, substantial carbon sequestration will be required (Wigley *et al*. 1996). At a minimum, it seems that an additional 4000–6000 MTOE yr^{-1} of non-fossil fuels may be required.

The consequences of this increased energy demand are as follows.

(1) Continued energy efficiency improvements will be needed.

(2) Fossil-fuel use may decrease, even with sequestration.

(3) Sustainable renewable energy use will continue to increase. Because some of the main opportunities will be for intermittent sources, solar and wind power, energy storage will be needed, or they will have to be restricted to a level consistent with that allowed for variability of output experienced by a utility. Folklore suggests this to be 10–15%.

(4) Nuclear energy use, fission and fusion, will continue to increase offering the advantage of steady-state electricity, meeting large local power demands, complementing the intermittent sources, and providing energy in regions with limited opportunities for fossil and renewable energies.

(5) A hydrogen economy will become even more attractive in this new situation, with sequestration of carbon it could sustain the use of fossil fuels, and hydrogen could replace oil and gas as a heavily traded resource (Johansson *et al*. 1993; Socolow 1997).

The mixture of approaches above can be an effective way of meeting the world's increasing needs for useful energy, while accommodating the disparate opportunities and needs of different countries. For research, the key goals are as follows.

(i) Develop and deploy energy-efficiency improvements, because reducing demand will make it easier to satisfy the needs of developing countries, slow the use of valuable non-renewable energy sources and reduce pollution.

(ii) Develop safe and cost-effective techniques for carbon sequestration: a goal of using not more than 10–15% of the fossil energy seems achievable (Herzog *et al*. 1997).

(iii) Develop and deploy renewable energies to allow indigenous resources to be more extensively used.

(iv) Develop and improve nuclear energy sources, both fission and fusion.

(v) Find better ways, internationally, of handling waste and securing operation (Fulkerson & Anderson 1996).

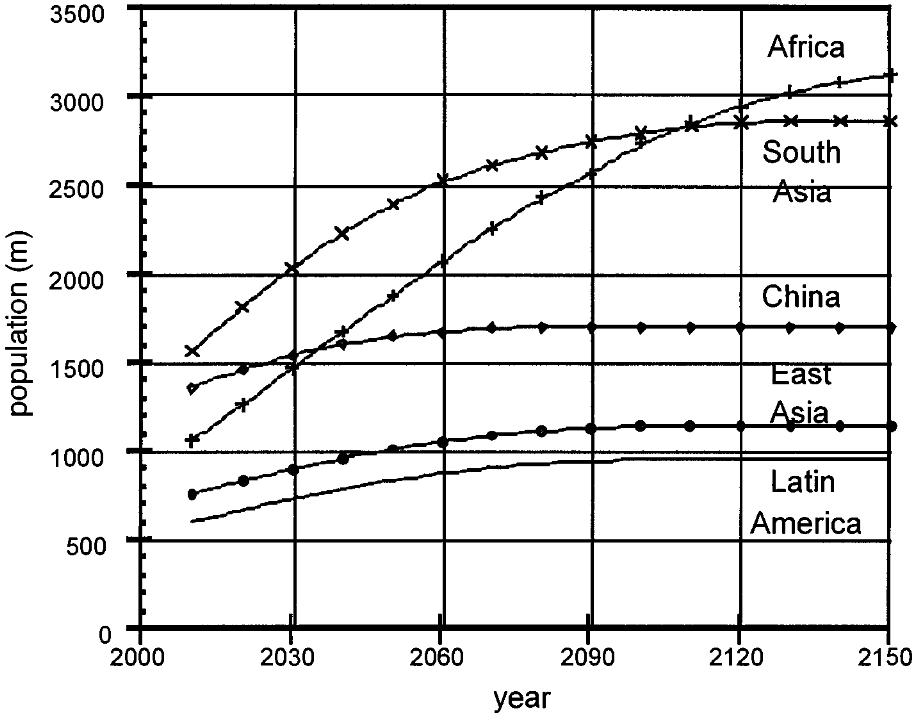

Figure 2. Projected populations for the five major developing regions of the world.

3. Reference cases

A simple analysis is made of reference cases in which the increases in per capita energy use and the deployment of more efficient systems lead to global and sectoral population growths in rough agreement with projections of the World Bank (Bos *et al*. 1994). These projections, interestingly, are based upon empirical trends but have no explicit relationship to energy use. The projected populations of the five major regions of the developing world, from the energy per capita model of Sheffield (1998), are shown in figure 2, those for the developed countries are taken from projections of the World Bank (Bos *et al*. 1994). The World Bank's estimates are based upon alternative projections of fertility and mortality rates for each country, drawing upon past experience.

The energy needed to satisfy the decreasing population growth rate is calculated for two cases. The starting point energy in 2010 for each region of the world is an average of the two energy scenarios considered by the International Energy Agency (IEA 1995). Only energy needs are considered in this analysis, but clearly, for a complete picture, other parameters such as food and water supply should be included.

Case 1 assumes that the average efficiency of energy production and use will improve steadily to 1.35× by 2050, 1.75× in 2100 and 2.0× in 2150, and that the developed countries will use energy efficiency to reduce per capita energy use and greenhouse-gas emissions from their level in 2000. The total energy use is similar to that of the low-demand variants of the LESS scenarios of the Intergovernmental Panel on Climate Change (IPCC 1995).

Table 1. *Projected energy demand for 2010–2150* (Mtoe yr^{-1})

case	2010	2030	2050	2075	2100	2150
developing 1	4 840	6 790	8 450	9 850	10 150	10 630
developed 1	7 230	7 020	6 510	6 020	5 420	4 960
total case 1	12 070	13 810	14 960	15 870	15 570	15 590
developing 2	4 930	7 200	9 300	11 150	11 850	11 760
developed 2	7 370	8 040	8 340	8 550	8 560	8 410
total case 2	12 300	15 240	17 640	19 700	20 410	20 170

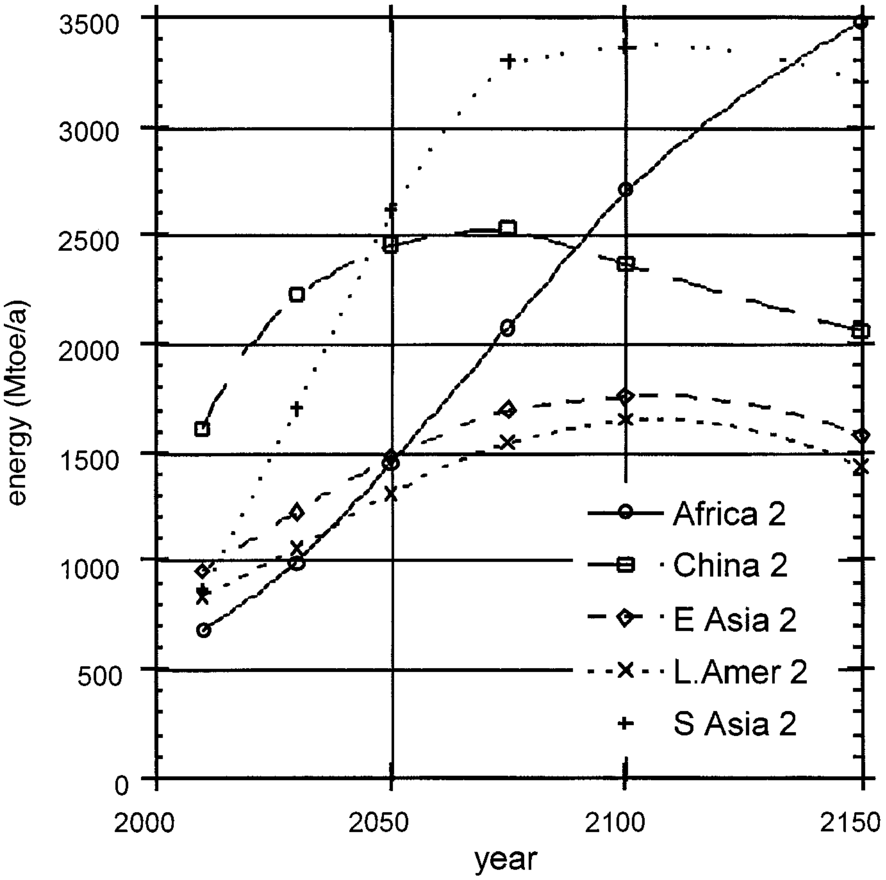

Figure 3. Projected annual energy use for the five major developing regions; case 2.

Case 2 assumes a lower rate of efficiency improvement of 1.25× in 2050, 1.50× in 2100 and 2.0× in 2150, and that the developed countries keep a fixed annual per capita energy use at the year 2000 level. The total energy use for this case is roughly halfway between the low- and high-demand cases of the IPCC study (IPCC 1995).

Details of the calculations are given in an earlier paper (Sheffield 1998). The energy needs for the developing countries under case 2 (Sheffield 1998) are shown in figure 3. In table 1, the projected energy use is shown for the five major developing areas and the more developed part of the world (North America, Europe OECD, Former Soviet Union and Central and Eastern Europe, Pacific OECD, and the Middle East).

It is assumed that countries will turn first to indigenous resources of energy to meet their needs, which will lead to an initial increase in fossil-fuel use during the first decades of the 21st century. However, it is also assumed that there will be a steady increase in renewables and nuclear energy so, from the latter part of the 21st century, fossil-fuel use may decrease and a very-long-term stable energy situation can emerge. The extent of energy resources are taken mainly from the World Energy Council's (WEC's) 1995 resource book (World Energy Council 1995) and for renewable energies from Johansson *et al*. (1993). The assumptions about use are that

(1) regions with limited fossil fuels will use them all, importing what additional fossil fuels they need;

(2) 90% of the world's projected hydropower will be exploited;

(3) about 50% of the projected biomass energy (Johansson *et al*. 1993; Larson & Williams 1995) will be exploited, a limitation set by concerns about sustainability (Pimentel 1995); and

(4) about 40% of the wind-power potential will be used, consistent with constraints on land use and need (Grubb & Meyer 1993). The balance of energy for each region is assumed to be provided by some combination of nuclear and 'solar' (includes modest amounts of geothermal, tide and wave power) energy.

4. Electricity production

The past trend towards an increasing fraction of electrical-energy use is expected to continue (IEA 1995). The increase may even accelerate if electricity-producing energy sources, such as hydro, nuclear, solar-electric, wind, 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 International Energy Agency (1995) allows for waste heat in describing the level of nuclear energy, but for hydropower uses only the electrical energy. The majority of electricity today is produced from fossil fuels 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 cogeneration heat use are accounted for in a blanket improvement in energy efficiency assumed for this study.

5. Energy sources

Using the assumptions above, estimates were made of the sources of energy for each of the ten major regions of the world. The aggregate use is shown in figure 4 (Sheffield 1998) for case 1. The numbers for the two cases are given in table 2.

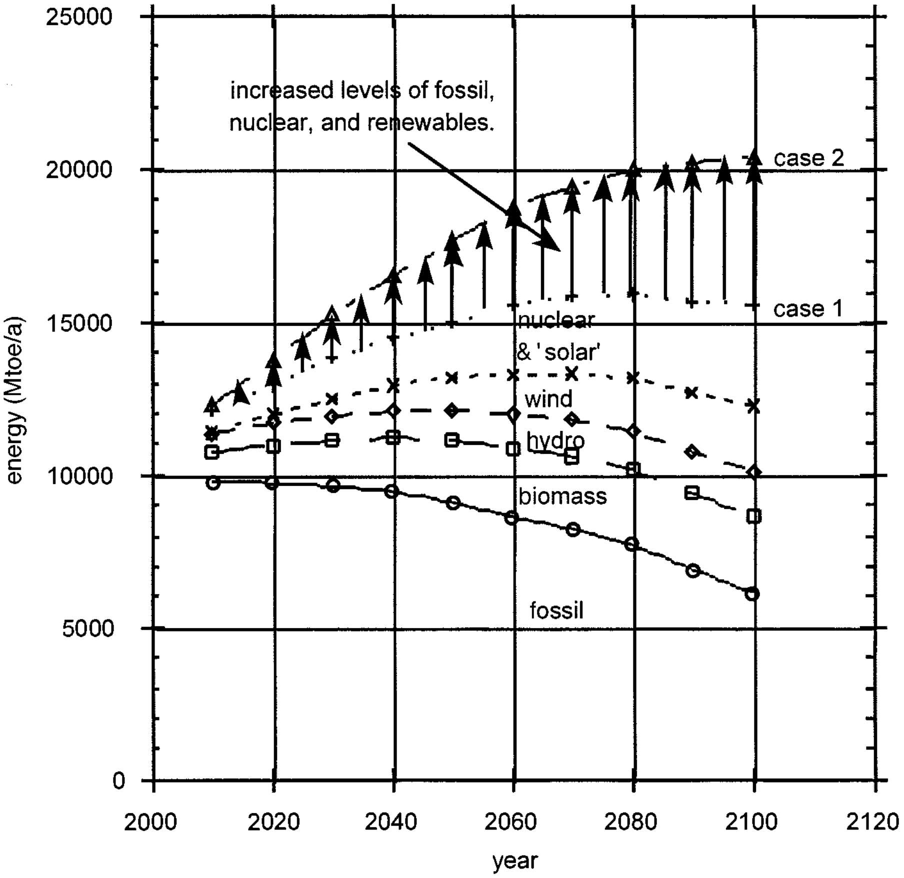

Figure 4. Example energy sources: cases 1 and 2.

Table 2. *Estimates of energy sources* (Mtoe yr^{-1})

energy source	case 2	case 1
fossil	8560	6140
biomass	2510	2510
hydropower	1460	1460
wind power	3350	2140
nuclear + 'solar'	4530	3320

(*a*) *Fossil energy*

Even with a massive increase in renewable and nuclear energies, approximately all indigenous conventional oil and gas resources would be used by 2100. The WEC estimates recoverable conventional oil and gas resources as 360 000 Mtoe yr^{-1}. The two cases require a use of 450 000–510 000 Mtoe yr^{-1} in the period 2010–2100, a deficit of 90 000–150 000 Mtoe yr^{-1}, ignoring the use from today to 2010. Shale oil and bitumen amount to another 560 000 Mtoe yr^{-1}, and could make up the difference if about 20% were recoverable. However, there would still be substantial coal reserves in 2100, about 3 300 000 Mtoe yr^{-1}, and an alternative solution would be the greater use of coal. In addition, even more massive deposits of methane hydrates are projected to exist, more than 10 000 000 Mtoe yr^{-1} (Max *et al*. 1997), and these might be exploited.

The choice to restrict or sustain high fossil-fuel use will presumably depend on the response to global warming concerns.

The availability of abundant low-cost fossil fuels will be important in helping the developing countries make the transition to stable populations. It is important that such a transition be made, and improved efficiency systems and alternative energy sources, both renewables and nuclear, be deployed, before the cost of fossil fuel rises beyond the reach of the poorer countries. Failure to stabilize population in any area of the world will lead to an unsustainable situation there, and a potentially disruptive situation for the world.

(*b*) *Carbon sequestration*

Carbon sequestration is a very important consideration if global warming concerns are taken seriously, since, without sequestration, fossil-fuel use might have to be reduced by the end of the next century to around 3000–4000 Mtoe yr^{-1} (Wigley *et al*. 1996). In the cases considered, the estimated carbon emissions are 630–740 GtC (gigatonnes of carbon) in the period 2010–2100, of which, maybe half would have to be sequestered to limit CO_2 concentrations to less than 450 ppm (Wigley *et al*. 1996). In terms of fossil fuel use, the cases considered in this paper are between the IPCC cases IS92c and IS92d (IPCC 1995).

There are many ways in which carbon may be sequestered (Turkenburg 1997; Herzog *et al*. 1997; Socolow 1997), including burial in depleted oil and gas wells, and deposition in saline aquifers and the oceans. The first three of these approaches are being used today. It is estimated that oil and gas wells could sequester 130–500 GtC, while saline aquifers might sequester between 90 and over 1000 GtC, and the oceans could potentially handle between 400 and more than 1200 GtC. There remain important practical questions of cost and safety to be resolved for the ocean and aquifer solutions before massive sequestration will be allowed. As can be seen from the reference cases, the required sequestration would use up quite a large percentage of estimated capacity even in the period to 2100.

(*c*) *Renewable energies*

Hydropower use is expected to increase, and about 90% of the potential resource listed by the World Energy Council (1995) is used. Biomass energy in various forms accounts for more than 10% of energy use today (more than 1000 Mtoe yr^{-1}) and estimates of a potential for 4500 Mtoe yr^{-1} have been made for biomass-intensive scenarios (Johansson *et al*. 1993; Larson & Williams 1995). Of this energy, about 2500 Mtoe yr^{-1} comes from agricultural and forestry residues and land fills, with the rest from dedicated energy crops. There is argument about the limits set by agricultural needs and sustainable land use (Pimentel 1995), and in this study the use is limited to 2500 Mtoe yr^{-1}.

The wind-power potential is huge, but restrictions on land use are expected to limit its deployment to about 40% of its potential (Grubb & Meyer 1993). Geothermal, tide and wave power have important niche possibilities in a number of countries but

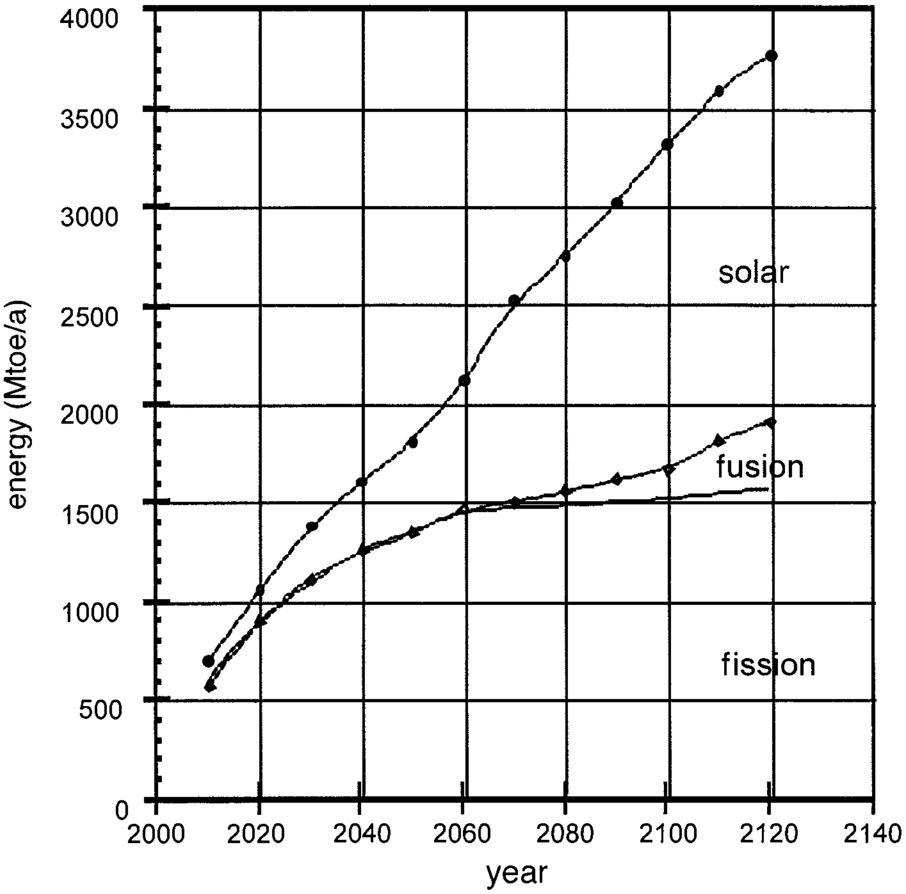

Figure 5. Example projection for case 1 of solar and nuclear energy fission and fusion.

their estimated total contribution is modest compared to the alternatives (IPCC 1995), and they are subsumed under the category 'solar'.

It is difficult to set a level for solar power, since, in principle, it could provide all the energy needs if developments lower the costs sufficiently. In this study it is assumed that it will play an important role in countries with high insolation, particularly to meet distributed energy needs and possibly for hydrogen production (Johansson *et al*. 1993; Socolow 1997).

(*d*) *Nuclear energy*

In the cases examined, substantial use must be made of nuclear and solar energies. Both sources have the advantage that they may be used widely and their production does not contribute to greenhouse-gas emissions. In practice, each has its pros and cons. An example distribution for case 1 is shown in figure 5; assuming that solar will be used mainly as a distributed energy source and in countries with high insolation; and that nuclear power will be used where massive central power generation and cogeneration are needed and needs cannot be met well by solar energy. In principle, either energy source might provide the total needed energy. Purely as an example, for the world, roughly equal amounts of solar and nuclear energy are assumed to be used. Today, nuclear energy (fossil-replacement value) contributes about 6% of the world's annual energy use. There remain the issues of public acceptance and the handling of waste.

(i) *Fission*

In 2050, the level of nuclear power use for case 1 (7800 TWh electric) is much more than the level in the 'renewables intensive study' (Johansson *et al.* 1993) (1850 TWh), but similar to the nuclear intensive case of the IPCC (1995) study (9350 TWh), which has a growth for fission power from about 330 GW_e today to about 3300 GW_e in 2100. With breeder reactors, the availability of natural resources would not place any major constraint on the development of nuclear energy generation over the next century, using currently known uranium resources (World Energy Council 1995).

(ii) *Fusion*

Fusion offers a safe long-term source of energy with abundant resources, for the deuterium cycle essentially unlimited resources, and many environmental advantages (Barabaschi 1996). Even the most unlikely accidents would be very limited in their effect and would not require public evacuation. There would be minimal contributions to greenhouse gases or acidic emissions. With careful choice of materials, the wastes from fusion power would not require isolation from the environment for any prolonged timespan. Nuclear proliferation problems are small for most perceived systems. Thus, in the nuclear area, fusion is a useful complement to fission energy and an insurance against limitations on fission energy use. Fusion energy production is assumed to start in around 2050.

Substantial progress has been made in recent years in both magnetic and inertial fusion research: (1) showing that energetic fusion products behave as expected in TFTR and JET (McGuire *et al.* 1996; Gibson 1998); (2) calibrating plasma modelling codes; and (3) 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 1998) in magnetic fusion, and the National Ignition Facility (NIF 1994) in inertial fusion. However, the ITER design activity may be extended for three years, and studies of a smaller facility are underway, taking advantage of advances since the original design was laid out. In addition, the work on NIF is not complemented, presently, by a large effort on inertial fusion energy, and the US no longer sets a timescale for fusion-energy development. Nevertheless, assuming the operation of NIF and ITER or similar facilities, it would still be possible to develop fusion energy around the middle of the next century in a well-coordinated world programme with success in the development of radiation-resistant materials and supporting technologies. Commercial plants might then be operating about the middle of the next century. The most likely initiators of the fusion era are countries that are using substantial fission power, plan more, have inadequate indigenous energy resources, and have the technical capability, e.g. Japan.

Build-up rates may be constrained by the energy payback time (about 1.5 years for some reference fusion plants; a desirable payback time is less than a year), and also a little by the tritium build-up rate (to support new plants) typically six months

Table 3. *Fusion energy production* (Mtoe yr^{-1}) *for 2100 and 2150*

examples	2100	2150
case 1	160	550
case 2	310	600

Table 4. *Potential energy sources for South Asia in 2100* (Mtoe yr^{-1})

source	demand	fossil	biomass	hydro	wind	nuclear	'solar'
case 1	2886	1449	340	150	190	370	387
case 2	3367	1690	340	150	310	430	447

(assuming that the deuterium–tritium cycle is used with a breeding blanket gain of 1.05). Consideration of these factors suggests that a doubling period of five years or less should be possible and would lead to a large net energy gain from fusion. 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 that do not have, in-house, all the skills needed (Fulkerson & Anderson 1996). For the example cases, the estimated fusion-energy production (fossil-fuel replacement value) is shown in table 3. Note that production of 100 Mtoe yr^{-1} will require 180 fusion plants of 1000 $\mathrm{MW_e}$ each operating with a 75% capacity factor.

Example: South Asia (the Indian subcontinent)

In terms of potential energy demand and the ability to meet it with indigenous resources, South Asia appears to have the greatest challenge. Resources of conventional fossil, biomass, hydro and wind energy are low in relation to the projected demands. Potential solutions are (1) the massive use of nuclear and solar energies; (2) substantial imports of fossil fuels; and (3) the use of methane hydrates, believed to be located off the coast of southern India. The potential demand and a possible solution are given in table 4.

It will be a challenge to provide the fossil fuels because, in both cases, indigenous resources will be depleted without substantial and continuing imports. To put the numbers in perspective, note that the total US energy use today is about 2300 Mtoe yr^{-1}.

Example: Europe OECD

The annual energy usage for cases 1 and 2 for this study are shown in table 5. (Note that the World Bank projects a relatively constant population for Europe OECD, at about 460 million people during the next century.) For comparison, the estimated energy demand in 2050 for the RIGES study (Johansson *et al.* 1993), which assumes a more rapid pace for efficiency improvements, is about 1030 Mtoe yr^{-1} on

Table 5. *Projected energy use in Europe OECD* (MTOE yr^{-1})

case	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
1	1722	1615	1512	1416	1325	1260	1198	1137	1079	1023
2	1746	1748	1750	1747	1743	1739	1735	1731	1727	1722

Table 6. *Example energy uses in Europe by source* (MTOE yr^{-1})

case	oil + gas	coal	biomass	hydro	wind	'solar'	fission	fusion	total
1/2050	500	155	160	110	150	10	240	—	1325
2/2050	598	265	160	110	255	60	295	—	1743
1/2100	100	63	200	130	230	60	220	20	1023
2/2100	179	333	200	130	405	145	290	40	1722

the same basis. The Holdren estimate (Holdren 1990), for a similarly efficient world, assumes 2.25 TOE yr^{-1} in the period 2060–2100, corresponding to 1035 MTOE yr^{-1} for Europe, and 22 500 MTOE yr^{-1} for the world in 2100. To put these numbers in perspective, note that the International Energy Agency estimate of annual energy use per capita in Europe in 2010 is about 3.7 TOE yr^{-1}.

The assumed distribution of energy among the different energy sources is shown in table 6 for 2050 and 2100.

Renewable energies evolve from the kind of levels discussed in the Atlas Project for 2010 (Atlas Project 1997) (68 MTOE yr^{-1} biomass, 'solar'; 9.5 MTOE yr^{-1}, fossil-replacement value; 68 MTOE yr^{-1} hydro; and 14 MTOE yr^{-1} wind). The biomass-intensive estimate of the RIGES study for 2050 is 337 MTOE yr^{-1} (Johansson *et al.* 1993). Wind-power resources are estimated by Grubb & Meyer (1993) to be 550 GW_e on average, or a fossil-equivalent value of 826 MTOE yr^{-1}. Hydropower resources are estimated to be 870 TWh a^{-1}, or 150 MTOE yr^{-1} equivalent.

The 'nuclear' levels are comparable with the nuclear-intensive LESS case of the IPCC (IPCC 1995), with a fossil-replacement value of 187 MTOE yr^{-1} in 2050 and 370 MTOE yr^{-1} in 2100.

The fossil-fuel usage assumes that essentially all of the resources listed by the World Energy Council (1995) will be used by 2100, with the exception of the large resources of coal in Germany and the United Kingdom. In the event that CO_2 sequestration is necessary, there is the possibility of sequestering it in depleted oil and gas wells, and in saline aquifers under the North Sea (Holloway 1996). The WEC cites recoverable fossil resources as 3300 MTOE yr^{-1} of oil, 4600 MTOE yr^{-1} of gas, 6800 MTOE yr^{-1} of peat and 35 200 MTOE yr^{-1} of coal. There is an additional estimate of 297 000 MTOE yr^{-1} of coal, of which more than 7000 MTOE yr^{-1} is listed as recoverable. For the example above, the total fossil use for case 2 is 51 500 MTOE yr^{-1} of oil and gas, which would clearly require the continuation of substantial imports, and 26 700 MTOE yr^{-1} of coal.

While, in principle, European needs might be met over the next century by a combination of only fossil and renewable energies, it seems sensible to satisfy some of the demand with nuclear energy to reduce fossil-fuel use and greenhouse-gas emissions, and use of the more attractive opportunities for renewable energies. In fact, even in the low-nuclear RIGES study (Johansson *et al*. 1993), nuclear accounts for a 92 Mtoe yr^{-1} fossil-replacement value in 2050. Fusion energy can, then, have a role to play as a complement to fission in the nuclear part of the energy mix, in the latter part of the next century.

6. Conclusions

It is possible to meet the energy demands of a world with a population that will nearly double by 2100, while increasing standards of living in all regions. However, achieving this end will require

(1) a substantial improvement in the efficiency of energy production and end-use;

(2) the deployment of all types of energy source to meet the varying opportunities and needs of the different regions; and (probably)

(3) the use of carbon sequestration to allow a continuation of the use of substantial amounts of fossil fuel, while limiting the growth of CO_2 concentrations in the atmosphere.

In the scenarios studied in this paper, a large increment in annual energy use will be required in the period 2100 and beyond, and nuclear power, both fission and fusion, can play a very important role in meeting this demand and the energy needs of countries with limited energy resources, and in minimizing greenhouse-gas emissions.

Provided the development of fusion energy continues at its recent pace, it should start playing an increasingly important role in the latter part of the next century.

This paper benefited from the thoughtful comments of the referees.

References

Atlas Project 1997 Atlas Project: Summary Findings. Energy technology: the next steps. ECSC-EC-ECAE, Brussels, Luxembourg 1997. Publication DG XVII-97/011.

Barabaschi, S. (Chair) 1996 Fusion programme evaluation. Euratrom report 17521, European Commission DG-XII, Brussels, Belgium.

Bos, E., Vu, E., My T., Massiah, E. & Bulatao, R. A. 1994 *World population projections: 1994–95 edition*. Baltimore and London: The Johns Hopkins University Press. (Published for the World Bank.)

Cohen, J. E. 1995 *How many people can the Earth support?* New York: W. W. Norton.

Fulkerson, W. F. & Anderson, T. 1996 World's energy appetite may crave nuclear power. *Univ. Tennessee Forum* **11**, 96–101.

Gibson, A. 1998 DT plasmas in JET: behavior and implications. *Bull. Am. Phys. Soc.* **42**, 2063.

Goldemberg, J. & Johansson, T. B. (eds) 1995 *Energy as an instrument for socio-economic development*, p. 9. New York: United Nations Development Programme.

Gouse, S. W., Gray, D. & Tomlinson, G. 1995 The transition to a sustainable world energy supply. Presented at the *16th Congress of the World Energy Council, Tokyo, Japan, October 1995.*

Grubb, M. J. & Meyer, N. I. 1993 Wind resources. In *Renewable energy: sources for fuels and electricity* (ed. T. B. Johansson *et al*.), p. 198. Washington, DC: Island.

Herzog, H., Drake, E. & Adams, E. 1997 CO_2 capture, reuse, and storage technologies for mitigating global climate change. A final report for DOE order no. DE-AF22-96PC01257, Energy Laboratory, Massachusetts Institute of Technology, Cambridge, MA.

Holdren, J. P. 1990 Energy in transition. *Scient. Am.*, September, pp. 157–163.

Holloway, S. 1996 An overview of the joule II project. The underground disposal of carbon dioxide. *Energy Convers. Mgmt* **37**, 1149–1154.

IEA 1995 *World energy outlook* (International Energy Agency). Paris: OECD.

IPCC 1995 *Impacts, adaptations and mitigation of climate change: scientific and technical analyses* (ed. R. T. Watson, M. C. Zinyowera, R. H. Moss & D. J. Dokken). Cambridge University Press.

ITER 1998 *Technical basis for the final design report, cost review, and safety analysis (FDR).* Vienna: International Energy Agency.

Johansson, T. B., Kelley, H., Reddy, A. K. N. & Williams, R. H. (eds) 1993 *Renewable energy: sources for fuels and electricity*, pp. 1–71. Washington, DC: Island.

Larson, E. D. & Williams, R. H. 1995 Biomass plantation energy systems and sustainable development. *Energy as an instrument for socio-economic development*, pp. 91–106. New York: United Nations Development Programme.

McGuire, K. M. (and 120 others) 1996 Physics of high performance deuterium–tritium plasmas in TFTR. In *International Atomic Energy Agency, Proc. of the Sixteenth Conf., Montreal, Canada, 7–11 October 1996*, vol. 1, p. 19.

Max, M. D., Pellanbarg, R. E. & Hurdle, B. G. 1997 Methane hydrate, a special clathrate: its attributes and potential. Naval Research Laboratory, Washington, DC, Report NRL/MR/6101–97-7926.

NIF 1994 Conceptual design report. National Ignition Facility, Lawrence Livermore National Laboratory, Livermore, CA, UCRL-PROP-117093.

Pimentel, D. 1995 Biomass fuel and environmental sustainability in agriculture. In *Issues in agricultural bioethics* (ed. T. B. Mepham, G. A. Tucker & J. Wiseman), pp. 215–228. Nottingham University Press.

Sheffield, J. 1998 Population growth and the role of energy use per capita. *Technological Forecasting and Social Change* **59**, 55–87.

Sheffield, J. 1999 *World population and energy growth: impact on the caribbean and the roles of energy efficiency and renewable energies.* Presentation to the Caribbean Academy of Sciences, Georgetown, Barbados. (In the press.)

Socolow, R. (ed.) 1997 Fuels decarbonization and carbon sequestration; report of a workshop. By the members of the report committee, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ, report PU/CEES, no. 302.

Turkenburg, W. C. 1997 Sustainable development, climate change, and carbon dioxide removal (CDR). *Energy Convers. Mgmt* (Suppl.) **38**, S3–S13. Amsterdam: Elsevier.

Wigley, T. M. L., Richels, R. & Edmonds, J. A. 1996 Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations. *Nature* **379**, 240.

World Energy Council 1995 *Survey of energy resources.* Oxford: Holywell.

Discussion

A. Gibson (*Bluebonnets, West End Cholsey, Oxfordshire, UK*). Dr Sheffield has indicated that fusion could be an important world energy resource in 2150, a resource that may be essential if widespread conflict between the 'haves' and the 'have nots' is to be avoided. To achieve this end, fusion energy research must be funded today, and it is important to try to quantify what a modern, developed society would be prepared to pay to realize this very-long-term future goal. For instance, if fusion energy research in the USA were to be funded by a tax on electricity, what level of tax does he think the US taxpayer could be persuaded to accept?

J. Sheffield. In general, there is not a lot of support for taxes on electricity to support energy R&D. However, I note that the Electrical Power Research Institute (EPRI) and the Gas Research Institute (GRI) are funded by contributions from utilities and, I think, gas distribution, respectively. Further, there are discussions about trying to get funding in the coming, liberalized US electricity system to find some fraction of renewables electricity (similar, perhaps, to the UK's Non Fossil Fuel Obligation (NOFFO) system?). I note that funding for EPRI and GRI has been decreasing recently. There is a move to put the Office of Fusion Energy 'sciences' budget under the science (high-energy physics, etc.) budget and not in the 'energy' budget. In summary, funding for fusion energy by a tax on electricity seems unlikely today.

P. Vandenplas (*Laboratory for Plasma Physics, Royal Military Academy, Brussels, Belgium*). The enormous promise of controlled magnetic fusion as a safe, environmentally friendly and inexhaustible way of meeting the growth in energy demand makes it imperative that the efforts to try making it commercially available by 2050 are not slackened. This is important in order to decrease the future output of greenhouse gases: yet many state that fusion will come too late to be considered for the latter. How does Dr Sheffield react to that argument, which appears incorrect?

J. Sheffield. The analysis of Wigley *et al.* (1996) indicates that, to hold CO_2 levels to less than pre-industrial levels will require reductions in world greenhouse gas emissions starting around 2050. One approach is to increase the use of non-fossil fuels from this time forward. In this regard, fusion energy would be a valuable asset. Second, if alternative fuels come in earlier than 2050, there will still be the need to provide the expected increasing energy demand after 2050.

M. Keilhacker (*JET Joint Undertaking, UK*). Why is the fusion community doing so badly in persuading politicians and the public at large to keep the fusion option going? Why can we not do as well as the high-energy physics community?

J. Sheffield. The answer lies in the United States. I was driving through Georgia a few weeks ago and petrol was 84 cents a gallon. It is very hard to persuade politicians that there is some crisis when they see huge amounts of oil and gas and it is very cheap.

High-energy physics does better because it's closer to God than we are.

J. F. Davies (*Wirral, UK*). If population migration is considered, it is difficult to see the population of India approaching 3 billion and that of the USA remaining at 300 million. Moreover, with the 'brain drain' from developing countries, these might be incapable of handling the technologies of fusion energy.

J. Sheffield. Migration is an important consideration. However, averaged over the world, it is not very large. The World Bank assumes that the US population will go from about 250 million to about 340 million by 2100, mainly due to immigration. This is a negligible part of the expected increase in world population. One has to be concerned at what will happen if certain areas go to unsustainable population levels. If the developing countries can raise their standards of living to equivalent to 2.5 TOE yr^{-1} today, they should be better able to handle advanced technologies.

But, as I stated, it seems that such technologies will most likely be handled by large, multinational, global companies.

K. Lackner (*Tokamak Physics Division, Garching, Germany*). I maintain that the USA is subsidizing fossil fuels to the tune of $170 billion a year through military expenditure that are justified by the need to insure the long-term availability of fuel resources. How can we get home to politicians the utility of a fuel source, which is by its nature universally available?

J. Sheffield. This is a comment that is often made. If you ask the question, 'Does the US need to import oil?' the answer is, 'No'. It would be perfectly possible to provide all the energy in the US from its own fossil resources, given time and given the technology. It's just cheaper to import oil.

G. H. Wolf (*Institute for Plasma Physics, Jülich, Germany*). When discussing the options for energy resources, Dr Sheffield also included a significant fraction of renewables, such as solar and wind. However, there the yet unsolved problem of storage systems may play an essential role concerning cost and economy in the case where their use exceeds that level which can be buffered by fossils or, for example, fusion power plants.

J. Sheffield. This is a very good point. Generally, to get intermittent electricity above about 10% of the total will require storage, or some buffer (e.g. hydropower, see the case of Denmark). There are two ways of increasing the percentage of intermittents: either develop better storage systems, or move to a hydrogen energy system. Both are being studied extensively.

R. D. Gill (*JET Joint Undertaking, UK*). Surely, introducing new energy sources, such as nuclear fission or fusion, with very high initial capital costs, into developing countries will be very difficult?

J. Sheffield. Yes, it will be difficult. Hence the comments on the need for it to be done internationally from a technical point of view (and waste management point of view). However, if the per capita energy use and standard of living improves, as indicated, these areas will be making the transition from developing to developed, at this time, and should be more able to handle the capital question. Note that the developed countries succeeded in achieving this transition at some time in the past.

P. Thomas (*JET Joint Undertaking, UK*). It has been said that one could optimize the world energy strategy by giving the developing world fossil fuels. Their economic productivity might then be so increased that they could build their own power stations. Is this a viable strategy?

J. Sheffield. If you look at energy resources today, there is plenty of clearly identified fossil fuel around, but it is not evenly distributed. If you believe that energy is important in enabling countries to improve their standard of living, then giving developing countries energy could widen their industrial base, lead to better education, and put them in a better position to absorb sophisticated energy systems like nuclear fusion.

You could turn the question round and ask, 'What would happen if the developing countries do not get energy, and their population does not stabilize?' It is mind-boggling to think about. It's frightening! If the population of Africa reached four billion, and their individual energy use remained the same, they could use just as much energy as that used by the other alternative of the present population (0.8 billion), with a decent energy use.

I. Cook (*UKAEA Fusion, Culham Science Centre, Oxfordshire, UK*). Will decision-makers be impressed by arguments based on demand and other projections, since these have frequently been wrong in the past? A more robust basis for arguing for the need to develop new energy sources might be the correlation Dr Sheffield showed between falling birth rates and rising per capita energy consumption, if this corresponds to a causal relationship. For then one could say, 'If you want to stabilize the world's population, you must develop new energy sources'. So, the question is, 'Is there a causal basis for the correlation, or is it sufficiently robust, for other reasons, to bear the weight of the argument?

J. Sheffield. One cannot prove a causal relationship between birth rate and annual per capita energy use, even though historic plots of one against the other are suggestive. However, one can point to a relationship between standard of living and annual per capita energy use (allowing for the efficiency of energy use) because most of the features commonly ascribed to standard of living require identifiable amounts of energy for their realization. It is then a simple matter to show how much energy would be required to provide a developing country level of energy across the world, for today's population or for some projected population. At a minimum, even allowing for significant efficiency improvements, it is easy to see that future annual energy demand could be in the range of 1.5 to over 3 times today's demand.

H. Bruhns (*European Commission, Brussels, Belgium*). Should improvements in energy efficiency be related to per capita consumption on the world average or rather to the one in industrialized countries where most could (or would have) to be done? Could Dr Sheffield comment on whether the long-term availability of fossil fuels in Europe differs from the overall and the US situations which have been discussed and what energy sources might step in if fossil fuels consumption had to be reduced in Europe. Also, what about dispersed and concentrated energy sources?

J. Sheffield. Efficiency improvements are needed in both developed and developing areas—in developed areas, to hold down energy demand while sustaining and enhancing standards of living; in developing areas, to raise standards of living while minimizing the costs of moving rapidly towards a developed country status.

Which energy sources will be needed in Europe and the role of fossil fuels depends upon the rate of efficiency improvements in Europe. In several projections, energy use is projected to range from a modest increase to a substantial decrease. Nuclear energy is generally projected to be an important contributor, e.g. 200–300 Mtoe yr^{-1} (thermal equivalent). Within this area, fusion can play a role for large central power generation.

M. Watkins (*JET Joint Undertaking, Oxfordshire, UK*). Where is the future funding of fusion coming from? Will it come from multinationals or be linked with the foreign policies of the industrialized nations?

J. Sheffield. Future funding of fusion will most likely be from governments until a demonstration power plant has operated successfully. If the annual budgets needed to develop fusion energy remain as high as typical present projections, and world budgets remain at roughly present levels, significant international collaboration and coordination will be required for the programme to be successful.

R. S. Pease (*West Ilsley, Newbury, UK*). Dr Sheffield gave a figure of 4.5 Gtoe yr^{-1} for the needs of South and Southeast Asia in 2100. Does this figure assume that energy efficiency is improved?

The thorium resources of India are well established: does he regard the development of the thorium fission power reactions as important?

J. Sheffield. Yes. It represents a population of about 3.6 billion people using about 1.25 Mtoe yr^{-1}, assuming an average improvement of 2 in the efficiency of energy use.

Yes. Clearly this can be a very important resource for India.

H. Bruhns. Does one of the relevant criteria for R&D decisions include the dependence of energy systems from natural events?

We know that in geological timescales there were several events which led to a disruptions of large sectors of life on Earth. Over historical time spans, we know of quite a number of events which deprived large parts of human society of the basis of existence. The probability of such events is low but finite. What would be the situation if such events were to occur within the next few centuries? Would fusion be able to provide added security to societies?

When estimating the usefulness of energy options, can one distinguish between the supply of energy to urban and rural populations?

J. Sheffield. The relation between standard of living and consumption of energy in the form of electricity is striking. The share of electricity in the overall energy demand is particularly strongly growing in highly developed urban society. It is expected that the share of world population living in densely populated urban (mostly coastal) regions will grow during the next five decades from presently 40% to 70% (Europe has currently a 55% urban population).