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POPULATION GROWTH RATE AND ENERGY CONSUMPTION CORRELATIONS: IMPLICATIONS FOR THE FUTURE

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1. Introduction

The fertility rate for women, in countries across the world at a particular time, shows a downward trend with increasing annual, per capita, commercial energy consumption, Goldemberg and Johansson [1]. An analysis of United Nations data [2] for the past 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 [3]. Thus, it appears that per capita energy use is a useful surrogate measure of the many factors which can influence population growth rate - emancipation of women, standard of living, education, etc., Cohen [4]. The transitional countries are those whose population growth rates have decreased, during this 25- to 30-year 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 (Figure 1). Similar trends can also be seen for smaller countries, e.g., in the Caribbean, Barbados, Cuba, Guadeloupe, and Martinique [5]. Related studies have been made by Gouse et al. [6]

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 which is captured by the simple empirical formula; $G (\%) = (E_c - E)/(1.6 * E^{**}0.38)$, for $E \leq E_C$; where E is the annual commercial per capita energy use in tonnes of oil equivalent (toe/cap.a), and E_C (toe/cap.a), the value of energy at which the growth rate becomes zero, is assumed to depend upon "cultural" factors [3].

If this trend continues, the transition of the world to the low growth rate and stable population - around 10 to 12 billion by 2100 to 2150, projected by the World Bank [7] and other organizations, will require a substantial increase in per capita energy use (water, materials, etc.) 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 $E_e = h_{eff} E$ is defined, in which h_{eff} is the efficiency improvement factor over that in the year 2000 e.g., if $h_{eff} = 1.25$, 1 toe of energy in 2020 is as useful as 1.25 toe was in 2000.
$G(\%) = (E_{ce} - E_e)/(1.6 * E_e^{**}0.38)$, for $E_e \leq E_{ce}$.

2. 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 agreement with projections of the World Bank [7]. The projected populations of the five major regions of the developing world are shown in Figure 2, those for the developed countries are taken from projections of the World Bank [7].

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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 [8].

Case 1 assumes that the average efficiency of energy production and use will improve steadily to h_{eff} = 1.35x by 2050, 1.75x in 2100 and 2.0x 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.

Case 2 assumes a lower rate of efficiency improvement of 1.25x in 2050, 1.50x in 2100, and 2.0x in 2150, and that the developed countries keep a fixed annual per capita energy use at the year 2000 level.

Details of the calculations are given in an earlier paper [3]. The energy needs for Case 2 are shown in Figure 3. In Table 1, the projected energy use is shown for the major five 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 leads 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 a decrease in the use of fossil fuels becomes possible and a very long term stable energy situation can emerge. The extent of energy resources are taken mainly from the World Energy Council's 1995 resource book [9]. The assumptions about use are that: regions with limited fossil fuels will use them all, importing what else they need; 90% of the projected world's hydropower will be exploited; about 50% of the projected biomass energy Johansson et al. [10] and Larson and Williams [11] will be exploited, a limitation set by concerns about sustainability; and about 40 % of the windpower potential will be used, consistent with constraints on land use and need, Grubb and Meyer [12]. The balance of energy for each region is assumed to be provided by some combination of nuclear and "solar" (includes geothermal, tide and wave power) energy.

3. Electricity production

The past trend towards an increasing fraction of electrical energy use is expected to continue IEA [8]. 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 IEA [8] 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 the blanket improvement in energy efficiency h_{eff} assumed for this study.

4. Energy sources

Using the assumptions above, estimates were made of the sources of energy for each of the major ten regions of the world. The aggregate use is shown in Figure 4, for Case 1. The numbers for Case 2 (Case 1 in parentheses) in 2100 are: fossil (gas, oil, and coal) 8560

(6140) Mtoe/a; biomass 2510 (2510) Mtoe/a; hydropower 1460 (1460) Mtoe/a; wind power 3350 (2140) Mtoe/a; and nuclear + "solar" 4530 (3320) Mtoe/a.

5. Conclusions

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. The two cases require a use of 450,000 to 510,000 Mtoe oil and gas plus about 400,000 Mtoe of coal in the period 2010 to 2100. This would lead to a deficit of 90,000 to 150,000 Mtoe of conventional oil and gas, ignoring the use from today to 2010. Shale oil and bitumen amount to another 560,000 Mtoe, 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, and an alternative solution would be the greater use of coal. In addition, even more massive deposits of methane hydrates are projected to exist, Max et al. [13], 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 to 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.

In the cases examined, substantial use must be made of nuclear and solar energies. While, in principle, either energy source might provide the total needed energy, 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 nuclear power will be used where massive central power generation and cogeneration are needed. Roughly equal amounts of solar and nuclear energy are used. Fusion energy production is assumed to start in 2050, and grow as a complement to fission energy.

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 the massive use of nuclear and solar energies, substantial imports of fossil fuels, and the use of methane hydrates - believed to be off the coast of southern India. The potential demand and a possible solution are given in Table 2.

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 U.S. energy use today is about 2,300 Mtoe/a.

Carbon sequestration is a very important consideration if global warming concerns are taken seriously, since without sequestration fossil fuel use might have to be limited in the next decades to around 3,000 to 4,000 Mtoe/a IPCC [14]. In the cases considered, the estimated carbon emissions are 630 to 740 GtC (gigatonnes of carbon) in the period 2010 to 2100, of which maybe half would have to be sequestered to meet emission reduction goals.

There are many ways in which carbon may be sequestered, Turkenburg [15], Herzog [16], and Socolow [17], 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. It is

estimated that oil and gas wells could sequester 130 to 500 GtC, while saline aquifers might sequester 90 to >1000 GtC, and the oceans could potentially handle 400 to >1200 GtC. There remain important practical questions of cost and safety to be resolved for this and the acquifer solution 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.

As a final comment, it appears that the availability of easily moveable, cheap fuel is essential for the developing areas to increase their per capita energy use, improve their standards of living, and stabilize their populations at a sustainable level. In the near term, fossil fuels can fulfill this role, within constraints set by environmental considerations. In the longer term, a sustainable solution requires the development of all energy sources to complement and ultimately replace the fossil fuels.

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Table 1. Projected energy demand for 2010 to 2150 in Mtoe/a.

Case	2010	2030	2050	2075	2100	2150
Developing 1	4840	6790	8450	9850	10150	10630
Developed 1	7230	7020	6510	6020	5420	4960
Total Case 1	12070	13810	14960	15870	15570	15590
Developing 2	4930	7200	9300	11150	11850	11760
Developed 2	7370	8040	8340	8550	8560	8410
Total Case 2	12300	15240	17640	19700	20410	20170

Table 2. Potential energy sources for South Asia in 2100.

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

Figure 1. Population growth rate versus annual energy per capita for the period 1965 to 1992.
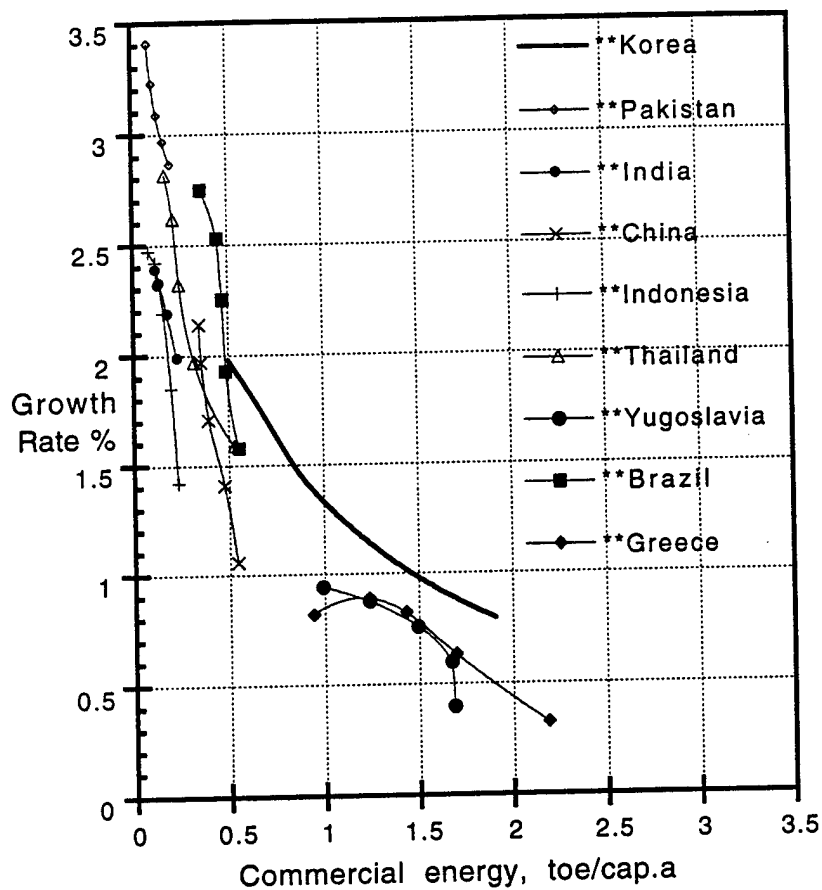
Figure 2. Projected populations for the 5 major developing regions of the world.
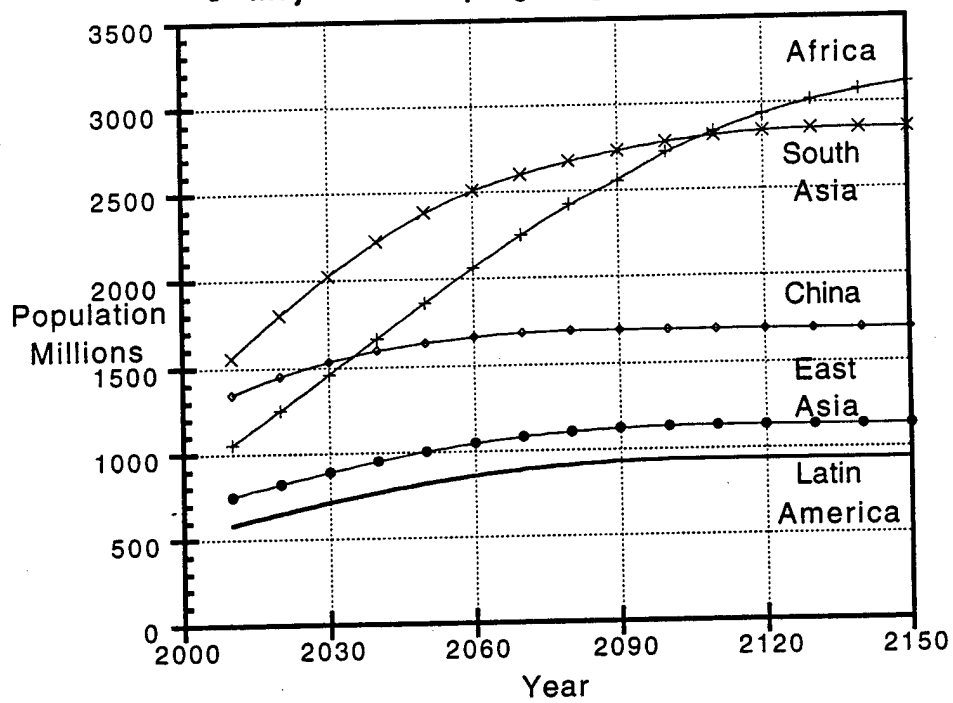
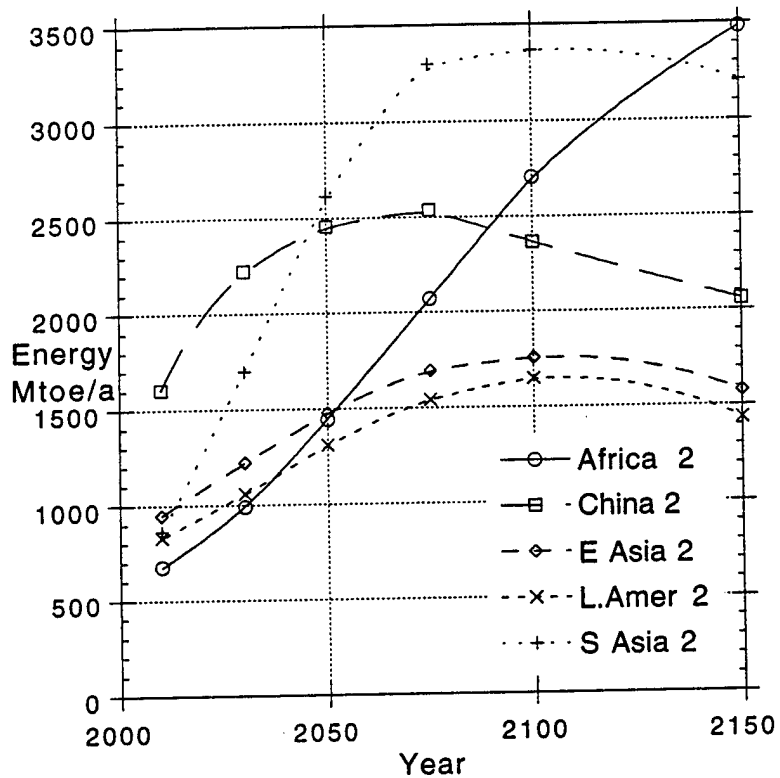Figure 3. Projected annual energy use for 5 major developing regions - case 2.

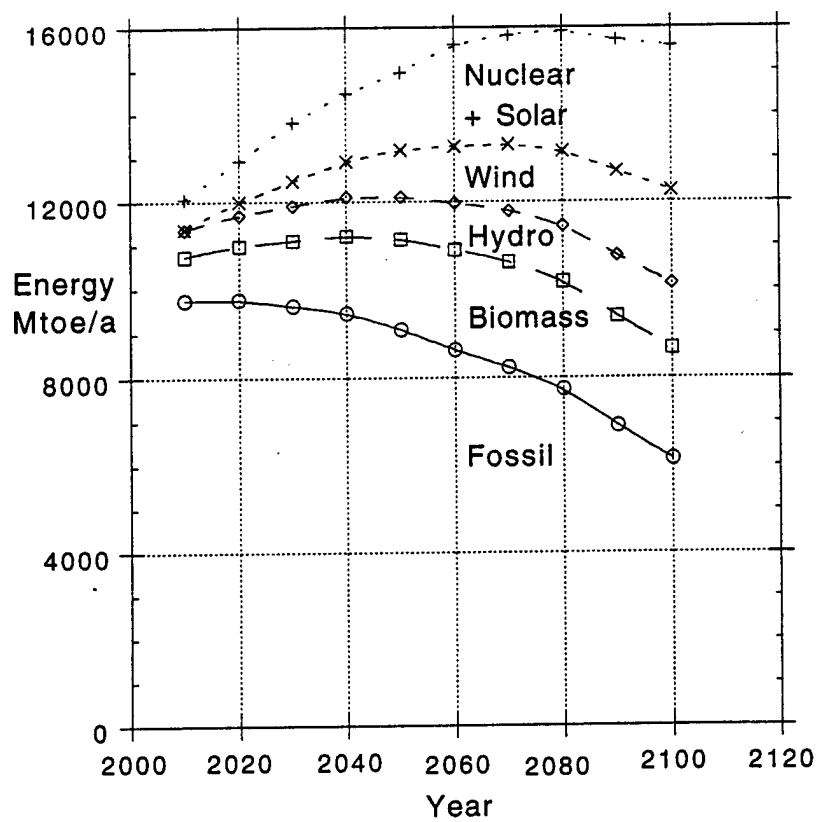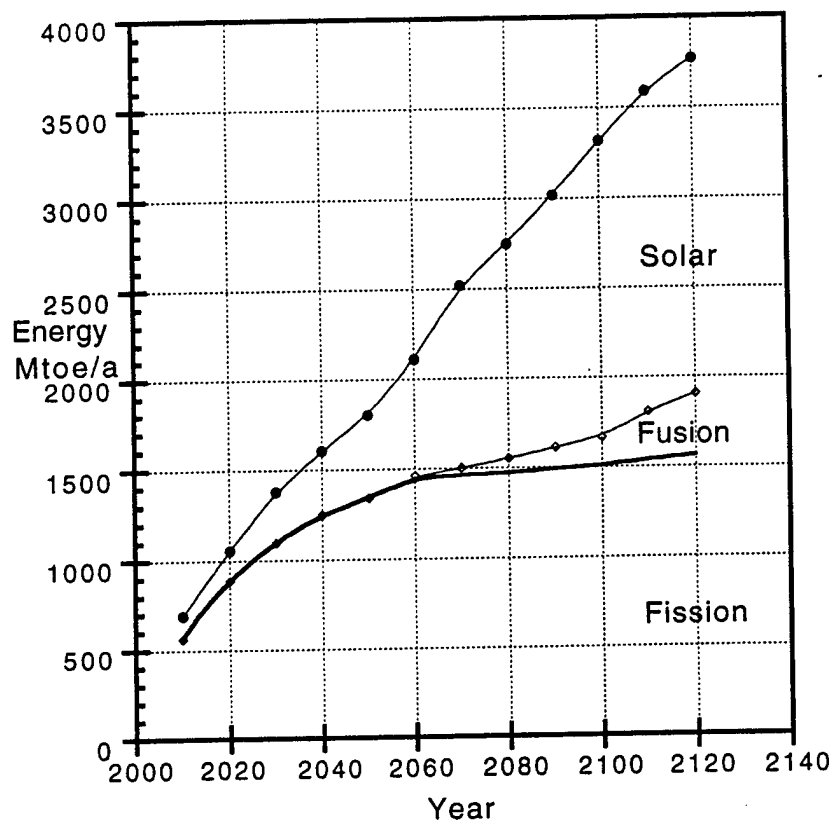**Figure 4. Example energy sources for case 1.**

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

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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 historic 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 to 2150. An assessment is then 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 utilize all energy sources, if the world is to find a sustainable future with an improved standard of living for the developing world.

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