

The One GigaHuman Earth

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1. Introduction

There are now (in 2009) a little less than 7 billion human beings on planet Earth. I believe that it is going to be difficult to find anyone who will assert that things are going to be better when there will be *7 trillion* human beings on Earth. The thought of there being one thousand humans for every one human here today would appear to me to be somewhat terrifying. Fortunately there is no chance of it happening.

However, many years ago there was an interesting experiment (unfortunately I cannot find the reference for the study. If any reader recognizes it and can help me, I would be very grateful). A number of mice were put in an enclosure, with unlimited access to food and water. They started reproducing and grew in numbers. And grew, and grew. When finally they decreased their reproduction rate and stopped growing in numbers, there were so many of them that they were living *literally* on top of each other, completely filling up the surface of the enclosure. Are we humans more intelligent than mice? Maybe.

If there would be only *7 thousands* humans on the whole Earth, it would not be too appealing either. Even if they would be all living in very close proximity, and even if they would have access to all the knowledge that we have accumulated so far, they could only afford a very primitive lifestyle and they would be always in danger of becoming extinct.

Therefore, between 7 thousands and 7 trillions, there must be an *optimal* number for the human population of Earth. Unfortunately, the term “optimal” may have as many different meanings as there are humans.

However, there should be agreement on one characteristic of the optimal number, i.e. that such number should be *sustainable*, i.e. it should be able to be maintained for a considerable time. It has been approximately ten thousand years since the agricultural revolution. Should we want to survive for at least another ten thousand years? May be this is too much? How about one thousand years?

To achieve such sustainability our use of *renewable resources* should be in line with their rate of renewability. Furthermore, our use of *non-renewable resources* should be based on complete recycling. The latter is almost certainly unrealistic. For any given level of average lifestyle, the *net* consumption of non-renewable resources would be directly

proportional to the size of the population. Therefore, the lowest rate would be obtained with the lowest acceptable size of the population.

Traditionally we have been categorizing existing countries into two groups, the **More Developed Countries (MDC)** and the **Less Developed Countries (LDC)**. In our definition the MDC's will include the USA, Canada, the European countries (including Russia), Japan, Australia and New Zealand. Currently there are approximately 1100 million humans in the MDCs and 5600 million humans in the LDCs.

Most humans in the MDCs would like to be able to enjoy a standard of materialistic living comparable to the one currently enjoyed by the top tier of their own populations. Most humans in the LDCs would like that also. The level of technology that allows for such a standard of living can only be maintained if there is a reasonably large population base.

We believe that a reasonable compromise can be achieved if the population of the Earth is reduced to **one billion humans (i.e. 1 GigaHuman) and be kept there**. In the following we are going to explore how that could be achieved and its consequences. One billion humans is about what the population of Earth is estimated to have been 200 years ago, at the beginning of the 1800's.

But in order to achieve such a goal there would have to be, first of all, a universal consensus. We are NOT going to explore how to accomplish that, but we will concern ourselves exclusively with the implications of its implementation.

Furthermore, in our analysis we will ignore the existence of all political boundaries, from the point of view of the allocation of resources.

NOTE: The analysis assumes as a base year the year 2007. Economic data is expressed in constant 2007 US dollars.

2. The Reference Case

Before we look at how to accomplish the reduction in population and its implications, we need to establish the “**reference case**”, i.e. what would happen if we do not do anything special; in other words, if we continue on the current trends. Some of the assumptions’ details will be discussed in the “Methodology” section at the end of this paper. We will call later the analysis based on our proposed population reduction the “**proposal case**”.

We will consider separately the case for the **USA**, then the case for the **other MDCs** and then the case for the **LDCs**. There are two reasons for doing that. The most important is that we have reasonably accurate and detailed data about the US and we are going to use that information as the base to make projections for the other cases.

The second is that the USA *intrinsic* fertility rate is close to the balance point, making it a convenient base for analysis. By “intrinsic” we mean the rate of growth that is based on the population already *in* the USA. The USA is also experiencing a net immigration that allows for the overall growth rate to be about 1%/year. The “other MDCs” have currently a fertility rate that is *less* than the equilibrium rate and their population is actually decreasing, although the decrease is partly offset by some immigration.

The LDCs, on the other hand, have an almost explosive growth rate. If we would assume that the current state of affairs would remain unchanged, the overall Earth population would increase to about 13 billion by the year 2050, 30 billion by the year 2100 and 160 billion by the year 2200. Nobody believes that such a thing will actually occur. There is a consensus that the growth rate of the LDCs will slow down and eventually will move toward the balancing point. There may be an element of wishful thinking about these assumptions, at least with regard with the rapidity of the slow down. We have chosen to make certain specific assumptions about the rate at which such growth decrease in the LDCs will actually occur..

The implications of such assumptions are shown in Fig. 2.1.

NOTE: All of our charts will only include data from 2007 forward.

Under these assumptions the Earth population will reach almost 10 billion humans in about 100 years and then will decline somewhat. We have chosen to adjust the fertility rates so that the population will level off at about 9.2 billion. This is almost certainly overly pessimistic. Most likely, after the population has reached its maximum, it will decline more significantly. Then, at some later time it will stabilize at a lower value. Unfortunately we have no clue at what rate the population might decline and at what value it might eventually stabilize. Our “worst case” assumption gives us an upper bound on the requirements.

2.1 Economic Implications

We now turn to the analysis of the economic implications. The methodology used to make the projections is explained in some detail in the Methodology section. Here we will limit ourselves to present the results of the analysis itself. However, there is an important point that has to be made. In order to make our projections we have had to make a large number of assumptions. Some are not very critical, but others are. The scenario that we present is only one of many “reasonable” scenarios that can be constructed. We believe it to be a realistic “middle ground” scenario, but it is certainly open to debate.

The main variables we are interested in are the **GDP** and the **pro-capite consumption**. The GDP provides us with a measure of **economic activity**, while the pro-capite consumption provides us with a measure of *materialistic standard of living*.

It should be noted that in the USA itself there is a difference of about a factor of two between the highest and lowest GDP per capita regions. In the MDCs such difference is even higher. Within the LDCs the difference is very large. There is a very large difference between the economy of the industrialized coast of China and the interior of sub-saharan Africa. Our data refers to the *aggregate* in each group.

Under our assumptions the GDP projections for the reference case are shown in Fig.2.2 for the period up to 2050. Our projections are very close to more detailed published projections, at least up to 2030. This shows a doubling of the world GDP in about 20 years and growing to a little less than four times the current value by the year 2050.

Currently the LDCs have jointly a GDP which is about 80% of all the MDCs (including the USA). In less than 10 years the LDCs’ GDP would equal that of the MDCs. In about 40 years it would be twice as much.

In Fig. 2.3 we show the results of extending the projections to 1000 years, as we have done for the population patterns, **under the assumption that there will not be any limitation due to physical resources**. By the year 2100 the total GDP would have increased to about 8 times what it is today. By the year 2100 the LDCs would have a GDP equal to three times the total of all MDCs. The political implications are hard to fathom.

However, a potential problem is best demonstrated by Fig. 2.4, which shows the pattern of growth for the **pro-capite consumption**, which, as we have said, is the appropriate measure for the *materialistic* standard of living. According to the projection, the LDCs would achieve in about 100 years the same level of pro-capite consumption as the USA has today. This means that about 8.5 billion people would have then the same level of standard of living that the USA 300 million people have today! The implications are staggering. Is this really realistic?

Apart from energy, which will be discussed in a later section, there is a high likelihood that limitations will occur due the availability of primary materials. The interesting thing

is that many sources of primary materials are found in the territories of the LDCs. If (or maybe, “when”) the demand for such resources should exceed the supply, the impact may be felt first by the MDCs, who would not be able themselves to expand their economies as expected. This would create economic conflicts which might lead to military conflicts. The perspective might not be pleasant.

2.2 The Food Implications

Is it going to be possible to feed as many as one and a half the people as there are today? In the last 50 years agriculture has made considerable improvements in productivity. Although there are shortages in some areas, this is due mostly to a failure of distribution, not of production. There is reasonable expectation that the improvements in productivity will continue, at least to some extent. It is therefore reasonable to presume that there should be no major impediment to grow enough food for everybody *at the basic subsistence level*. The problem is that with the expected increase in the standard of living there will be increased demand for “higher quality” food. To produce 100 calories of beef it takes considerable more land than to produce 100 calories of wheat. This will lead to additional demands on agricultural production. It is not obvious that it will be possible to satisfy the demand of a population that not only has increased in size, but also has increased its demands for higher quality food.

Although the proper unit to use for large areas is the “square kilometer”, it is most common to use the “hectare”, which is equal to 0.01 square kilometer (and approximately 2.5 acres, for those more used to American style units). We will conform to this practice.

Currently the MDCs (including the USA) have under cultivation about 1.2 billion hectares, or approximately 1 hectare/human. This allows them to have a rich diet. In order to provide a comparable diet to the whole population (consistent with the increased level of standard of living) we would require 9 billion hectares of agricultural land, compared with the current total of 5 billion hectares. Such total would be equal to approximately 60% of all available land! There are two conflicting variables to take into account. On one hand it is likely that we are going to see some additional increase in agricultural productivity. On the other hand any new land brought under cultivation would be intrinsically less productive than the land currently in use. Which variable will be predominant is hard to tell.

We will assume that the USA and other MDCs will essentially keep the current food consumption, i.e. they will not require additional pro capite food production. We will assume that over time the LDCs will reach the same level of food consumption. We will also assume a net total increase in food productivity of 50%. Therefore the total land requirement for food production would be about 6 billion hectares or about 1 billion hectares more than it is being used today.

Modern, highly productive agriculture is based on the extensive use of fertilizers and pesticides. Most fertilizers use combinations of Nitrogen (N) (often in the form of ammonia), Phosphorus (P) and Potassium (K). Nitrogen can be obtained from the

atmosphere through the use of energy. Phosphorus is obtained from phosphates and Potassium from Potash, both of which are mined. It appears that the reserves of Potash are extensive and would not be likely to become an impediment very soon.

The same cannot be said for phosphates. Currently they are used at the rate of 40 million tons a year. Any increase in total agricultural production would almost certainly imply an almost proportional increase in phosphate consumption, although there are possibilities for partial recovery of the phosphates used but not exploited by the agricultural products. As we shall see a little later, all the known land phosphate reserves are not adequate. There are known deposits under the oceans, but the ability to exploit them at an acceptable cost is yet to be ascertained.

Agriculture requires water. There is some concern that water for agriculture may become scarce. However, there is also strong evidence that water is not used efficiently at this time. We will ignore the problem for the purpose of this study.

2.3 The Energy Demand Implications

One of the most interesting problems is how to feed the Earth's humans' appetite for energy. One of the problems with energy analysis is the number of different units that are used to express its production or consumption. We choose to express all data in the "correct" energy metric unit, i.e. the **joule**, or, more precisely, the **hexajoule (HJ)**, i.e. 10^{18} joules. In the Methodology section we discuss in detail the problem of measuring energy production and consumption.

The energy consumption is closely related to the value of the GDP. However, the ratio, i.e. the number of joules/\$ actually utilized, has been decreasing over the last few years. Part of the decrease is due to energy efficiency engendered by the higher cost of energy and part is due to the change in the composition of the GDP, toward a higher proportion of "services" relative to "goods". There is plausible evidence that a dollar of "services" costs less energy than a dollar of "goods". How far this decrease is going to continue is difficult to predict. In the Methodology section we will discuss in more detail our assumptions. At present (2007 data) the contributions of the main sources of energy to yearly production are approximately as follows:

Carbon Fossil Fuels		
Oil	180 HJ/year	36%
Gas	121 HJ/year	24%
Coal	138 HJ/year	27%
Other		
Nuclear	30 HJ/year	6%
Miscellaneous	35 HJ/year	7%
TOTAL	504 HJ/year	100%

The “Miscellaneous” group includes hydroelectrical energy, wind energy, solar energy and some other minor contributors. In order to look at the implications of the future energy demands we need to make some assumptions regarding the use of each of these energy sources. Current projections appear to indicate that the above ratios would remain stable, at least for the initial time frame. Note that the above values are measured at the *primary* level (thermal or otherwise) and not at the electricity production level.

This is viewed from the **production** point of view. There is a difference in accounting for the energy when we look from the “use” point of view. For example when we consume oil to produce electricity, for each joule of the oil *chemical energy* that we expend we generate about 0.3 joule of *electrical energy*, of which only about 0.27 joule will reach the ultimate user. More details on this issue are given in the Methodology section.

If we look at the consumption from the **use** point of view, we have the following numbers (on a worldwide basis):

Air transportation (as jet fuel)	10.0 HJ/year
Ground transportation (at the wheel)	21.5 HJ/year
Electricity (at the outlet)	59.1 HJ/year
Heating/Industrial (at the usage point)	205.1 HJ/year
Total	295.7 HJ/year

The **use** energy requirements under our assumptions are shown in Figs.2.5a for the first 100 years and 2.5b for the whole 1000 years.

The chart shows that by the 2030 the “use” energy requirements would double and that most of the increase would occur in the LDCs. The trend would continue in later years, so that essentially all of the additional energy demand will continue to come from the LDC’s. by the year 2050 the energy requirement would be about 3 times higher than it is today.

By the time the demand would stabilize (in about 700 years) the total demand would increase to about 7000 HJ/year or over 20 times the current rate of consumption.

The LDC fraction of the total would increase from about 50% today to about 70% by 2050 and to over 80% by the year 2200, as shown in Fig. 2.6.

Looking at the same data from the point of view of the usage, Fig. 2.7 shows the transportation energy demand. Since, as we shall see, ultimately the heating/industrial component of the demand would have to be provided by electricity, we show in Fig 2.8 the *total* electricity demand, including that needed to meet the heating/industrial demands.

2.3.1 Carbon fossil fuels

How will such demand be met? Currently 87% of the primary energy demand is met by **carbon fossil fuels**, as shown above. All carbon fossil fuels share one property, namely that their total amount available on the planet is finite. What is the value of that amount is obviously not known. There are “known” reserves, but how much additional reserves may be available, but not yet discovered, is a matter of conjecture. The optimists point to the fact that about $\frac{3}{4}$ of the earth surface is covered with water and that there are still a lot of potential discoveries to be made under the oceans. However, the technology for exploration and exploitation of such deep ocean underwater reserves *at an acceptable cost* may not be there. The rates of discovery of ground and coastal waters based reserves of oil and gas have been decreasing rapidly and are now well below the rate of production. There is theoretical and experimental evidence that we cannot be optimistic about a change in the trend. Furthermore, there is also theoretical and experimental evidence that the rate of production may decrease rapidly with the reduction in reserves. There is a so called “Huppert curve” that appears to be a reasonable estimate of future production. Although it is controversial, we will use it as the basis of our projections.

NOTE: In the following analysis we will assume that all reserves would be equally available to everybody, without limitations of politics or geography. Reality would be much more complex.

We are first going to explore what would happen if we just continue on the current path of relying almost exclusively on carbon fossil fuels, with the minimal addition of nuclear and solar energy as currently deployed (which we are going to label the “business-as-usual” case). We are going to assume a fuel usage strategy that uses oil only for transportation, as much as it is possible. The results are shown in Figs. 2.9, 2.10 and 2.11 for oil, gas and coal respectively.

The above production curves are controversial. The specific shape depends on a number of assumptions that have some experimental support, but are not without criticism. However, the area under each of the production curve is equal to the total fuel available for extraction, including the estimate for future discoveries. It is possible that actual discoveries may differ from the assumption, but it is unlikely that such differences would be very large. Therefore, while the exact shape of each curve may be debated, the total integral (i.e. the area under the curve) is not likely to be much different than the one hypothesized. The actual production might peak earlier or later, but in about 100 years all production of carbon fossil fuels would become negligible.

Particular attention needs to be made given to the transportation energy. It currently represents 17% of the total and it is mainly met with oil consumption. About 12% of that 17%, (i.e. 2% of the total) is used for aviation fuel.

As Fig. 2.12 shows, by about the year 2025 the oil production will not be able to meet the demands of *total* transportation. By the year 2070 it would not be able to meet the demands of *air* transportation. This is important because the options for shifting to a different source of energy are more limited in the case of transportation and practically nil for air transportation.

The problem with the business-as-usual approach is illustrated in Fig.2.13, which shows the unmet excess energy demand. Starting at about the year 2015, the carbon fossil fuels and the non-fossil energy at the current level of production are unable to satisfy the world energy demands and the discrepancy grows very quickly. In order to handle the problem we must develop quickly higher capabilities in non-carbon-fossil energy, beyond what is already being done.

2.3.3 Non-carbon-fossil energy

There are essentially three sources of non-carbon-fossil energy, namely:

- Nuclear power
- Solar power
- Biofuels

Other options like hydroelectric and geothermal energies have essentially been played out, with relatively moderate additions possible. Wind power is limited to special situations and it is unlikely to play a major role. Currently such “miscellaneous” energy sources provide 7% of the total energy. We assume that such percentage would be maintained, although this may be overoptimistic.

2.3.3.1 Nuclear Power

Nuclear power is the cheapest form of energy available, except for natural gas, which is only marginally cheaper (“The cost of generating electricity”, The Royal Academy of Engineers, London, March 2004). It should have been used much more extensively than it actually has been. The objections that were used to discourage its use were based on ignorance and the irrational fears associated with the word “nuclear”.

In order to provide a 1 HJ/year, a nuclear power plant working 24 hours a day, but with normal maintenance shutdown periods, would have to have a nominal capacity of approximately 40 GW (Gigawatts).

If the whole requirement shown in Fig. 2.13 should be provided by nuclear power it would have to quickly add approximately about 25 HJ/year/year or approximately 1000 GW/year. In the 70's, when nuclear power was at its highest level of production, it could install about 20 GW/year. With modern technology and the right level of motivation the industry could certainly improve on that level. However, the ability to provide 50 times the capability would appear to require considerable time, if it is possible at all.

The problem with nuclear power is that current technology (i.e. based on nuclear fission) also requires a fossil fuel, namely uranium. The estimated total reserve of uranium on land is about 5 million tons. If we could only use the U235 isotope (as in most of current power plants) this would provide only about 2000 HJ (thermal). Using breeder reactors one can theoretically exploit U238 and Thorium. If they could be exploited 100%, they could provide up to 400,000 HJ. This is probably unlikely to happen. We will assume, somewhat arbitrarily, that the total amount of fissionable material reserve will provide 200,000 HJ.

Depending on the overall level of nuclear power that we choose to install, the above reserve will last only a few hundred years, as we will see a little later.

The oceans contain a lot of Uranium. However, the relative density is very low, 3 parts in 10^9 . We do not know of any estimate of the cost and difficulties associated with the extraction of Uranium from sea water. In order to meet the maximum energy requirements of approximately 30,000 thermal HJ/year one would have to move about 6,000,000 cubic meters per second, equal to approximately 2000 times the flow of the Niagara Falls, at its peak flow. Also, there is the major problem of what to do with the processed, uranium free water. If it is dumped in the same location where it is picked up, that would quickly dilute the uranium content, since the natural rate of water mixing would not keep up with the flow. The ideal place to do the operation might be at the Panama isthmus, by sucking the water in from one ocean and dropping it in the other ocean.

We choose to assume that such extraction is unlikely to be practical.

This implies that IN THE VERY LONG RUN fission nuclear power cannot be relied upon as a source of energy.

The above only deals with **fission** nuclear power. There is hope that we can derive energy from **fusion** nuclear power. However, such hopes have been frustrated for many years. There is no way at this time that we can postulate realizable, industrial level energy production through nuclear fusion at any specific time in the future. On the other hand, such eventuality might come to pass, in which case the whole energy picture would change considerably.

Nuclear power plants produce electricity. The typical plant today has a power of about 1-2 GW. Small nuclear power plants (with about 50-200 MW power) are being developed. However, this may still create a problem for small, remote communities or farms. Bringing in electricity through transmission lines may not always be economically feasible. A possible solution would be to use the electricity to produce hydrogen through electrolysis, ship the hydrogen to the remote locations and then use it to generate electricity locally with hydrogen fuel cells or to power mechanical equipment through hydrogen internal combustion engines. The latter may be less efficient than fuel cells, but may be less costly to purchase.

2.3.3.2 Solar Power

The power from solar irradiation is available just about everywhere, although conditions are better in some areas than in others. Current solar panels, of either the crystalline or amorphous variety, can convert the radiation energy to electrical energy with a moderately low, but acceptable efficiency. The *net average* productivity of a solar panel depends on many factors:

1. The energy cost of production
2. The average efficiency of the cells over the lifetime of the panel
3. The average yearly solar irradiation at the chosen location.

Assuming some improvements on the current average capabilities, we will assume that a 1 square meter crystalline panel *under ideal conditions* will provide about 1 GJ a year.

When using solar power as a minor source of energy, one can assume that when the sun is not shining (at night and on rainy days) the missing power can be supplied by other sources. When solar power is the major source of power this does not work. One must provide some means for storing energy during the good times, to be used during other times. Electrical batteries are too expensive at this time to be considered. Probably the simplest way is to build two lakes, at different altitudes. We can then use the solar power to pump water from the lower lake to the upper lake when the sun is up and use the water flow from the upper lake to the lower lake to provide power on a steady basis.

If solar power is the primary source of power, it must be able to provide energy year round. This implies that ideally the areas utilized should be within the tropics, where the difference in irradiation between long day and short day seasons are relatively modest. A plant that would be located at about 40 degrees North latitude would be able to provide in winter less than half the power than in the summer. This implies that either the plant would have to be sized for the “worst case” power level or that an adequate amount of energy storage would have to be provided. Today there are two peaks a year in electricity usage, in the middle of the cold season and in the middle of the warm season, with the latter one being usually somewhat higher (particularly in warm climates) because of air conditioning. But this is due to the fact that today most space heating is done with gas or heating oil. When all fossil fuels have disappeared, all of the space heating will have to be done with electricity and therefore the middle of the night in the middle of the cold season will be the period of maximum energy demand, exactly when solar energy will be at the minimum.

In order to provide one Hexajoule of energy a year we need an array of about 1 billion square meters or 100,000 hectares. As an example, we will assume that the two storage lakes would be 200 meters deep and separated by an altitude of about 400 meters. To support the ability to provide power on a steady basis, each lake would have to have an area of about 30,000 hectares. That would increase the total area required to more than

160,000 hectares per HJ/year. For plants located in the tropics, probably only a reserve of one third of that would be required, for a total of less of about 120,000 hectares per HJ/year. For simplicity we will use the value of 140,000 hectares per HJ/year.

One additional problem to take into account is that in most cases the areas which would represent optimal locations for the solar panel arrays are not those that lend themselves to the construction of the required storage lakes. This means that in practice the lakes would have to be located elsewhere and that the electricity would have to be transmitted from the solar panel array location to the storage lakes location, implying some additional losses.

In order to meet the demand of the first 50 years, we need to increase the installed power by about 25 HJ/year/year. This means that we have to develop *each year* over 3 million hectares of solar panel arrays and associated lakes. This would require a production rate of almost 25 billion square meters a year of solar panels. Since eventually nuclear energy becomes irrelevant, solar energy will have to satisfy the full eventual requirements.

At current costs for solar panels that would be expensive. However, increasing the production rate of solar panels to meet the requirements would drastically drop the cost of manufacturing. The current average cost of energy (at the production source) is about 1 US cent per Megajoule. At the current ratio of about 7 MJ/\$ this represents 7% of GDP. At the projected ultimate rate of 3.5 Megajoules/US\$ this implies a cost of about 3.5% of GDP. The cost of solar energy is currently about 5 times higher. If the costs can be brought down even to 2-3 times the current average costs, that would imply a cost of about 10% of GDP, which would be quite acceptable (particularly if there are no other alternatives!).

The problem with small, remote communities would also exist with solar power, but mainly for high latitude locations, where local solar power installations would be very inefficient because of limited irradiation. The same solution outlined above, i.e. hydrogen as intermediary energy storage, would apply.

2.3.3.3 Biofuels

In recent years there has been considerable interest and development in the area of **biofuels**, i.e. fuels derived from either land or marine vegetation. Brazil has been in the forefront of using sugarcane derived ethanol to provide a significant portion of their transportation energy requirements. While sugar cane is a somewhat efficient producer of ethanol, its cultivation is limited to selected regions and cannot be used on the large scale that future energy needs require.

In the USA there has been considerable interest in corn derived ethanol. Political pressure has actually mandated a level of production of such fuel to be blended with gasoline in certain states. The production of corn ethanol is extremely inefficient from the energy point of view. For each unit of ethanol energy produced, about 0.7 units of energy must

be expended. The gross production of ethanol is about 3000 liters/year/hectare. If we assume that the energy expended in production comes from the ethanol itself, the *net* production is about 900 liters/year/hectare, equivalent to about 20 GJ/year/hectare. That means that to produce 1 HJ a year one would need an area of about 50 million hectares. To provide the equivalent of over 8000 HJ/year it would take over 400 billion hectares, which is about 8 times the whole surface of the earth (including oceans).

However, ethanol could be more feasible if conceived not as a *source* of energy, but as a *intermediate storage medium*, exclusively for *ground* transportation purposes. To clarify this point we need to look at the problem of transportation energy in more detail. Most of the energy used in ground transportation comes now from gasoline and diesel. With minor changes to current engines, ethanol can be substituted for gasoline. It would be possible then to use all of the *gross* ethanol production for ground transportation. The energy used for the production of ethanol could come from the other sources, i.e. either nuclear or solar. If we did that, the ethanol net production would increase to 65 GJ/year/hectare, or about 15 million hectares per HJ/year. The total ultimate *use* demand for ground transportation energy is approximately 700 HJ/year. Assuming a fuel efficiency factor of 0.33, this implies an ethanol need of over 2000 HJ/year requiring about 30 billion hectares of land. Again, this is more than all available land. Therefore **corn** ethanol would appear to be unacceptable as a long term solution.

Other biofuel approaches may provide a higher energy per hectare. For example some cellulosic ethanol is purported to achieve up to 200 GJ/year/hectare (gross). We will assume that “optimal” biofuels for ground transportation may have a **net** yield of 130 GJ/year/hectare. Even with such productivity the land demands *for the reference case* would still be beyond reach, needing 15 billion hectares of land.

The air transportation industry currently uses jet fuel which cannot be easily replaced by ethanol, since ethanol has a much lower amount of energy per unit weight. They are looking at a plant called “jathropa” from which it is possible to derive a fuel that has the appropriate characteristics to substitute current jet fuel. It is estimated that jathropa might have a fuel yield of about 80 GJ/Year/hectare. Given the ultimate air transportation requirements of about 240 HJ/year, this would require about 3 billion hectares. When you add this to the 6 billion hectares required for agriculture we would have a total of over 9 billion hectares, which is almost certainly difficult to achieve. The energy inefficiency of biofuels can be best appreciated by the following numbers:

Solar energy received by irradiation:	70,000	GJ/hectare/year
Solar energy captured by solar panels	10,000	GJ/hectare/year
Solar energy average (with overhead)	7,000	GJ/hectare/year
Energy in Biofuels (cellulosic ethanol)	130	GJ/hectare/year

In order to grow the plants from which biofuels are derived, there will be a need of fertilizers and therefore of phosphates. We do not know the amount of phosphates per hectare necessary to grow jathropa. We have chosen to assume conservatively that they

will need only half as much as needed to grow foods. With that assumption the phosphate situation would be as shown in Fig. 2.14.

Note that the reserves go negative around the year 2400 and reach -55000 by the year 3000. This means that in order to survive until the year 3000 we must find additional reserves of phosphates equal to about twice currently known reserves.

Biofuels can only be justified when they are the only solution, as they currently are for aviation applications. Any additional use of biofuels will reduce the availability of phosphate for food production, possibly leading to food shortages. To propose the use of biofuels for anything other than jet fuel is a crime. People who do so should be tried for crimes against humanity.

2.3.4 Surface Transportation

If biofuels are not practical, how are we going to solve the problem of surface transportation? There are three possible approaches that we know of, namely:

1. Battery operated vehicles
2. Hydrogen fuel cells operated vehicles
3. Hydrogen combustion engine operated vehicles

All of these solutions depend on *electricity* as the primary energy source.

Battery operated vehicles are potentially the most energy efficient. From the point of electricity production to the wheels of the vehicle (assuming that we are dealing with a ground vehicle) the efficiency may be of the order of 50%, which is about twice as efficient as the current 25% or so with fuel operated vehicles. In order for the solution to be feasible, however, the batteries must provide a typical car with a range of at least 300 kilometers *and* they must be capable of relatively fast recharge when exhausted. Currently only lithium-ion batteries appear to fit the bill and they are very expensive. To support such vehicles a network of fast recharging stations must be provided with approximately the same density as current gas stations. The problem of distributing electricity to these recharging stations would not be trivial.

A critical problem is due to the fact that it would be difficult to develop a substantial network of recharging stations until there is a substantial number of battery operated vehicles, while it would be difficult to have a substantial number of battery operated vehicles until there is such a network.

Battery operation would not meet the requirements of farm equipment that cannot be moved to a recharging station. Also it would be inadequate to meet the needs of isolated communities (for example on small islands) that cannot justify their own local power generation system. Also battery operation would not be applicable to ship operation, since they must be capable of very long non-stop voyages.

Both of the other two solutions depend on creating a *hydrogen infrastructure*. This would consist of *hydrogen producing facilities* that would use electricity to extract hydrogen from water through electrolysis. This process is not very efficient. It is typically estimated that it is about 50% efficient, i.e. that only about 50% of the *electrical energy* expended is eventually available as *chemical energy* in the hydrogen produced. We note in passing that such hydrogen producing facilities would be needed in any case in order to supply the hydrogen necessary for the production of ammonia for fertilizers. In addition, one would have to create a network of *hydrogen stations* capable of delivering the hydrogen to the users at the retail level, similar to current gas stations. It should be noted that the problem of supplying such stations would be exactly equivalent to today's problem for gas stations. Hydrogen can be easily transported, therefore eliminating the problem of supplying remote locations.

The difference between solutions 2 and 3 is the way hydrogen is used.

In the case of *hydrogen fuel cells* the hydrogen would allow the fuel cells to produce electricity which in turn would be used to operate the vehicle. The efficiency of converting the chemical energy of the hydrogen into mechanical energy at the wheels is estimated to be about 40%. The overall energy efficiency would then be about 20%.

Current hydrogen fuel cell technology uses precious metals as catalysts. Unless a more available substitute is found, this would probably exclude the applicability of this solution on a worldwide large scale to possibly billions of vehicles. In addition we would have the same problem as for battery operation in breaking the vicious cycle of which would have to come first, a large number of fuel cell vehicles or a large network of hydrogen distributors.

The third solution is based on using the hydrogen as a fuel in regular combustion engines. There are two choices, each applicable to a different subset of situations.

For standard ground vehicles one can develop a *dual use* internal combustion engine that will take either gasoline or hydrogen as its fuel. Such an engine would not be optimally efficient in either mode, but it would be adequately efficient. As a hydrogen fueled engine it could be expected to be 25%-30% efficient. Its overall efficiency would therefore be around 12%-15%. Most likely such vehicles would come in hybrid-electric format, therefore optimizing their efficiency. The key advantage of this solution is that current gas stations could be slowly expanded to provide hydrogen and a vehicle incapable of finding a hydrogen refueling station could then operate its engine as a gasoline engine. This would allow for a gradual transition from a gasoline based ground transportation infrastructure to a hydrogen based one.

The second choice is to use hydrogen as the fuel for *steam engine*. Steam for the steam engines can be generated by the burning of any fuel. This solution would be the solution of choice for large ships and possibly for other heavy equipment. Also in this case the boilers can be easily switched between different fuels, therefore allowing for an easy transition.

We believe that only the third solution is the practical one. Although it is the least energy efficient is the only one that allows us to “get there from here”. Furthermore is the one whose basic technologies are most similar to the one currently in use, therefore making the process of design, manufacturing and maintenance of engines and vehicles the most straightforward.

2.3.5 An overall scenario

In order to meet the energy demand we can choose over a variety of options regarding the degree of reliance on nuclear or solar power. Since eventually all power must come from solar installations, it may be reasonable to ask if nuclear power should be used at all. There are two primary reasons. First, nuclear power is certainly cheaper initially, probably by about a factor of 5. The cost differential may disappear over the years, but in the meantime it would be significant enough to make an important difference. Second, both nuclear and solar power rate of new installations will be limited, particularly in the early years. By using both of them we can better meet the initial energy demand. There is also a third reason, namely that nuclear power would be the energy source of choice in those areas where solar irradiation is only minimally available, like in high latitude areas.

Our strategy would be to maximize the use of nuclear and solar power, minimizing the use of carbon fossil fuels. Furthermore we will assume an optimistic strategy of switching from oil to hydrogen for surface transportation and of switching from oil derived jet fuel to bio-jet-fuel. The intent is to save as much as possible of oil for petrochemical use and to leave as much as possible of carbon fossil fuels in the ground in order to minimize CO₂ emissions.

We have chosen to assume that the rate of installation of new nuclear power plants can be increased at the rate of 20% per year, implying a doubling every 4 years, and that this rate of increase would be kept for about 16 years. After that the production rate would become constant. After 60 years we start to reduce the production rate and eventually we would stabilize it after 140 years, to a level that allows to maintain a small percentage of energy produced by nuclear power to meet the requirements of special situations.

We have chosen to assume that the production rate of solar power would increase initially at the rate of 25% per year, implying a doubling about every three years. The rate would then be stabilized after about 30 years.

This would lead to the production rates for oil, gas, and coal shown in Figs 2.15, 2.16 and 2.17. Notice that in all case a substantial portion of the current reserves would be left into the ground, for potentially different uses.

Fig. 2.18 shows the rate of production of biofuels for air transportation. In our assumptions we have allowed the transition to bio-jet-fuel to start after 20 years and become total in about 50 years.

Fig. 2.19 shows the amount of nuclear power. The total installed nuclear power would reach a maximum of about 240 HJ/year in about 60 years, and then would decrease toward an equilibrium value of about 30 HJ/year. This would allow for the use of nuclear power where is more appropriate than solar power, at least for a couple thousand years.

Finally Fig. 2.20 shows both the nuclear and solar productions that would be realized under the above assumptions. Quite clearly nuclear power would only play a marginal role, but it would be useful in the early stages. After about 30 years solar power would provide essentially all of the required power. In our assumptions *surface* transportation would be handled by hydrogen fuel. Therefore the power requirements shown above include the electricity required for the production of hydrogen.

Both solar power and biofuels require land. The overall land requirements are shown in Fig. 2.21.

The total requirement of over 10 billion hectares is unlikely to be achievable, since it represents about 70% of the entire earth land surface. While the land requirements for solar power can be met on any ground area, as long as the irradiation is adequate, the agricultural and biofuels requirements must be met by agriculturally viable land. It is unlikely that we can increase the current amount of such land, from 5 to 9 billion hectares.

2.3.5 The CO₂ Emissions Problem

Since the invention of fire humans have been adding CO₂ to the atmosphere, through the burning of wood, coal, oil and other fossil fuels (in addition to the amount they exhale, but that is only about 4% of the current level of emission). What happens to the CO₂ that is added is not completely clear. Some is absorbed by vegetation (some of which is then returned to the atmosphere, by forest fires or wood decomposition), some is absorbed by the oceans and, of course, some is left in the atmosphere. It is estimated that in the last century alone the percentage of CO₂ in the atmosphere has grown from around 280 parts per million to around 380 parts per million. A simple model of the CO₂ flow that is in very good agreement with past observations is discussed in the Methodology section and will be used for our projections.

There is some consensus that in the last century the average temperature of Earth has been increasing. There is some consensus that at least part of that increase may be the result of the increase in atmospheric CO₂. As a result, there is some pressure toward reducing the level of CO₂ emissions.

The three major components of CO₂ emissions are the burning of oil, natural gas and coal. The contribution of each fuel, relative to its energy contribution, is given below (where “Mt” stands for “Million of metric tons of CO₂”):

Oil	59 Mt/HJ
Gas	48 Mt/HJ
Coal	87 Mt/HJ

Fig. 2.22 shows the situation for the reference case, under our previously described scenario. Note that the maximum rate of emissions occurs at around the year 2030 and that after that the rate decreases rapidly, becoming negligible by about year 2050.

There are two keys to the reduction in CO₂ emissions.

The first factor is the decrease of energy used per unit of GDP. We have already assumed what we believe to be an aggressive rate of reduction in that factor, and the results are already included in Fig. 2.22.

The second factor is the reduction of the rate of CO₂ emissions per unit of consumed energy. That can be accomplished in two ways, namely;

1. By shifting to less CO₂ intensive forms of energy production;
2. By reducing the actual rate of CO₂ dispersed in the atmosphere due to the burning of fossil fuels.

The only reasonable alternative for the first choice is to switch to other forms of energy as we have already outlined.

The second objective can be achieved through the process of **CO₂ sequestration**. This consists on capturing most of the CO₂ produced in the burning of fossil fuels and transforming it in either liquid CO₂ or in solid carbonates. The resulting products would then be stored somewhere (and hopefully never released!!). The technology is being investigated in a few pilot projects and it is not fully developed, but it appears to be quite promising. This procedure can only be applied to industrial level energy installations, not to fuels used in transportation or in household heating. We will assume that the percentage of “sequesterable” CO₂ is about 70 % of the total produced. We will also assume that such rate can be reached over a period of about 50 years.

The results are shown in Fig. 2.23. Under the above assumptions the emission rate will peak around the year 2020 and then would start decreasing. However, the overall difference is not very significant, because by the time sequestration becomes widespread our strategy has already reduced the emissions considerably.

In Fig. 2.24 we show the estimated effects of CO₂ emissions on the CO₂ concentration in the atmosphere. From the current value of about 380 ppm we would reach a maximum of about 470 ppm without sequestration and of about 445 ppm with sequestration. In both case the concentration would decline toward a postulated equilibrium value of less than 300 ppm after about 200 years.

As we will discuss a little later, there is no realistic way to accelerate the transition to CO₂ free energy sources in such a way as to diminish the rate of CO₂ production below

the one projected in Fig. 2.24. Sequestration appears to be the only avenue to decrease the effects on the atmosphere, to the modest extent shown.

In Fig. 2.25 we show the difference in CO₂ concentration achieved by the reference case just discussed and the business-as-usual case discussed earlier.

The aggressive shift to nuclear power and solar power in the reference case provides a considerable improvement in the CO₂ concentration with respect to the business-as-usual case.

2.4 Conclusions

Is a population of 9 billion people “sustainable”? Clearly there is a level of standard of living at which it is possible. It is questionable that sustainability can be achieved at the level of standard of living that we have hypothesized in our analysis, as being obtainable **in the absence of resource constraints**. The land areas that would have to be dedicated to additional food production, solar energy and biofuels production are so large as to be difficult to achieve. Furthermore the issue of phosphate production would need to find a solution.

An additional problem is that there would be considerable difference between the MDCs and the LDCs. Since we have hypothesized that the MDCs pro capite food requirements would not change and since their total population also would remain approximately constant, their land requirement for food would actually decrease due to the assumed additional productivity. It turns out that the freed up land is just about enough to supply their requirements of air transportation biofuels. They would have “only” to find additional land for the solar power installations. That would be for the USA an area a little less than the total of Arizona and New Mexico, while for the other MDCs would be an area approximately equal to the area of Spain and Ukraine. Not easy, but maybe not absurd.

The problem for the LDCs would be staggering. They currently have about 3.8 billion hectares under cultivation. They would have to increase the cultivated land (for both food and air transportation biofuels) to over 8 billion hectares, i.e. they would have to more than double the area. In addition they would have to find more than another 1 billion hectares for solar power production.

India’s own total requirements for example would be a little less than 1.4 billion hectares, which is more than 4 times its total land area! Of course, they could import the food, fuel and energy from abroad, but it is unlikely that such an option would be feasible on such a scale.

In our opinion a stable population of 9 billion people is not sustainable.

It is almost certain that some form of “natural” reduction will occur, but at what rate nobody can realistically predict.

3. The Proposal Case

Let's now consider the effects of our proposed reduction in population to 1 Billion humans.

When thinking about reducing the population of Earth, one might think about wars, famine or pestilence. Apart from the fact that such occurrences have not been very effective on their own, it is doubtful that we could achieve agreement on using them to reduce population. It would appear that the only means is through some form of reduction in births, leaving the natural occurrence of deaths to take care of the problem.

Our original thinking was that the simplest and most effective way would be to require that every woman would be sterilized after the first child. This would be a simple rule to enforce and it would guarantee that the ethnic mix of the population would remain constant. The equilibrium fertility rate is about 2.1 child/woman. By cutting the number of births to 1 child/woman we would accomplish a considerably fast rate of population reduction. In order to achieve the goal of reducing the population to 1 billion the strategy would have to be maintained for about 60 years. After that, we would have to return to the equilibrium rate of 2.1 child/woman.

However, we realize that the probability to achieve worldwide consensus on such a strategy is essentially nil.

We propose therefore that we would work toward a more gradual reduction in average fertility. The current trends, which we have incorporated in our reference case, imply that the LDCs will decrease their birth rate to approximate equilibrium in about 100 years. At the same time the other MDCs will slowly increase their rate toward equilibrium. The USA will be almost in equilibrium, on the basis of *intrinsic* birth rate, but would be growing because of immigration. We propose that we "convince" the world to move toward the pattern of fertility rate shown in Fig. 3.1.

It should be noted that after the initial convergence of the three curves, they would follow the same pattern, therefore approximately maintaining the same ethnic balance as it existed at the moment of convergence (i.e. by the year 2080) This would lead to the population evolution shown in Fig. 3.2.

It would take about 300 years to achieve the new equilibrium. The difference between the reference and the proposal case is shown in Fig. 3.3.

3.1 Economic Implications

Under similar assumptions as the ones we have used for the reference case, the GDP projection for the proposal case is shown in Fig. 3.4.

Note that the GDP peaks around the years 2150 and then slowly decreases until it stabilizes around the year 2800. This is due to the fact that in the late 2100s the rate of decrease in population exceeds the rate of increase in the pro-capite GDP.

In fig. 3.5 we show the difference between the total GDP in the reference and proposal cases. Notice that for the first 60 years there is no appreciable difference. The difference starts around the year 2100 and then becomes quickly significant. In the long run the proposal case total GDP is only about one sixth of the total GDP for the reference case. It is worth noting that the use of most natural resources would be proportional to the GDP. Therefore all such uses would be about one sixth of the reference case.

Fig. 3.6 shows the **pro-capite consumption**. There are two interesting implications. First, the pro capite consumption grows to a value quite a bit higher than the one achieved in the reference case. Second, the values for the USA, MDCs and LDCs become practically identical very quickly.

This is shown in more detail in Fig.3.7 in which we compare the pro capite consumption of the USA in the reference and proposal cases, and in Fig. 3.8 where we compare the ratio of the pro capite consumption of the LDCs to the USA, in both the reference and proposal cases.

The key issue is that the values of all three groups converge quickly. We believe that this is an important issue. It is reasonable to expect that world tensions would be eased in the presence of more uniform standard of living across the world.

3.2 The Food Implications

In the proposal case there is obviously no problem with the food supply. It is however important to estimate the total requirement of agricultural land. Using the same assumptions as in the reference case, there will be an ultimate need of only 0.7 billion hectares. This would leave about 4.3 billion hectares of the current 5 billion hectares of agricultural land available for other uses.

3.3 The Energy Demand Implications

Fig. 3.9 provides the estimate for the energy requirements in the proposal case. In Fig. 3.10 we show the difference for the total energy requirement between the reference and the proposal cases.

It is interesting to note that for the first 60 years there is no noticeable difference. This is because, as we have already noted earlier, there is no appreciable difference in the total GDP in the two cases. The difference start showing around the 70th year and obviously increases from then on. By the year 2130 the proposal case reaches a level that is approximately five times the value at the beginning of the exercise and then decreases

slowly until the year 2230, when it stabilizes around a level which is about one sixth of the corresponding one for the reference case.

Figs 3.11 and 3.12 show the demand for the air and ground transportation and for the total electricity demands.

3.3.1 An Overall Scenario

There is very little difference in the first 100 years between the reference and proposal cases. Therefore the overall implications for the carbon fossil fuels and the associated CO₂ emissions are about the same in both cases.

The situations for biofuels for air transportation, for nuclear power and for solar power are shown Figs 3.13, 3.14 and 3.15. The overall implications of the difference between the reference and the proposal cases may be best appreciated by looking at the land requirements for the proposal case, as shown in Fig. 3.16.

From the current value of 5 billion hectares the requirement would decrease to about 1.3 billion hectares. The freed up land could be used for other purposes, like reforestation. A very interesting implication is shown in Fig. 3.17 that gives the expected requirements for phosphate.

In the proposal case the phosphate reserves would last for another 1000 years beyond the year 3000.

3.4 Other Issues

While the reduction in population will lead to a much higher standard of living for everybody, the transition will not be completely painless. We will examine some of the issues.

3.4.1 Migration

Today the USA population is growing about 1% per year, of which 0.7% is due to migration, primarily from Mexico. Europe is also accepting some migration from Africa and the Middle Est. According to our proposal the populations of both the USA and the other MDCs would decrease by about a factor of 7. However, the MDCs already have a high quality infrastructure, appropriate for the current levels of population. As populations would dwindle, a considerable portion of that infrastructure would be “wasted”, because there is no need for it. On the other hand, in the LDCs, even with a reducing population, the infrastructure, particularly in the early phases, would still below par. The natural solution would be for people from the LDCs to migrate to the MDCs in increasing numbers. The obvious choices would be for people from Latin America to migrate toward the USA and Canada, while people from Africa might migrate toward

Europe. People from the poorest regions of Asia could go either way or even toward Australia and New Zealand. One might venture the guess that the population of the MDC's might actually decrease only by a factor of three, arriving at a population which is about double the one hypothesized in our Fig. 3.2.

The suggested migration would change the USA and Canada to countries with a majority of catholic, Spanish/Portuguese speaking people. Europe would acquire a brown/black majority with Islamic or African native religion background. This would lead to substantial political, ethnical and cultural problems.

3.4.2 Age distribution

One issue which is often mentioned as a problem when populations are decreasing is that a smaller number of workers will be unable to support an increasingly aging population. The key variable is the ratio of total population to workers. This measures how many people (including itself) each worker must support. Currently that ratio is about 2 for the USA, 2.6 for other MDCs and 2.7 for the LDCs. This is mainly because the USA has the highest level of workers among the people of working age. We have assumed that over the years the ratios would converge.

Fig. 3.18 shows the evolution of the ratios for the USA, other MDCs and LDCs in the reference case.

Fig. 3.19 shows the evolution in the proposal case. In the beginning all ratios would be somewhat lower, because of the lower number of children. After about 100 years the ratios would start increasing to values in the 2.3 to 2.5 range. This is lower than today for the MDCs and the LDCs and only slightly higher for the USA.

Let's look at the situation in more detail for the USA. There are three groups of non-working people that must be supported by the working people, namely:

- The youth (people between 0 and 18)
- The non-working adults (people between 18 and 65 who are not working)
- The seniors (people over 65)

Fig. 3.20 shows the relative percentage of the three groups for the proposal case. From the year 2007 to the year 2150 there is a strong decline in the percentage of youth, while there is an increase in the percentage of seniors. However, the overall total changes very little.

It should be noted that the cost of supporting a youth is comparable to the one of supporting a senior. In addition to the average consumption, a youth require additional cost for its *education*, while a senior require additional *health care* costs. It turns out that the two components are about equal (in the USA).

The effect on the pro- capite consumption has been already taken into account in the data of Fig. 3.6, showing no appreciable effect. There are two reasons for that. The first is that the rate of increase of the dependent ratio is considerably lower than the rate of increase of pro capite GDP, with the net effect being just a slower growth in pro capite consumption over what would have happened otherwise. The second is that, as discussed in detail in the methodology section, a *decrease in the number of workers* implies an increase in the amount of assets per worker and therefore *implies an increase in the productivity of each worker*.

However, there will be a problem in the nature of the type of employment due to the change in age distribution, as we will discuss below.

3.4.3 Teachers

The group of people most directly affected by the reduction in birth rate is obviously the school teachers. The need for them will start to reduce right away and will keep reducing for some time.

We have analyzed in some detail the situation for the USA. With the exception of two short periods, the situation can be handled by just hiring fewer teachers. Only for two short periods one would have to actually make redundant a few teachers.

The situation for the other MDCs would be similar. For the LDCs the problem would be different, since there is already a scarcity of teachers in many areas.

3.4.4 Health Workers

There is an opposite problem for the health workers (i.e. doctors, nurses, medical technicians, etc.). The reason is the overabundance of seniors during the transitional years to the new equilibrium. It is normally estimated that in the USA seniors require health services at a rate approximately three times higher than non-seniors. This will require a higher percentage of job market entrants to go into the health field for a number of years. For the USA that would be from about 10% (which is the norm) to about 16%. This would appear to be manageable.

3.4.5 Housing

A reduction in population by a factor of almost 7 implies a similar reduction in the housing requirement and consequently a major restructuring of the towns. The reduction in population is accompanied by an increase in the average standard of living. This would imply that the lower quality housing would be abandoned while people move in redundant, higher income housing. However, the problem would be with the change in size of the towns. A reduction of a factor of 7 in housing needs would translate in a reduction of about a factor of 2.5 in the average diameter of a town (assuming unchanged

housing density). It is difficult to predict if people would choose to decrease the density and live further away from the downtown area or abandon the more distant suburbs.

The rate of population reduction would be around 1.5% per year, while the normal rate of housing obsolescence may be only 0.5% per year. This implies that the construction industry would have to become in part a *destruction* industry. This could be alleviated in the USA and MDCs if there is a significant increase in immigration to take advantage of the existing infrastructure of the more industrialized countries.

3.4.6 The role of governments

During the transition to the new equilibrium, there would be considerable demographic and economic dislocations. It is unlikely that “natural market forces” would provide for a smooth handling of the situations. Almost certainly there would be a need for a stronger government role in advance planning and in providing the necessary “safety nets” to maintain an orderly transition. The ability of governments to actually do the right things is probably questionable. The political repercussions might not be pleasant.

3.5 Summary

It is extremely unlikely that the food and energy requirements of the *reference case* can be met as originally described. The lack of availability of energy will become a limiting factor on the total GDP growth, after the 50th year or thereabout. How the limitations on the total GDP will be reflected on the limitations for the various countries and regions is extremely difficult to forecast.

On the other hand, the requirements of the *proposal case* appear to be reasonably manageable. There are problems during the transition period, but they appear to be manageable. After a somewhat disrupting transition period, we would however reach a very sustainable situation, at a *high* and *homogenous* standard of living.

4. Review and Conclusions

We have analyzed two scenarios associated with the possible evolutions of the earth population. We have had the arrogance of making projections for up to 1000 years. I hope the reader appreciates that we do not really believe that things would evolve exactly along the predicted lines. Our intent was to follow certain assumptions to the logical conclusions. Many things may occur in a thousand years that we cannot fathom at this time. If we look back at a thousand years ago we can certainly see that no one then could have predicted the current state of world affairs.

On the other hand there are things that we believe we know about the future.

We believe that the total land area of the earth will not change appreciably. Even in the presence of a total meltdown of the Antarctica and Greenland ice sheets, with a concomitant sea rise of about 60-70 meters, the total land area will only change by a few percentage points.

We believe that the solar irradiation is not likely to change much.

We believe that while some surprising discoveries of oil, gas, coal and uranium deposits might occur, that would only delay the time of their ultimate exhaustion by a few decades or possibly a century or two, but will not change the fundamental issue.

We believe that we know the process of photosynthesis well enough that it is unlikely that the ability of vegetation to capture CO₂ and transforming it in usable carbon based fuel can be improved by a considerable amount.

One thing we do NOT know and that is the potential for future availability of **fusion** nuclear power. The probability of fusion nuclear power providing energy on an industrial scale before the year 2050 is extremely low. However, what may develop beyond that date is highly conjectural.

In constructing our analysis we have had to make a number of assumptions. We have attempted to choose those assumptions on what we believe to be a “middle ground” basis, but that could be challenged.

The most fundamental assumptions have to do with the expected growth of the GDP. The aggregate numbers may appear to be staggering. However, the projected rate of increase is comparable to what the world has experienced in the last 50 years. The problem has to do with the availability of natural resources. We have discussed the energy and land problems in some detail, but we have not investigated other possible “show stoppers”. If other resources should represent a stronger limit, the problems with energy and land may recede in importance.

One important assumption that is common to the cases we have investigated is the rate of energy consumption per dollar of GDP. Our choice has been “moderately aggressive”, i.e. we have assumed a reduction from the current level of 7 MJoule/\$ down to 3.5 MJoule/\$. This may appear too conservative to some people. However, there are many factors to take into account. For example, the only way to reduce the energy used for heating is by reducing the actual *heating output*; there is very little room for efficiency improvements. While we can improve the efficiency of *present* electric power using devices, that may be compensated by our using bigger devices (like bigger TVs) and newer devices yet to be developed.

One major problem that has appeared in our analysis is the one of air transportation. We have no realistic alternatives to jet fuel (or something like it) for the foreseeable future. The production of a jet-fuel-like product appears to have substantial implications on land usage. For the “reference case” the numbers appear to be somewhat overwhelming. It would appear that one would have to lower significantly the ratio of air transportation energy use to GDP. It may mean a shift to more high speed land based transportation, at least for intracontinental transportation. The advantage of ground transportation is that electricity can be used as the energy source. The problem is not as significant *in the long run* for the cases of reduced population.

The use of biofuels (particularly corn ethanol) for ground transportation appears to be untenable. This means that we must shift our land transportation technology to one based on electricity. There are two primary options:

1. Use battery operated vehicles; this has the advantage of higher energy efficiency (probably about 50%), but the cost of batteries is extremely high at this time.
2. Use hydrogen as an energy storage medium, with vehicles using fuel cells (with an overall energy efficiency of about 20%) or hydrogen combustion engines (with an overall energy efficiency of probably about 15%).

We believe that the only viable solution is a transition to a hydrogen based infrastructure and to hydrogen combustion engines, because of the problems associated with the transition away from fossil fuels.

The sustainability of a 9 billion humans population at a high level of standard of living is extremely doubtful. It is likely that after reaching the level of 9 billion humans the population may naturally decrease. However, it is unlikely that such decrease will occur at a fast enough rate as to avoid major economic dislocations. It would appear that some form of governmental pressure would have to be exercised to engender a faster reduction rate that would occur otherwise.

If the ultimate target should be one billion humans, as we suggest, or a somewhat higher value will always be open to debate.

5. Methodology

5.1 Population

In order to estimate the evolution on the populations of the three groups that we divided the world in, namely the USA, the other MDCs and the LDCs, we need three major pieces of information about each:

1. The distribution of each population by age at beginning (separately for males and females)
2. The expected fertility of females, by age and time
3. The death rate, by age and time (separately for males and females)

We have detailed data for the USA. For the other MDCs and LDCs it would have been extremely difficult to collect equivalent data. However, we do have some overall data, like the average age today, the overall fertility rate and the life expectancy for many of the countries involved.

We chose to take the USA data as point of departure and then “reasonably” modify the data in order to match the known parameters for the other MDCs and for the LDCs. This is not a very satisfactory approach, but we hope that it did not introduce major distortions.

A problem with the USA data is that the actual age distribution today bears little resemblance to what that distribution should be under equilibrium conditions, given the current values of death rates, as shown in Fig. 5.1.

The primary reason for the discrepancy is the “baby boom” of the post-World-War-II period (and the associated secondary “baby boom”). Another reason is that the age distribution of immigrants does not match the expected equilibrium one. However, when we project the changes in population *according to the current assumed fertility and death rates*, the future distribution converges to the expected equilibrium one relatively quickly. For example, for the USA after 50 years the distribution looks as in Fig. 5.2.

Therefore we assume that any initial discrepancies would be quickly absorbed in the future projections.

5.2 GDP

The GDP is the result of two primary factors, namely the number of workers and the value of the assets available for production. In order to estimate the GDP for future years we need to formulate assumptions about four factors, namely

1. The relation between GDP and the current values of the number of workers and of the value of production assets;
2. The change in the number of workers;
3. The rate of production asset loss;
4. The rate of investment in new production assets.

Estimates about each of these factors involve a number of assumptions. It is therefore possible to create a large number of plausible scenarios.

We make two fundamental assumptions, namely:

1. In the long run the USA, the other MDCs and the LDCs will converge toward a common economic framework;
2. Such common framework will be along the lines of the natural evolution of the USA framework.

While the first assumption is reasonably defensible, the second one is somewhat less so, but it appears to us to be the “simplest” assumption.

We will now discuss our assumptions regarding the four factors listed above.

5.2.1 GDP vs. number of workers and value of production assets

In a previous study on the history of the US economy (“The US Economy from 1950 to 2008, History and Analysis”, by Cesare A. Galtieri) we found an interesting relationship between the **productivity**, i.e. the **GDP/year/worker** and the **production assets/worker**. It is shown in Fig. 5.3, expressed in constant 2007 US dollars.

The linear fit shown on the graph corresponds to the equation

$$\mathbf{GDP/worker = 19,300 + 0.322*assets/worker}$$

which can be recast as

$$\mathbf{GDP = 19,300*workers + 0.322*assets}$$

It might be tempting to assume that the above relationship would continue to apply to the USA. Unfortunately that is unrealistic, since it would lead to future GDP values that are so high as to be not credible. It would appear reasonable to assume that the contribution of assets to productivity (per unit of assets) would decrease with the increasing value of the assets. We will assume in fact the following form of the relationship:

$$\mathbf{GDP/worker = A + B*(1-exp(-assets/worker/C))}$$

For the USA the constants A is set to 19,300, as suggested by the above referenced analysis. The constant C is set, somewhat arbitrarily, at 3000. The constant B is then

adjusted to match the actual data for 2007. We assume that the same constants apply to the other MDCs. On that basis we can use the formula to estimate the current value of the production assets, since we know the number of workers.

We cannot use the same approach for the LDCs because it leads to an unacceptably low value for the production assets. We must assume that the “constant” A has currently a lower value and that it will grow to the same value of the USA over time. Similarly, it would appear that we must choose a lower value for the current value of the constant C. The resulting assumption is of the form:

$$\text{GDP/worker} = (A0 + A1*(1-\exp(-(\text{year}-2007)/t1))) + B0*(1-\exp(\text{assets/worker}/(C0+C1*(1-\exp(-(\text{year}-2007)/t2))))))$$

with the constant values given below:

$$A0 = 10,000, A1=9,300, t1=25, C0=2000, C1=1000, t2=25$$

and the constant B0 adjusted to match current values.

5.2.2 Number of workers

The number of workers is determined by two factors, namely:

1. the number of people of **working age**;
2. the percentage of working age people actually working.

These two factors are different for each of the three groups we are dealing with, i.e. the USA, the other MDCs and the LDCs. Furthermore the two factors are different for men and women. From the demographic data for the three groups we can determine the first factor for both men and women, once we select a definition of “working age”. In the past it was common to use the range of 14-65 years old. This was reasonable when a large fraction of the people were involved in agriculture. Today in the USA and other MDCs few people start working before they are 18 years old and because of improving life expectancy many people keep working beyond the “classical’ retirement age of 65. The situation is somewhat different in the LDCs, but it is reasonable to assume that over time the situation will become similar.

There are considerable differences among the three groups regarding the percentages of working age people actually working. The USA have the highest percentages, for both men and women, with the LDCs having the lowest percentages. We have assumed also in this case that the percentages of all three groups will converge and will converge toward the current values for the USA.

5.2.3 Assets Loss

During production of the GDP sole assets are “used up”. This asset loss is due to two distinct factors, namely the *time factor* (i.e. senescence or obsolescence) and the *use factor* (i.e. wear and tear). How much is due to each is not easily ascertained. We have assumed that about 2/3 of the observed rate of asset loss is due to the time factor and 1/3 to the use factor. Our estimate is that about 2% of the value of all assets is lost due to the time factor and that about 3% of the value of GDP is represented by the assets use factor.

5.2.4 Investment Rate

Most of the GDP goes to personal consumption. However, a considerable amount must go to compensate for the asset loss discussed above and (if possible) to the addition of new assets in order to increase the future values of GDP. The *gross* rate of investment for the USA is currently about 17% of GDP. We have assumed that about the same percentage applies to the other MDCs. The rate for the LDC is higher, being probably between 20% and 25%. We have assumed that over time such rates will decrease and all converge to about 12%. The reason is that otherwise the increase in GDP would appear to be not credible.

How realistic is this methodology? We believe that the general assumption about the relationship of the GDP and the assets is very realistic. The question is the choice of the values of the coefficients. It would appear that our choice gives estimates that are very much in agreement with other “official” estimates for the first 25-50 years. Beyond that we have no data with which to make comparisons. While it is unlikely that the future will evolve exactly along the lines projected, we believe that the general pattern is realistic. In actual reality things may occur a little faster or a little slower than we project, but the general pattern of the predicted trends should apply.

5.3 Energy

As we stated earlier we will measure the energy from all sources in Hexajoules. The conversion ratios for the other commonly used units are (approximately) as follows:

1 QBTU (Quadrillion British Thermal Unit)	= 1.05	HJ
1 BKWH (Billion Kilowatt Hour)	= 0.0036	HJ
1 BBl (1 Billion barrel (oil))	= 5.8	HJ
1 Tcm (Trillion cubic meter (gas))	= 38.4	HJ
1 Bst (1 Billion short tons (coal))	= 21	HJ

However, just adding up the energy used from the various sources may be misleading. To explain the problem, consider the case of the energy used in ground transportation. Today almost all of such energy is used in the form of gasoline or diesel, which are themselves derived from fossil oil. For each joule of oil energy expended, only about 0.25 joule reach the wheels of the vehicle. It is reasonable to expect that improvements in combustion

engine design and the expanding use of hybrid technologies will improve that ratio to about 0.33.

In the long run, all fossil fuels will be exhausted and the energy needed to move the automobiles and trucks will have to come from some other source. If the source is one or another form of biofuels (ethanol, biodiesel, etc.), the relationship between “production” level energy and “use” level energy will be approximately the same, so there is no issue. However, if instead there is a change to electric vehicles, the situation would be quite different. For each joule of electricity produced at the power plant only about 0.9 joule will reach the user electric outlet. The batteries used in the vehicles will have probably an efficiency of about 80%. The transfer of energy from the batteries, through the electric motor to the wheels may have an efficiency of 80% to 90%. In aggregate, for every joule produced at the power plant about 0.5 to 0.6 joules will reach the wheels of the vehicle. This is considerably better than carbon fuels.

Another option is to use electric energy to produce hydrogen and then use hydrogen to power vehicles, possibly through hydrogen fuel cells. In that case the expected overall efficiency will be about 25%, due to a 50% loss in the production of hydrogen and another 50% loss for the efficiency of fuel cells.

Another example has to do with electricity. We can measure the consumption at the “electrical outlet”, at the power plant output or at the power plant input, i.e. to the level of “fuel” used for the production of electricity. As mentioned above, there is an approximate 10% loss in the transmission of electricity from power plant to outlet. If a carbon fossil fuel is used for the production of electricity, only about 30% of the fuel energy content will be available as electricity output at the power plant.

In order to project future energy requirements we need therefore to separate the evolution of **energy use** from the evolution of **usable energy production**. To do so in truly accurate way is beyond the scope of this study. However, we will distinguish a few situations that are most important.

Most important is however the fact that the consumption of energy in a community is tightly related to the GDP of that community. However, the ratio of energy consumption (in joules) to the GDP (in constant dollars) varies somewhat from community to community and changes with time. Following are some examples (in constant 2007 dollars):

	1980	2006
USA	11.9	7.0 MJoule/\$
France	6.5	5.1 MJoule/\$
China	29.2	10.8 MJoule/\$

The numbers for China are patently absurd and demonstrate the well known fact that “official” GDP estimates for less developed countries are gross underestimates of the

“real” value of economic activity. However, as time goes by and the LDCs become more and more industrialized, the GDP estimates will become more meaningful.

The current world average energy/GDP ratio is 7.0 MJoule/\$.

5.3.1 Transportation

We have to distinguish between **air transportation** and **surface transportation**.

For air transportation there is no realistic substitute for jet fuel except another fuel with similar energy/weight characteristics. One current proposal, as discussed earlier, is to use a fuel developed from the jathropa plant. We assume that the ratio of passenger-hours of flight to the value of GDP will not change, but that the efficiency of jets will improve, so that in the future only about 80% of current fuel requirements will be needed for the same air transportation load.

The *primary* energy used for surface transportation will change, from carbon fossil fuels to either biofuels or nuclear or solar produced electricity. The change to biofuels is untenable.

We assume that the amount of driving that will be done by people, both for personal and business reasons, will maintain the same relationship to GDP as of today. Therefore the energy used by vehicles, *at the wheel*, can only decrease if the vehicles average weight changes or if the vehicles will drive more slowly. We have chosen to assume, somewhat optimistically, that the ratio to GDP will decrease to about 80% of what it is today. The amount of electricity to be used to provide energy to the wheels will depend on the choice of technology.

5.3.2 Electricity

The production of electricity from carbon fossil fuels will disappear in about 100 years or so. The only realistic primary energy sources for electricity are going to be nuclear and solar power.

Nuclear power plants capacity is sometimes expressed in term of the *thermal* capacity and sometimes in term of their *electrical* capacity. The ratio appears to be that electrical capacity is about 35% of thermal capacity. That ratio is not likely to change much.

The efficiency of solar cells is likely to improve, but not by a major factor. We have chosen to assume a constant efficiency, which may be somewhat pessimistic.

The rate of **use** of electricity *relative to GDP* will depend on two contradictory changes:

1. The efficiency of **current** devices using electricity is likely to improve;
2. There are going to be **new** devices that will use electricity.

How the two will balance is hard to prognosticate. We have chosen to assume that the rate will improve by about 50% over the years.

5.3.3 Heating/Industrial

The remainder of energy production is used for space heating and a number of industrial direct uses of fuels. In the absence of any specific analysis we have chosen to assume that the rate of use of such energy will also decrease to 60% of current value (relative to GDP). Admittedly, this is a just an arbitrary guess.

5.4 CO2 Concentration

One of the current concerns is the increase of the atmospheric concentration of CO₂. The current methodology uses the measurement on the Mauna Kea volcano on the island of Hawaii as the reference standard. The average midyear data is shown in Fig. 5.4.

The increasing concentration is presumed to be due to the continuous addition of CO₂ to the atmosphere by human activities, of which the burning of carbon fossil fuels is the most important one. Not all of the CO₂ added by human activities actually stays in the atmosphere. A certain portion is absorbed by both the land and the oceans. In addition, some CO₂ is actually added to the atmosphere by land and ocean emissions. The estimate of the amount of CO₂ added by human activities is shown in Fig. 5.5, together with the amount of actual atmosphere increase. The unit of measurement is the **Petagram of Carbon (PgC)**, i.e. 10¹⁵ grams of carbon.

A simplistic model of the relation between CO₂ addition and CO₂ concentration is of the form:

$$C(t+1) = \alpha * C(t) + 0.47 * (E + H(t))$$

Where C(t) is the concentration at time t, E is the addition from land and ocean (which we assume to be a constant) and H(t) is amount added by human activities at time t. The best fit with the experimental data is obtained with

$$\begin{aligned} \alpha &= 0.981 \\ E &= 10 \end{aligned}$$

The comparison between the actual CO₂ concentration and the estimated one according to the model is shown in Fig. 5.6, showing a quite good agreement.

Fig. 5.7 shows the corresponding actual and estimated values for the net uptake of ocean and land, showing a good **average** agreement.

We will use the given model to make our predictions for future CO₂ atmospheric concentration.