Just Too Many People: Towards a Sustainable Future Earth

Alan M. Kadin
Princeton Junction, NJ, USA
amkadin@alumni.princeton.edu
Feb. 2014

Abstract
Our modern civilization is built on cheap energy from fossil fuels, which produces carbon dioxide, which produces global warming. The only way to avoid catastrophe is to shift away from fossil fuels to solar and nuclear energy, well before all fossil fuel reserves have been burned. But this transition cannot be achieved with a projected global population of 10 billion (10B); we need to return to a level of 100 to 200 years ago, when the population was ~1-2B. A peaceful transition is possible only if humanity collectively takes ownership of the problem.

I. Introduction to Global Population

The global population has been increasing exponentially for centuries, as is evident in the semi-log plot shown in Figure 1. It first passed one billion (1B) in 1804, 2B in 1927, and is presently more than 7B. The growth rate reached a maximum around 1960 (~ 2 % per year), and the rate since decreased to about 1.1% per year, but the population is still increasing toward about 10B in 2050. I argue that a population of 10B is not sustainable in the long run, and that we need to return toward a population ~1B. Only at this reduced level can we expect to maintain a reasonable standard of living within a stable environment, based on solar and nuclear energy sources.

The solid line in Fig. 1 (up to 2000) is a fit to a phenomenological equation given by Sergei Kapitza (1996):

$$P(t) = 4.43 \arctan[\frac{42}{2007-t}], \quad (1)$$

where P is the global population in billions, and t is the date in years. This clearly doesn't work for the future (it goes negative), but it is remarkably accurate retrospectively. Estimates for the future come from Wikipedia (http://en.wikipedia.org/wiki/World_population).

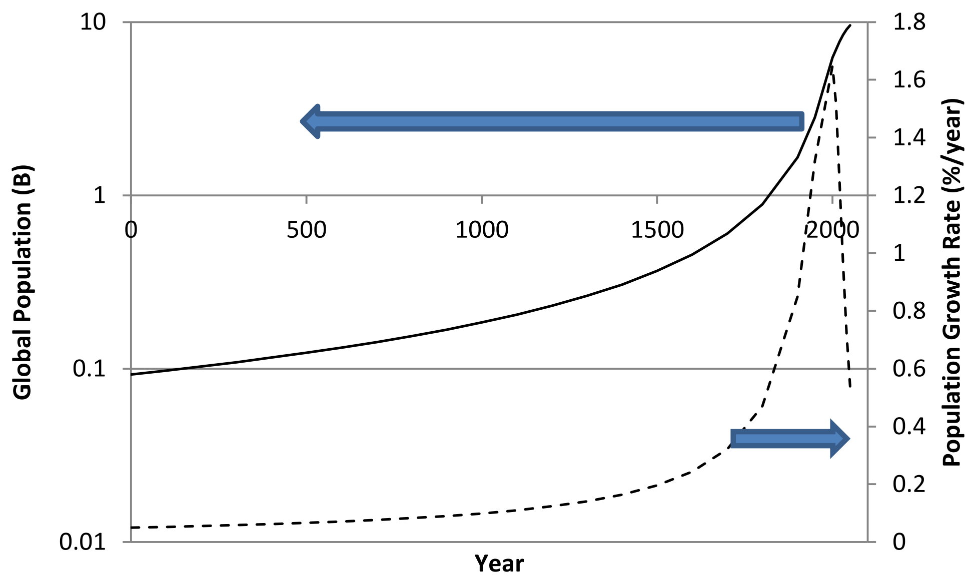

Fig. 1. Estimated global population over the past 2000 years, on a semi-logarithmic plot to emphasize the exponential growth. Also shown is the population growth rate (dashed line).

Concerns about global overpopulation are not new. Before the first billion, Thomas Robert Malthus (1798) published his classic essay, "An Essay on the Principle of Population", in which he warned that exponential growth will inevitably outpace fixed resources:

> *"The power of population is indefinitely greater than the power in the earth to produce subsistence for man. Population, when unchecked, increases in a geometrical ratio. Subsistence increases only in an arithmetical ratio. A slight acquaintance with numbers will shew the immensity of the first power in comparison of the second."*

Malthus predicted that global population would inevitably be limited by famine and epidemic disease, and that the majority of the world's people would therefore always be living a marginal existence. The Malthusian catastrophe has not come to pass, largely because of increased productivity and public health, as a consequence of modern science and technology. But can this really continue forever?

In the 20th century, the issue of overpopulation was publicized again by Stanford Biology Professor Paul Ehrlich (1968) in "The Population Bomb", in the context of environmental damage and food production:

> "*The battle to feed all of humanity is over. In the 1970s hundreds of millions of people will starve to death in spite of any crash programs embarked upon now."*

This disaster did not happen, either; agricultural productivity continued to improve dramatically throughout the world (the "Green Revolution").

Still, the arguments remain compelling; the question really becomes one of identifying a stable "carrying capacity" for the earth, and when it will be reached. More quantitative simulations of population and economic growth were first presented by a group of MIT researchers as "Limits to Growth" (Meadows, et al., 1972) under the sponsorship of the Club of Rome (http://www.ClubOfRome.org), a European-based group concerned with the global implications of population growth. These simulations predicted a collapse of global economies and populations in the next century, if trends were not changed.

A more recent element in global implications of human population is the development of detailed climate models of human-induced (anthropogenic) global warming (see http://en.wikipedia.org/wiki/Climate_change). The first analysis of global warming associated with an increase of CO_2 in the atmosphere was provided by the Swedish physical chemist Svante Arrhenius in 1896, and he later suggested that anthropogenic CO_2 from fossil fuels might make a significant impact upon global temperature. But this was not taken seriously until recent decades, when accurate global temperature data combined with computer models to show conclusively both that temperatures have been rising and that anthropogenic CO_2 is responsible for this. Recent reports of the Intergovernmental Panel on Climate Change (IPCC, http://www.ipcc.ch/) have summarized the growing scientific consensus. See Houghton, 2005, and Orbach, 2011, for recent reviews directed to physicists.

Other recent analyses have focused on upcoming global shortages of specific key resources, such as the petroleum that lubricates much of the world economy. Princeton Geology Professor Kenneth Deffeyes (see https://www.princeton.edu/hubbert/) has written several books on the topic of "Peak Oil", the theory that the easy oil has already been extracted from the ground, and that the future holds decreased production at sharply increased prices. While recent progress in hydraulic fracturing ("fracking") may have reduced these concerns, this reprieve is only temporary.

My view is that all of these problems – food production, energy resources, and global warming – become worse as the population increases, and conversely would be more manageable with a much smaller global population. Furthermore, the problem of a transition to a smaller population becomes more difficult the longer it is delayed, as critical resources become further depleted. I suggest an eventual sustainable global population of order 1B, but this value is difficult to determine accurately. Others have identified other values for the global carrying capacity, such as 2B (Pimentel, 1999). While a need for population reduction would seem to be obvious, some have denied that population is a problem at all, see, e.g., economist Julian Simon (1980).

II. A Simple Model for Global Population Dynamics

Let me get a bit more quantitative. As a physicist, I like to use simplified quantitative models with analytic solutions. So consider the following differential equation to describe population growth:

$$\frac{dP}{dt} = -\frac{P}{\tau} + \frac{fP}{2\tau}. \qquad (2)$$

Here P represents the world population, τ the mean lifetime, and f the average fertility rate. The first term on the right represents exponential decrease due to deaths; the second term represents exponential increase due to births. This model is obviously oversimplified, in that it has no population distribution, and assumes random death and reproduction. This might be more appropriate for a population of neutrons in a nuclear reactor, or maybe a population of bacteria. (This is *not* to suggest that human populations are like atomic bombs or disease infestations, but the mathematics are similar.) But let us consider its implications for population change.

Eq. (2) can be rewritten $\frac{dP}{dt} = \alpha P$, where $\alpha = \frac{f-2}{2\tau}$ is the exponential growth rate. The general solution is

$$P(t) = P(0)\exp[\int_0^t \alpha(t)dt] \approx P(0)\exp(\alpha t), \qquad (3)$$

where the latter form is for constant α. This yields a steady-state population with $\alpha=0$ if $f = 2$, i.e., an average fertility of two children per woman. This also leads to exponential growth if $f > 2$, and exponential reduction if $f < 2$. This shows why the semi-log plot in Fig. 1 is the natural form to display population growth; $\alpha(t)$ is simply the slope of the curve on this semi-log plot.

However, this also suggests that the growth rate will decrease if τ increases, which seems counterintuitive. Surely increasing the human lifespan would be expected to increase population growth; isn't this what happened in recent centuries? But Eq. (2) has only a single time scale, and increasing τ is equivalent to increasing the generation time, which would decrease the growth rate. What happened in recent centuries was mostly that the mortality rate went down among infants and children, due to reductions in infectious diseases. This increased the effective fertility rate by permitting these children to reach reproductive age, when they could have children themselves. So for this simplified model, one should regard f as the number of children surviving to adulthood. Increasing the lifespan of the elderly does increase the population somewhat, but it does not increase the exponential growth rate, since the elderly do not (typically) continue to have children.

With this understanding, a typical average fertility rate in the past century was about 4. This leads to $\frac{dP}{dt} = -\frac{P}{\tau} + \frac{2P}{\tau}$, which has a solution $P(t) = P(0)\exp\left(+\frac{t}{\tau}\right)$, as shown in Fig. 2. Let us assume that the mean lifetime is $\tau = 75$ years. Then the population will rise by a factor of $e = 2.7$ in 75 years, and will double in $75\ell n(2) = 52$

years. Taking the first term in the Taylor series, P will increase by a factor of $\frac{1}{75} = 1.3\%$ each year. (For comparison, the estimated global population growth rate was 1.9% in 1960 and is 1.1% today.)

In contrast, now take a fertility rate *f* = 1, corresponding essentially to the Chinese one-child policy, considered by many to be extreme. Eq. (2) then becomes $\frac{dP}{dt} = -\frac{P}{\tau} + \frac{P}{2\tau}$, with solution $P = P(0)\exp\left(-\frac{t}{2\tau}\right)$, also shown in Fig. 2. Taking the same τ = 75 years, this says that the population will fall by $\frac{1}{150} = 0.65\%$ per year. The time to reduce by a factor of two is 150 ℓn(2) = 104 years. This model suggests that a sudden decrease in the fertility rate (from, say, 4 to 1) would immediately start to reduce the population. This is obviously incorrect; the Chinese started their one-child policy in 1979, and their population is still increasing. This reflects the change in the population distribution, which requires ~ 50 years to reach a new steady-state distribution.

But let us say that by 2050, the population grows to ~ 10B, and the fertility rate suddenly decreases from ~ 3-4 down to 1. How long will it take for the population to decrease to 5B? Including this transient delay, about 155 years! How long to 1 B? 50 + 150 ℓn(10) = 395 years. The point of this analysis is that population decline is very slow, even making the extreme assumption of a one-child policy worldwide. If we assume that 10B people are not sustainable but 1B people are, there is a 400-year transition period. Are there sufficient resources to make this transition?

There are, of course, more rapid ways to decrease the population: mass starvation, epidemics of incurable diseases, and nuclear world wars. But international policies should work to avoid these terrible possibilities. The problem is that if severe shortages develop in essential key resources (energy supplies, food, strategic materials), or climate change leads to critical crop failures, that will tend to cause the international trading system to break down, leading to wars and other disasters. The only way to avoid these problems in the future is to recognize the central role of population, and to initiate an effort not only to decrease population *growth*, but to shrink the population itself on a global scale. This will be difficult, but the alternatives would be worse.

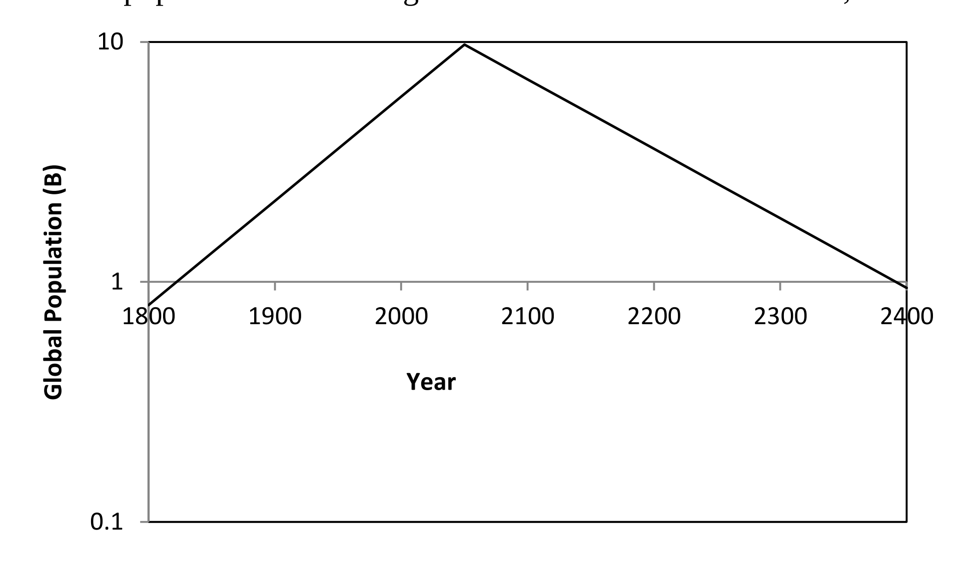

Fig. 2. Exponential growth and reduction of global population based on simple model in Eq. 2. The vertical axis is on a log scale, while the horizontal axis is in years, assuming a sudden change in fertility at the year 2050. The line on the left corresponds to growth with a fertility rate of 3.5; the line on the right corresponds to population decrease with a fertility rate of 1.

III. Myths about the Future of Global Population

1) World population is not a problem!

There is a widespread belief that only the rapid uncontrolled growth of population is a concern. And since the population growth rate has slowed in the developed countries, a trend that appears to be spreading to the developing world as well, this growth rate problem will solve itself. But the real problem is not only the growth rate; it is the population level itself.

There is even a belief (common among economists) that population growth is essential for economic growth, and that population decline must inevitably lead to reduced standards of living. But is there really evidence for that? Certainly there have been situations where a local economic collapse has led to population decrease (due in part to emigration), but that does not imply causality in the other direction.

Furthermore, exponential growth cannot occur forever in a world with finite resources. The only question is whether the current level is larger or smaller than the sustainable level. The analysis below suggests that we are already well above a sustainable level, which might be ~ 1B. The problem is not the living space needed for each person, but rather the global footprint for all of the energy and resources that a person needs to maintain a modern standard of living.

Another widespread belief is that in terms of environmental impact, the key problem is wasteful usage of resources in the developed countries. In contrast, since much of the developing world is not consuming large amounts of energy and resources on the world market, their large populations do not matter. This analysis is wrong on several levels. First, large populations of poor people in developing countries do consume substantial resources outside of international trade, including destruction and degradation of non-renewable forests, water supplies, and other local natural resources. Second, these populations are no longer isolated from the modern world, and form a destabilizing wild card in their own countries and beyond. And third, as they become more urbanized, their consumption patterns will become more similar to those in the developed countries. Such large populations are not sustainable.

2) Science and Technology will solve our energy/resource/climate problems.

It is certainly true that science and technology have led to substantial improvements in the standard of living of people over the past several hundred years. But this has been primarily a result of the harnessing of cheap fossil fuels for large-scale industrial production and energy-intensive agriculture. We cannot count on similar improvements in the future.

Looking back, scientific research into thermodynamics and electromagnetics in the 19th century prepared the way for application to energy, transportation, and radio technologies in the 20th century. Similarly, scientific research into nuclear, atomic, and solid state physics in the early 20th century prepared the way for applications in the latter half of the 20th century, to nuclear power and information technologies. The Internet is certainly affecting people worldwide, but it is not clear how the Internet can address long-term problems in energy, resources, and climate. And while 21st century genetic science and biotechnology may lead to more efficient biofuels and drought resistant crops, it is difficult to see the scientific basis for something entirely new that can be expected to solve the increasingly difficult problems facing ever larger world populations. We are approaching fundamental limits of energy utilization on a global scale.

3) Space is the future of humanity.

A different kind of myth is the belief that the future of human beings is in space. Humans evolved as creatures of the earth, and can only survive in space by taking substantial chunks of earth environment with them. That is extremely energy intensive, as well as potentially dangerous. An estimate of the required energy can be made by considering the now-retired U.S. space shuttle, which required about 20 TJ to go into orbit. See, e.g., http://en.wikipedia.org/wiki/Energy_efficiency_in_transportation#Rockets. With a crew of 7, this corresponds to about 3 TJ per person. This should be compared to the average power consumed in the US, ~ 10 kW per person. An energy of 3 TJ corresponds to the entire energy consumption of an American for 10 years! Alternatively, it is the entire energy consumption of the US for 1 second! There is no way a significant fraction of the global population will ever be able to leave the earth. Furthermore, there are no other hospitable environments anywhere else in the solar system, and human interstellar travel makes very little sense. The distances, time scales, and energies are just too large, by orders of magnitude.

The purpose of the space program should not be to send men to Mars, but to make life better for people on earth. For example, unmanned orbiting satellites for communications, GPS, weather and climate observations, and space telescopes are irreplaceable parts of 21st century technological infrastructure. Furthermore, space probes can keep track of orbiting asteroids and comets to make sure that none of them will cause major catastrophes by striking the earth, or to divert them if they are coming too close. But the belief that the future of humanity is somewhere out in space is just another myth that diverts us from addressing the real problems here at home.

IV. Agriculture, Industry, Urbanization, and Power Gain

Humans evolved over millions of years as small groups of nomadic hunter-gatherers. However, that changed dramatically with the agricultural revolution, starting ~ 10,000 years ago in several places on the globe. Within a few thousand years, farmers domesticated plants and animals and spread across the world. Reliable food supplies enabled larger families, increasing population growth rates. Indeed, traditional agricultural societies valued high fertility and large families, in part because young children could work on the farm.

Another critical aspect of agriculture is the use of domesticated draft animals to multiply the effective human power and productivity. One can think of a person as a machine producing ~ 75 W of useful power (see http://en.wikipedia.org/wiki/Human_power). In comparison, 1 Horsepower (Hp) = 746 W, ~ 10 times greater. So in general, a man with a horse or ox might be 10 times as productive as a man alone. Furthermore, horses, oxen, camels, donkeys, and llamas are all ruminants, which means that they can graze on cellulosic plants that are not edible by humans, and so the animals do not compete with people for food. These draft animals can also be used for transportation of heavy loads, although typically at speeds not significantly faster than humans.

Society changed dramatically yet again in the industrial revolution of the past 200 years. Human productivity jumped another factor of 10 through the use of heat engines that harnessed the power of fire to produce useful work. While people have always burned wood, the industrial revolution was really launched by the power of cheap fossil fuels: coal starting in the 19th century and oil in the 20th century. These heat engines enabled rapid transportation, starting with the locomotive and going on to the automobile, and later the airplane. Heat engines also enabled electrical power, through coal-fired power plants, which ran steam engines that drove electromagnetic generators. A heat engine run in reverse is a refrigerator, which transformed the food industry, or an air conditioner, which transformed the livability of hot climates.

The average per capita power usage in developed nations is ~ 7.5 kW, 100x larger than the basic human power, and about 10 Hp. (A car may be up to several hundred Hp.) This power multiplier, combined with relatively efficient thermodynamic and electrical systems that turn this power to useful work, has been the primary basis for the industrial revolution.

This same power gain enabled much higher productivity in agriculture, freeing people to work in industry in the newly developing cities. And the cities themselves could increase their radius by a factor of 10, since transportation speeds jumped from ~ 3 miles per hour to ~ 30 miles per hour (from 5 to 50 kph). This enabled the population of a city to increase by 100, and more including the 3rd dimension enabled by elevators.

Cities also brought about a social transformation, changing the predominant values from promoting high fertility to promoting high productivity and consumption by educated workers, including women. As a result, the fertility rate has decreased sharply as populations have become increasingly urbanized. In most modern developed nations, if one sets aside immigration from higher-fertility regions, population growth has virtually stopped, and some populations are even decreasing slightly. A similar decrease in fertility is predicted for the developing nations in the remainder of the century, as they also become urbanized. One can argue that this fertility decrease is an adaptive response to increases in local urban population density. However, it is not a feedback response to the global population, so there is no reason to believe that a steady-state global population of 10B is sustainable for the long term.

Our modern industrial economy is built on cheap fossil fuels to produce power that enhances the innate human productivity of both food and consumer products. Fossil fuels are now being consumed at a rate whereby oil and gas may run out before the end of the 21st century, while coal may last for several centuries. Further, there are not near-term alternatives that can substantially replace fossil fuels. At this point, the question may be which disaster happens first, running out of fossil fuels, or excessive global warming. The only way to solve both problems is to decrease the global population, in a transition that will likely take several centuries.

VI. Climate Change and Fossil Fuels

It has long been known that gases in the earth's atmosphere absorb thermal infrared radiation from the surface of the earth, enabling the earth's steady-state temperature due to solar radiation to be much higher (about 14 ºC or 25 ºF) than it would be otherwise. The major gases are CO_2 and H_2O, both of which are exchanged with the land and the oceans. Burning fossil fuels produce both of these gases, but CO_2 is more critical since it lasts much longer in the atmosphere, more than 100 years. The atmospheric models include complex feedback loops coupling the atmosphere to carbon reservoirs in the oceans and on land, but the key equation is the following:

$$\Delta T(t) = 4\ln[\frac{C(t)}{C0}], \qquad (4)$$

where ΔT is the temperature rise (in ºC) relative to pre-industrial conditions, C_0 is the pre-industrial CO_2 concentration in the atmosphere (280 ppm), and C(t) is the concentration based on fossil fuel emissions. This corresponds to a 3 K temperature increase for every doubling of C(t) above the pre-industrial value. The current concentration is C = 400 ppm, corresponding to ΔT = 1.5 ºC. If present trends continue, by 2100 the addition of ~ 150 billion tons of CO_2 (150 Gt) in the atmosphere is projected to lead to a concentration of ~ 1000 ppm, corresponding to ΔT = 5ºC or 9ºF (from Houghton, 2005, Fig. 12). This would have many negative consequences, including a rise in sea level by ~50 cm or more. This may not seem like much, but much of the global population lives in low-lying regions near the coast, and this rise would increase further for several centuries even without a further increase in CO_2. Further, this would start to melt the Greenland ice cap, which could lead eventually to a sea level rise of several meters or more.

There have been several proposed techniques to counter global warming. One is carbon sequestration, essentially burying CO_2 deep underground. While this has been demonstrated on a small scale (Herzog 2011), expense and safety issues may prevent this from being used on the massive scale required. Alternatively, it would be possible to reduce solar heating by injecting large quantities of aerosols into the upper atmosphere, but this might also reduce crop yields in some locations. Furthermore, global warming would create some winners, among nations with large holdings in polar regions (Alaska, Canada, Russia, Greenland, Scandinavia). This would seem to make major international efforts to counter global warming practically unachievable.

Another approach would be to radically reduce the usage of fossil fuels. But our entire industrial society is based on cheap energy. As long as cheap fossil fuels are available and alternative energy sources are much more expensive, fossil fuels will continue to be used, and global warming will continue unabated.

VII. Steering the Future?

The only way out of this conundrum is to decrease the global population by up to a factor of 10 from the expected peak, to perhaps 1B people worldwide. At this level, it should be possible to maintain an energy-intensive civilization based on a combination of solar and nuclear energy, compatible with global resources and avoiding the worst of global warming. This transition will likely take several hundred years, but it is important to start as soon as possible. This will require reducing the effective fertility rate to ~ 1 child. Given the biological and social pressures to encourage child-bearing, can this be achieved without coercion? All traditional societies and traditional religions have encouraged large families, which is why there are now so many people. Under these circumstances, is there any hope for a sharp reduction in the birth rate?

I believe that there is, given that such reductions in fertility follow on population trajectories that are already present in many developed countries. Historically, women married young and started having children immediately. Now the trend is for women to delay marriage and child-bearing while they pursue education and establish careers. Previously, children provided the primary system of old-age retirement and care. This is transitioning to a system of government-provided pensions and elder care. Small apartments in expensive cities favor few children, or none at all. Childlessness is becoming more socially acceptable than it used to be. These trends are likely to continue, and need to be supported by governments.

To put solar energy in perspective, note that the total solar energy absorbed by the earth is ~ 90 PW (where P = peta = 10^{15}), of which ~ 27 PW is absorbed by the land (http://en.wikipedia.org/wiki/Earth's_energy_budget). That compares to the global energy currently consumed, ~ 15 TW, more than 1000 times smaller (see, e.g., http://en.wikipedia.org/wiki/World_energy_consumption). That would suggest supplying the total energy requirements with solar energy using a very small fraction of the land area; an efficiency of 5% covering 1% of the land would generate ~ 15 TW. Currently, low-cost solar photovoltaic cells typically have efficiency of a few percent, with more expensive cells ~ 10% or more (http://en.wikipedia.org/wiki/Photovoltaics). Furthermore, solar energy requires storage to be a major contributor to total electric power, and batteries may be too expensive. One solution would use solar photovoltaic to hydrolyze water, to generate hydrogen which can be transmitted via pipeline. Present global photovoltaic capacity is ~ 0.1 TW, but growing fast.

Another alternative is to harvest solar energy using photosynthesis, to generate biofuels. However, biofuels are likely to complete with food for arable land; thus increasing the price of food. That has already been happening with corn-based ethanol. Biofuels have been growing, now accounting for ~ 3% of transportation fuel use, partly based on government subsidies, but it is unclear whether they make sense for the long run. The efficiency of photosynthesis is actually quite low, and a recent analysis has questioned whether biofuels makes sense, in comparison with photovoltaics (Michel, 2012).

Nuclear power (http://en.wikipedia.org/wiki/Nuclear_power) does not depend on fossil fuels, and does not produce CO_2, so it really needs to be considered as a future supplement to solar power. Nuclear fission reactors based on U-235 now generate ~ 13% of electricity worldwide. There have been continuing concerns with safety and cost of fission reactors, as well as with long-term storage of nuclear wastes and potential diversion to nuclear weapons. Furthermore, U-235 reactors do not effectively make use of the majority U-238 atoms, which can be made fissionable by absorption of a neutron to create Pu-239. Breeder reactors use the uranium resources more efficiently, as well as decreasing the volume of nuclear wastes. A completely different fuel cycle is based on thorium (Moir 2005). This is also effectively a breeder; Th-232 can absorb a neutron to produce fissionable U-233. Thorium is more plentiful than uranium worldwide, and may be less susceptible to diversion for nuclear weapons. Other advanced reactor designs (including nuclear fusion) are being investigated, and may offer future opportunities.

In conclusion, global warming and resource limitations make it imperative that the global population be decreased as soon as possible. Our modern industrial society requires continued access to cheap energy for maintaining agricultural productivity and quality of life. Technological improvements in solar and nuclear power will be required to make the transition from the era of fossil fuels to one of sustainability. Now is the time to start steering the future in this direction.

References

Arrhenius, Svante (1896), "On the Influence of Carbonic Acid in the Air on the Temperature of the Ground", Philos. Mag., Series 5, vol. 41, p. 237, available online at http://www.globalwarmingart.com/images/1/18/Arrhenius.pdf

Deffeyes, Kenneth (2001), "Hubbert's Peak: The Impending World Oil Shortage", Princeton University Press. Also Deffeyes (2005), "Beyond Oil: The View from Hubbert's Peak", Princeton U. Press. See also https://www.princeton.edu/hubbert/.

Ehrlich, Paul (1968), "The Population Bomb", Ballentine Books. Chapter 1 is available online at http://faculty.washington.edu/jhannah/geog270aut07/readings/population/Ehrlich%20-%20Population%20Bomb%20Ch1.pdf. See also http://en.wikipedia.org/wiki/The_Population_Bomb

Herzog, Howard (2011), "Scaling up CO_2 capture and storage: From megatons to gigatons", Energy Economics, vol. 33, p. 597. Available online at http://e40-hjh-server1.mit.edu/pdf/Herzog_EnergyEconomics_Dec2010.pdf.

Houghton, John (2005), "Global Warming", Reports on Progress in Physics, vol. 68, p. 1343.

Kapitza, Sergei (1996), "The Phenomenological Theory of World Population Growth", Physics-Uspekhi, vol. 23, p. 57. Also Kapitza (2010), "On the Theory of Global Population Growth", Physics-Uspekhi, vol. 53, p. 1287, available online at http://iopscience.iop.org/1063-7869/53/12/A06/pdf/1063-7869_53_12_A06.pdf.

Malthus, Thomas Robert (1798), "An Essay on the Principle of Population", available online at http://www.esp.org/books/malthus/population/malthus.pdf

Meadows, Donella (1972), with Dennis Meadows, Jorgen Randers, and William Behrens, "The Limits to Growth", Universe Books. Available online at http://www.donellameadows.org/wp-content/userfiles/Limits-to-Growth-digital-scan-version.pdf. See also http://en.wikipedia.org/wiki/The_Limits_to_Growth

Michel, Harmut (2012), "The Nonsense of Biofuels", Angewandte Chemie, vol. 51, p. 2516 (2012). Available online at http://onlinelibrary.wiley.com/doi/10.1002/anie.201200218/full

Moir, Ralph and Edward Teller (2005), "Thorium-Fueled Underground Power Plant Based on Molten Salt Technology", Nuclear Technology, vol. 151, p. 334. Available online at http://ralphmoir.com/media/moir_teller.pdf. See also R. Hargraves and Moir (2010), "Liquid Fluoride Thorium Reactors", American Scientist, vol. 98, p. 304. http://www.ralphmoir.com/wp-content/uploads/2012/10/hargraves2010_2.pdf

Orbach, Raymond (2011), "Our Sustainable Earth", Reports on Progress in Physics, vol. 74, 112801.

Pimentel, David (1999), "Will Limits of the Earth's Resources Control Human Numbers?", Environment, Development and Sustainability, vol. 1, p. 19. Available online at http://www.civil.uwaterloo.ca/maknight/courses/CIVE240-05/week3/Pimentel(1999).pdf

Simon, Julian L. (1980), "Resources, Population, Environment: An Oversupply of Bad News", Science, Vol. 208, p. 1431. Available online at http://www.nrel.colostate.edu/ftp/conant/Courses/NR120_fall_08/unit1/readings/simon_1980.pdf