Economics, Thermodynamics and Entropy – the impact of resources and climate change on economic output.

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Abstract: This paper stems from previous research and publications of the writer, in particular papers of 1982 and 2007, two books *'Thermoeconomics'* (3rd edition 2012) and *'Entropy Man'* (2015), and a number of working papers.

The paper sets out some trends in renewable and non-renewable resources, including energy, key metals & minerals, humankind, water, land & soil, and food production, and the potential for these to act as constraints to output. Some trends in climate change are presented, in as much as they may affect the course of economic output.

Keywords: Thermodynamics, economics, entropy, production, money, employment.

Biographical note: John Bryant is director of VOCAT International Ltd, a company specialising in economic research and expert witness services. He has degrees in engineering and management science, and his career appointments have included group economist for a large multi-national engineering corporation and economist and investment analyst for a stock broking group.

Resource Dynamics and the Economy

Prior to the era of industrial man, much of human capital and effort was devoted to interaction with Nature's forces and to utilising *natural resource capital* that is of a *renewable* or *organic* kind. Continuous energy from the Sun, a little from beneath the surface of the Earth, plus gravity, all involving entropy generation, combined with the position and properties of the Earth, powers all the forces of Nature: climate, seasons, ocean and atmospheric movement, precipitation, water flow to rivers and aquifers and the carbon cycle, enabling the propagation/regeneration of natural resources of top-soils, forests, plants, animals *[including humans]*, insects, fish and other living matter. Such resources are consumed and then returned to Nature over time in complex, inter-reacting regenerative cycles, which cycles have existed for millions of years. The life cycles of the processes involved can be measured from the short term to the very long term, but with a significant annual, seasonal element affecting many.

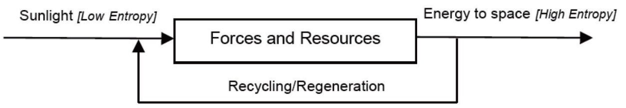


Figure 1 Pre-industrial Force and Resource Regeneration.

With the dawn of industrial man came the development and utilisation of resources which may be regarded on a human timescale as being *non-renewable*, in particular, energy in the form of coal, oil and natural gas, and some key minerals and metals, allied to increased entropy generation to the system, enabling the human population to advance in size and to acquire significant amounts of *manufactured capital*. A more recent effect has been an impact on natural resource capital, previously regarded as renewable, such as topsoil, forests, water and food sources. Terms of potential degradation and overuse come to mind for these.

The format of this paper is to set out some of the dynamics of resources; and then to examine empirically world trends of key non-renewable and renewable resources and climate change.

Non-Renewable Resource Dynamics

Turning first to non-renewable resources exploited by man, these do not have an input from Nature or the Sun, and mostly do not have a recycling/regeneration component, only an output of productive content, the flow of which is determined at the initial stage by such factors as their use or utility to human activity, the estimated quantities and qualities of economically recoverable resource reserves, their ease of abstraction, and the costs of transport and development and energy consumed to bring them to final demand. In respect of resources such as copper, iron and others, a proportion can at some stage be recycled back into the production system via scrap reclamation. Development of non-renewable resources in the long-term follows a well-known S-shaped path as illustrated by figure 2.

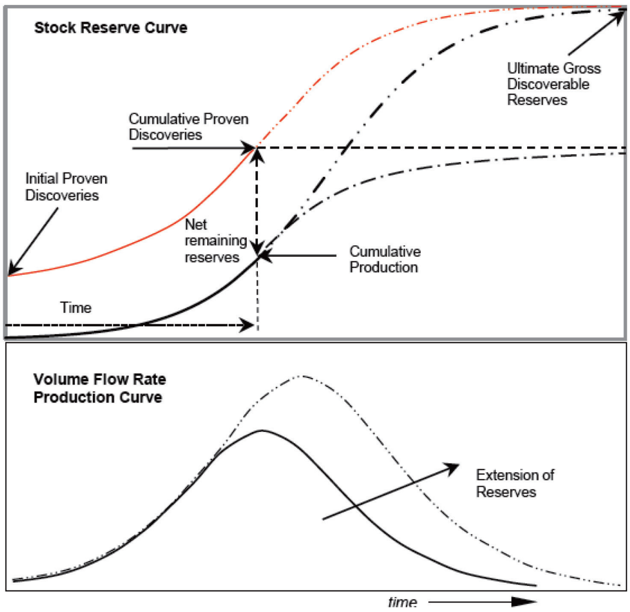


Figure 2 A Non-renewable resource reserve.

At a particular point in time information may be known of volume production rates and cumulative production to date, and knowledge of remaining net proven reserves that are being tapped can also be estimated, from for example geological data. What is not known for certain is what other reserves may be discovered or become recoverable in the future. It can be seen that production climbs to a peak at about the midpoint of known reserves *[used and yet to be used]*, and thereafter declines as reserves dwindle. Further discoveries may extend the life of a non-renewable resource, such that the peak of the production curve moves further to the right.

Superimposed on the long-term development curve are other factors, some short term, including: elasticity effects, changes in production output and prices arising from the impact of world economic activity/trade, political and aggressive conflicts, the impact of resource agency management and ownership in regulating output, the discovery or not of further reserves to extend the life of a resource, the reliability of disclosed data of reserves, the impact of changing technology to develop resources originally deemed uneconomic, the effect of a declining return on investment as tail resources become more difficult to mine *[the energy equivalent is EROI: energy return on energy invested]*, the development of substitute resources, and side-effects such as possible climate change and damage to some parts of the eco-system. The combination of all these effects makes for a complex picture of the development and subsequent demise of a non-renewable resource.

Dealing only with the long-term path to develop a non-renewable resource, the standard descriptive model, particularly applicable to oil and gas, is that based on the Hubbert equation *[M King Hubbert (1903-1989)],* which in turn is based on the Logistic/Verhulst equation *[Pierre Verhulst (1804-1849)]*. For the mathematicians, the following expression summarises the relationship between the production volume flow and the resource size:

$$V = \varphi\left(\frac{N_C N_R}{R}\right)$$

Where **V** is the production volume flow rate, $\mathbf{N_C}$ is the cumulative production or reserve used up to date, which grows with time, $\mathbf{N_R}$ is the net remaining reserve**,** which declines with time as the resource is used up, and **φ** is the frequency rate *[the inverse of the decay time over which the reserve is being depleted – similar also to the rate of return **r** and the inverse of the lifetime coefficient **ω**, that were described in the first paper]*. And last, **R** is the total proven reserve, arithmetically equated to cumulative production over time plus net remaining reserves *[$R = N_C + N_R$]*.

The solution to the above relationship is a logistic S-shaped path of reserve development, as shown in figures 2 and 3. For interested readers the mathematical formula is given in the notes to this paper. It can be proved that maximum or *peak* output volume flow occurs at the mid-points of the production and reserve curves.

As with a production stock, an economic entropy function can be developed for a resource stock in terms of its *activity* rate. A first step is to consider a stock where the caprices of its users are neutral; that is, the only forces and constraints acting on the stock are those emanating from the stock itself, and not the human consumers or controllers of production. The stock forces are the amount of the stock used up, being the cumulative production to date $\mathbf{N_C}$, and the net remaining stock left to be used up $\mathbf{N_R}$.

If we assume that the amount of *active* stock left to be used $\mathbf{N_R}$ is a proportion **b** of the total stock **R**, i.e. **bR**, then the cumulative production or stock used up $\mathbf{N_C}$, rendered *inactive*, would be expressed as **(1-b)R**. All other factors being equal, it can be proved that the entropy function for a resource stock can be expressed as:

$$S_2 - S_1 = k \ln\left(\frac{b_2}{b_1}\right)\left(\frac{1-b_2}{1-b_1}\right) \qquad k = 1 \text{ for an economic good}$$

relating the change in entropy flow to the relative proportions of the stock remaining and the stock used up. A formal proof of this relationship is set out in the notes to this paper. Figure 3 shows the loci of all the factors.

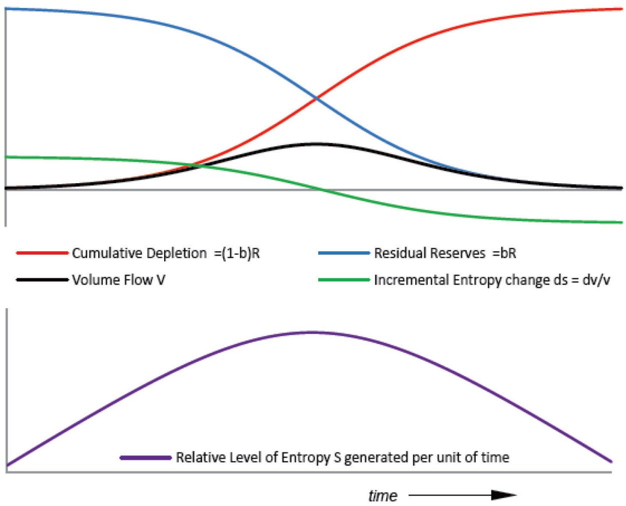


*Figure 3 Loci of residual reserves $\mathbf{N_R}$ [=bR], cumulative production or resource depletion $\mathbf{N_C}$ [=(1-b)R], volume flow **V**, incremental entropy change **dS** [assuming an elastic index **n=1**], and the relative level of entropy generation **S** per unit of time over the life of the resource.*

The system maximises its rate of entropy generation at the point of maximum output volume flow per unit of proven reserve, thereafter output flow reduces as change in entropy generation becomes negative. Should additional reserves be discovered or reserve recovery factors be improved, these will create a new economic entropy gain, extending the lifetime of the resources and arresting the impact of a decline in entropy generation arising. Thus the production rate is advanced, and the depletion rate is set back.

The practicalities of life, however, indicate that humans play a significant part in demand and supply with regard to resources. Oil is an obvious example here, whereby controls on production, political impacts, wars and the vagaries of business cycles and prices, mean that production rates can be manipulated above and below the natural rates for a resource, giving rise to significant changes in the elastic index between price and demand volume flow.

A way forward perhaps is first to set out an ideal economic relationship similar to that developed in the first paper, but this time with output value flow **G=PV** *[price x volume flow]* being equated to the total proven reserve quantity **R** multiplied by its index of trading value **T**:

$$PV = RT$$

Dividing both sides by the proven reserve quantity **R**, and letting **v** = **V/R**, being the *specific volume* flow rate per unit of proven reserve, gives a simple relationship of price multiplied by the specific volume flow rate, equal to the index of trading value for the stock, which is variable.

$$Pv = T$$

The specific volume flow rate **v** will accord with the caprices of supply and demand, as impacted by humans controlling the output of resource reserves, and by humans directing their requirements to different part of the world. Thus one could imagine a *polytropic* relationship between price and volume, as formally derived in the first paper, but this time between price and output volume flow per unit of proven reserve **v**, of the form:

$$P(v)^n = C$$

Where **n** is an elastic index, which is impacted by human factors of supply and demand. And without setting out all the mathematics again, the end result would be an entropy relationship of the form:

$$dS = (\omega - \omega n + 1)\left(\frac{dv}{v}\right)$$

Equating change in entropy generation or utility consumption rates for a resource stock in *monetary terms* to the marginal entropic index ***[ω-ωn+1]***, and the output or consumption per unit of the proven reserve **v** *[=**V/R**]*.

Clearly however, if economic factors of supply and demand interject such that the elastic index is above or below the value 1, then a complex non-equilibrium relationship ensues, with price *[in money terms]* and output flow continually seeking over time to equalise the position.

Renewable Resource Dynamics

The dynamics of renewable resources are more complex than those of non-renewables since, as shown in figure 1, input factors and recycling/ regeneration feedback loops must also be taken into account. Renewable resources can be subdivided into those defined as a stock, such as plant life, animate life and soil, and those arising from a flow from a stock, such as sunlight, wind, ocean currents and river flow.

In an ideal scenario it might be imagined that available renewable resources would remain in tune with the demands placed on them by humankind and other living organisms, and that as fast as they are consumed or utilised they are recycled by Nature and/or regenerated by the Sun, and thereby the population carrying capacities of humankind and other living organisms, feeding on the resources, would be maintained at relatively steady states. A scenario of this kind is, however, unlikely. Ebb and flow of renewable resources is a normal feature, historically being brought about by changes in known natural factors such as seasons and climate. The impact of human endeavour has been a more recent factor.

As the human population and its share of the fruits of the Earth grow, spurred on by the entropy and utility gains to be had to the benefit of humans, even with renewable resources there may come a time when the fixed size of the Earth and its inter-reacting systems will pose constraining forces to further expansion of human acquisitiveness, resulting in a ceiling to or reduced entropy generation by humans, This is not to say definitively that Malthusian or Gaian hypotheses of Earth systems development will very shortly prevail catastrophically to cut human activities to size *[and thereby also activities of other living things]*, but we should all be mindful of and concur with the ways in which the ecosystems of the Earth act to regulate matters, in order to avoid such an occurrence. Humanity has faced significant population collapses in past ages, arising from varied causes.

A well-known concept in population dynamics is that of carrying capacity, equating to the maximum population size of a life form or of a renewable resource that can be sustained over the long term within an environment such as the Earth, without a decline ensuing. Estimation of carrying capacity, however, is not an easy task. As with a non-renewable resource, a logistic S-shaped curve is a common way of illustrating the concept, except that whereas non-renewable resource reserves decline until they are used up, renewable resources can grow until they approach the carrying capacity, unless depleted by predatory species or other factors. Other matters to consider also are that competition between species, human or otherwise, can occur with regard to foraging shared resources, and that while some species populations might be considered to be *'prey'*, others could be regarded as being *'predators'*, feeding off the prey, such that a population can vary up and down in size, or even become extinct.

The two most common approaches to modelling renewable resource dynamics are the Lotka-Volterra predator/prey model *[Alfred Lotka (1860-1949), Vito Volterra (1860-1940)]*, and Resource Ratio or R* theory *[David Tilman (1949-)]*.

The Lotka-Volterra model is set out on a resource-size and time basis, with the rates of growth *[or decline]* of predator and prey being expressed as a set of differential equations relating the rates of change of predator and prey populations to their size and to the interaction between each other. For example, prey **x** might be a field of corn or grazing animals. It is then assumed to have an unlimited energy or food supply, and to reproduce exponentially at the rate of **α**, unless consumed by predators **y**, consumption being represented by a function **β** of the contact **xy** between predators and prey.

$$\frac{dx}{dt} = \alpha x - \beta xy \qquad \text{and} \qquad \frac{dy}{dt} = \delta xy - \varepsilon y$$

Likewise the net growth/decline in numbers of predators **y** *[a human population or a pack of wolves for example]* would be governed by a function **δ** of the contact **xy** between predators and prey, less the death rate **ε** of the predators.

The reality to this model of course is that prey do not have an unlimited food supply *[the Earth being finite in size, and subject to seasonal and other natural variations]* which adds a further dimension to the process. Essentially, predators depend on their harvest of prey, and prey depend upon the Sun, Nature and the eco-system to reproduce themselves. If the predators have a high consumption rate of prey such that prey are gradually reduced in number, the sources on which the predators depend reduce and the predators face a subsequent potential decline in population. The most obvious human examples of this effect are potential over-fishing of the oceans, over-farming of arable land, over-drawing of aquifers and deforestation. Using up renewable resources *[many environmentalists might say squandering]* in an unsustainable way entails a potential degradation of the Earth's resources in the short-term ecological timescale. Man has become a virulent predator. The chart at figure 4 illustrates the concept of the Lotka-Volterra model, with the trend of prey preceding that of predators.

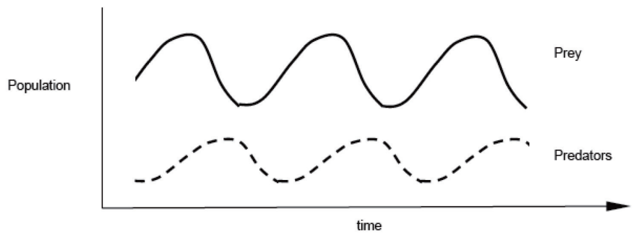


Figure 4 Lotka-Volterra Model - Population of predators & prey over time.

It all gets rather complicated, particularly when trying to build some realism into the situation, entailing computer simulation. A famous example of this is the model built for the Club of Rome in the 1972 book *Limits to Growth [Meadows, Meadows, Randers, Behrens, Massachusetts Institute of Technology],* which was composed of a network of interrelating factors, including population, arable land, energy *[non-renewable]*, industrial capital and production, CO_2 pollution, fish stocks, and a waste function. The conclusions reached in the book met with significant resistance from a modelling point of view, and as world economic growth has continued since that time, the venture lost some following. More recently *Limits to Growth* has been revisited by Turner *[2008]* with the conclusion that thirty years of historical data compared favourably with the "business-as-usual" "standard run" scenario, but did not compare favourably with other scenarios involving comprehensive use of technology or stabilizing behaviour and policies.

The second approach, Resource Ratio or R* theory *[David Tilman (1949-)]* , posits the proposition that a species' ability to maintain itself will be governed by the level R* of the limiting resource that it depends on which results in zero net growth in the species' population. Thus, at resource levels below R*, species' population growth will be negative, and vice versa, when resource levels are above R*, population growth will be positive. Taking matters further, the species that is able to survive at the lowest level of a limiting resource will be the best competitor for that resource. And not surprisingly the survivability of a species will also depend upon the supply and consumption rates of the resource(s) on which it feeds. R* theory also makes some connections between species dominance, the number of limiting resources and the number of species that can coexist.

There exists a significant body of academic research into dynamic analysis using one or both of the above approaches. Brander & Taylor *[1998]* have examined the collapse of the Easter Island economy. Their *[Cobb-Douglas]* utility function related to both harvested and manufactured goods. Motesharrei, Rivas and Kalnay *[2014]* have built a Lotka-Volterra logistic model incorporating inequalities in income and a combined resource factor covering renewables, non-renewables and renewable flows. They concluded that an unequal society reflected the reality of the world and that collapse was hard to avoid. Miller et al *[2005]* have reviewed 20 years' use of the Resource-Ratio theory, covering 1333 papers. Of these 26 provided tests of the theory, with 75% supporting the conclusions. A key prediction was that species dominance varied with the ratio of resource availabilities. A selection of the literature is included in the references to this paper.

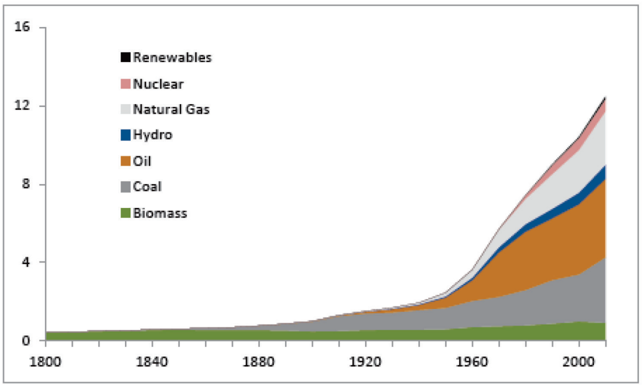
In respect of entropy generation, the principle to remember is that prey species consume and convert productive content/energy from the Sun and renewable resources into useful productive content/energy to sustain themselves *[with some waste value left over]*, thereby maintaining their entropy at a low level, but in the process create a large entropy gain to the environment from the consumption of the renewable resources. And likewise, one step further on, predator species consume and convert productive content/energy from prey into useful productive content/energy to sustain themselves *[with some waste value left over]*, thereby maintaining their entropy at a low level, but again in the process creating a large entropy gain to the environment from the consumption of the prey. Subsequently a further entropy rise occurs as predators die off and are recycled to the resources.

Entropy creation is a never ending, rolling, additive process, with one consumer/resource chasing another. Each species seeks over time to adapt its population size in response to any changes in the constraints acting upon it, the difference between size and constraint being related to the entropy difference pertaining. The process continues until the entropy difference has been annulled, at which point an equilibrium position has been reached with population size matching the constraint. But of course, Nature being what it is, an equilibrium position may never be sustained for more than a fleeting moment before other changes occur to create another non-zero entropy change, and once again the system has to react, to seek to annul the change – the Maximum Entropy Principle.

A last point to make in respect of resource dynamics is that humankind creates rather more manufactured capital than do other living things. Birds and bees build nests and some animals and insects dig holes for homes, but many other living things do not commandeer productive content for anything other than food. Humankind is a voracious consumer upon the Earth, and its entropy footprint is likewise very large. Should a significant constriction of resources occur, then much of the edifice of manufactured capital that humans have built for themselves could crumble, with an irreversible increase in entropy.

Energy in the Economy

Economic systems of developed and developing countries have become progressively embedded in an energy base, to provide a source of productive power and human wealth and well-being. Energy consumption *[technically exergy, or useful energy consumption]* provides electricity, powers machines in industry and computers, provides heat for industry and homes, and powers road, rail and sea transport. Fishing and agriculture in developed economies are now heavily dependent on energy, rather than human or animal power. Figure 5 illustrates the inexorable rise in energy use, mostly based on non-renewable resources of coal, oil and natural gas, and table 1 sets out the range of human and industrial assets that currently require energy consumption in order to function fully.



Sources: BP Statistical Review, Vaclav Smil

Figure 5 World Primary Energy Consumption – Gtonnes p.a. oil equivalent.

Table 1 US Net Stock Fixed Assets & Consumer Durables held by private and gov't agencies in 2007.

$bn	*Total*	*%*	*$bn*	*Total*	*%*
Equipment & Software			***Structures***		
Computers/Software	$669.9	1.4	*Residential*	$18,142.8	38.9
Communications	$555.4	1.2	*Offices*	$2,247.9	4.8
Medical Equipment	$269.2	0.6	*Commercial*	$1,868.1	4.0
Office Equipment	$188.3	0.4	*Hospitals*	$931.9	2.0
Engines Turbines	$83.5	0.2	*Manufacturing*	$1,242.8	2.7
Electrical transmission	$358.4	0.8	*Power*	$1,472.0	3.2
Industrial M/c	$1,041.0	2.2	*Communication*	$485.8	1.0
Trucks/buses	$1,577.9	3.4	*Petroleum/Nat Gas*	$832.6	1.8
Autos	$714.5	1.5	*Mining*	$57.2	0.1
Aircraft, airborne equipt	$456.5	1.0	*Railroads*	$298.7	0.6
Ships, boats	$207.7	0.4	*Farms*	$307.8	0.7
Railroad equipment	$101.5	0.2	*Highways/Streets*	$2,634.1	5.7
Agricultural M/c	$147.0	0.3	*Military*	$391.4	0.8
Construction M/c	$149.8	0.3	*Transportation*	$532.4	1.1
Mining/Oilfield Equipt	$49.5	0.1	*Educational*	$1,971.2	4.2
Videos/Computers TV	$793.5	1.7	*Sewers & Water*	$912.0	2.0
Appliances	$204.2	0.4	*Other*	$2,030.3	4.4
Other	$2,690.7	5.8			
Total Equipt & Software	**$10,258.5**	**22.0**	***Total Structures***	**$36,359.0**	**78.0**
			Net Capital Stock & Consumer Durables ($bn)	**$46,617.5**	**100.0**
			Population (millions)	**301.23**	
			Assets/head ($)	**$154,800**	

www.bea.gov Fixed asset tables 3 and 11b

Non-renewable energy is now an international commodity, and few countries with a significant manufacturing and commercial base can now be described as 'closed' with respect to it. Of the major economies, only Russia, Mexico and Canada can claim to be net exporters of oil. In the natural gas market, the USA and Europe are now net importers of gas via pipelines respectively from Canada and Russia, though the technology of fracking may perhaps change this. Only in the coal industry is consumption met mostly by local production, with China, USA and India accounting for two thirds of world production and consumption. In 2013, eight developed countries with just 11% of world population *[USA, Japan, Germany, Canada, UK, South Korea, Italy and France,]* accounted for 34% of world GDP, and 31% of primary energy consumption; with China, Russia and India bringing the latter total up to 66%.

By common practice, the units used to measure energy production and consumption are those of weight *[tonnes of oil equivalent]*, volume *[barrels of oil, billions cubic metres of gas (bcm)]* or the heat value of sources of energy *[Joules, BTUs]*. These can be equated to 'productive content' or exergy if account is taken of the net energy delivered to the environmental average.

Figures 6 and 7 summarise the development and relationship of primary energy consumption and electricity generation to GDP and population over several decades for some key countries.

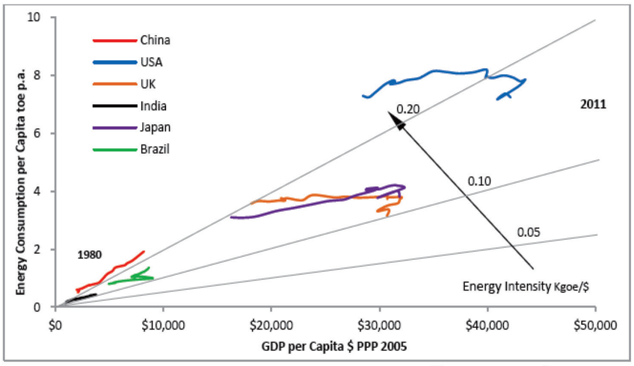


Figure 6 Primary Energy Consumption p.a. per capita, GDP per Capita (PPP 2005) and Energy Intensity. 1980 – 2011.

In some developed economies, energy consumption per capita has begun to level off, if not decline, indeed in the 2008 recession it declined significantly. But in the developing world, illustrated by China and India, energy consumption per capita continues to grow. Energy intensity *[energy consumption/GDP]* has fallen significantly for the developed countries, and continues to do so. However, bearing in mind that electricity production accounts for some 40% of primary energy consumption, it should be noted that per capita electricity consumption is still rising, associated with only a small decline in electricity intensity *[electricity consumption/GDP]*. Thus a significant part of the reduction in energy intensity has been owing to improved efficiency in conversion of energy into electricity. It should be cautioned however that ultimately the laws of thermodynamics place limits on the level of efficiency that can be obtained.

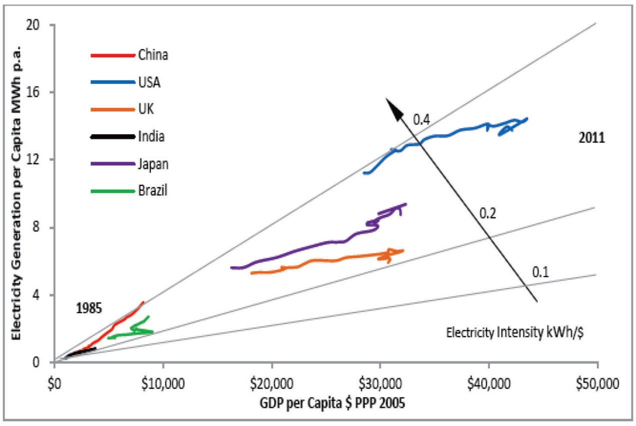
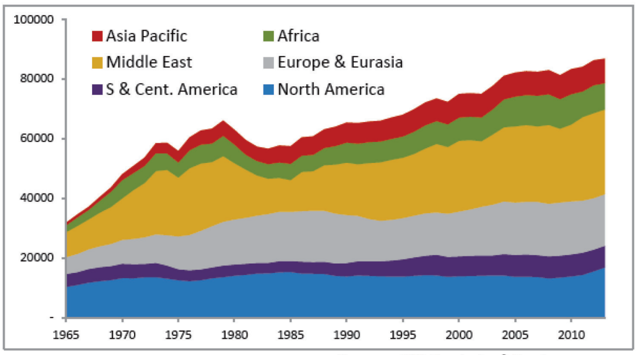


Figure 7 Electricity Generation p.a. per capita, GDP per capita (PPP 2005) and Electricity Intensity. 1985 – 2011.

Figures 6 and 7 are useful in respect of making projections of the future. For example, on the basis that world population eventually reaches 10 billion, and that the developing world aspires to and reaches European levels of affluence, one might venture that world GDP might increase by a factor of 4 and, combined with improvements in efficiency and reductions in energy and electrical intensity, energy consumption would increase by a factor of 2. Whether Nature and the resources of the Earth could cope with such increases without a deleterious effect must be a matter for investigation.

Oil and Natural Gas

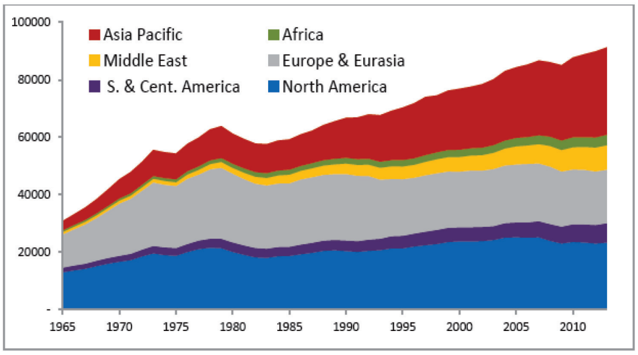
Figures 8 – 11 set out charts of world production and consumption of conventional oil and natural gas.



Source: BP Statistical Review

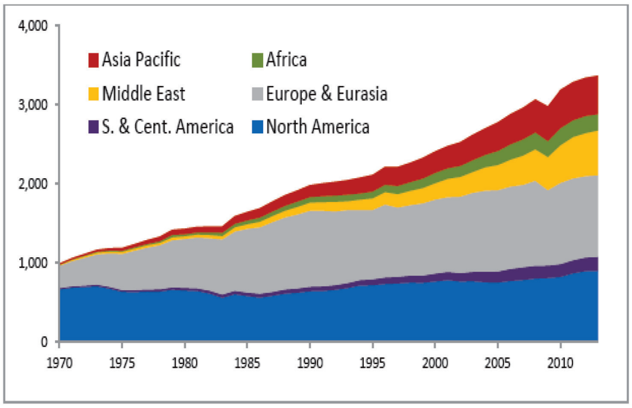
Figure 8 World Oil Consumption – 000's barrels/day.

World oil production has continued to climb, interrupted significantly only by the period in the early 80's at the time of the Gulf war, when Saudi output temporarily halved. Outside the Middle East, discoveries have occurred in the North Sea, Venezuela *[Orinoco belt – heavy oil]*, Nigeria, China and Indonesia. In terms of consumption, US demand expanded a little to the mid 80's but has declined a little since then. US production, however, has recently expanded on the back of light, tight oil from fracking, which may change the balance of supply against demand. European demand has remained static. The big expansion of demand of more recent times has been that of China, with increases also in Brazil, Saudi Arabia and Iran.



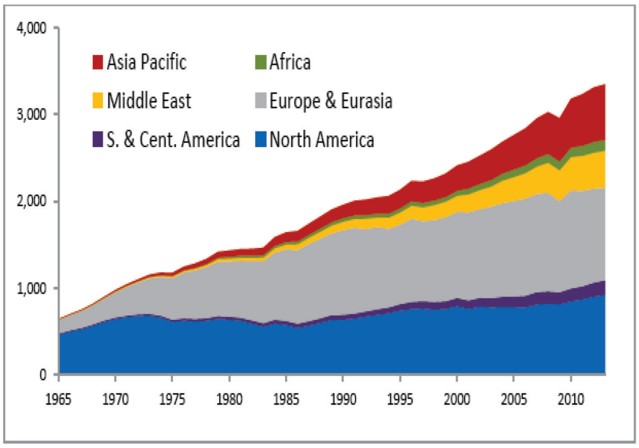
Source: BP Statistical Review

Figure 9 World Oil Consumption – 000's barrels/day.



Source: BP Statistical Review

Figure 10 World Natural Gas Production - bcm p.a



Source: BP Statistical Review

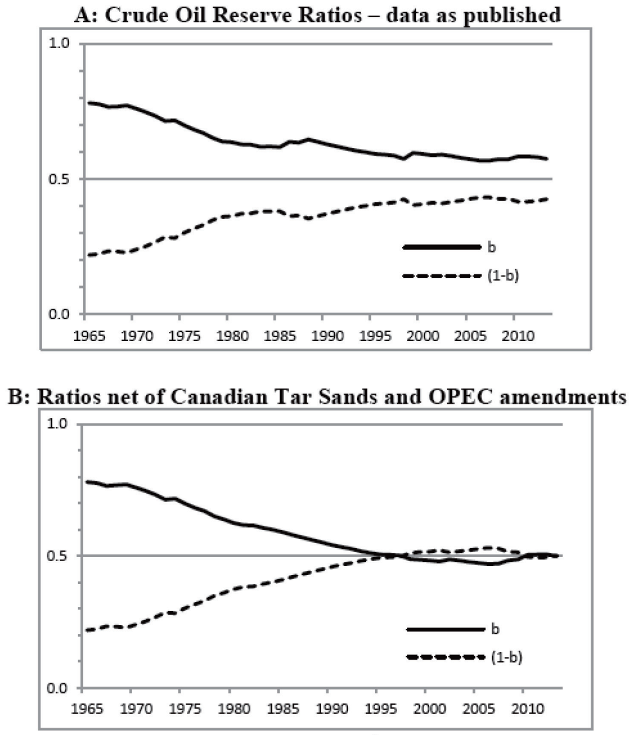
Figure 11 World Natural Gas Consumption - bcm p.a.

World natural gas production has expanded greatly, with the biggest growth occurring in Russia. Elsewhere, production has expanded in USA, Canada, the North Sea, Iran, Saudi Arabia, Algeria, Indonesia and Malaysia. Recent increases in US production are owing to the advent of shale gas production from fracking. In terms of consumption, Europe has benefitted significantly from the Russian discoveries. Rises have also occurred in the Gulf area and Japan, the latter for LNG *[liquefied natural gas]*.

Recalling now the development earlier in this paper of the schematics of a non-renewable resource and when a peak in output is likely to occur, then indicators that may be key as to how close this point is in the proceedings are the ratios of the remaining reserves and of cumulative production to date to the total proven reserves discovered to date. If these are close to each other, then the likelihood is that a peak is about to be or has passed – given known information about resource reserves at the time. This is not to say that no more discoveries will be forthcoming to increase the size of the net reserves remaining.

There exists an extensive literature on the subject of *peak oil* and *peak gas*. A particular issue often highlighted is that of reconciling data from published sources *[Oil & Gas Journal, IEA, EIA, BP]* to individual non-published field data from the industry *[IHS]* and research of independent authors *[Laherrére, Robelius, Campbell and others]*. A paper by Owen, Inderwildi & King *[Energy Policy 2010]* sets out succinctly the key points relating to oil reserves and the degree of reliance that can be placed on figures from sources of reporting. Particular issues they highlight include: use of backdated reserve classes 1P *[proven]*, 2P *[proven & probable]* or 3P *[proven, probable & possible]*, inclusion of unconventional oil grades with poor EROI *[Canadian tar sands]*, upward revisions to past discoveries, and false additions in the 1980s *[OPEC]*.

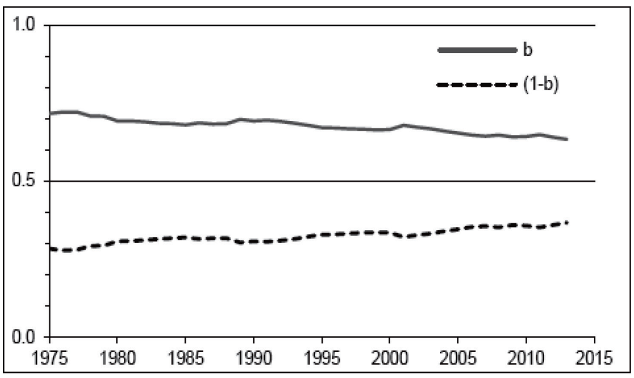
The charts at figure 12 illustrate the trend for crude oil of the ratio of remaining reserves/total proven reserves ***(b)*** and of the ratio of cumulative production/total proven reserves ***(1-b)***. Chart A shows the ratios inclusive of Canadian tar sands and OPEC published reserves. Chart B shows the world ratios excluding tar sands and the OPEC adjustments highlighted by Owen et al. On the basis of published data, chart A shows that the ratio of net remaining reserves to total proven reserves has declined, and that of cumulative production to total proven reserves has risen, with both levelling off by around 2000 onwards.



Data sources: BP Statistical Review, OPEC

Figure 12 World Oil reserve ratios.
*Ratios of Net remaining reserves/Total proven reserves [**b = N_R/R**] and of Cumulative production/ Total proven reserves [**(1-b) = N_C/R**]. .*
Adjustments constructed by Bryant for selected OPEC countries and Canadian tar sands, as per paper by Owen et al.

If adjustments for Canadian tar sands, with a low EROI, and for OPEC oil quota changes are made, however, as per chart B, it would appear that peak oil has arrived with the ratios **b** and **(1-b)** meeting each other, though as yet they have continued at around a midpoint, with some rebound, likely arising from growth in shale oil fracking. Conventional wisdom has it that, once past 'peak oil', world oil production will slowly begin to decline – the decline occurring over decades. Figure 13 shows a similar set of ratios for world natural gas.



Data Source: BP Statistical Review.

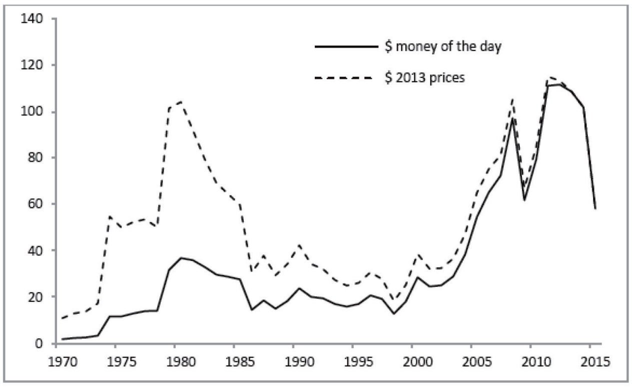
Figure 13 World Natural Gas reserve ratios
*Ratio Net remaining reserves/Proven reserves [**b = N_R/R**] and Cumulative Production/Proven reserves [**(1-b) = N_C/R**].*

The trend for natural gas is much lower, suggesting a peak perhaps about three – four decades away, but depending also on any further switch into natural gas.

For both oil and gas, any future discoveries of reserves, including fracking, could extend the time at which a peak may occur.

In respect of crude oil, an alternative means of assessing the impact of changes in the market is by reference to the world crude oil price relative to the consumption/gross proven reserves ratio, to measure changes in elasticity and hence changes in economic entropy/utility, as described earlier. Figure 9.9 sets out the annual crude oil price in US $ from 1970 to 2015, At the time of writing *[2015]* oil prices had declined sharply against the trend to a low of $47/barrel, indicating surplus capacity in the short term, but subsequently rebounding to $60.

In the early 1970s OPEC countries unilaterally increased prices by a factor of four; which rise did not altogether equate to the demand and supply forces in play. Subsequently consumption and then production declined. The beginning of the 1980s saw another hike in oil prices, arising from the 1979 Iranian revolution and the Iran-Iraq war. Subsequently also, OPEC cut its production to try to maintain the price level.



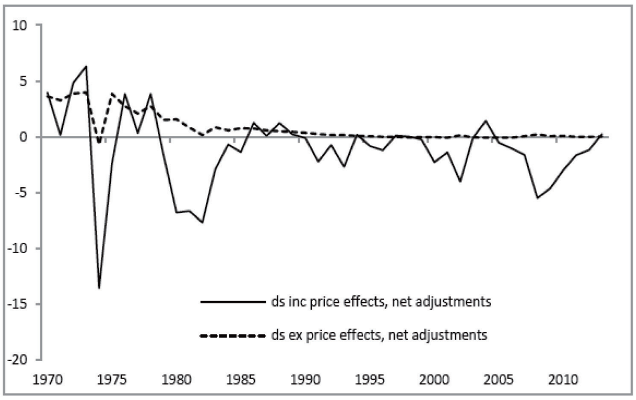
Data sources: BP Statistical Review (-2013), Investing.com (2014-)

Figure 14 Crude Oil Price $/barrel current and 2013 price base.

In 1985/86 OPEC production was no longer held back and a price drop ensued in 1986. There was a brief price increase in 1990 following the invasion of Kuwait by Iraq. From 2000 onwards prices began to rise inexorably, following a restrictive production policy by OPEC members. The world economic crisis of 2008 onwards saw oil prices slashed, though subsequently they rebounded to even higher levels. With the more recent rise of expensive fracked oil production, principally in the USA, oil producers in the Middle East have maintained their production levels, with a consequent reduction in oil prices. At the time of writing this scene has yet to play out, with oil prices at very low values.

The world oil market is therefore one where human and political decisions have significant impacts on prices, and consequently one might expect that changes in economic entropy generation would occur, either side of the long-run position.

The author has attempted to construct a picture of economic entropy change for the world oil market for the period 1970-2013, as shown in figure 15, but with only annual historical figures of oil production, consumption, reserves and prices available to him, he considers the result so far to be unsatisfactory, particularly with regard to elasticity. The relative accuracy of some historical reserve estimates, as highlighted by the paper of Owen, Inderwildi & King, also has an impact. The quality of the analysis will likely be improved if quarterly or monthly data were available, but such was not available for this paper.



Data Sources: BP Statistical Review, OPEC

Figure 15 Economic Entropy % change for changes in ratios of oil consumption/proven reserves and price 1970-2013.
[Reserve adjustments constructed by Bryant for selected OPEC countries and Canadian tar sands, as per paper by Owen et al.]

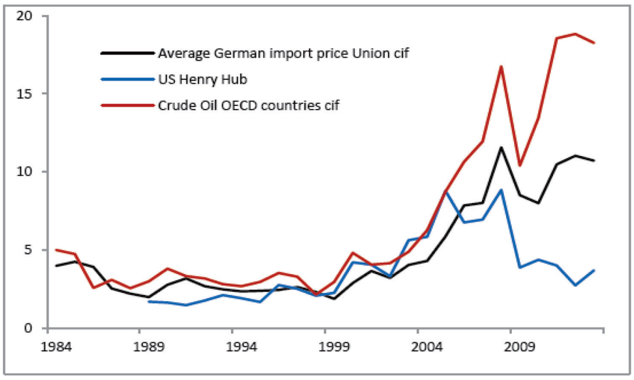
In summary, however, the dashed line in the chart at figure 15 shows the economic entropy change associated only with changes in the ratio **b** of residual reserves to total proven reserves discovered. As would be expected it starts at a positive level and reduces gradually to zero at about 1995, as the maximum output level approaches *[The kink in the curve at 1973/74 is partly owing to an abrupt change in world reserves, as recorded in OPEC records]*. The trend is echoed by the chart of the reserve ratios illustrated at figure 12, and accords also with the declining incremental change of entropy illustrated by the dashed line in the upper chart of figure 3. As yet the long-run oil entropy generation change curve has not moved into negative territory. The solid line at figure 15, however, shows the variations introduced by the ups and down of world oil prices, impacting on elasticity and hence entropy generation change. The world events of 1973, 1980, 1990, 2000 and 2008, already noted in the narrative, can be seen to move the curve at the selected points.

The author considers that more work needs to be carried out in this area to improve the analysis.

Of course, if new proven reserves of oil and/or natural gas are found *[including fracking]*, of sufficient economically extractable volume to increase significantly the ratio of proven reserves remaining to total proven reserves found, or real improvements are obtained for recovery factors applied to 'oil in place', or long-term recessive forces occur to reduce demand for energy, then peak production may be put off for a further period. On the assumption, however, that a peak will eventually be reached, it may be expected that production will then gradually decline in level over decades, corresponding approximately to the right-hand side of the production curves at figures 2 and 3.

In respect of natural gas, a world market approach to entropy/utility has not been attempted, owing to significant divergence of price trends. While European gas prices appear to follow those of the world oil market, in the USA gas prices have reduced, owing much to the introduction of fracking.

The technology of hydraulic fracturing or 'fracking' involves injecting a fluid made up of water, sand and various chemicals deep into the ground, causing nearby shale rock to crack, creating fissures for natural gas and oil to collect – so called shale gas and tight oil.



Data Source: BP Statistical Review

Figure 16 World natural gas and oil prices US $/million Btu.

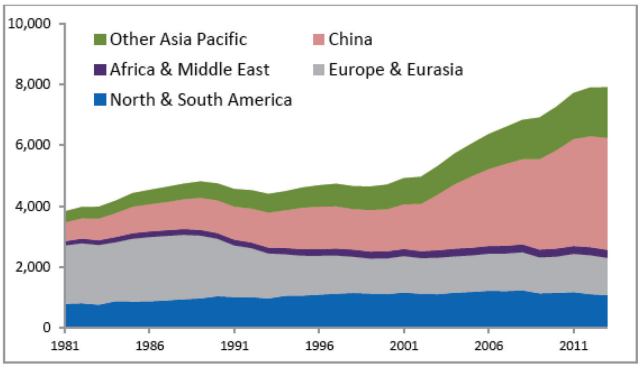
Such a technology could undoubtedly unlock substantial additional energy reserves. However, individual shale discoveries as found tend to last for only a short time, before prospectors have to move on to new sweet spots. A report of David Hughes *[Drill Baby Drill 2013 Post Carbon Institute]* indicates first year declines as much as 60-70%. Opponents to the technology cite environmental, safety and health hazards, such as water and air contamination, and potential earthquakes. The recent upturn in US oil and gas production is significantly owing to fracking. Further technology developments may follow.

A potential longer-term source of energy is that of gas hydrates, effectively solid methane and other gas particles surrounded by frozen water. Geologists estimate that there are very large amounts situated around the world, in seafloor sediments and in permafrost sediments in the frozen tundra of Siberia. The obstacles and risks associated with this source of energy are significant. First, reaching down through deep water, and then drilling down several thousand feet to reach the deposits, and second, methane hydrate is unstable once it is removed from its surrounding high pressure, giving rise to the problem of leakage on its way to the surface. Environmental concerns also exist: first, the possibility of destabilising the seabed, causing underwater landslides and potential tsunamis, and second, the release of large amounts of leaking methane into the atmosphere – methane is a much more potent greenhouse gas than carbon dioxide.

Coal

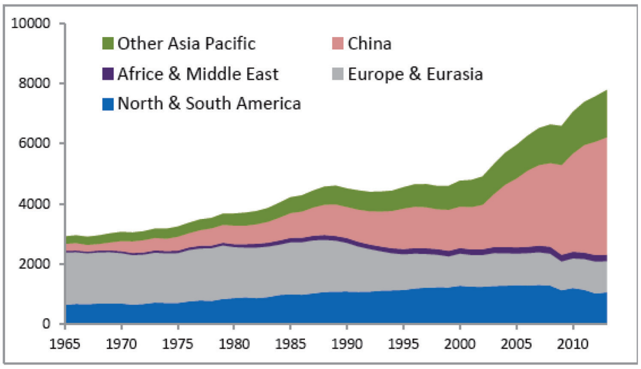
Besides oil and natural gas reserves, there is also some debate as to the extent of world coal reserves. According to the BP Statistical Review, total world remaining proven coal reserves at 2013 stood at 892 billion tonnes of coal; split 45% deep-mined bituminous/anthracite and 55% surface-mined lignite/sub-bituminous - the latter being of inferior quality to the former. More than three-quarters of these reserves are held by six countries: USA, Russia, China, Australia, India and South Africa. Coal is not widely-transported worldwide, being predominantly consumed in the country where it is produced. China and USA account for 60% of production and consumption. Figures 17 and 18 summarise production and consumption trends.

World coal demand and supply in America, Europe and Eurasia has continued on a steady and now declining path, whereas demand and supply in China has grown rapidly, with India and Australia also growing, the latter partly to supply China.



Source: BP Statistical Review

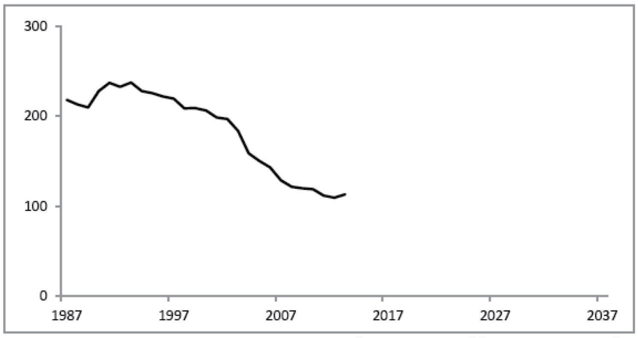
Figure 17 World coal production – Bituminous, Anthracite, Non-bituminous, Lignite M tonnes p.a.



Source: BP Statistical Review

Figure 18 World coal consumption – Bituminous, Anthracite, Non-bituminous, Lignite M tonnes p.a.

The chart at figure 19 indicates that over the years the net reserves remaining/production ratio has been steadily falling and now stands at 113 years, based on 2013 production levels. The rate of fall is currently about 5 years per year of advancement, inferring that potentially remaining reserves will likely cease to be of benefit rather sooner than a century.



Source: BP Statistical Review, World Energy Council

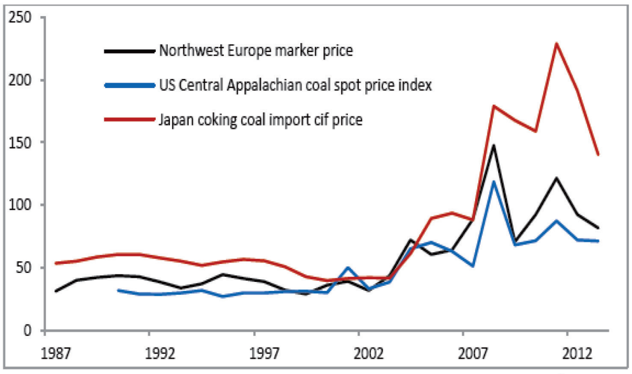
Figure 19 Ratio remaining coal reserves/current production rate – years.

A cautionary note regarding reserves is that the figures published by BP are those collated by the World Energy Council, which generally are only re-assessed every three years or so. However the last WEC figures for China relate back to 1992 *[62.2 bn tonnes bituminous/anthracite, 52.3 bn tonnes sub-bituminous/lignite, total 115.5 bn tonnes]*.

Dr Minqi Li *[article July 2011 The Oil Drum]*, however, states that Chinese news releases for 2001-2003 indicate reserves in the region of 189 bn tonnes, though the 'reserve base' *[published in the Chinese Statistical Yearbook]*, inclusive of mining losses, was higher at about 334 bn tonnes. The WEC reserve figures for China are likely therefore to be understated by a factor of about 40%. This would have the effect of raising the curve at figure 19 just a little in the short term, though the long term will unlikely be much affected.

A number of papers have been published using a Hubbert linearization approach to estimating world coal reserves and when 'peak coal' output is likely to occur *[Mohr, Evans (2009) Fuel; Rutledge (2011) Int'l Journal Coal Geology; Patzek, Croft (2011) Energy]*. On these bases, peak coal may be in the range 8-10 bn tonnes p.a. and occur between the present and two decades hence, with exhaustion perhaps 60 years away. Factors particularly hastening the outcome are the rate of growth of Chinese demand, and decreasing EROI as remaining reserves near their end and thinner seams are worked. The UK coal industry is a case in point. At its peak in 1910 output reached 264m tons p.a., employing more than a million people. Ninety years later it had reduced to 31m tons p.a.

Figure 20 illustrates trends in world coal prices. As with the natural gas market, owing to divergence of local coal price trends a world market approach to entropy/utility has not been attempted in this book.

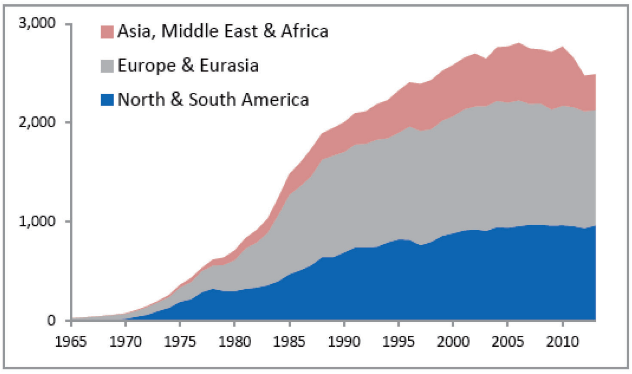


Source: BP Statistical Review

Figure20 World coal prices US$/tonne.

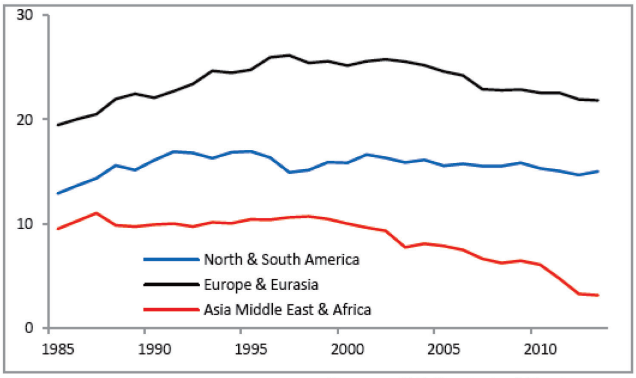
Nuclear Power

Nuclear power, although having low operating costs compared to fossil-fired plant, entails high capital costs and high waste and decommissioning costs, with waste potentially accumulating much beyond many generations of humankind. Nuclear capacity carries with it heightened risks of safety and security compared to conventional power plant. Figure 21 summarises world electricity consumption from nuclear power to the present time. After the rise of the 70s and 80s, growth began to slow down, and by about 2004 it had flattened off. Following the Fukushima Daichii tsunami disaster in 2011, consumption has fallen *[mostly in Japan]*. Figure 22 confirms that nuclear generated electricity has lost share to other capacity.



Source: BP Statistical Review

Figure 21 World electricity consumption from Nuclear capacity TWh p.a



Source: BP Statistical Review

Figure 22 Percent share electricity consumption from Nuclear capacity.

Notwithstanding the declining share of electricity consumption taken by nuclear power, the World Nuclear Association *[WNA]* reports that a number of countries are planning to build more capacity to be operable by 2030.

Table 2 Reactor Capacity, Operable & Planned – MWe January 2015

Country	Operable	Under construction	Planned	Proposed
USA	98756	6018	6063	26000
France	63130	1720	1720	1100
Japan	42569	3036	12947	4145
Russia	25264	7968	32780	16000
South Korea	20656	6870	11640	
China	19095	29548	71220	128000
Canada	13553		1500	3800
Ukraine	13168		1900	12000
Germany	12003			
UK	10038		6680	8920
India	5302	4300	21300	40000
Other	54194	14054	35830	100205
World	377728	73514	203580	340170

Source: World Nuclear Association

Notable additional capacity planned or proposed, set out at table 2, includes that of China, Russia, India and USA. Such future capacity, should it come to pass, will entail significant increased requirements for uranium.

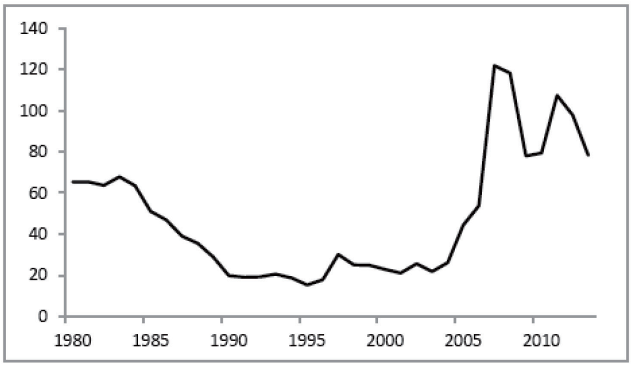
Historically uranium mine production has varied from about 60-70,000 tonnes in the 1980s down to about 35,000 in 1998, but with demand being significantly in advance of this. The shortfall has traditionally come from the decommissioning of Russian and US nuclear warheads, though this source is now gradually coming to a close. Since 2000 mine production has begun to rise again, reaching 59,637 tonnes in 2013. The WNA calculate that requirements in 2014 for uranium will approach 66,000 tonnes, only a little above current production levels.

Figures of the Red book published by OECD and the International Atomic Energy Agency project world mine production capability rising from 73,405 tonnes p.a. in 2011 to 109,400 by 2035, with two-thirds of this coming from just three countries, Kazakhstan, Australia and Canada. Such a production level would meet a significant proportion of the WNA estimate of planned and proposed capacity set out in table 2.

Currently, total reserves of uranium from traditional sources are estimated at about 5.3 million tonnes *[WNA 2011]*; this suggests a reserves/production ratio of 89 years. As with the analysis for coal *[see figure 19]*, with a likely pickup in demand in the next two decades, the ratio could then come down significantly, raising the prospect of *'peak uranium'* under current technology. Roper *[2013]* has calculated that a peak may be reached by 2040, with production rapidly scaling down thereafter.

Potential advances in nuclear technology over the current predominating PWR system that may impact on the above include the extraction of uranium from seawater, the development of fast breeder reactors and the use of the Thorium cycle. As yet none of these technologies has reached a useful stage, and set against this is the potential for further nuclear mishaps such as Three Mile Island, Chernobyl and Fukushima, and possible terrorist threats, raising NIMBY and NIABY objections.

Figure 23 sets out a chart of uranium spot contracts €/kg.



Source: Euratom Supply Agency

Figure 23 Uranium spot contract €/kg.

The price index has followed to some extent the trend of world crude oil prices, shown at figure 14.

Energy Return On Energy Invested (EROI)

The notion of EROI measures the net energy benefit to human society of investing in particular energy sources. At high values, there is little difference in benefit, but at low values, from about 5 downwards, the net % benefit to society reduces at an increasingly rapid rate. A ratio of 1:1 represents a break-even point, below which there is no perceived benefit in investing in a source of energy.

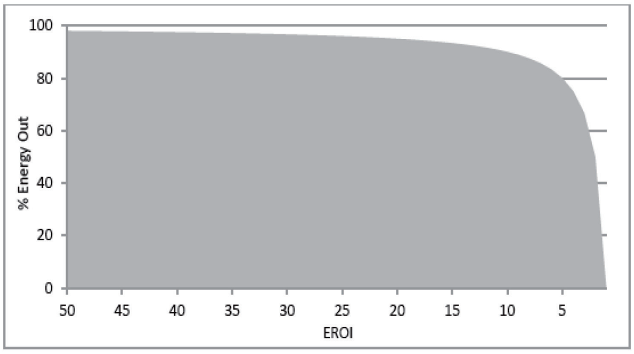


Figure 24 Energy Return on Energy Invested.

Measurement of the ratio depends upon how inclusive along the path from the source of the energy to the consumer one travels. In the case of oil, for example, one could measure it at the wellhead after extraction, further on after refining it into products, and still further after transporting the products across the globe to the point of use. Last one could measure the actual benefit from consuming the delivered product net of engine efficiency losses. At each stage losses occur, which a final consumer cannot utilise; effectively a series of entropy gains. Clearly, however, some humans *[other than the final consumer]* at each stage between the point of extraction and the point of consumption have benefited from their role in the industry. Taking into account all the interim stages therefore, an EROI figure much in excess of 1 is to be looked for when assessing alternative forms of energy.

There exists an extensive literature on the subject, which the author cannot pretend to improve upon, but it is worthwhile summating the main points impacting on the energy market. Hall, Lambert et al *[Energy Policy 2013]* set out a summary of the literature. They conclude that, worldwide, coal has an EROI of 46:1, oil & gas 20:1, tar sands 4:1, and oil shale 7:1. Analysis for nuclear energy suggests a mean EROI of 14:1. Ethanol and biomass have low figures, 5:1 and 2:1 respectively. Among the renewables *[which technically are not part of this section]* hydroelectric power has an EROI of 84, wind 18:1 and solar *[photovoltaic]* 10.

A positive point for renewables of wind and solar is the high quality of electric energy delivered, but a negative point is that they are less reliable and predictable, arising from changes in weather and hours of sunshine. A key point raised by Hall, Lambert et al is that global oil and gas EROI values have been declining over the last two decades or so; in the US, for example, from over 15 in 1990 down to about 10 in 2010, which may be owing to depletion. They note, however, that results for fracking may be high.

In respect of fracking, Yaritani & Matsushima *[Energies 2014]* suggest an EROI for shale gas of 12 when delivered to the consumer, but caution that this might change as production moves off 'sweet spots'.

All of the above indicates that some loss of net energy has and may continue to occur, in line with the gradual reduction in the ratio of net remaining reserves to gross proven reserves of resources set out in this paper.

Metals & Minerals

Aside from non-renewable sources of energy, the US Geological Survey *[USGS]* lists around eighty metals and minerals of importance to humans, though one might subdivide some of these, such as the rare-earths, of which there are seventeen *[from Scandium to Lutetium]*. Restrictions on space necessarily mean that only three sectors can be looked at in this paper: steel, cement and aluminium, though these cover much of the larger scale aspects of human industrial activity. Based on a paper by Gutowski, Ashby et al *[2013]* these alone account for about a fifth of total world primary energy consumption, with plastics bringing the total to about a quarter. They also have significant carbon footprints. The paper & board industry is also a large energy user, though this comes under the heading of renewable resources.

Steel

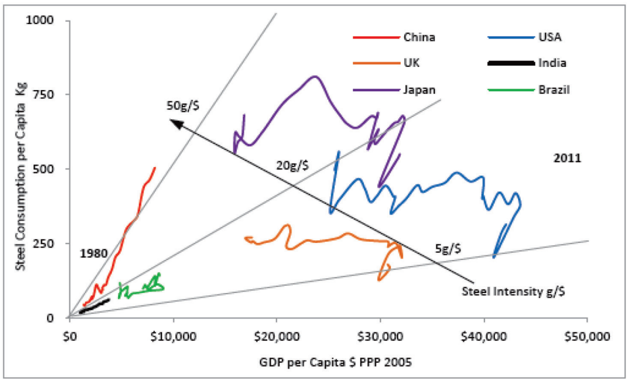
Steel consumption is one of the key inputs to becoming a developed country, though its use and the means of production depend upon the relative stage of industrialisation. During the early stages, the chief means of producing steel is by mining iron ore *[haematite]*, which is then mixed with coke *[a form of coal]*, limestone and air *[oxygen]* in a blast furnace to produce pig-iron. The molten pig-iron, which is carbon rich, is then transferred to a large BOS *[basic oxygen steelmaking]* vessel along with some scrap steel, and pure oxygen is then blown into it via a water-cooled lance, to reduce the carbon content of the iron to a desired level to make steel. These processes take place at high temperatures, typically in the range 1300 - 1900ºC.

In a developed economy, however, where significant amounts of scrap metal are already available, the process can instead be partly replaced by an electric arc furnace. Cold scrap metal can be charged into the furnace, and a very large three-phase electric current passed through it to melt the scrap *[at about 1200ºC]* to which appropriate amounts of other elements can be added to give the steel particular desired properties.

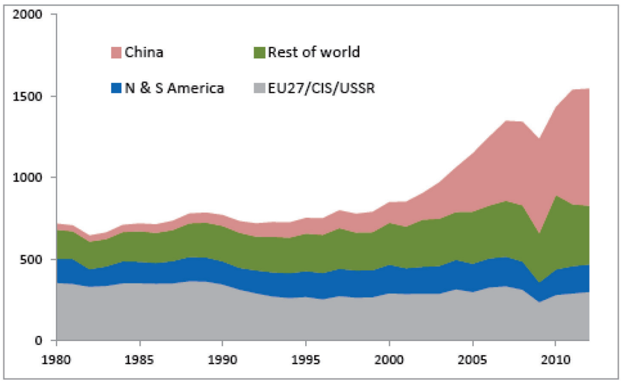
Although steel-making is a very high energy consuming industry, the World Steel Association estimate that energy consumption per tonne of crude steel produced in North America, Japan and Europe has been reduced by about 50% since 1975. The use of recycled scrap has reduced the need for raw iron-ore and coke burning significantly, with recycling rates at 2007 estimated to be 83% overall. For developing economies however, such as China and India, the main route into steel is still by the traditional blast furnace and BOS route.

A particular point to note is that of steel intensity, measured as the level of steel consumed/GDP, relative to the GDP per head of population. For developing economies, the steel/GDP intensity ratio rapidly grows, but as an economy matures, with an accumulated infrastructure, steel intensity peaks and then begins to decline. The chart at figure 25 illustrates this effect.

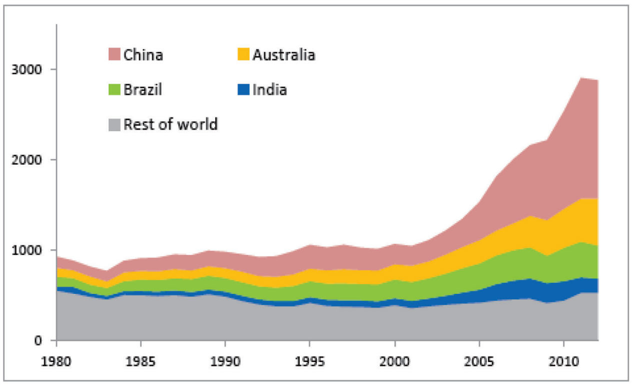
In China, growth of steel consumption per capita and steel intensity per unit of GDP is high, whereas, in the USA, UK and Japan, usage per head has levelled, and steel intensity is rapidly reducing, as these economies turn to other goals for economic affluence. To a significant extent this trend reflects also changes in primary energy intensity in an economy, as illustrated by figure 6. Figure 26 illustrates the growth in world production of steel, and figure 27, the growth in world iron ore production



Sources: Penn World, World Steel Association
Figure 25 Steel consumption per capita versus GDP per capita. 1980 - 2011.



Source: WSA
Figure 26 World steel production Mtonnes p.a.



Source: WSA
Figure 27 World iron ore production M tonnes p.a.

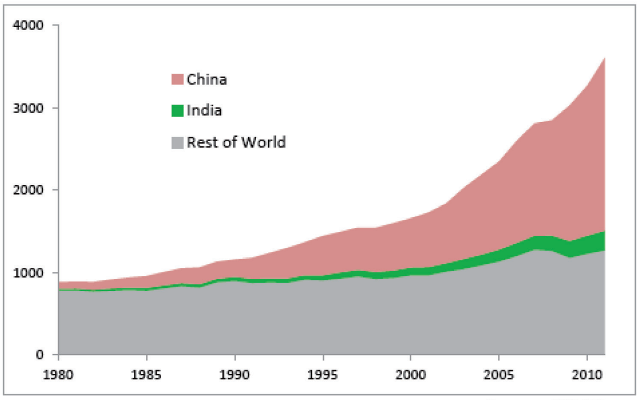
Steel production has doubled in the last decade, the rise mostly concentrated in China, accompanied to a lesser extent by other developing nations such as India. This has led to a tripling of world iron ore production. Readers should note also that a significant proportion of Australian iron ore production is exported to China.

While the USGS estimate that world crude iron ore reserves are about 170 billion tonnes, equal to about 58 years at current production rates, total crude iron ore resources, as yet untapped, are greater than 800 billion tonnes, equivalent to about 270 years at current production rates. It is not thought therefore that iron ore resources pose a problem in terms of a possible peak. Of rather more concern would be a potential peak in energy supplies, in particular coking coal, and a general rise in electricity prices should supply becomes restricted.

Cement

Cement, combined with sand, aggregates and water, is a basic input to the world building industry. It is produced by passing limestone and calcium silicate based aggregates through a large steel rotary kiln lined with refractory bricks. Hot gases, produced by burning coal, gas or oil in an external furnace or by a flame inside the kiln, are passed over the aggregate at a temperature of about 1500ºC. As with steel it relies on an energy source for its formation. Cement is manufactured all over the world.

The relationship of cement consumption to an economy is similar to that depicted for steel set out in the chart at figure 25, but with cement per head and cement intensity to GDP, replacing those for steel. Developing countries such as China, India and Brazil tend to have rising cement consumption per head and rising cement/GDP intensities, whereas developed economies, such as Japan, USA and the UK, have declining consumption and intensity rates. Figure 28 illustrates world production to date.



Source: USGS
Figure 28 World cement production M tonnes p.a.

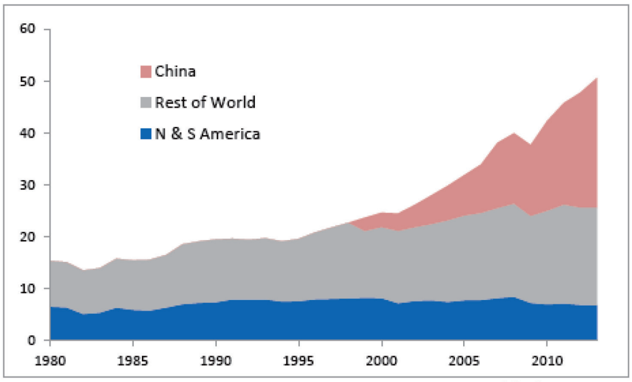
World production is dominated by China, which commands more than half of output, and rising.

The USGS indicates that although individual reserves are subject to exhaustion, cement raw materials are geologically widespread and abundant and future shortages are not anticipated. In the construction sector, concrete *[made from cement]* competes with substitutes such as brick, aluminium and steel, though it does not have much tensile strength, which is the reason why large buildings are built with steel-reinforced concrete. In road building, the main competitor is asphalt.

Aluminium

Primary aluminium ultimately comes from bauxite, which is one of the most abundant minerals in the Earth's crust. Initially alumina *[aluminium oxide]* ore is extracted from bauxite via the Bayer process, involving crushing the bauxite, and then combining it with hot sodium hydroxide under pressure. The alumina ore produced is then taken through the Hall-Héroult process, whereby it is dissolved in molten cryolite at about 1000ºC. The mixture is then electrolysed by passing low voltage direct current through it, depositing aluminium at the cathode. As with steel and cement, it is a hungry energy consumer, though mainly of electricity.

Aluminium's key properties are its high strength, light weight, resistance to oxidation and ability to conduct electricity. Figure 29 summarises world production of aluminium.



Source: World Aluminium

Figure 29 World aluminium production M tonnes p.a.

A similar picture to steel and cement emerges, with increased production occurring in developing countries, and level production in developed countries. China, again, is rapidly developing to dominate world production.

Renewable Resources

In contrast to non-renewable resources, which involve once and for all use and a gradual reduction in reserves, renewable resources involve repeated use, up to a carrying capacity, but subject also to factors which might impact at different times to limit the size of that capacity. The chief resources that come within this description include the following:

- Humankind
- Water
- Land and soil
- Plant life
- Animate life
- Energy from sunlight and movements in wind and water

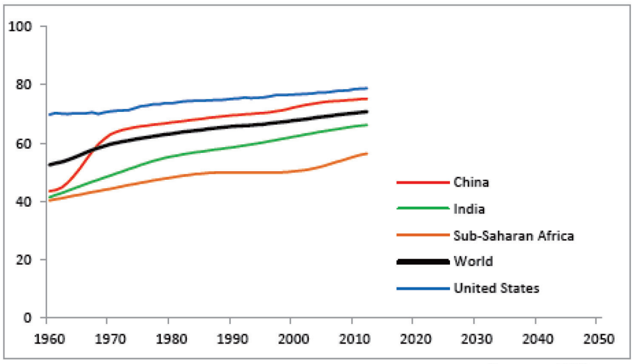
Not included in the above list are changes in the atmospheric climate of the Earth, which will be looked at later.

From the discussion earlier in this paper, it is self-evident that some animate life, including humankind, would be regarded as predatory, being dependent upon prey and resources to sustain themselves, but that other animate life would be seen more as prey. However, even a cow could be regarded as predatory with regard to the grass and vegetation that it relies on for succour, and likewise, grass and vegetation in turn compete for water, soil and sunlight for their sustenance. Thus all living renewable resources operate via complex stocks, flows and interrelating chains and feedback mechanisms.

Humankind

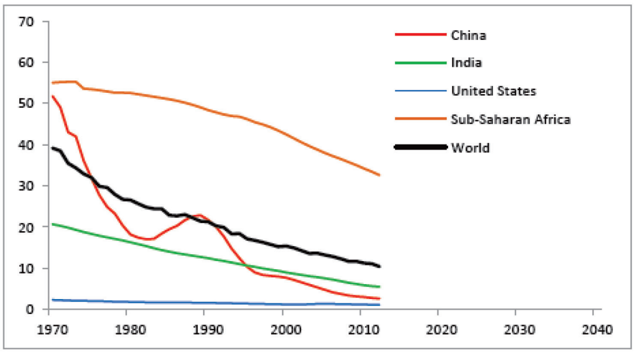
In this section we look at the development of the human race, in particular more recent trends which might indicate whether the world population is approaching a peak, is continuing to grow or may decline in the coming decades. Succeeding sections deal with some of the other resources with regard to the extent to which they might impact on the human population or, in reverse, their size and condition has been influenced by growth in human population and activities.

Comprehensive demographic statistics collected by the UN Department of Economic & Social Affairs indicate three very clear population trends. Figure 30 shows changes in longevity for selected economic areas, figure 31 incidence of deaths of children under five among all deaths and figure 32 the development of fertility per woman.



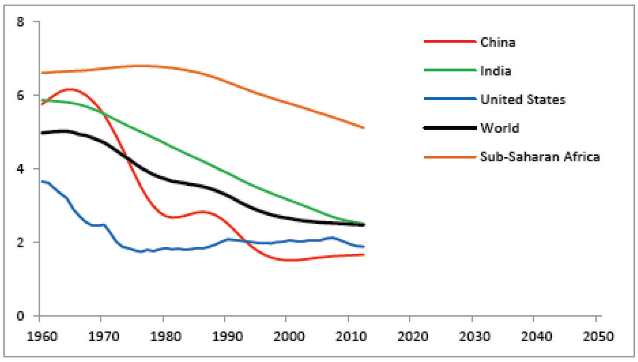
Source: UN

Figure 30 Life expectancy at birth (male & female) years.



Source: UN

Figure 31 % of deaths of children under 5 years to total deaths.

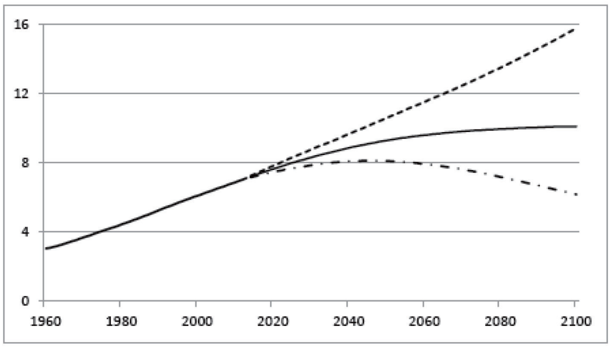


Source: UN

Figure 32 Fertility per woman aged 15-44 (number of children).

Life expectancy has risen in most countries over the last five decades, with an indication that this may continue for some time. Growth in economic wealth & well-being and the benefits of scientific advances are the likely forces at work, as a significant input to the trend has been the reduction in the death rate of young children. The latter in particular means that parents in most parts of the world currently do not need to plan for large families in order to propagate and sustain the species. A follow on from this trend has been a significant decline in fertility per woman, which appears likely to fall further, perhaps even to an average rate around 2 within two or three decades or so. Only in Africa is a rate above 2 likely by 2050, though even here a downward trend is evident.

A consequence of a continuing low fertility rate and a rise in longevity is that population will continue to rise for a few generations until the crude death and birth rates begin to meet each other. For a sufficiently low average fertility rate, perhaps a little over 2 for the world, population will begin to level off. For a very low fertility rate, eventually population will begin to decline. The United Nations have produced updated *[2010]* projections of world population, based on a number of scenarios, of which three are illustrated at figure 33. They assume that average world fertility rates per woman will eventually reach: low 1.5, medium 2.0, and high 2.5; with a resulting spread of population: from a peak and decline, to level or on to continued growth.



Source: UN Department of Economic & Social Affairs population division

Figure 33 World population prospects – the 2010 revision billions people.

Exactly what trajectory will eventually come to pass, however, will depend upon the unfolding forces at work and world events. Mass effects, such as famine and recurrence of disease, or a restriction on resources, could curtail some of the benefits that humans have previously enjoyed, resulting perhaps in a step backwards in economic development.

Water

Water is an essential ingredient to sustenance of all life forms. Summaries by Shiklomanov *[IHP UNESCO 1998]* and Gleich & Palaniappan *[Proceedings National Academy of Sciences 2010]* indicate that the Earth contains a vast amount of it – 1,386 million km^3 *[cubic kilometres]* – but of this, 97.5% is made up of saline water and only 2.5% fresh water. Of the latter small proportion, 68.7% is locked into the Arctic, Antarctic and mountainous regions in the shape of ice and permanent snow cover, and another 30% *[10.5 million km^3]* appears as fresh groundwater around the world. Only a relatively small amount, 1.3%, appears in lakes, wetlands, rivers and clouds. Every year the Earth's hydrological cycle turns over in the region of 577,000 km^3 of water, 502,800 km^3 evaporating from the Earth's oceans and 74,200 km^3 from the land; but in the other direction rather more of the turnover, 119,000 km^3, falls as precipitation to the land, leaving 2,200 km^3 to aquifer groundwater and in the region of 42,600 km^3 per year as runoff to rivers, eventually to be returned to the oceans. These amounts alter slightly with the complex eco-cycles that the Earth moves through. Table 3 illustrates Shiklomanov's estimate of world water resource flow by geographic area, along with updated data of human population for 1994.

1994	Human Population millions mid-year	Land Area millions km^2	Average Water Resources km^3/year	Potential water availability per human m^3/year
Europe *	729	10.5	2,900	3,980
North & Cent America	455	24.3	7,890	17,300
South America	317	17.9	12,030	37,900
Asia +	3,432	43.5	13,510	3,940
Oceania	29	9.0	2,404	82,900
Africa	699	30.1	4,050	5,790
World	5,661	135.3	42,784	7,560

Source: Shiklomanov World Water Resources IHP UNESCO 1998
** inc FSU*
+ inc Siberia & far East Russia

Table 3 World water resources 1994.

While water is a renewable resource, it has variable cycles of renewal. Shiklomanov estimates that, compared to soil moisture, which has an annual cycle *[according to seasonal fluctuations]*, by contrast groundwater is recharged slowly, over some 1400 years, with lakes in between at 17 years. Consequently, the two key water sources essential to land-based life are precipitation to the soil and river runoff. Groundwater becomes important to humans for areas of the Earth that are short of the main sources of water, and then only for the short term, because of its long recharge period. Fresh water, predominantly from rivers, is the key resource for human industrial activity and agricultural irrigation. The top fifty rivers of the world account for approaching half of total river water resources.

Compared to some energy and material resources, which may have some substitutability between each other, water cannot be substituted. It is its own substitute. Outside of river flow and local precipitation, it is expensive either to transport from other areas or to produce from ocean-water; the latter by desalination, requiring energy consumption to evaporate it as salt-free steam before condensing back to liquid for use.

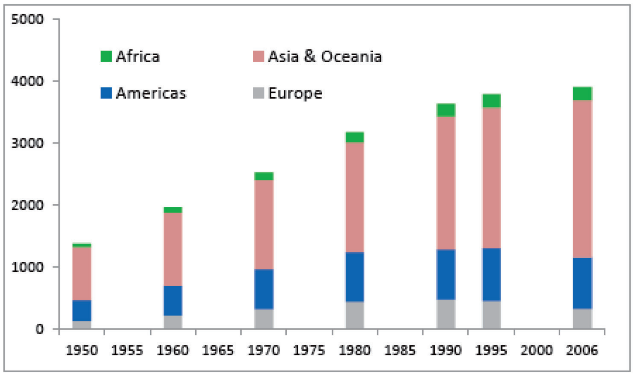
Available data of renewable freshwater withdrawal and consumption are not standardised and are collected from a variety of sources *[see The World's Water - Gleich et al]*, being either measured directly or modelled based on specific assumptions. Some data are recent and some many years old. Consequently care should be exercised when applying such data to derive conclusions. The writer does not profess to be an expert in these matters. Table 4 is a summary of more recent world water withdrawals by continent.

2006	Population millions mid-year	Total Water Withdrawals km^3/year	Of which %			Withdrawals per head m^3/year
			Municipal	Industrial	Agricultural	
Europe	732	333	22	56	22	455
N America	332	604	14	43	43	1,819
Cent & S America	566	225	22	12	66	398
Asia	3968	2507	9	10	81	632
Oceania	34	19	26	16	58	558
Africa	924	214	13	5	82	232
World	6556	3902	12	19	69	595

Source: UN World Water Development Report 2014 p178 indicator 6

Table 4 World water withdrawals 2006.

These figures, alongside those of Shiklomanov *[World Water Resources IHP UNESCO 1998],* indicate that world water withdrawals are continuing to escalate, as shown in figure 34, yet average available water resources, as per table 3, remain about the same.



Sources: Shiklomanov World Water Resources IHP UNESCO 1998
UN World Water Development Report 2014

Figure 34 World water withdrawals km^3/year.

The major area of increase in water withdrawals has been Asia, in particular, China and India.

Gleich and Palaniappan *[The World's Water 2008-09]* estimate that about one-third of the world's human population lives in countries with moderate to high water stress, defined by the United Nations to be water consumption that exceeds 10% of renewable freshwater resources. A working paper of Gasset, Reig et al *[World Resources Institute, Dec 2013]* ranks hydrological indicators of countries, river basins and most populous river basins, using the ratio of annual water withdrawals to annual renewable supply to measure baseline water stress. Countries high on the list include those in the Middle East, Mongolia, Pakistan, Spain and India. River basins with high water stress include Indus and Ganges *[India]* and Yongding He, Liao He and Huang He *[China]*. Gleich *[The World's Water 2008-09]* concludes that China in particular has developed a set of water quality and quantity problems as severe as any on the planet.

A paper by Wada, Ludivicus et al *[Geophysical Research Letters Vol 27 L20402 (2010)]* concludes that global depletion of groundwater resources has increased, from 126km^3 *[±32km^3]* in 1960 to 283km^3 *[±40km^3]* in 2000. At 2000, depletion per annum was equal to 39% of global annual groundwater abstraction. Particular hotspots included North-East China, North-East Pakistan, North-West India, some parts of the USA, Iran, Yemen and South-East Spain. Such depletion has run-off into rivers, ultimately to the oceans, giving rise to an increase in sea-level. Figures of the 4th edition of the UN World Water Development Report *[figure 3.8 WWDR4]* indicate that groundwater abstractions are growing rapidly.

Water stress and availability worldwide will likely pose a potential constraint in the future, engendering negative forces to limit or reduce output, with effects across national boundaries.

Land & Soil

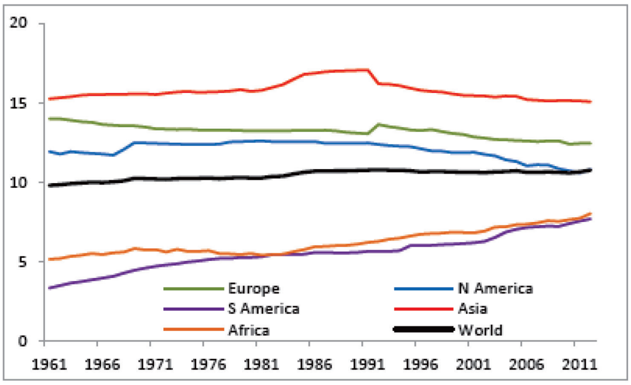
Besides water, the states of land and soil resources are also key factors on which the carrying capacities of human, animal and plant life depend. Food-balance statistics for 2011 *[FAOSTAT]* indicate that, worldwide, average food supply per human per day was estimated to be 2,868 kcals, but of this only 34 kcals or 1¼% came from fish, seafood & aquatic products. Preserving cropland and maintaining soil fertility therefore should be of highest importance to human welfare. Table 5 summarises the distribution of world land by type of use.

Around Year 2000	Total Land M Ha	Of which %					
		Cultivated	Grassland Woodland Ecosystem	Forest	Sparsely vegetated & barren	Settlement & Infra - structure	Inland Water
Europe *	2243	13.5	32.8	44.4	6.7	1.0	1.6
N America	2090	11.0	32.2	29.1	21.6	0.7	5.4
Cent & S America	2036	8.4	37.6	46.5	5.3	0.7	1.5
Africa	2986	8.2	37.4	17.4	35.2	0.8	1.0
Asia	3096	18.2	25.7	17.3	35.4	2.4	1.0
Oceania	842	6.2	62.5	15.6	15.1	0.1	0.5
World	13293	11.7	34.7	28.1	22.5	1.1	1.9

Source: FAO UN SOLAW Report 2 Table 1, GAEZ 2009.
*Inc Russia, Siberia

Table 5 Regional distribution of land use/cover - millions Ha.

Given that the total land surface of the Earth is approximately constant in size *[barring changes in lake size and sea level]*, it is of interest to note movements in it use, in particular, the share taken by arable land, as shown in figure 35.



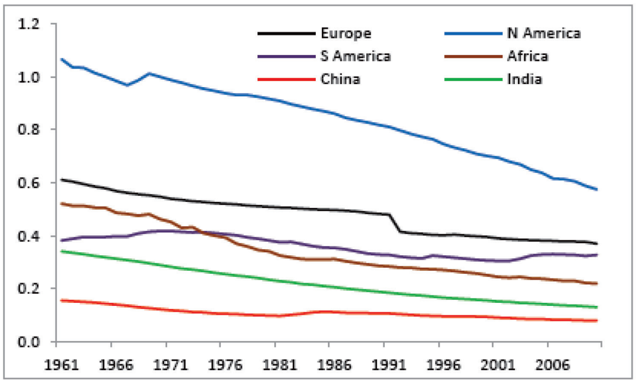
Source: FAOSTAT

Figure 35 Arable land as a percent of Total land.

Until about 1990, world arable land as a percent of the total had been rising, but thereafter it began to level off *[the kinks in the Asia/Europe lines likely arise from a switch in allocation of East Russia to the statistics]*. However, the figures for 1990 onwards hide some underlying changes: first, a gradual decline in the proportions in Europe, North America and Asia, likely arising from land degradation, soil erosion and a switch to industry; and offsetting this, a rise in the proportions for Africa and South America. Second, alongside the latter, has been a reduction in the share of forest land to the total in these areas: South America from 54.1% down to 49.1%, and Africa from 25.3% down to 22.5%.

Given the rise in world human population over the last five decades, the amount of arable land *per capita*, on which crops can be grown to feed each human being, has fallen dramatically.

Currently the world figure is about 0.2Ha *[equivalent to an area 40 x 50 metres per person]* and appears set to decline further. While food for humans comes also from the oceans *[fish]* and grassland *[animals]*, the chief source is still that that can be grown on arable land.



Source: FAOSTAT

Figure36 Arable land per capita – Ha.

The main factors describing the states of land and soil worldwide are the extent and trends of land degradation, soil erosion and desertification. Land degradation measures the negative changes in the capacity of the ecosystem to provide goods and services. One might venture that the effect of this would impact on all living things and not just humans. Soil erosion has a narrower scope than land degradation and is concerned with absolute soil losses in terms of topsoil and nutrients, including soil carbon. Desertification refers to land degradation in arid, semi-arid and sub-humid lands that has become practically irretrievable.

Erosion occurs when soil is left exposed to raindrops or wind energy, with generally the finer more nutrient matter being flushed away, leaving less nutrient stuff behind. However, top-soil covered by plant biomass and/or trees, living or dead, is sheltered significantly from this effect. Pimental and Burgess *[Agriculture 2013, 3]* indicate that eroded soil contains three times as much nutrient per unit of weight than the remaining soil left behind. Crawford *[World Economic Forum Dec 14. 201226]* points out that just a handful of good topsoil literally contains billions of microorganisms which recycle organic material, and that moderately degraded soil will hold much less water than healthy soil. Lal *[Food Sec. (2009) 1:45-57]* concludes that soil degradation reduces crop yields. Thus preventing soil erosion is one of the keys to maintaining the productivity of agricultural land.

A key driver to land degradation is the activity of humans to change the world to their *[short-term]* benefit, though changes in climatic variations also have an input. Human activities cited by UNCCD *[UN Convention to Combat Desertification]* impacting on trends include deforestation, overgrazing, improper irrigation practices, poverty and political instability. According to UNCCD, severe land degradation now affects 168 countries across the world.

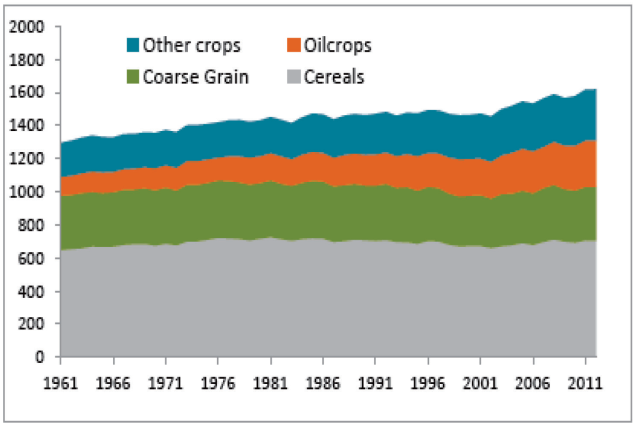
The UN has undertaken a number of initiatives to investigate and measure the problem. Oldeman, Hakkeling et al *[ISRIC 1991]* have collected data on some key indicators for national, regional and global areas. The method employed to provide the data was by mapping individual small areas of the world and combining them together. Key indicators included types of degradation *[water, wind, chemical etc]*, the degree and extent of degradation, and their causes, such as deforestation, overgrazing, agricultural and industrial activities, and over-exploitation of vegetation. About 15% of the Earth's land surface was found to be degraded in some way, and of this about 15% was at a strong/extreme level. Areas with high degradation included parts of Asia, Africa and Central America.

Nachtergaele, Biancalani and Petri *[Thematic report 3 SOLAW 2011]* state that land degradation processes are on-going over a large part of the land surface of the Earth. For less populated areas, most of the degradation was owing to soil erosion and biodiversity loss, whereas in most agricultural areas, soil depletion, pollution and water shortages were common. They concluded that 25% of global land degradation was at a high level, and that high land degradation was associated with a high level of poverty *[figures 6 and 7 of the report]*.

A particular problem with land resources is that global time series data are hard to find in order to measure trends in degradation, and the extent to which matters may be improving or worsening. A recent UNCCD report *[Drylands Desertification]* states that 24% of global land was degraded between 1981 and 2003; though this was offset by 16% showing an improvement. An ISRIC report 2008/01 *[GLADA report 5]* indicates that land degradation is cumulative and that the 15% figure for the 1991 report referred earlier in this section has now risen to 24%.

Pimental and Burgess *[Agriculture 2013, 3]* estimate that about 10 million ha of cropland are lost each year, owing to soil erosion, and that the losses are highest in Asia, Africa and South America. Their figure implies a loss of cropland at an annual rate of about 0.6% p.a., which may not sound very much, but cumulatively over a number of years, can escalate to a very large reduction. Land resources are being degraded year by year, impacting on their ability to regenerate themselves, and thereby provide the basis on which to grow food to feed humans and other animate life. Thus what was a renewable resource is gradually being turned into a non-renewable one.

Figure 37 illustrates the development of the key harvested areas in the world: cereals *[wheat and rice]*, coarse grains *[maize, barley, oats, sorghum]*, oil crops *[soybeans, groundnuts, olives, rapeseed]* and other crops *[roots, tubers, pulses, tree-nuts, fibre crops, vegetables, fruit]*. World area harvested for cereals has not risen above levels seen in the mid-70s, and that for coarse grain has declined by 5% over the same period. The areas for oil crops and other crops have expanded significantly, however, to take the overall area harvested to 1620 MHa, about 15% above that for the mid-70s.



Source: FAOSTAT

Figure 37 World area harvested – M ha – by main crop type.

Human Dietary Trends

The UN FAO *[Statistics Division report October 2008]* sets out a recommended minimum dietary energy supply *[DES]* per human in the world of 2414 kcals/day *[equivalent to about 2.8kWh]*. The measure is derived from food balance sheets compiled by the FAO. This figure is not far removed from the value of 2600 kcals estimated by MacKay *[Sustainable Energy – without the Hot Air, (2008)]* for a moderately active person weighing 65kg. The FAO figure provides a base to calculate the relative level of human food deprivation around the world. Figure 38 illustrates trends since 1961 for some major countries and geographic areas.

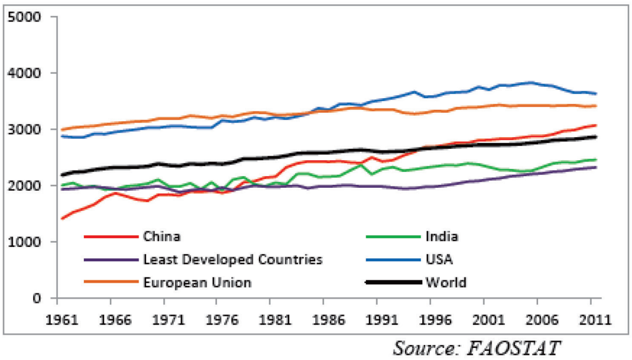


Figure 38 Grand total food-supply per capita: – kcals/day.

In general, food supply per capita has gradually risen, with the average for the world reaching 2868 kcals/day by 2011, in excess of the minimum recommended daily dietary requirement. As might be expected, there is a wide distribution about the average, with the USA reaching 3,833 in 2005, though it has since declined a little since then. At the other end of the scale are the least developed countries averaging 2324 in 2011, with some much below this level. Of particular note is the rapid rise in food supply per capita achieved by China over the 50-year period. The World Health Organisation reports *[fact sheet 311]* that, worldwide, obesity has nearly doubled since 1980, with 1.4 billion adults being overweight and 0.5 billion being obese.

A trend that has become more prevalent is that of rising meat consumption, as illustrated by figure 39. It is well-known that energy input required to produce a given weight of food varies by type of food, from corn at about 1kWh per kg up to 70kWh for a kilogram of beef *[Sources: McKay, Sustainable Energy – without the Hot Air (2008); Ghanta, The Oil Drum (2010)]*. These figures do not include the power costs associated with farming machinery, fertilising, refrigerating and transporting food around the world. In addition, significant numbers of cattle and poultry are now fattened on corn and grain rather than reared on grass/pasture land.

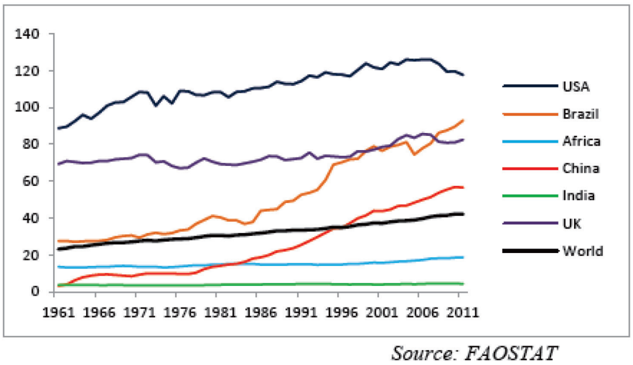


Figure 39 supply meat per capita: – kg/year.

Thus the trend towards meat consumption has magnified the load on cultivated land significantly. An article of Worldwatch Institute *[Is meat sustainable? Vol 17 No. 4 (2004)]*, concludes that meat-eating is becoming a problem for everyone on the planet.

The Green Revolution and Yield

The 1960's saw a transfer of technology from the developed to the developing world concerning high yielding varieties of grain, and increasing use of irrigation, fertilisers and pesticides to improve crops yields, which has continued to the present day. Figures 40 and 41 show the inexorable rise in wheat and maize yields since 1961. Similar rises in yield have occurred in the world of rice.

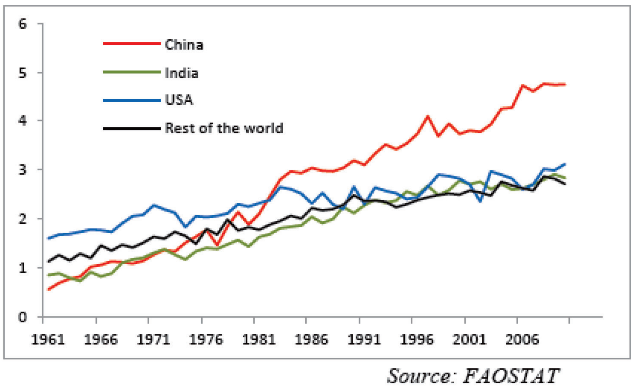


Figure 40 World wheat yield – tonnes/ha p.a.

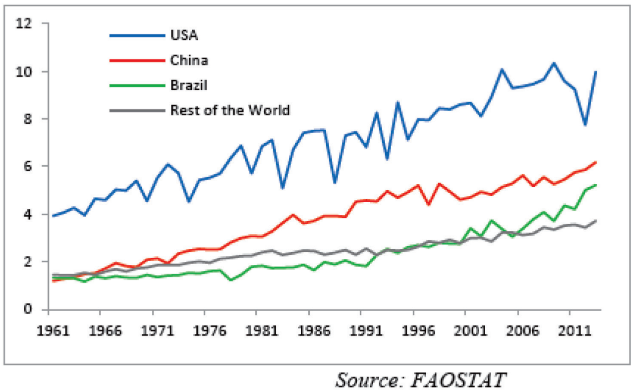


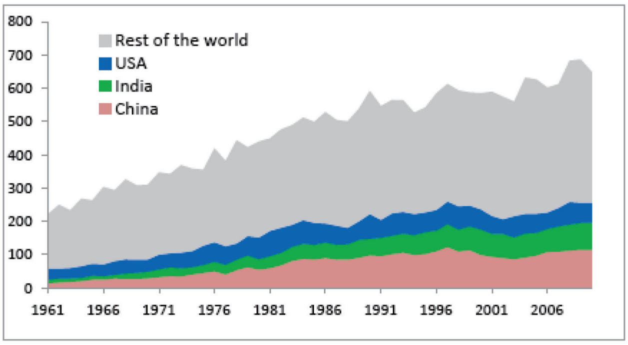
Figure 41 World maize yield – tonnes/ha p.a.

Many of the trends however do not exhibit exponential growth, but are more linear in shape, implying that as time goes on rises in production levels may slow down. Grassini, Kent et al *[Nature Communications Dec 2013]*, after reviewing trends for all the main countries in each of the world's continents, come to the same conclusion, and that there is also strong evidence of yield plateaus in some of the world's most intensive cropping systems, though a number of years may be required before a plateau can be deemed to be statistically significant. Hypotheses cited that may be contributing to possible plateaus include: biophysical yield ceilings for specific crops, land degradation, shifts to regions with poorer soils and climate, policies on the use of fertilisers and pesticides, and poor R&D in agricultural research.

Time series of the UN FAO concerning fertiliser production *[nitrogen, phosphate and potash]* are not continuous, owing to a change in data methodology, and it is not possible therefore to deduce a long term trend. Production figures over the last decade however show a gradual rise from 152Mt p.a. up to 208Mt p.a. in 2012.

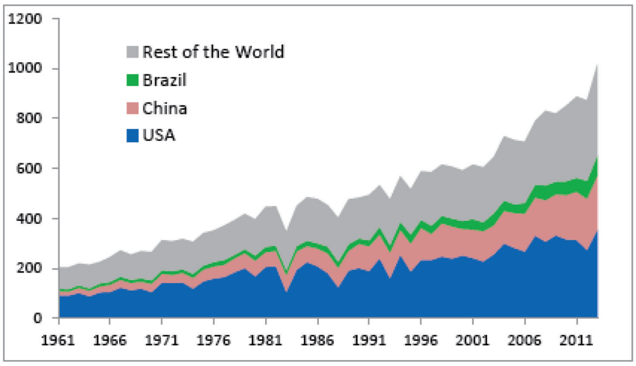
Cereal and Grain Production

Figures 42-43 illustrate key trends for world production of wheat and maize.



Source: FAOSTAT

Figure 42 World wheat production – M tonnes p.a.



Source: FAOSTAT

Figure 43 World maize production – M tonnes p.a.

In respect of wheat, at 2010 world area harvested had declined by more than 9% from a peak in 1981, with the decline being more marked for the USA *[41% since 1981]* and China *[18% since 1986]*. World yield per hectare continues to rise, though not exponentially. Chinese yield per acre has escalated dramatically. The net of these two trends appears to be for a continuing rise in production but at gradually reducing rates, with the possibility of peaking, perhaps in under two decades. World production per head of population peaked in 1990 at 111kg/hd, but is now down to 94kg/hd in 2010, a reduction of more than 15%.

World maize appears to be unstoppable, with area harvested, yield and production all escalating. However, the increase has been more than off-set by declines in other coarse grains, such as barley, oats, rye and millet. World rice production, not illustrated, has shown significant growth, though not as fast as that of maize.

Meat

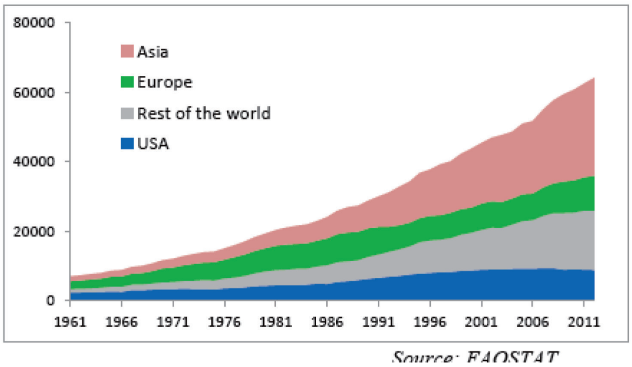
Turning now to meat, as noted at figure 39 earlier, meat consumption worldwide has been rising, particularly in China and Brazil, though none has reached the level sustained by USA. Table 6 summarises the world position between 1961 and 2012.

While all stocks have risen, that for chickens has expanded by more than 5-fold, with pig production also showing high growth. The short period for a chicken to come to maturity is a particular feature. Figures 44 and 45 illustrate production trends of these two livestock types in more detail.

Table 6 World Livestock Production

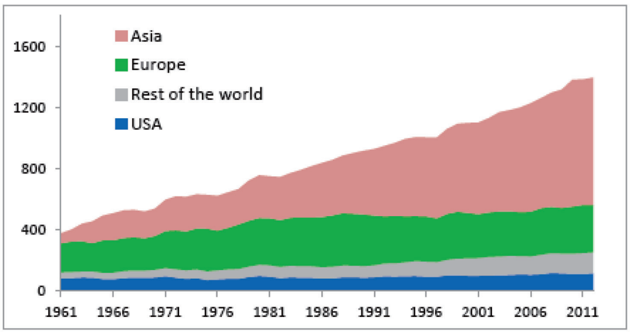
		Stock	Stock per Human	Slaughtered	Production	Production per Human
		Millions	No.	Millions p.a.	M Tonne p.a.	kg p.a.
Cattle & Buffalo	1961	1030.5	0.33	180.7	28.8	9.3
	2012	1676.8	0.24	321.2	66.9	9.5
Poultry & Birds	1961	4355.1	1.41	7014.6	8.9	2.9
	2012	23399.4	3.30	64135.7	105.6	14.9
Sheep & Goats	1961	1343.0	0.44	433.6	6.0	2.0
	2012	2160.0	0.31	975.8	13.8	1.9
Pigs	1961	406.2	0.13	376.4	24.7	8.0
	2012	969.9	0.14	1394.5	109.1	15.4

Source: FAOSTAT



Source: FAOSTAT

Figure 44 World chickens slaughtered – millions p.a.



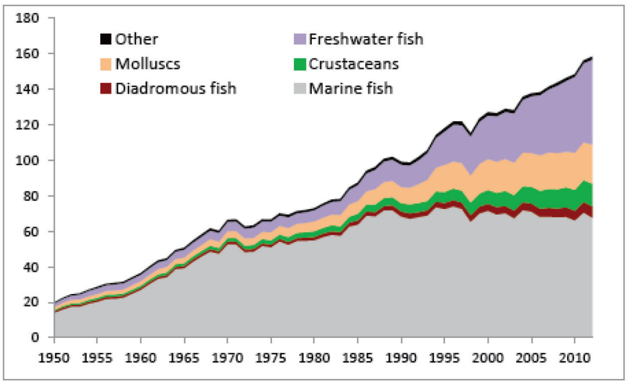
Source: FAOSTAT

Figure 45 World pigs slaughtered – millions p.a.

Livestock, of course, provide multiple benefits to humans besides being sources of meat – including milk, eggs, wool and skins. However, they are also significant emitters of greenhouse gases, methane and nitrous oxide,

Fish

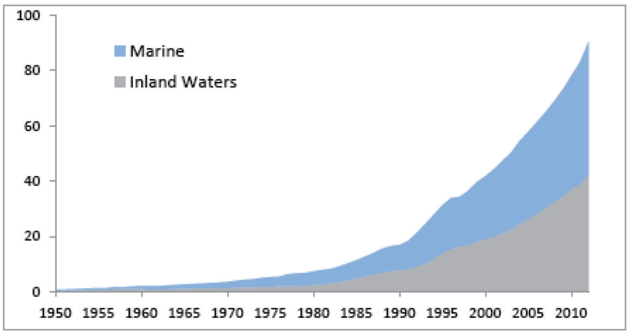
The world's fishing industry has long been the subject of debate with regard to fish stocks and the extent to which those in particular parts of the world have been over-exploited or depleted. A FAO newsroom summary of a UN FAO report *[Review of the State of World Marine Fisheries Resources 2012]*, sets out, area by area, the degree to which each has been fished. Overall, 3% are regarded to be underexploited, 20% moderately exploited, 52% fully exploited, 17% overexploited, 7% depleted and 1% recovering from depletion. All of the oceans have areas where particular fish species have been over-fished and depleted through human activity. The result has entailed the introduction of fishing quotas and suspensions in order to allow stocks to replenish themselves over time. The net result of this has been to call a halt to expansion of marine capture production, as highlighted in figure 46, though offsetting the fall back in marine fishing, however, has been an increase in freshwater fishing.



Source: FAO FISHSTAT

Figure 46 World capture production – M tonnes p.a.

Bostock, McAndrew, et al *[Phil. Trans. R. Society 365 (2010)]* state that growth in aquaculture has been driven by favourable economics in intensive farming, with China being the largest producer. The majority of freshwater aquaculture is pond based requiring controlled eutrophication using fertilisers as well as feedstuffs from grain and other crops *[somewhat similar to the fattening of animals in meat production processes, again adding pressure to land-based agriculture]*. Figure 47 illustrates trends in world aquaculture.



Source: FAO FISHSTAT

Figure 47 World aquaculture production – M tonnes p.a.

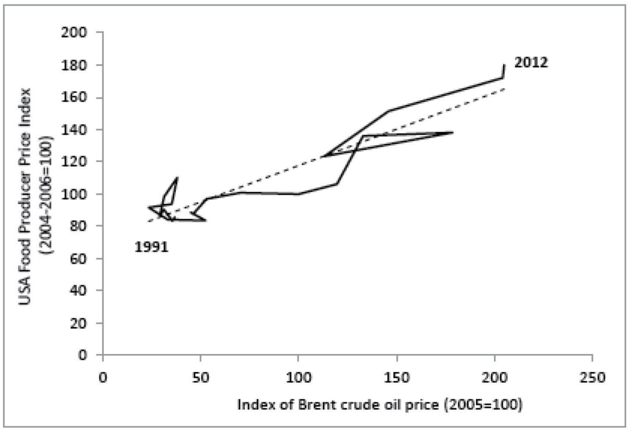
Food Supply & Energy Consumption

According to the UN FAO *[Issue paper: Energy-Smart Food for People and Climate (2011)]*, the food sector accounts for around 30% of the world's energy consumption. For high GDP countries, the greater proportion of energy consumption is for processing and transport, whereas for low GDP countries, cooking consumes the higher share. Primary farming alone *[cropping, pastoral & intensive livestock, aquaculture & fishing]* accounts for about a fifth of food energy consumption. The rest occurs higher up the trading chain. One has only to think of the mechanical activities involved in tilling the land, sowing seed, irrigation, producing and adding fertiliser, harvesting crops, transporting to food centres *[often across oceans]*, processing in factories and distributing to retailers, to see how energy consumption *[mostly non-renewable]* is accounted for.

It is of interest to compare the dietary energy supply/day per human obtainable from food *[see section on human dietary trends]* with primary energy consumption per capita, the latter providing the energy to power machines, provide human comfort and transport food, goods and commodities around the world. At standard conversion ratios, 2868 kcals/day of food is equivalent to about 3.33 kWh of energy intake, whereas, on average, each human in the world, as part of an economic system, effectively also consumes about 56.5 kWh of primary energy per day *[coal, gas, oil etc. Source primary energy data: BP Statistical yearbook 2013]*. The latter figure varies significantly by country. Primary energy consumption per capita for India, for example, is only 14.8 kWh, whereas that for USA is fifteen times higher at 225.6kWh. Nevertheless, taking the UN FAO world estimate of 30% of primary energy consumption for the food sector, then 30% of 56.5 kWh per head equates to 18.8 kWh, just to get 3.33 kWh of food value to each consumer in the world, a mark-up of more than 5½ times.

Clearly, without the availability of primary energy, many people in the world would have to find alternative, life-changing self-sufficient means of feeding themselves. Returning to home-grown food *[as per a war scenario]* in a city complex might be difficult. One is reminded of the resource ratio approach described at chapter 8, which concluded that the species that is able to survive at the lowest level of a limiting resource will be the best competitor for that resource.

Given that the production costs of food to the point of the consumer contain substantial energy costs and that a significant amount of that energy is related to oil *[to power farm machinery, transport across land and oceans etc]*, it would not be surprising if food prices relate in some way to world energy prices. The chart at figure 48 displays the USA food producer index set against Brent crude oil price index from 1991 to 2012.



Sources: BP Statistical Review, FAOSTAT

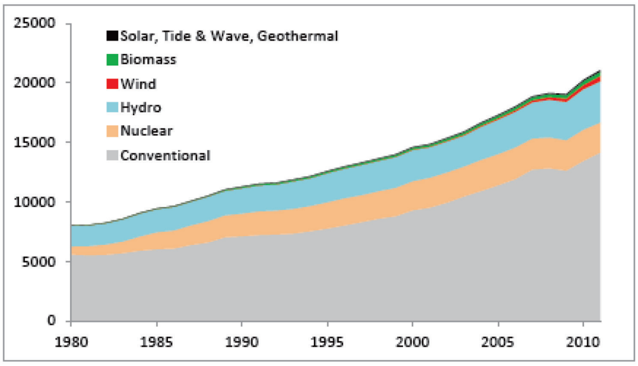
Figure 48 USA food price index v Brent crude oil price.

The author considers that there is a reasonable correlation between the two factors displayed *[correlation coefficient R^2=0.87]* for the time interval illustrated, though this might reduce if, for example, a relation between oil prices to European food prices is tried, or prices pertaining before 1991 *[a different time series]* are included in the data. It remains to be seen as to the effect more recent trends in oil prices may have.

It follows from the above that trends in world energy, in particular oil, which is used to power ocean and land transport and farm machinery, will likely impact on the world food industry.

Renewable Energy

Renewable energy has been cited as providing a solution to the problem of carbon emissions arising from the burning of fossil fuels by humans. The chief renewable energy sources are: hydroelectric generators mostly sited at dams, wind turbines sited on exposed land or above shallow sea areas, solar energy converters *[PV (photo-voltaic) and CSP (concentrated solar power)]*, biomass burning *[wood, agricultural and food waste]*, geothermal power plants sited mostly over naturally occurring hot fissures to the Earth, and energy derived from tidal or wave movement. All of these energy sources are utilised to provide electrical energy. Figure 49 illustrates world annual electrical output so far set against the key non-renewal sources of conventional power plant *[coal, gas and oil]* and current nuclear energy technology.



Source: EIA

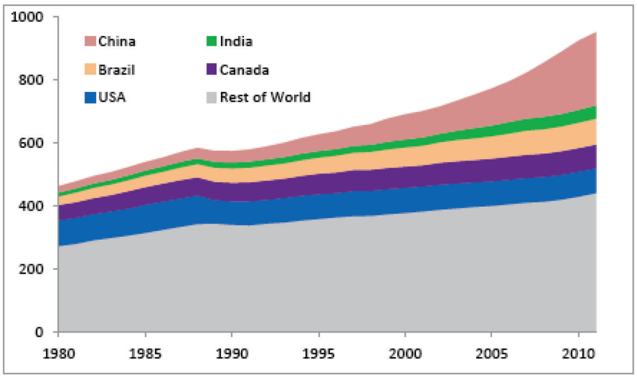
Figure 49 World production of electricity by energy source –TWh p.a.

With the exception of hydro-electric power, renewable energy has yet to make a substantial impact on world markets, although clearly change is beginning to occur. At 2011 hydroelectric power provided 16.5% of world electrical generation, and the other renewables 4.5%, with the rest provided by nuclear and conventional plant.

Jacobson and Delucchi *[Energy Policy 39 (2011)]* have estimated the technology requirements at 2030 to convert a world of predominantly fossil-powered energy infrastructure to one involving renewables of wind, water and sunlight, including several million wind turbines, large numbers of CSPs, 1.7 billion rooftop PVs, along with additional hydro-electric and other technology capacity. Their world would be populated with battery-operated vehicles *[BEVs]* and would require the use of additional land for footprint and spacing for renewable power plant.

Hydro-electric Power

Of all the renewables, hydroelectric power generation offers an ideal solution to replacing fossil-fired plant. It has a high EROI *[see section on EROI]*, its energy efficiency is very high, since no fuel is burnt, and it has no carbon emissions, other than those created from the input of engineering plant and construction materials. Hydro power can be ramped up and down quickly *[around 1-2 minutes from nothing to full power]* and it is therefore ideal for meeting changing load requirements. Consequently it may not necessarily be used for continuous base load, as geothermal and nuclear plant are *[their output is not easy to change up and down]*. The main cost of hydro power is the capital cost, since it generally involves the building of a dam and the creation of a reservoir, which may involve disruption to, and permanent submergence, of upstream local eco-habitat. Figure 50 summarises installed capacity in the world.



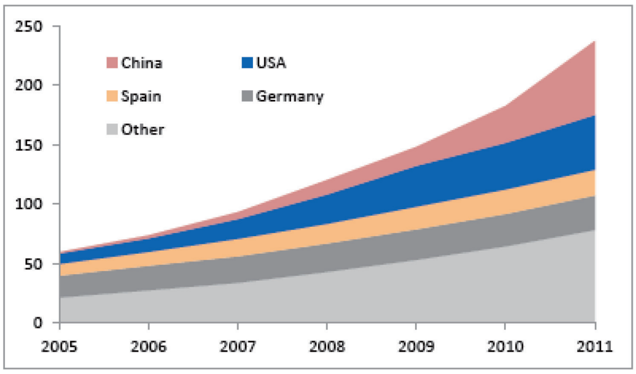
Source: EIA

Figure 50 World installed capacity hydroelectric power – GW.

While future growth of hydroelectric power may be limited by available and potential geological/landscape opportunities and considerations, it appears, nevertheless to be proceeding apace, with China leading the field in investment.

Wind

In terms of the provision of electrical power capacity, wind energy is a relatively recent entrant to the global market, though its growth rate has been quite high. Figure 51 illustrates the trend in capacity since 2005:



Source: EIA

Figure 51 World wind energy installed capacity to 2011 – GW.

World capacity growth has averaged about 25-30% p.a. since 2005, with China rapidly overtaking other key countries. The 2014 Global Wind Energy Council report indicates that by 2013 global installed capacity had risen to 318 GW; with China alone accounting for more than 91 GW, and USA 61 GW. A number of countries have achieved quite high levels of wind power penetration, such as Denmark, Portugal, Spain and Germany.

A particular problem with wind energy is that wind force cannot be guaranteed, being neither constant nor geographically evenly spread. Consequently load factors are low, at about 21-22% on average across the world.

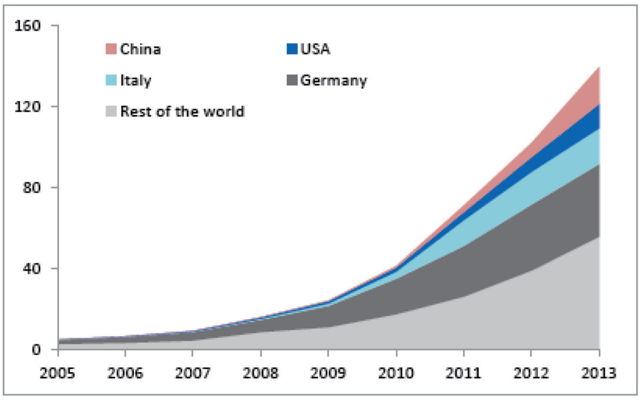
Wind turbines tend to be sited on open or high areas of land, or over shallow waters to maximise their efficacy. Denholm, Hand et al *[NREL (2009)]*, report that land-based wind energy installations, on average, occupy about 0.3 HA per MW of capacity.

Solar

Besides hydroelectric and wind, solar energy is the other main contributor to the renewable energy sector. It is broadly split into two technology types; first, photovoltaic *[PV]* systems that convert sunlight directly into electricity, and second, concentrated solar power *[CSP]* systems that use lenses or mirrors allied to tracking systems to focus large areas of sunlight into a small beam, which is then used as a heat source in a power plant. PV systems are ideal for individual and medium-sized consumers, whereas CSP systems are suited to large scale complexes.

As with wind-powered systems, solar energy collectors have low load factors, arising first from the natural day/night cycle coupled to seasonal changes, and second the impact of cloud occlusion and latitude on the strength of sunlight falling on the receivers. Solar systems are more suited to countries having hot climates, but even then load factors only average at about 10%; meaning that for much of the time they are not providing energy output. To offset a low load factor, ideally electrical energy produced needs to be stored, so that it can be used also at times when the Sun has gone down. Technology to store power in car batteries is one such idea. Ong, Campbell et al *[NREL (2013)]* report that solar energy installations, on average, directly occupy about 3 HA of land per MW of capacity.

Figure 52 illustrates the rapid rise in solar power installations across the world. Germany is currently the largest producer of solar energy.



Source: BP

Figure 52 World solar PV energy installed capacity to 2013 – GW.

Other Renewable Energy

Space does not allow consideration of other sources of renewable energy, such as geothermal, biomass, and tide/wave movement. Compared to hydroelectric, wind and solar energy, however, they are currently relatively small in potential, or are specialised. Geothermal energy, for example, is currently produced in only a few countries, such as USA, Indonesia, Philippines, Mexico, Italy and Iceland, having particular geological features.

The Atmosphere, Oceans & Cryosphere

More than anything else on Earth, the physical movements and changes in the atmosphere, oceans and cryosphere are vivid examples of entropy in action. High intensity *[short wavelength]* heat flux arrives from the Sun at a total solar irradiance rate of about 1361 W/m^2 *[Kopp et al 2005]*, averaging out at about 340 W/m^2 across the surface of the Earth, but varying a little with solar and orbital cycles. Some of the heat flux is absorbed by the atmosphere, some is reflected back to space by the clouds/atmosphere and by the Earth's surface *[depending upon the relative albedo]*, and the rest is absorbed at the surface, ultimately providing energy for life forms to flourish, and heat to warm the air and evaporate water, the latter rising to form clouds which turn to precipitation as latent heat is removed. In addition, low intensity *[long wavelength]* heat flux is radiated directly from the land and oceans out into space, and to the atmosphere, some of latter of which is radiated back by clouds and greenhouse gases, and some is then radiated onwards to space. The greenhouse gases, through their selective blocking of parts of the spectrum of the outgoing long-wave radiation, enable the temperature at the Earth's surface to be maintained at an average, bearable level of about 15ºC. In the absence of these gases, the temperature would be quite a bit colder, at about -18 ºC on average, which would not be conducive to life forms.

Because the heat flux from the Sun impacting on the Earth varies with intensity, from a high level between the Earth's tropics to a very low level around the poles, and according to daily, seasonal and other movements as the Earth rotates about its' axis and orbits the Sun, the atmosphere is constantly in motion, having large-scale, localised, convective and chaotic elements. The directions of winds north and south of the Equator are also influenced by the Coriolis Effect as the Earth rotates. The winds help to re-distribute energy potentials from the tropics towards the poles, and have a significant impact on ocean waves and the circulation of ocean waters around the Earth. The whole process involves continuous degradation of the Sun's energy flux and net production of entropy, as Earth systems forever strive to proceed towards equilibrium states. This brings to mind the Le Châtelier principle which we met in the first of these two papers. Nature is never in balance.

The Earth's systems and climate have been the subject of a number of researchers *[Paltridge (1975), Lorenz (2001), Ozawa (2003), Jenkins (2004), Goody (2007), Kleidon (2009), Pascale et al (2009), and others]*, concluding that a variety of irreversible processes are taking place continuously, which are described by the entropy production rate. Ozawa et al *[2003]*, reviewing the maximum entropy production principle, have calculated a global entropy budget for the Earth *[see table 7]*, based on in-coming and out-going radiative energy fluxes, and on the temperatures at the surface of the Sun, at the top of the Earth's atmosphere and at the surface of the Earth.

	$WK^{-1}m^{-2}$
Solar short-wave radiation absorbed by the Atmosphere	0.367
Solar short-wave radiation absorbed at the surface of the Earth	0.469
Convection and turbulent processes in the Atmosphere	0.046
Long-wave radiation from the Earth's surface absorbed by the Atmosphere	0.018
Total	0.900

[$WK^{-1}m^{-2}$ Watts per degree Kelvin, per metre squared of area]
Source: Ozawa et al 2003, American Geophysical Union

Table 7 Global Entropy Budget for the Earth.

Clearly, at the global level, entropy production and change constitute the natural state of affairs, and one might hazard that this would percolate in some way towards and among the subsystems of the Earth – atmospheric, hydrologic, geologic, carbon and biotic cycles.

In respect of life, the carbon cycle is vitally important. The diagram at figure 53 sets out a very simple summary of the stocks and flows of carbon, circa 1990.

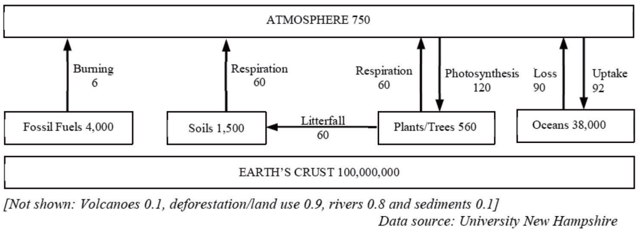


Figure 53 Simplified carbon cycle circa 1990. GtC [for stocks], GtC p.a. [for flows].

Anthropogenic emissions apart, exchange of carbon through respiration, litterfall and photosynthesis for soil and vegetation, and through losses and uptake of the oceans, is approximately in balance, but subject to changes in solar and other activity. Continuing anthropogenic emissions, however, throw the system significantly out of balance, with the atmosphere initially accumulating the excess carbon in the form of carbon dioxide, unmatched by an immediate sink to reduce the level back down again. One might expect that the Earth's subsidiary systems would each react in some individual, unspecified way to meet the position over time, transferring some of the carbon elsewhere within the Earth's ambit, such as the oceans. Figures of Global Carbon Budget 2014 *[Le Quéré, R et al]* indicate that fossil fuel and cement carbon emissions have risen further, from 6.1 GtC p.a. in 1990 to 9.9 GtC p.a. in 2013, adding to the atmosphere.

The last two decades have seen an escalating interest in the effects of climate change as summarised by IPCC *[Intergovernmental Panel for Climate Change]*, and by the Stern Review *[2006]*. It is not the place of this paper to supplant the work done, though it is relevant to set out the main trends to date, while keeping an open mind concerning man's understanding of the way processes work and the directions in which matters may progress; in particular, the potential for climate change to act as a constraint on economic activity, concerning production and consumption, and the potential effects of climate feedbacks such as water vapour, the albedo, land carbon, methane hydrates and permafrost *[methane]*.

Probably the single most important indicator encapsulating the effects has been the rise of more than 1.1ºC in the global average surface temperature *[HadCRUT4 combined land and ocean]* from the mid-19th century to the present day *[see figure 54]*, which rise appears to be continuing, though there have been some periods of decline or flattening *[late 19th century, immediate post world war II]*. Figures of the Met Office Hadley Centre *[HadCRUT4]*, indicate that the temperature anomaly continues to climb, reaching a peak in 2015 of 0.745ºC, and continuing upwards into 2016.

Warmer atmosphere, land and ocean surfaces, affecting latent heat and thermal expansion, imply that changes in sea level and the extent of ice in the cryosphere may also occur. IPCC report that it was very likely the mean rate of rise of global average sea level was 2mm per year between 1971 and 2010, which rate has escalated more recently. However, between 1979 and 2012, while the annual mean Arctic sea ice extent very likely decreased by 3.5-4.1% per decade, that for the Antarctic area increased by 1.2-1.8% per decade.

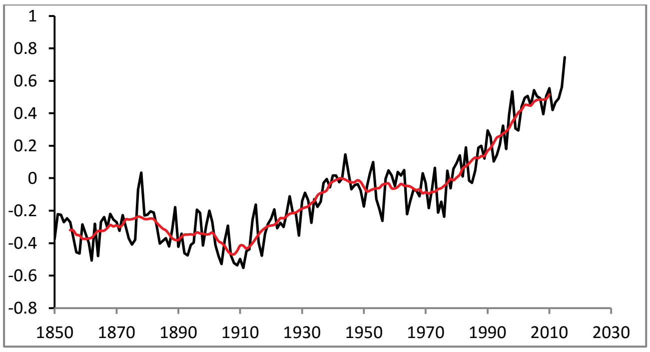


Figure 54 HadCRUT4 global annually averaged surface temperature anomalies 1850-2015 ºC, relative to 1961-90, with a centred 11-year moving average inserted.

Even so, IPCC report that over the last two decades both the Greenland and Antarctic ice sheets have been losing mass, glaciers have continued to shrink almost worldwide, the extent of Northern Hemisphere snow cover has decreased since the mid-20th century and permafrost temperatures have increased in most regions since the early 1980's. It is thought that if all the ice in Greenland melted then sea level could rise by about 7m. The equivalent figure for Antarctica is over 60m. A follow on effect of a reduction in ice and snow cover is a reduction in the albedo or reflective effect, increasing the amount of solar radiation absorbed at the Earth's surface, with a consequent effect on surface temperature.

The generally accepted origins of the rise in temperature which has occurred are those of radiative forcings, measuring the influence of factors that alter the balance of incoming and outgoing energy *[in W/m^2]* of the Earth-atmosphere system. Contributing factors include changes in energy flux from the Sun, volcanic activity, changes in the concentrations of greenhouse gases and others, including human activity.

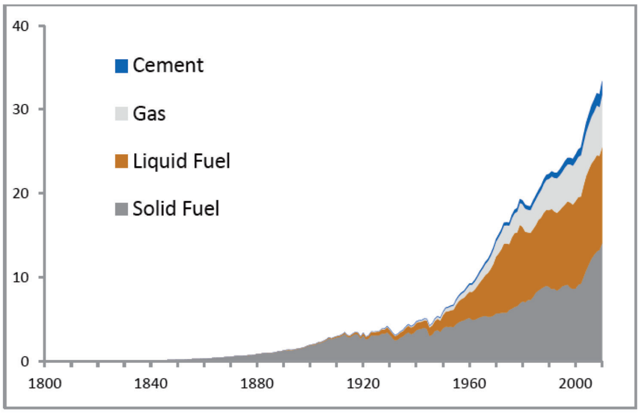
In respect of human activity, the predominant influences must be those impacting on changes in the atmosphere and in land use; in particular, anthropogenic emissions to the atmosphere of carbon dioxide *[CO_2]*, methane *[CH_4]* and nitrous oxide *[N_2O]*, and deforestation, the latter affecting the level of photosynthesis and hence the removal rate of CO_2 from the atmosphere. Greenhouse gases, *once accumulated*, by their nature tend to linger in the atmosphere for a number of years, CO_2 up to 200 years, CH_4 about 12 years and N_2O about 110 years. Water vapour on the other hand has a short lifetime in the atmosphere – of the order of hours to a week or so on average. Historic figures indicate that atmospheric concentrations of CO_2, CH_4 and N_2O have risen significantly, and at increased rates since 1960. As at September 2014 the level of CO_2 in the atmosphere stood at 395.9 ppmv.

	CO_2	CH_4	N_2O
Year	ppmv	ppbv	ppbv
1850	285.1	801	275.4
1960	317.1	1263	291.4
2014	395.9	1792	326.5

Sources: NASA GISS, CSIRO Cape Grim (September 2014)

Table 8 Atmospheric concentrations of greenhouse gases.

Figure 55 shows the inexorable rise in CO_2 emissions, and table 9 is instructive of the mass of carbon dioxide now in the Earth's atmosphere:



Source: Carbon Dioxide Information Analysis Center

Figure 55 World Emissions of CO_2 arising from burning Fossil Fuels Gtonnes p.a.

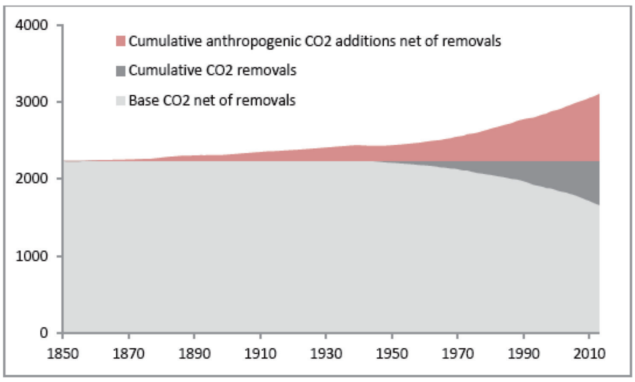
Table 9 Mass of CO_2 in the atmosphere.

	Concentration	**Mass**
Year	*ppmv*	*$GtCO_2$*
1850	285.1	2229
2014 (CSIRO September)	395.9	3096
Net Increase 1850-2014	110.8	867

Assumptions:
Mass of Atmosphere: 5.148 x 10^6 Gtonnes [Trenberth, Smith 2005]
Mass/Volume adjustment CO_2/Air 44.001/28.97 = 1.519

The net mass of 867 $GtCO_2$ added to the atmosphere between 1850 and 2014 can be compared to the gross cumulative mass of annual anthropogenic CO_2 generated from fossil sources for the period 1850 – 2013 inclusive, which amounted to 1,439 $GtCO_2$. Thus only 572 $GtCO_2$ *[1439 – 867]* or 39.7% has been re-absorbed so far at the Earth's surface *[mostly by the oceans]* over the 164 years that have passed. Archer et al *[2009]* confirm that the time required to absorb anthropogenic CO_2 depends upon the total amount of emissions.

The chart at figure 56 summarises the mass of CO_2 in the atmosphere over time. Changes in land use have not been included. CO_2 removed has been equated to the gross anthropogenic emissions added to the atmosphere less the net rise in atmospheric CO_2.



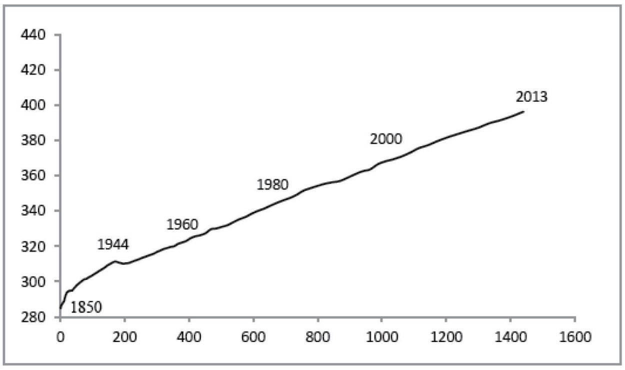
Data sources: GISS CDIAC

Figure 56 Global mass of CO_2 in the atmosphere $GtCO_2$ 1850 – 2013.

Amounts of anthropogenic CO_2 began to accumulate in the atmosphere from the late 19th century onwards, but it was not until post world war II that some of these began to percolate downwards, the latter principally to the oceans, altering ocean acidity and chemistry, and thereby creating a ripple effect onwards to the marine biotic system. According to Oceana.org, particular species that may be affected include plankton, sea snails, sea urchins, squid, and life forms that depend upon calcification to survive.

The chart at figure 57 illustrates the relationship between the concentration of CO_2 in the atmosphere *[by volume]* and *cumulative* anthropogenic additions of CO_2 to the atmosphere from fossil sources *[by mass]* from 1850 to 2013. The relationship appears to be almost linear, affected only by some removals to the Earth.

Should the human race reduce drastically, and irrevocably, its emissions of CO_2, one might expect the curve to flatten off gradually, and eventually to turn down, though possibly hundreds of years in the future. As yet there is little sign that this will occur.

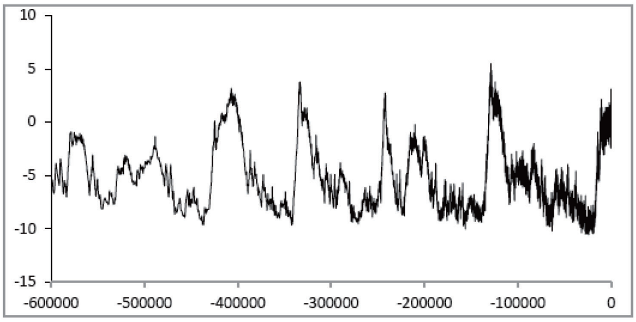


Data sources: GISS CDIAC

Figure 57 Global mean atmospheric concentration of CO_2 ppmv [y-axis] versus gross cumulative anthropogenic additions of CO_2 to the atmosphere from fossil sources $GtCO_2$ [x-axis] 1850 – 2013.

A note of caution should be sounded with regard to the measurement of CO_2 in the atmosphere. From 1958 onwards accurate measurements were made possible via an analyzer at the Scripps Institute, Mauna Loa and from flask samples from other sites *[The Keeling Curve]*. Prior to that, only sporadic measurements had been made, with gaps of some years between each. To fill the gaps in older periods many researchers rely on data from ice-cores *[Etheridge et al 1996]* which themselves have gaps of 6-7 years or more between each measurement. Thus annual figures going back before 1958 rely on averaging between each point, which could lead to hiding some short term trends.

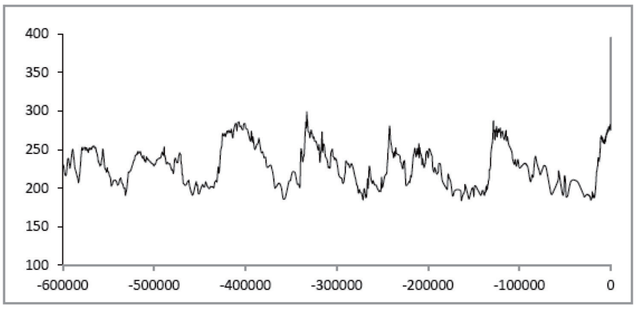
For longer timescales, it is well-known that past changes in atmospheric temperature and the concentrations of greenhouse gases can be deduced with a high degree of confidence from polar ice-core paleo-climate records; temperature being related to the relative presence of isotopes, either of oxygen *[$\delta^{18}O$]* or of deuterium *[D or ^2H]* in the water, and greenhouse gases to samples from the air bubbles trapped in the ice-cores. Figure 58 shows the variation in the temperature anomaly measured from the ice-core data obtained from the Dome C site of the European Project for Ice Coring in Antarctica *[EPICA]* in East Antarctica. The original core, measuring 3,190 metres deep, covers a period from the present back to about 800,000 years ago. Data are not evenly spaced *[physically or in terms of time]* down the core; much of the temperature data for instance is concentrated in the first 200,000 years before the present, which might explain the crowding of the line towards the right in figure 58. The temperature anomaly has varied in cycles, around 100,000 years in length, over a range of up to 15ºC. The more recent paleo-climate record indicates that the temperature anomaly may be at or about the upper end of a cycle.



Source: NOAA. EPICA Dome C Ice Core Temperature Estimates Jouzel, J., et al. 2007

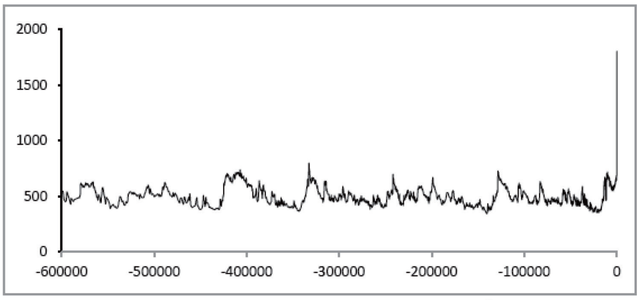
Figure 58 Estimate of temperature anomaly ºC years before 1950 [relative to the average of the last 1000 years].

Figures 59 and 60 show the concentrations of carbon dioxide and methane over the same period. The last record of the ice-core indicated concentrations for CO_2 at 280.4 ppmv and CH_4 at 907 ppbv respectively. Figures for the current concentrations of the gases have been added by the writer to illustrate the recent large jumps, to 395.9 ppmv and 1792 ppbv respectively.



Source: NOAA. EPICA Dome C Ice Core 800KYr Carbon Dioxide Data Lüthi, D., et al. 2008

Figure 59 Estimates of atmospheric carbon dioxide concentration ppmv



Source: NOAA. EPICA Dome C Ice Core 800KYr Methane Data Lüthi, D., et al. 2008

Figure 60 Estimates of atmospheric methane concentration ppbv.

Considering only the CO_2 data of the paleo ice-cores *[i.e. excluding the data added to the chart at figure 59 by the writer]*, then a significant coupling of temperature level with the concentration of CO_2 in the atmosphere can be seen, as over the long-term they appear to follow similar cyclical paths.

A number of observers, however, have pointed to specific parts of the data which appear to show that temperature changes *lead* those of the CO_2 concentrations – by as much as a thousand years – whereas one might have expected the reverse if greenhouse gases are presumed to be the agents of temperature rise.

Parrenin et al *[2013]* have revisited the ice-core data in an attempt to resolve this problem. In an ice-core, temperature and CO_2 concentration are not read off at the same levels of the core. The researchers developed a different method to measure different ages of gas and ice, by reference to the presence of a nitrogen isotope *[$\delta^{15}N$]* in the core. They could find no significant asynchrony between gas concentrations and temperature data, indicating that Antarctic temperature did not begin to rise hundreds of years before the concentration of atmospheric CO_2, as was suggested by earlier studies. Nevertheless, in the writer's view, more research in this area would be of great value to add confidence to any conclusion.

Tripati et al *[2009]* confirm that atmospheric CO_2 is closely coupled with both temperature and sea-level, though for periods earlier than 800,000 years the position is much less certain. They estimate that during the middle Miocene *[around 11-16 ma]* CO_2 levels were similar to those of the present time; temperatures were 3-6ºC warmer and sea level was 25-40 metres higher than at present.

With regard to more recent trends, a paper of Lockwood & Fröhlich *[Proc.R.Soc.2007 463]* concluded that while the Sun has been a significant influence on both pre and post-industrial climate changes, the observed rise in global temperature after 1985 cannot be ascribed to solar variability. Svensmark and Friis-Christensen *[Danish National Space Centre]*, however, reply to the Lockwood & Fröhlich paper by the use of an inversion of cosmic ray flux as an index of solar activity, and consider that the Sun still appears to be the main forcing agent in climate change. The author defers to experts in the field as to the weight to be attached to the Svensmark and Friis-Christensen reply.

From all of the foregoing, it is apparent that from 1850 to the present time there has been a coupling between the concentration of CO_2 in the atmosphere and cumulative anthropogenic emissions of CO_2 arising from burning fossil fuels *[see figure 61]*. Further, that an increase in atmospheric temperature occurred over the same period which, for more recent periods, cannot be explained purely by solar variance. It is reasonable to conclude that anthropogenic emissions of CO_2 do have some relation to, and influence on, the level of atmospheric temperature. Figure 61 illustrates the relationship *[A similar chart is presented at figure SPM10 of the IPCC WGIAR5 summary for policymakers, but including only decadal points]*.

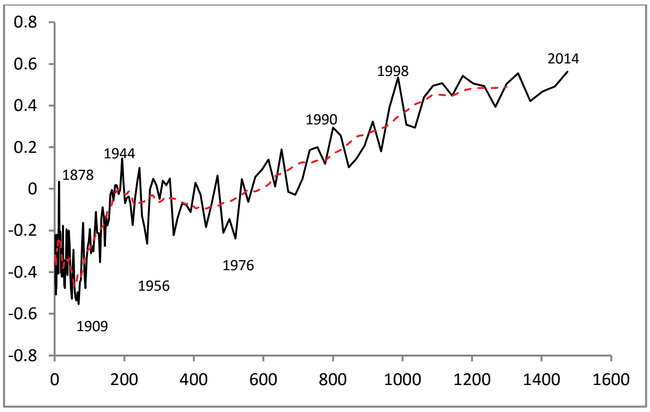
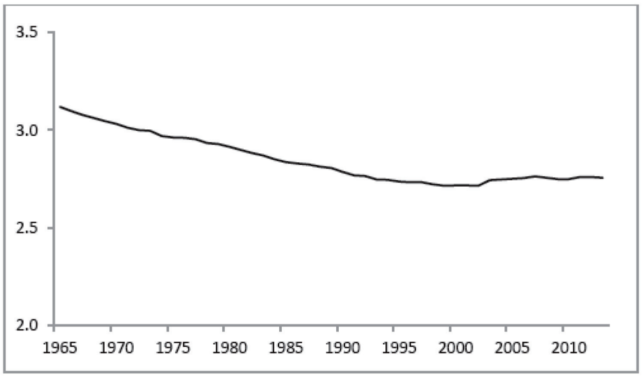


Figure 61 Global temperature anomaly ºC [y-axis] as a function of cumulative anthropogenic emissions of CO_2 to the atmosphere $GtCO_2$ [x-axis] 1850 – 2014, with a centred 11-year moving average inserted.

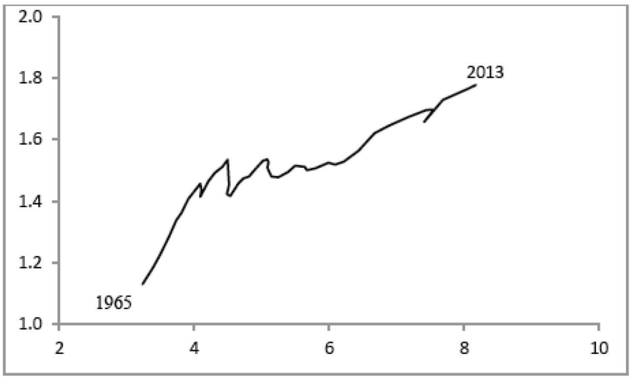
Continuing further, readers may note first, from the charts at figures 5 and 55, that anthropogenic CO_2 emissions have followed a very similar path to that of the rapidly escalating rise of world primary energy consumption, though subject to any changes in fuel mix, in particular towards renewable energy. The International Energy Agency *[World Energy Outlook 2013]* report however that as of 2013 the share of fossil energy in the global mix was 82%, the same as it was in 1988, 25 years previously. On this basis it is reasonable to conclude that emissions of CO_2 are still strongly related to primary energy consumed. Figure 62 summarises changes in the ratio of world CO_2 emissions to primary energy consumption. The ratio declined to about year 2000, but thereafter has increased a little.



Source: BP Statistical Review

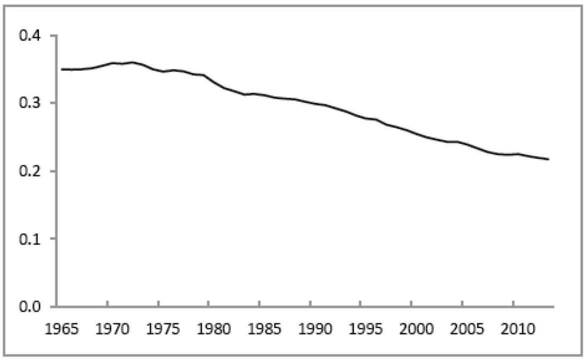
Figure 62 Ratio global emissions CO_2 $GtCO_2$ p.a. to primary energy consumption Gtonnes p.a. oil equivalent 1965 – 2013.

Second, energy consumption is also related to GDP through changes in energy intensity of use *[primary energy consumption per $ of GDP]*. Figure 6 illustrates declining energy intensities for the developed economies, but offset by fairly level energy intensities for developing countries, with the result that, overall, world primary energy consumption per head of human population continues to rise, as shown in figure 63. Should developing countries subsequently emulate the developed countries in reducing their energy intensity ratio, then one might expect the curve in the chart to curl further to the right. Figure 64 shows the net effect to date on the global energy intensity ratio.



Sources: BP Statistical Review, Angus Maddison, OECD Development Centre Studies: "World Economy – A millennium perspective", CIA, UN

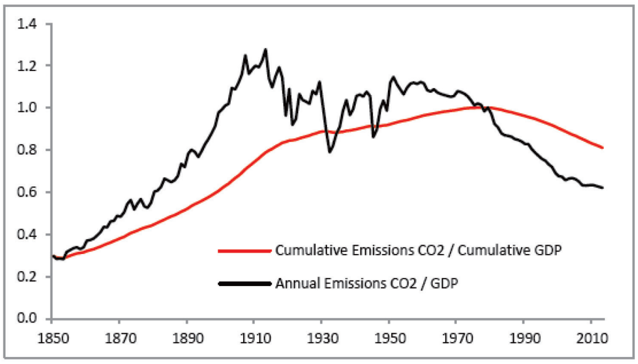
Figure 63 Global primary energy consumption per capita tonnes oil equiv p.a. [y-axis] as a function of world GDP per head $000 p.a. at 1990 prices [x-axis] 1965 – 2013.



Sources: BP Statistical Review, Angus Maddison, OECD Development Centre Studies: "World Economy – A millennium perspective", CIA

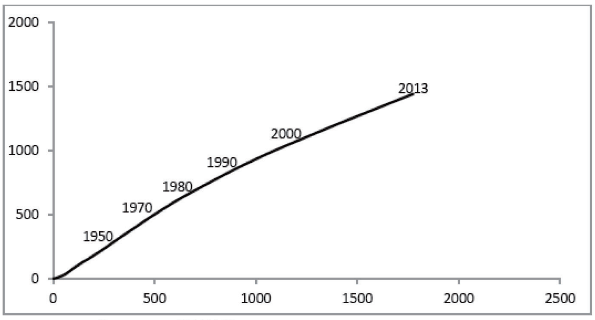
Figure 64 Ratio global primary energy consumption to GDP Kgoe/$ [1990 prices] 1965 – 2013.

Combining all the effects of all these trends, then figure 65 shows the trend of the world annual and cumulative emissions intensity ratios $kgCO_2$ per $ GDP *[1990 prices]* 1850 – 2013, and figure 66 shows the relationship of *cumulative* emissions of CO_2 to *cumulative* world GDP 1850 – 2013. The Maddison study from which the GDP figures are taken provides only four estimates of world GDP prior to 1950, when GDP *[at 1990 prices]* was then $5,336 billion. For the purposes of the charts, annual GDP figures in between each of the pre-1950 Maddison GDP estimates *[1940, 1913, 1900 and 1870]* were approximated on an interpolated basis. This was a reasonable procedure to take, as the pre-1950 figures for cumulative world GDP were small, relative to those after 1950, and do not significantly affect the accuracy of the longer-term trend.



Sources: CDIAC, Angus Maddison, OECD Development Centre Studies: "World Economy – A millennium perspective", CIA

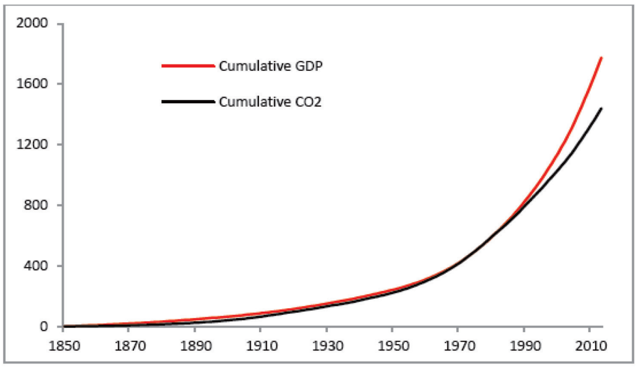
Figure 65 World emissions intensity ratio $kgCO_2$/ $ GDP 1990 prices 1850 – 2013.



Sources: CDIAC, Angus Maddison, OECD Development Centre Studies: "World Economy – A millennium perspective", CIA

Figure 66 Cumulative global emissions CO_2 $GtCO_2$ [y-axis] as a function of cumulative world GDP $ trillion 1990 prices [x-axis] 1850 – 2013.

Figure 67 puts the time dimension of figure 66, showing that cumulative GDP and cumulative CO_2 emissions are rapidly escalating.



Data Sources: GISS CDIAC,
Angus Maddison, OECD Development Centre Studies: "World Economy – A millennium perspective", CIA

Figure 67 Cumulative world emissions CO_2 $GtCO_2$, and cumulative world GDP $ trillion1990 prices, 1850 – 2013.

A number of observations are pertinent.

First, as long as GDP remains dependent upon fossil energy to power its base, and GDP is able to advance further, then the emissions will continue to rise with a consequent upward effect on the temperature anomaly.

Second, it will be a matter of evidence as to how far the emissions intensity ratio illustrated at figure 65 will eventually fall, through changes in efficiency and switches to non-fossil energy, such as to divorce emissions from GDP.

Third, because the world's energy consumption rate is still increasing significantly in order to fuel a growing anthropogenic appetite for GDP, for a given increase in cumulative GDP *[and thereby cumulative CO_2 emissions]*, the number of years between the starting and finishing points is reducing, and the situation is escalating as the years go by. Figure 67 illustrates this effect. On current trends, cumulative emissions to the atmosphere could double in the space of two decades or so and rapidly escalate thereafter, *assuming that energy consumption and GDP are able to continue growing*.

Extrapolations of the trend lines at figure 67 correspond approximately to the higher end scenario ranges set out by IPCC *[Representative Concentration Pathways RCP6.0 and RCP8.5, Table TS1 WGIIIAR5]*, with cumulative emissions between years 2011-2100 approaching 3620 – 7010 $GtCO_2$, along with a temperature anomaly range of 3.1 - 4.8ºC *[relative to 1850 – 1900]*, though IPCC indicate that with appropriate actions to mitigate climate change *[RCPs 2.6 and 4.5]* the temperature anomaly might be reduced to a range 1.5 – 2.9ºC. They indicate, however, that this would require a significant reduction in the level of projected cumulative world emissions to the atmosphere between years 2011-2100, to a range of 630 – 3340 $GtCO_2$.

Figure TS.7 IPCC WGIII AR5 technical summary sets out variations of four main factors linking to carbon production: world *[human]* population, GDP per capita, energy intensity of GDP and the carbon intensity of energy consumption. Superimposed on these factors are divisions by main geographic area, and subdivisions by energy sector and by consumer, such as transport, residential and industry, with a projection of emissions of each of the gases *[CO_2, CH_4 N_2O]* into the future. The exercise was carried out by several agencies, and included scenario variations such as conventional or abundant gas and many others. In all, more than 160,000 projections were made. In respect of population, the projected variants reflected much of what is set out in this paper with regard to UN estimates of human population growth. With regard to estimates of future GDP per capita, however, the majority of the IPCC model projections made are of the exponential kind, forever into the future, albeit with varying growth rates assumed, generally in a range of 1 - 2½% compound, against a historic trend of 1.4%, implying world GDP per capita in 2100 in the range 2½ - 8½ times the level in 2013.

Some of the models in the IPCC projections *[Pik and IIASA]* make use of Cobb-Douglas and Augmented Solow models, which project forward exponentially only the capital and labour/human capital cost components of GDP, and make no reference to the productive contribution of the resources consumed *[other than the ratio of energy consumed per unit of GDP]*. It will be recalled however that the work of Ayres and Hümmel showed that traditional economic theory explained very little of growth compared to natural resource energy, with around two-thirds of productivity in fact arising from energy consumption and only a small percentage from human labour.

It will be a matter of evidence therefore as to the extent to which world GDP per capita will be able to grow in the face of an escalating effect from first, climate change, impacting on the ability of the eco-system and humanity to cope with the changes, and second, potential limits on the amounts of resources that will be available *[energy and other forms]* that have been highlighted in this paper; the evidence of trends in world human population growth alone indicating, perhaps subconsciously, a potential ceiling in about 2050. Exponential growth in a finite and dynamic world cannot be assumed. A discussion of this prospect is set out in the final part of this paper.

IPCC have set out an analysis of major areas in specific parts of the world expected to be affected by climate change, which analysis the author would not challenge. The areas included:

- Physical systems:
  - Glaciers, snow and ice
  - Rivers, lakes, flooding and drought
  - Sea level and coastal erosion
- Biological Systems:
  - Terrestrial ecosystems
  - Marine ecosystems
  - Wildfire
- Human & managed systems:
  - Food production
  - Livelihood and health
  - Economics

Specific effects include:

- Reduced glacier mass and forest cover
- Reduced crop yield – particularly wheat and maize
- Increased precipitation towards the poles
- Increased drought in temperate zones
- Increased flooding in tropical zones and low lying lands
- Movement and displacement of some species to track climate change
- Under-nutrition
- Food & water-borne infections
- Extreme weather events
- Mental health and violence
- Increased insecurity, nationally and internationally
- Conflict, land grabs and resettlements

Burke, Hsiang and Miguel *[Nature 2015, Science 2013]* have produced papers on a global non-linear effect of temperature on economic production and the influence of climate on conflict. Dell et al *[American Economic Journal 2012]* have produced a paper concerning temperature shocks and economic growth. On the basis of these papers, substantial reductions in economic output might be expected, accompanied by social conflict and a widening of global income inequality.

On the evidence to date, further significant rises in global air temperature and water levels will occur, which ultimately will cause a reduction in output to some if not many economies through a loss of agricultural farming capacity, loss of habitation located in low-lying areas liable to sea flooding, and entail a consequent large-scale write-off of capital stock. Of more concern, however, is the effect on the eco-system, which humankind has previously mostly ignored, and which will affect the quality and quantity of natural capital, which in turn will impact on sustainability.

There is of course nothing initially to prevent world economies continuing along a *'same as usual'* path, with governments endeavouring to satisfy their populace by delivering economic growth and the wherewithal to service debt, but in the absence of concerted action among the international community to reduce fossil energy consumption, ultimately the Earth will do it for us, in ways that individually may not seem fair to humankind, and with a lasting effect. On present trends, it appears likely that action at best may be of a delayed, iterative kind in response to accumulating environmental disasters, affecting individual areas and countries in the world.

Table 10 summarises current and cumulative emissions by major country, along with figures of population, GDP and primary energy consumption, and the ratios connecting all these variables. It is reasonable to assert that countries with high emissions, currently and historically, are those more likely to be impacting on anthropogenic contributions to global warming. Sixteen countries, headed by China and USA, account for 76% of current global emissions *[2013]*, 71% of cumulative emissions *[1965-2013]*, 75% of primary energy consumption *[2013]* and 70% of world GDP *[2013]*, but only 59% of population *[2013]*.

On a cumulative basis, Poland, South Africa, Australia, Ukraine and the Netherlands have also been high emitters; and Saudi Arabia, USA, Canada and South Korea currently have very high emissions per capita.

It is perhaps inevitable that some countries may be less committed to change than others, and some may feel that their response should be less than others by virtue of history and their relative economic development. Nature, however, makes no such distinction.

Country	CO_2 Output	Cumulative CO_2 1965-2013	CO_2/Hd	Carbon Intensity CO_2/PEC	Primary Energy Consumption	Energy Intensity Energy/GDP	GDP PPP	Population	GDP/Hd	PEC/Hd	Emission Intensity CO_2/GDP
	$MtCO_2$ pa	$MtCO_2$	tCO_2 pa	ratio	mn toe pa	Kgoe/$	bn $ pa	mn	$ pa	toe pa	Kg/$
China	9524.3	149550	7.02	3.339	2852.4	0.1765	16158	1357.4	11904	2.101	0.5894
USA	5931.4	266979	18.76	2.618	2265.8	0.1349	16800	316.1	53148	7.168	0.3531
India	1931.1	34309	1.54	3.246	595.0	0.0878	6774	1252.1	5410	0.475	0.2851
Russia	1714.2	53287	11.95	2.452	699.0	0.2020	3461	143.5	24118	4.871	0.4953
Japan	1397.4	54548	10.98	2.948	474.0	0.1025	4624	127.3	36324	3.723	0.3022
Germany	842.8	48020	10.46	2.593	325.0	0.0930	3494	80.6	43350	4.022	0.2412
South Korea	768.1	15539	15.30	2.831	271.3	0.1630	1664	50.2	33147	5.404	0.4616
Saudi Arabia	632.0	12150	21.94	2.776	227.7	0.1469	1550	28.8	53819	7.906	0.4077
Iran	630.6	12167	8.15	2.585	243.9	0.2021	1207	77.4	15594	3.151	0.5225
Canada	616.7	24166	17.52	1.853	332.9	0.2189	1521	35.2	43210	9.457	0.4055
Brazil	541.1	12645	2.70	1.905	284.0	0.0943	3012	200.4	15030	1.417	0.1796
Indonesia	523.3	9008	2.09	3.102	168.7	0.0706	2388	249.9	9556	0.675	0.2191
UK	513.4	30286	8.01	2.567	200.0	0.0862	2320	64.1	36193	3.120	0.2213
Mexico	499.4	13616	4.08	2.656	188.0	0.0933	2014	122.3	16468	1.537	0.2480
Italy	383.1	19934	6.41	2.412	158.8	0.0774	2052	59.8	34314	2.656	0.1867
France	385.6	21314	5.84	1.552	248.4	0.1019	2437	66.0	36924	3.764	0.1582
Rest of World	8259.9	321253	2.85	2.585	3195.5	0.1053	30352	2893.4	10490	1.104	0.2721
World	35094.4	1098771	4.93	2.757	12730.4	0.1250	101828	7124.5	14293	1.787	0.3446

Source: BP Statistical Review, World Bank

Table 10 CO_2 output, Primary energy consumption, GDP and Population 2013

Economics, Entropy and a Sustainable World

In the first paper it was highlighted that everything on Earth is subject to the Laws of Thermodynamics and the generation of entropy, and that we humans are no exception to this. Subsequently, the theme was developed that human economic processes mimic the Laws of Thermodynamics in several ways: first when comparing economic flow to gas systems, second the similarity between the economic concept of utility consumed and entropy generated out of consumption, and third, the structure of economic production and consumption process set against the workings of chemical thermodynamic processes. Economist Paul Samuelson drew attention to the subject, when he pointed to the Le Châtelier Principle and classical thermodynamics to explain the constrained maximisation problem, and although he did not live to proceed on to develop the notion of entropy his thought was certainly an intuitive one, well in advance of his time.

Economic expenditure on consumption involves the generation of entropy, and both individual humans and manufactured capital, through a lifetime of service, ultimately also degrade, entailing irreversible production of entropy. It's a fact of life.

One of the main conclusions of these two papers is that the rate of economic entropy production in an economic system can be equated to a logarithmic function of potential economic demand activity **V**, modified by the level of any supply constraints **X** acting upon it. Thus, in a similar presentation to the Boltzmann equation, economic entropy activity can be enshrined as:

$$S = k \ln\left(\frac{V}{X}\right)$$ *[where k=1 for an economic entity]*

or

$$dS = \left(\frac{dV}{V}\right) - \left(\frac{dX}{X}\right)$$

Empirical evidence, concerning money and employment set out in the first paper lent support to this relationship with regard to the US and UK economies, and this paper examined the dynamics of a non-renewable resource such as oil, with the proportion of reserves used to date equating to a gathering constraint.

Other constraining forces could also impact on the above relationship, in particular those arising from outside the economic process, such as climate change and man's impact on the ecosystem and renewable resources, ultimately degrading the sustainability of natural capital.

Turning now to the neo-classical approach to economics; sustainability in an economic system in practice boils down to maximisation of utility, as a function of economic consumption and output, leading to the accumulation of manufactured capital owned by humans. In respect of natural capital, it is assumed that either it does not impose a constraint on human economic activity, or that unlimited substitution can be made between human-engineered capital and natural capital. Thus the only constraint placed upon economic consumers is that of a budget constraint – how much they have available to spend at any time – being dependent only upon human economic management. At first sight, therefore, it could be argued that maximising the consumption of utility just follows the Laws of Thermodynamics, seeking to maximise entropy production through consumption of goods and services; with projections of the future being made on the basis of extensions of growth of the human populace and of manufactured capital alone.

This says nothing about potential constraints imposed by outside systems, however, such as resources or the environment, which may have a bearing on consumers' choices. It is just assumed that these can if necessary be replaced or circumvented over time by human ingenuity through the economic process, or be treated as one off 'external shocks'. A production function that included only humans and manufactured capital would be useless without resources, and a projection into the future would be meaningless.

To be fair, consideration of resource and environmental constraints has been a periodic, transient visitor to the economic world in the past, but which has eventually been shunted to the side-lines as humanity has found a way round. Peak oil in the USA has come and gone twice, and the green revolution has put off what many thought would be a limit to world food production. While a Malthusian would say that a finite world might, in the ultimate, impose potential constraints upon the level of activity of humankind, an optimist would place faith in human ingenuity in the process.

In 1972 the Club of Rome published the results of a dynamic feedback model of the global system *[Limits to Growth: Meadows, Randers et al – since updated to 2005]*, though this met with considerable resistance from the economic world at that time, and subsequently was largely put to one side as world economic activity continued unabated. More recently Sverdrup et al *[2011]* have devised a World Model 5 based on similar dynamic modelling principles, though it remains to be seen as to how seriously the economic world will take this. More work will likely need to be done, and on a broader and larger scale, if it is to have any impact at all on conventional economic wisdom.

If it is accepted that human driven economic systems seek to maximise entropy production in some manner, as do other Earth systems, then one might proceed further to consider the question of whether such a goal is consistent with sustainability of *both* economic and ecological systems. The evidence appears to indicate that the world is gradually moving from a position where the only constraints to economic growth have been those arising from human economic management, to a position where natural capital is progressively being seen as a potential constraint in the scheme of things. Moreover, because natural capital is complex and involves some long timescales, the current position has been developing for some time without humankind being generally aware of the situation.

Neo-classical economics is not able to cater for this change in affairs, primarily because it is built on the notion of a circular flow of value between labour and manufactured capital alone, with little or no recognition that true value ultimately comes from resources and from natural capital, albeit that humankind provides the intelligence and management to harvest and garner these treasures. This has meant that until recently ecological economics has been regarded overwhelmingly as a side issue to mainstream economic thought. A considerable shift in accepted wisdom is needed, away from a viewpoint that science has little or nothing to offer economics, towards structuring around disciplines incorporating terms and measures that relate to current accepted scientific understanding of the way the world works.

At a wider level humankind is only just beginning to comprehend how complex the eco-systems of planet Earth are, and what *Homo Economicus* may be doing to move them away from their equilibrium position, perhaps irrevocably. Numerous species of animate life are now threatened with decimation and some with extinction. Would Darwin, credited with the theory of evolution, have contemplated such a significant acceleration in extinction rates over such a short time?

Perhaps the biggest constraint that now exists is the sheer size of the human population that has grown on the back of economic capital, based on the consumption of non-renewable and renewable resources. And here evidence is now coming to the fore that perhaps, unconsciously, humanity is beginning to acknowledge both its effect on the world system, and in reverse, the effect of the world system on humanity. Growth in the human population is beginning to slow down to the point at which it may eventually decline. While much of this could be pointed to dramatic improvements in healthcare, if resource availability and world ecological problems did not pose potential constraints, would not human population advance its horizon even further? The evidence suggests perhaps a more cautious view of the future, with 'peak humanity' on the horizon.

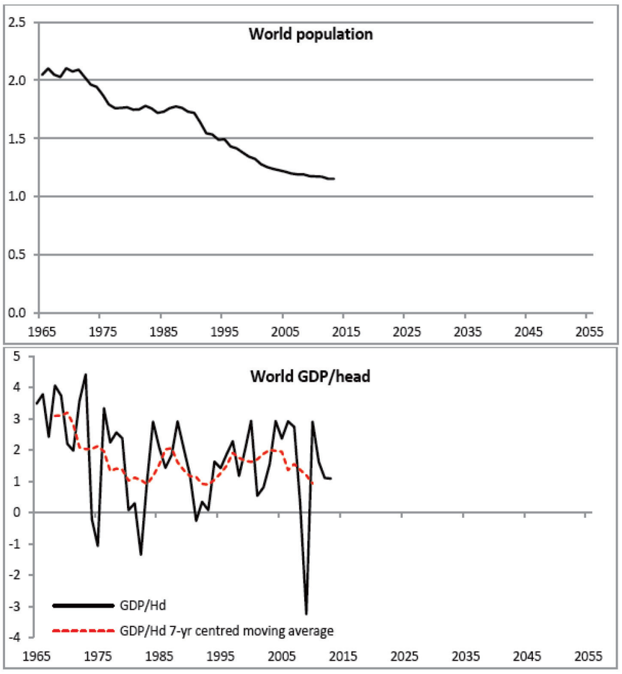
In respect of non-renewable resources, it would appear currently that peak oil has arrived, modified only by the impact of fracking in the USA. Peak coal may occur from the present to three decades away, with peak gas being up to three decades away. Nuclear power, under current technology, may have the same horizon. The production of metals and minerals, such as steel *[iron]*, cement, aluminium and others, vital to economic activity, is dependent upon the consumption of large amounts of non-renewable energy. On the other hand, one cannot discount entirely the possibility that further resource discoveries and technologies may come about to add to the remarkable developments of the last two centuries.

Turning now to renewable resources, a number of alarm bells are beginning to ring. Growth in world water withdrawals is beginning to slow down, and baseline water stress is rising significantly in particular areas of the world. The amount of arable land per head of population has been declining significantly, mostly owing to the rise in population. Soil erosion and degradation is on the increase, impacting on the residual amount of cropland available to grow crops. Despite these negative signs, food supply per capita worldwide is still increasing, particularly that of meat. That food supply has been able to grow, thus supporting population growth, has been owing to the green revolution, based on the use of irrigation, fertilisers and pesticides to increase yields. Fish production is still rising, though three-quarters of stocks are now regarded as being in the fully-exploited to depleted range. Other than hydro-electric power, renewable energy sources have yet to make a significant impact.

The world's food supply to humans via trade across land and oceans, however, is heavily dependent upon the consumption of non-renewable energy, in particular, oil. Without the latter, many people will have to find alternative, life changing, self-sufficient means of feeding themselves, leading to competition over land and associated resources.

All of the above leads the author to believe that tightening in the availability of resources is going to have a significant effect on future long-term growth in world GDP, even though the world energy/GDP intensity ratio is declining. On this basis growth in world economic output over the next few decades, and beyond, is going to be progressively harder and harder to obtain. The charts at figure 69 illustrate per cent growth in world population and GDP per head to the present time.

On current trends there is a high level of probability that the growth rate in world human population will continue to decline, with population peaking around 9.2 billion by 2050, three and a half decades ahead. With regard to growth in world GDP per head, however, the future is much more difficult to predict, partly because of the large spread of change per year brought about by business cycle effects and factors such as energy upheavals. Comparison with the chart of economic entropy change for the world oil industry at figure 15 for instance, reveals the same downturn points of 1973, 1980, 1990, 2000 and 2008.



Data source: World Bank

Figure 69 Growth rates of world population and GDP per head. % p.a. 1965-2013.

Purely on a historical basis, a trend line for GDP/head from about 1980 to 2013 would suggest an average compound, exponential rate of 1.4% p.a., achieving a doubling of world GDP by 2050. Some of the model growth rates for GDP/head assumed by IPCC are much higher than this however, projecting a level of GDP by 2050 in a range up to 4 times the current level and much higher by 2100.

Set against these figures, however, are the trends in resource markets, alluded to in this paper, which might lead one to expect a declining trend in growth of output per head over the next three and a half decades, should resource availability flatten off further. A trend line from 1965 onwards for instance, would suggest a declining rate, approaching zero growth in world GDP per capita by 2050, with some countries above this and some below. This scenario is supported by the work of Burke et al and Dell et al, referred to earlier in this paper.

Perversely, given the amount of airing that the advent of climate change has received, for a world where GDP per capita growth has subsequently declined over a few decades to a low or even a negative level, then growth in the amount of greenhouse gases released annually to the atmosphere might be expected to slow, perhaps at some time in the future effecting a reduction in the present rate of increase in temperature. Nevertheless, some aspects of climate change seem likely to persist, entailing reductions in economic activity for some vulnerable areas in the world, and involving movements in populace, civil and political unrest and some write-offs of both human-engineered and natural capital. On the other hand, economic man might endeavour to continue efforts to expand output, adding pressure to climate change.

Significant variations exist regarding individual per capita economic wealth, both at international and national levels. Just ten countries account for 35% of world GDP, but only 13% of world population *[source: World Bank]*. It is a matter of evidence as to the geographic source of the resources funding this economic wealth. Japan for example has few natural resources, yet has managed in the second half of the 20th century to build an economy based on processing resource value imported from elsewhere, such as metal ores and energy, combined with technology know-how.

It can be readily appreciated, therefore, that those with a 'poorer' lot might aspire to catch up with those more fortunate, particularly if economic and technology tools are at hand to facilitate this. In the more recent past both China and India, with very large burgeoning populations, have grasped the genie that economics has offered developed economies, and are setting about becoming the manufacturing hub of the world. This involves consuming increasingly large amounts of energy and other resources. Currently these areas of the world have higher economic growth rates than those of the developed countries, though it remains to be seen as to the effect that potential resource limitations and degradation might have in the future.

From the development in the first paper, it was shown that the notion of utility in an economic sense is closely related to that of entropy, and that maximising potential entropy production is consistent with both natural processes and those arising in 'man-made' economic systems. A formal link between output flow and maximisation of potential entropy production can only be established however if account is taken of constraints acting upon economic systems. These constraints take the form of factors that can affect flow of output; not just a budget constraint, but specific factors that can influence whether output goes up or down. Factors identified in these two papers include not only traditional economic ones such as money supply, production capacity and employment, but those involving natural capital, such as resource constraints – both renewable and non-renewable – and those constraints arising from the eco-system such as climate change.

From a thermodynamic viewpoint a process is more sustainable if less harmful losses of useful energy/productive content occur. This is more likely for a renewable resource, as losses generated from consumption can gradually be replaced by those of new resources entering the flow, nurtured by Nature and the Sun. However the position with a renewable resource is not guaranteed, for if over time the rate of usage inclusive of Second Law losses is greater than the rate of replacement, it is likely that the resource will gradually reduce in size, in the manner of a non-renewable resource. Strong sustainability on a thermodynamic basis therefore will only be achieved if humankind just abstracts value that can be fully replaced by the Sun, through the interlinking eco-systems and subsystems humankind relate to, such that future generations of humanity and life on Earth can prosper in sustainable harmony, without the ecological system being compromised.

For example, draining marine life from some oceanic areas *[including removing seabed life via trawling]* to a level where the stock biomass has negative marginal growth affects reproduction, with an ensuing decline in stock levels, which may also affect other higher and lower level species in the aquatic system. It follows that if the human population continues to grow alongside a declining marine stock, then at some point particular oceanic areas could become barren and reduce their support to human life and other living forms.

The same logic follows regarding the use of land to grow food and nurture farm animals. Consuming even more energy to produce fertilisers may improve yields, but forever reducing arable land and degrading soils in favour of production of consumptive products is a negative a factor. No amount of exponential projection of human GDP will restore the base on which food is grown. The net effect of a global policy that followed the weak sustainability path is that irretrievable natural resource depletion and ecosystem damage could escalate to a position where global constraints might force a retrenchment, if not something much more serious.

All of the above suggests that the key path to promoting strong sustainability may not be by humankind burning its way out by producing more GDP to feed its growing population in the hope that technology will solve the problem, but by consuming less. It is however quite contrary to human nature to reduce voluntarily an appetite for more, if not faced with an immediate constraint, and it is unlikely that individual nations and people would be willing to give up their way of living to the benefit of others unless, by international agreement and enforcement of such an agreement, each may be persuaded to reduce consumption if all suffer together. To date, international agreements on climate change policy, destruction of rainforests and harvesting of the oceans have not so far resulted in a significant change from the path of 'same as usual'.

Even if action were taken, it is human nature *[the entropy maximisation principle again]* that humankind having made a saving in one direction, would wish to go out and use the saving for something else. Thus just reducing expenditure on a non-renewable form of energy to replace it with another 'sustainable' form may leave GDP proceeding apace, but the threat of more population and short-term consumption of other resources such as food and potential overloading of the eco-system would remain.

In times past, the most effective occurrences that have persuaded both governments and populace to pull together to solve a problem have been in times of war and of recession/depression with reduced income. These were times when the populace experienced 'real' pain from a constraint or force, as opposed to being told that a 'threat' of pain might occur in some period ahead.

Human actions to ensure a high level of strong sustainability rest on the populace of all countries taking a much longer term view than hitherto has been the case, based on continued review and research into links between human and ecological systems. Nevertheless the advent of modern communications has meant that most people in the world are by now aware of the problem, even if singly and collectively they have so far done little to change their ways. Ingenuity and thought may play a part in the solution, but technology on it own will not provide an answer.

All this suggests that possibly a more likely outcome in the decades to come is eventually some reduced sustainability of natural capital, affecting carrying capacity, with an associated effect on human activity, a levelling out or even a decline in population and, over time, adjustment of economic output to levels commensurate with prevailing constraints.

Notes

Solution to Logistic Equation

The general solution to a logistic reserve equation is as follows:

$$N_c = \frac{RN_{C0}e^{\varphi t}}{R + N_{C0}(e^{\varphi t} - 1)}$$

Where $\mathbf{N_c}$ is the cumulative reserve used up, **R** is the total proven reserve, $\mathbf{N_{c0}}$ is the starting cumulative reserve used up, **t** is time and **φ** is the intrinsic frequency rate of consumption per time interval.

Reserve Entropy

Let the volume flow arising from remaining reserves be equated to:

$$V_R = R\varphi b$$

where **R** is the total proven reserve, **φ** is the frequency rate and **b** is the proportion of remaining reserves to total reserves.

Hence the volume flow that will no longer available is equated to:

$$V_C = R\varphi(1 - b)$$

From our entropy relationship, the incremental entropy change will be equated to:

$$dS_{reserve} = \left(\frac{dV}{V}\right)_R - \left(\frac{dV}{V}\right)_C$$

Substituting, and remembering that **R** and **φ** will both cancel out, we have:

$$dS_{reserve} = \left(\frac{db}{b}\right)_R - \left(\frac{-db}{1-b}\right)_C$$

Thence:

$$dS_{reserve} = \left(\frac{db}{b(1-b)}\right) \quad \text{Or:}$$

$$(S_2 - S_1)_{reserve} = \ln\left(\frac{b_2}{b_1}\right)\left(\frac{1-b_2}{1-b_1}\right)$$

Bibliography & References

Ackerman, F. Stanton, E. (2012) Climate risks and carbon prices: revising the social cost of carbon. *Economics-ejournal.org.*

Andrews, T. Gregory, J. M. and Webb, M. J. in press. The dependence of radiative forcing and feedback on evolving patterns of surface temperature change in climate models. *J. Climate.*

Baumgärtner, S. (2002) Thermodynamics and the economics of absolute scarcity, *2nd World Congress of Environmental and Resource Economists, June 24-27, 2002, Monterey, CA, USA.*

Beck, Ernst-Georg. (2007) 180 years of atmospheric CO_2 gas analysis by chemical methods. *Energy & Environment Vol 18 No 2.*

Bluedorn, J. The human capital augmented Solow model (2002) *Economics 101B - Macroeconomic Theory.*

Bostock, J. McAndrew, B et al. (2010) Aquaculture: global status and trends, *Phil. Trans. R. Soc. B. 365 2897-2912.*

Braconnot, P. et al. (2012) The paleoclimate modelling inter-comparison project, *Nature Climate Change 2, 417-424.*

Brander, J.A. (1998) The simple economics of Easter Island: a Ricardo-Malthus model of renewable resource use. *American Economic Review, Vol 88 No. 1, 119-138.*

Broadbalk Open Access Data (Rothampsted), Long term winter wheat grain yields, and changes in soil organic carbon.

Buitenzorgy, M. Ancev, T. (2013) Global water trends: does democracy matter? *57th Ann Conf Australian Agricultural and Resource Economics Society.*

Burke, M. Hsiang, S.M. and Miguel, E. (2015) Global non-linear effect of temperature on economic production. *Nature doi:10.1038/nature15725.*

Church, N.(2005) Why our food is so dependent on oil, *Powerswitch UK.*

Costanza, R. et al. (2014) Changes in the global value of ecosystem services. G*lobal Environmental Change 26 (2014) 152-158.*

Crawford, J. (2014) What if the world's soil runs out? *World Economic Forum.*

Crowley, T.J. (2000) Causes of climate change over the past 1000 years, *Science Vol 289.*

Dell, M. Jones, B.F. Olken, B.A. (2012) Temperature shocks and economic growth: evidence from the last half century. *American Economic Journal: Macroeconomics 2012, 4(3):66-95.*

Denholm, P. Hand, M. Jackson, M. Ong, S. (2009) Land-use requirements of modern wind power plants in the United States, *Natonal Renewable Energy Laboratory NREL/TP-6A2-45834.*

Ecosystems and human well-being: wetlands and water synthesis (2005) *Millenium Ecosystem Assessment.*

Energy-smart food for people and climate (2011): *Issue paper FAO, UN.*

Epoch Times staff (2011) Fertiliser overuse damages agriculture and environment in China. *Epoch Times.*

Etheridge, D.M. Steele, L.P. Langensfelds, R.L. Francey, R.J. Historical CO_2 Records from Law Dome DE09, DE08-2, DSS Ice Cores, *Division Atmospheric Research, CSIRO.*

FAO (2008) Methodology for the measurement of food deprivation.

FAO (2013) Review of the state of world marine fisheries resources.

FAO UN (2013) Current world fertiliser trends and outlook to 2016.

Fisher, H. Wahlen, M. Smith, J. Mastroianni, D. Deck, B. (1999) Ice core records of atmospheric CO_2 around the last three glacial terminations, *Science Vol 283.*

Fixen, P.E. (2009) World fertiliser nutrient reserves - a view to the future. *Better Crops Vol 93 No. 3.*

Fox, T. (2014) Global food - waste not want not, *IMECHE.*

Friedlingstein, P. et al.(2012) Uncertainties in CMIP5 climate projections due to carbon cycle feedback, *American Meteorological Society Vol 27.*

Fuglie, K. Wang, S.L. (2012) New evidence points to robust but uneven productivity growth in global agriculture, *Farm Economy.*

Fuglie, K. Wang, S.L. (2012) Productivity growth in global agriculture shifting to developing countries.

Fuglie, K.O. Wang, S.L. Ball, E. (2012) Productivity growth in agriculture: an international perspective. *CAB International.*

Gassert, F. Reig, P. Luo, T. Maddocks, A. (2013) Aqueduct and river basin rankings. A weighted aggregation of spatially distinct hydrological indicators. *World Resources Institute.*

Ghanta, P. List of foods by environmental impact and energy efficiency. *The Oil Drum.*

Gleick, P.H. China and water. The World's Water 2008-2009. *worldwater.org.*

Gleick, P.H. Heberger, M. Water and conflict. The World's Water 2008-2009. *worldwater.org.*
Gleick, P.H. Palaniappan, M. (2010) Peak water limits to freshwater withdrawal and use. *PNAS vol 107 No. 25 11155-11162.*
Global status of wind power report, *Global Wind Energy Council.*
Goody, R. (2007) Maximum entropy production in climate theory. *American Meteorological Society.*
Grassini, P. Eskridge, K.M. Cassman, K.G. (2013) Distinguishing between yield advances and yield plateaus in historical crop production trends. *Nature Communications, Macmillan.*
Grinsted, A. Moore, J.C. Jevrejeva, S. (2009) Reconstructing sea level from paleo and projected temperatures 200 to 2100AD *Springer-Verlag.*
Gupta, A.J. Hall, A.S. (2011) A review of the past and current state of EROI data. *Sustainability 2011, 3, 1796-1809.*
Hall, C.A.S. Lambert, J.G. Balogh, S.B. (2013) EROI of different fuels and the implications for society. *Energy Policy 64 (2014) 141-152.*
Hallegatte, S. (2011) The economic growth impact of sea-level rise, *Sustainable Development Network, World Bank.*
Hansen, J. et al. (2007) Climate change and trace gases. *Phil Trans. R. Soc. A 365.*
Hansen, J. Sata, M. (2004) Greenhouse gas growth rates, *NASA GISS, Columbia University Earth Institute PNAS.*
Hansen, J. Sato, M. Kharecha, P. von Schuckmann, Karina. Earth's energy imbalance and implications. *NASA GISS, Columbia University Earth Institute, Centre National de la Recherche Scientifique.*
Harris, W. How frozen fuel works. *Science.howstuffworks.com*
Hawkins, E. Sutton, R. (2009) The potential to narrow uncertainty in regional climate productions. *American Meteorological Society 1095-1107.*
Holloway, J. Roberts, I. Rush, A. China's steel industry, *Reserve Bank Australia.*
Hope, C. (2011) The PAGE09 integrated assessment model: a technical description, *Cambridge Judge Business School Working Papers.*
Hsiang, S.M. Burke, M. Miguel, E. (2013) Quantifying the Influence of Climate on Human Conflict. *Science Sept 2013, Vol 341.*
Hubbert, M.K. (1956) Nuclear energy and the fossil fuels. *American Petroleum Institute, Spring meeting, Southern District.*
Hubbert, M.K. (1965) National Academy of Sciences Report on Energy Resources: reply, *AAPG Bulletin, Oct. 1965, v.49 n.10 p.1720-1727.*
Huber, M. Knutti, R. (2014) Natural variability, radiative forcing and climate response in the recent hiatus reconciled. *Nature Geoscience.*
Hugelius, G. et al. (2013) A new data set for estimating organic carbon storage to 3 m depth in soils of the northern circumpolar permafrost region, *Earth Syst Sci Data 5, 393-402.*
Hughes, J.D. (2012) The energy sustainability dilemma: Powering the future in a finite world.
Hughes, J.D. (2013) Drill baby drill, *Post Carbon Institute.*
IPCC WGIAR5.
IPCC WGIIAR5.
IPCC WGIIIAR5.
Jacobson, M.Z. Delucchi, M.A. (2011) Providing all global energy with win, water and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials, *Energy Policy 39 (2011) 1154-1169, Elsevier.*
Jamail, Dahr. (2013) The coming instant planetary emergency, *The Nation.*
Jenkins, A.D. Maximum entropy production and climate change effects, *Bjerknes Centre for Climate Research.*
Kesler, S.E. Mineral supply and demand into the 21st century, *USGS.*
Kharecha, P. Hansen, J. (2007) Implications of "peak oil" for atmospheric CO_2 and climate, *NASA GISS.*
Kleidon, A. (2010) Non-equilibrium thermodynamics, maximum entropy production and Earth-system evolution. *Phil.Trans. R.Soc 368.*
Kleidon, A. Lorenz, R. (2004) Non-equilibrium thermodynamics and the production of entropy: life, Earth, and beyond. *Springer Verlag.*
Kopp, G. Lawrence, G. Rottman, G. (2005) The total irradiance monitor, *Solar Physics 230: 129-139 Springer.*
Laherrere, J. (2005) Forecasting production from discovery, *ASPO Lisbon May 19–20, 2005*
Laherrere, J. (2005) 'Forecasting production from discovery'. *ASPO. Lisbon May 19-20, 2005.*
Laherrere, J. (2006) 'Fossil fuels: What future?' *China Institute of International Studies. Workshop October 2006, Beijing.*
Lal, R. (2009) Soil degradation as a reason for inadequate human nutrition. *Food Sec 1:45-57 Springer Science.*
Lambert, J et al. (2012) EROI of global energy resources. *St University of New York. DFID - 59717.*
Lane, T. (2014) Desertification: land degradation under a changing climate. *Climatica.*
Li, M. (2011) Peak coal and China, *The Oil Drum.*
Lockwood, M. Fröhlich, C. (2007) Recent oppositely directed trends in solar climate forcings and the global mean surface air temperature. *Proc. R. Soc. A 463.*
Lotka, A.J (1920) Analytical note of certain rhythmic relations in organic systems, *Proc. Natl. Acad. Sci.USA 6 410-415.*
Lotka, A.J. (1925) Elements of physical biology, *William and Wilkins.*
Lucarini, V. Fraedrich, K. Lunkeit, F. (2010) Thermodynamics of climate change: generalized sensitivities. *Atmos.Chem.Phys. Discuss., 10, 3699-3715.*
Lynas, M. Six Degrees: Our future on a hotter planet. *Harper Collins.*
Mackay, D.J.C. (2008) 'Sustainable Energy – without the hot air', *UIT Cambridge Ltd, ISBN 978-0-9544529-3-3.*
Malthus, T. R. (1798) An essay on the principle of population.
Marcott, S.A. Shakum, J.D. Clark, P.U. Mix, A. C. (2013) A reconstruction of regional and global temperature for the past 11,300 years, *Science Vol 339 no. 6124 1198-1201.*
Masson-Delmotte, V. et al. (2006) Past temperature from ice cores, *Clim. Past. 145-165 European Geosciences Union.*
Meadows, D.H. Meadows, D. L. Randers, J. (1992) Beyond the limits: confronting global collapse,envisioning a sustainable future. *Chelsea Green Publishing Company*.
Meadows, D.H. Meadows, D. L. Randers, J. (2005) Limits to growth. The 30 year update. *University Press, New York.*
Meadows, D.H. Meadows, D. L. Randers, J. Behrens III, W.W. (1972),The limits to growth. *Universe Books.*
Miller, T.E. Burns, J.H. et al. (2005) A critical review of twenty years' use of the resource-ratio theory. *The American Naturalist Vol. 165, No. 4.*
Mohr, S.H. Evans, G.M. (2009) Forecasting coal production until 2100. *Fuel, Elsevier.*
Moriaty, M. Honnery, D. (2009) What energy levels can the Earth sustain? *Energy Policy 37 2469-2474.*
Motesharrei, S. Rivas, J. Kalnay, E. (2014) Human and nature dynamics: Modelling inequality and use of resources in the collapse or sustainability of societies. *Ecological Economics. Vol. 101 90-102.*
Müller, I. (2012) Socio-thermodynamics - evolutionary potentials in a population of hawks and doves. *Entropy 14 1285-1295.*
Nachtergael, F. Bruisman, J. Valbo-Jorgensen, J. Bartley, D. (2011) The state of the world's land and water resources for food and agriculture. *SOLAW background report TR01.*
Nachtergaele, F. Biancalani, R. Petri, M. (2011) Land degradation. *State of Land and Water Resources (SOLAW) background thematic report 3 FAO.*
Nelson, S.A. (2013) The ocean-atmosphere system, *Tulane University.*
Nordell, B. It is all about thermal energy storage, *Luleå University of Technology, Sweden.*
Oldeman, L.R. Hakkeling, R.T.A. Sombroek, W.G. (1990) Human-induced soil degradation. *GLASOD, ISRIC report 1990/07.*
Open Working Group Sustainable Development Goals (2014) Desertification, land degradation and drought. *UNCCD.*
Owen, N. Inderwildi, O.R. King, D.A. (2010) The status of conventional world oil reserves - hype or cause for concern? *Energy Policy 38 4743-4749*.
Ozawa, H. Ohmura, A. Lorenz, R.D. Pujol, T. (2003) The second law of thermodynamics and the global climate system: A review of the maximum entropy peoduction principle, *Reviews of Geophysics, 41, 4 / 1018 American Geophysical Union.*
Ozawa, H. Shimokawa, S. Sakuma, H. Ohmura, A. (2003) Entropy and climate: The nature of entropy change in the global climate system. *Climate variations research program.*
Palaniappan, M. Gleick, P.H. Peak Water. The World's Water 2008-2009. *worldwater.org.*
Paltridge, G.W. (1979) Climate and thernodynamic systems of maximum dissipation, *Nature Vol 279 Issue 5719 630-631.*

Parrenin, F. et al (2013) Synchronous change of atmospheric CO_2 and Antarctic temperature during the last deglacial warming, *Science Vol 339 n. 6123 pp. 1060-1063.*
Pascale, S. Gregory, J.M. Ambaum, M. Tailleux, R. (2009) Climate entropy budget of the HadCM3 atmosphere-ocean general circumation model and of FAMOUS, its low resolution version, *Clim Dyn, Springer Verlag.*
Pascale, S. Gregory, J.M. Ambaum, M. Tailleux, R. Lucarini, V. (2012) Vertical and horizontal processes in the global atmosphere and the maximum entropy production conjecture, *Earth Syst. Dynam, 3, 19-32,*
Patzek, T.W. Croft, G.D. (2010) A global coal production forecast with multi-Hubbert cycle analysis. *Energy 35 3102-3122.*
Peixoto, J.P. Oort, A.H. De Almeida, M. Tomé, A. (1991) Entropy budget of the atmosphere, *Journal of Geophysical Research, Vol. 96 No. D6 10,981-10988.*
Penning de Vries, F.W.T. Van Keulen, H. Rabbinge, H. Luyten, J.C. (1995) Biophysical limits to global food production, *International Food Policy Research Institute.*
Petit, J.R. Jouzel, J. et al. (1999) Climate and atmospheric history of the past 420,000 years from the Vostock ice core, Antarctica. *Nature Vol 399.*
Pimental, D. Burgess, M. (2013) Soil erosion threatens food production. *Agriculture 3, 443-463.*
Pimental, D. Williamson, S. Alexander, C.E. Gonzales-Pagan, O. Kontak, C. Mulkey, S.E. (2008) Reducing energy inputs in the US food system. *Hum Ecol.Springer Science.*
Primary aluminium production, *World Aluminium, International Aluminium Institute.*
Richardson, C. Courvisanos, J. Crawford, J.W. (2011) Towards a synthetic economic modelling tool for sustainable exploitation of ecosystems, *Ann. N.Y. Acad.Sci. 1219 171-184.*
Rockström. J. (2009) A safe operating space for humanity. Nature. Vol 461
Roper, L.D. (2013) Uranium depletion. arts.bev.net.
Rowley, R.J. Kostelnick, J.C. Braaten, D. Li, X. Meisel, J. (2007) Risk of rising sea level to population and land area, EOS Transactions, American Geophysical Union.
Rűhl, C. (2014) Energy in 2013: Taking stock. World Petroleum Congress.
Rűhl, C. Appleby, P. Fennema, J. Naumov, A. Schaffer, M. (2012) Economic development and the demand for energy: a historical perspective on the next 20 years. Energy Policy Vol 50.
Rutledge, D. (2011) Estimating long-term world coal production with logit and probit transforms. International Journal of Goal Geology. 85 (2011) 23-33.
Santer, B.D. et al. (2013) Human and natural influences on the changing thermal structure of the atmosphere. Proc. National Academy of Sciences. Vol 110, No. 43.
Schlenker, W. Roberts, M.J. (2008) Estimating the impact of climate change on crop yields: the importance of non-linear temperature effects. NBER w13799.
Schlosser, E. Temperature reconstruction using ice cores, Inst Meteorology and Geophysics, University of Innsbruck.
Schneider, R. et al (2013) A reconstruction of atmospheric carbon dioxide and its stable carbon isotopic composition from the penultimate glacial maximum to the last glacial inception. Clim. Past, 9, 2507-2523.
Slingo, J. (2013) Statistical models and the global temperature record, *Met Office.*
Stephens, G.L. O'Brien, D.M. (1993) Entropy and climate. I: ERBE observations of the entropy production of the Earth. *Q.J.R. Meteorol. Soc. 119 121-152.*
Stern, N. (2006) Stern review on the economics of climate change. *HM Treasury, London.*
Stern, N. (2013) Economic growth, poverty reduction and managing climate change. *LSE, Grantham Research Institute on Climate Change and the Environment.*
Svensmark, H. Friis-Christensen, E. Reply to Lockwood and Frölich - The persistent role of the Sun in climate forcing. *Danish National Space Centre Scientific Report 3/2007.*
Trenberth, K.E. Smith, L. (2005) The mass of the atmosphere: a constraint on global analyses. *J. Climate,18, 864-875.*
Tripati, A. Roberts, C.D. Eagle, R.A. (2009) Coupling of CO_2 and ice sheet stability over majore climate transitions of the last 20 m years, *Science Vol 326.*
van Vuuren, D.P. et al. (2011) The representative concentration pathways: an over view, *Climatic Change (2011) 109:5-31 Springer.*
Wu, W. Liu, Y. (2010) Radiation entropy flux and entropy production of the Earth system. *Reviews of Geophysics, 48, American Geophysical Union.*