THERMO ECONOMICS IN A FINITE WORLD

John Bryant BSc MSc CEng FIMechE FEWI

VOCAT INTERNATIONAL LTD
Consultancy, Research & Expert Witness Services
August 2007

Introduction

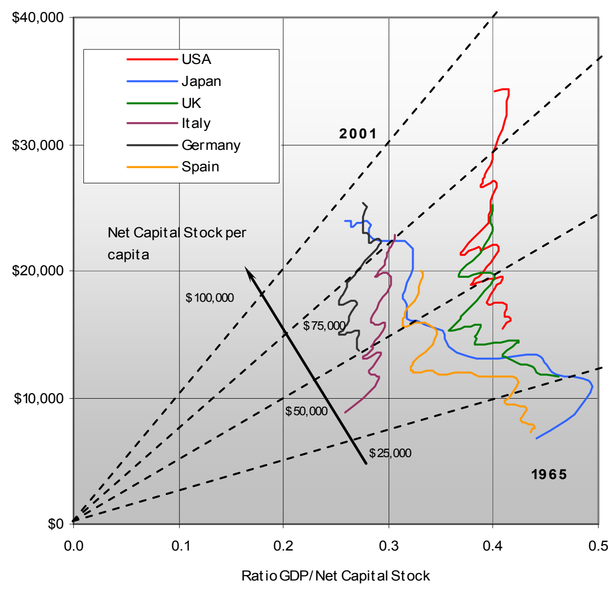
The origins of this article arose from previous research into the connections between the disciplines of economics and thermodynamics, begun more than a quarter of a century ago, culminating in a paper published in 1982[1], which was subsequently followed up by a presentation to an international symposium, hosted by the Hungarian government, concerning East-West approaches to the energy problem. Since that time the boundaries of knowledge have expanded, and in 2007 a more advanced paper was published[2].

The last decade has seen the emergence of concern and debate about climate change and the impact of greenhouse gases on world ecological and economic systems, much arising from the burning of carbon-based fuels. Comprehensive research has been carried out by the Intergovernmental Panel on Climate Change (IPCC). There has been some revival of interest, though now more cautious, in the views propounded by the *Club of Rome* and '*Limits to Growth'* three decades ago.

Economic systems, particularly of developed countries, have become progressively embedded in an energy base, to provide a source of productive power and human wealth. Economics and energy are seen as being very much related to one another. This was the thesis of the original 1982 paper, though as a thermodynamic analogy of the workings of economic systems, rather than the use per se of energy in an economy. Whereas a simple conventional economic production system might be set out as:

[capital K, labour L, resources B] = Output (G)

Figure 1. GDP per capita ($PPP 2000) versus Ratio GDP / Net Capital Stock 1965 - 2001
(Germany 1971 onwards)



Source: OECD, Penn World

with no special regard for system limits, other than those of the business/trade cycle, investment for the future and acceptable supply and demand variations; under a thermo-economic system due regard has to be taken of the impact of any restrictions, including waste/residue (D) and other relevant factors.

Moreover, the system incorporates *Le Chatelier* feedback mechanisms to increase or decrease the forward path, according to the impact of any key factor, with a two-way arrow to signify that the reaction can speed up, slow down, or even stop. In addition, a restriction affecting one business, market or economy can affect another, via their interlinking requirements. Thus the format for output G might be modified as follows, with values a, b, c, x and y representing the proportions of each factor in the process:

$$aK + bL + cB \Leftrightarrow xG + yD$$

Development

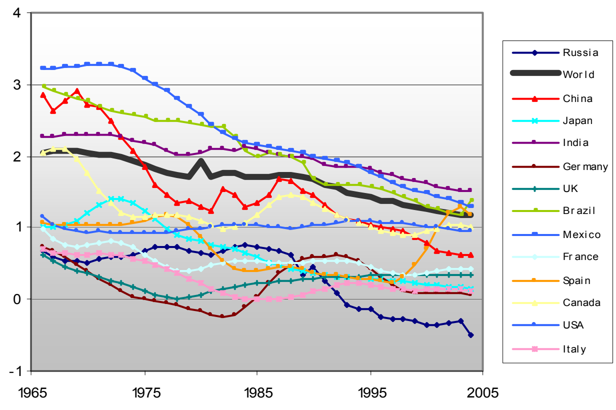
Until comparatively recently, much account of the impact of resource and waste factors has not seriously had to be taken, except at the micro-economic level. Oil, gas, minerals, water, land, food and agricultural factors have all been found to feed the human economic system. For example, in 1980 world gas reserves stood at about 85 trillion m^3 *(source: BP)* representing 58 years at current production. In 2006, the comparable figures were 181 trillion m^3 and 63 years respectively. Figure 1 opposite shows that virtually up to the present time major economies have been able to advance long-term, relatively unscathed by outside factors. GDP per capita for the older developed countries, such as USA, Germany, Italy and UK has inexorably advanced against a relatively constant level of GDP/capital stock – bar business/trade cycle effects. In the case of Japan and Spain, after initial high growth and investment, GDP growth slowed and the curves then shifted to the left. Outside the West, other economies have joined this process, such as China, South Korea, Taiwan and some East European and Middle Eastern countries. With the aid of economics and technology, humankind is progressively, and ever more efficiently, consuming resources of the world, in many cases without replacing/recycling much of them. It is fair to say, however, that some countries, such as Germany, have and are installing increasingly more comprehensive recycling measures to offset this trend.

Population

Associated with the benefits of economic growth has been a increase in population. It is a matter of opinion as to whether population size may be approaching a ceiling within a finite world. There are indications that feedback in the system, perhaps along the lines described above, has reduced birth rates in some areas of the world. Between 1980 and 2004, population growth in East and West Europe has been only 10%. However, growth elsewhere has been larger—North America 34%, Asia & Oceania 44%, Central & South America 52%, Africa 85% and the Middle East 93%. In China, measures to control family size are now in place, though the total population is still projected to rise for some while yet. The US Census Bureau projects a world population level of 9bn by 2042, 36% more than at present.

1. Bryant J. (1982) 'A Thermodynamic Approach to Economics', *Energy Economics, Vol 4, No.1, pp. 36-50.*
2. Bryant J. (2007) 'A Thermodynamic Theory of Economics' *International Journal of Exergy' Vol 4, No. 3, pp. 302-337.*

Figure 2. World Population Growth Rates % pa. 1965-2004



Source: UN, Penn World

Table 1.	GDP PPP		Population		Energy Consumption	
	2006		2007		2006	
	bn $ pa.	%	mn	%	mn toe pa.	%
USA	13130	19.9	301.1	4.6	2326.4	21.4
China	10170	15.4	1321.9	20.0	1697.8	15.6
Japan	4218	6.4	127.4	1.9	520.3	4.8
India	4156	6.3	1129.9	17.1	423.2	3.9
Germany	2630	4.0	82.4	1.2	328.5	3.0
UK	1930	2.9	60.8	0.9	226.6	2.1
France	1891	2.9	63.7	1.0	262.6	2.4
Italy	1756	2.7	58.1	0.9	182.2	1.7
Russia	1746	2.6	141.4	2.1	704.9	6.5
Brazil	1655	2.5	190.0	2.9	206.5	1.9
Korea (South)	1196	1.8	49.0	0.7	225.8	2.1
Canada	1178	1.8	33.4	0.5	322.3	3.0
Mexico	1149	1.7	108.7	1.6	154.2	1.4
Spain	1109	1.7	40.4	0.6	145.8	1.3
Australia	675	1.0	20.4	0.3	120.8	1.1
Rest World	17361	26.3	2873.6	43.5	3030.6	27.9
World	**65950**	**100.0**	**6602.2**	**100.0**	**10878.5**	**100.0**

Source: CIA, BP

Energy

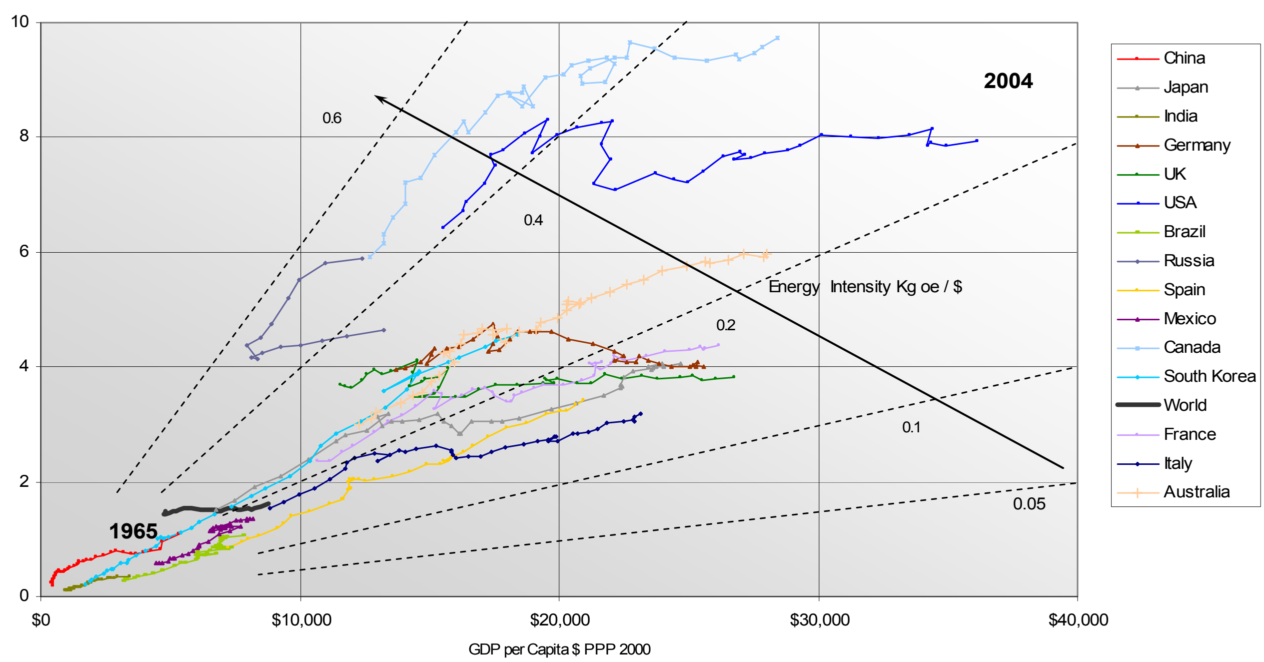
Energy consumption has played a major role in the development of the world economy, having grown nearly threefold between 1965 and 2006 to 10.9 billion tonnes per annum oil equivalent. Figure 3 illustrates the development of primary energy consumption per capita and GDP (PPP) per capita for the four-decade period from 1965—2004 for key economies, with the cross-reference of energy intensity. The picture is one of economies at different stages of development from emerging-industrial through to post-industrial.

At the left had side, China is currently going through a significant industrial phase, with India further behind. Chinese per capita GDP and energy consumption, both low, are rising fast, but with energy intensity, after an initial high level, coming down to about 0.2 kg oil equivalent per $ of output. Further along the development path are Brazil and Mexico, followed by South Korea, with energy intensity still about 0.2 kg/$, but with energy consumption per capita much higher, in the region of 2-4 tonnes oil equivalent per annum. The lines for Spain, Italy and Japan illustrate a further phase, where energy intensity begins to fall, having passed the main industrial phase, with energy consumption per capita beginning to level off.

The lines for France, Germany and UK illustrate the final phase, where energy demand per capita has flattened off at about 4 tonnes oil equivalent per annum, and with energy intensity in the region of 0.15 kg/$ and falling.

Outside this envelope of curves are USA, Canada, Australia and Russia. US energy consumption per capita is twice European and Japanese levels, but energy intensity has fallen by half over the period to a little above 0.2kg oe/$. Canadian per capita energy consumption is even higher. Australian energy consumption per capita continues to rise, although energy intensity has remained steady from 1980 onwards at about 0.3 kg oe/$. Last, the Russian economy has both high energy intensity and high per capita energy consumption. With the recovery of the Russian economy since 1996, energy intensity has begun to fall.

Figure 3. Primary Energy Consumption per capita (toe/hd pa.) versus GDP per capita pa.
1965 - 2004
(Russia 1990 onwards, Germany 1970 onwards, World 1980 onwards, Rest of World 1980 onwards)

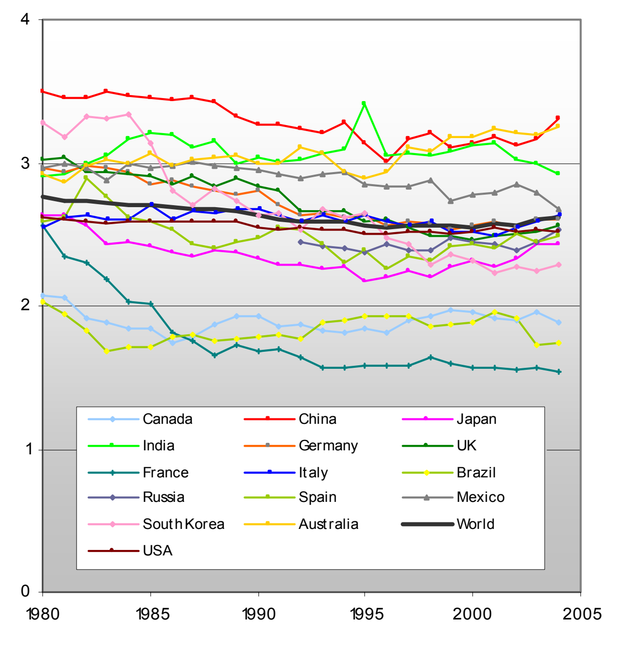


Source: BP, Penn World

Climate Change

The studies carried out by the IPCC, Stern Review and UKCIP02 all point to the necessity to reduce or contain the impact of greenhouse gases on the world climate and atmospheric temperature, though there continues to be some debate on the probable outcome. The scenarios painted by the agencies do, however, illustrate a point of this paper, that restrictions placed on economic systems can potentially affect their forward path in quite a dramatic way; and the impact of the analyses presented to a world audience may enact feedback to construct policies to change the shape of the future. Approximately 55% of world CO_2 emissions increases arise from fossil fuel use, the rest from deforestation, agriculture and other areas *(IPCC SPM 1)*. Figure 4 shows how emissions from consumption and flaring of fossil fuels have varied in relation to primary energy consumption for key countries and the world:

Figure 4. Ratio CO2 Emissions from consumption & flaring of fossil fuels / Primary energy consumption t CO2 / t oe



Sources: EIA, BP

Although emissions from fossil use have been rising, in many cases their ratio to energy consumption has declined. The French ratio in particular has shown a marked drop, partly arising from the high level of nuclear input into electricity generation. Ratios for Australia and Japan are rising. Clearly if all countries emulated France by introducing a large nuclear programme, or developed other technologies, such as renewable and wind power, carbon sequestration and vehicle drive technology, then there is much room for improvement in the world emissions ratio. However, over the 24-year period to 2004, the world ratio has declined by only 5%, and it is a matter of confidence, probability, and the results of national efforts as to how much further the ratio will actually decline in future decades.

The same will apply to projections of energy intensity, the trend of which is displayed at figure 3 for a 39-year period. From the chart, on the basis of the trends, it is conceivable that for many European countries a figure near to 0.1 kg oe / $ or lower might be attainable, particularly if past the industrial phase. For developing countries this may be more difficult. The Chinese figure in 2004 is about the same as it was in 1998. In the 34-year period between 1970 and 2004, the US was able to halve energy intensity to 0.22 kg oe / $, with a continuing trend downwards. Australia, Canada and Russia, however, appear to have much further to go, though local conditions should be taken into account.

After Chernobyl and Three Mile Island, and prior to the studies of IPCC, nuclear technology had lost some of its shine, taking into account the potential for future terrorism, nuclear accidents and having to bear the full cost of storing some waste perhaps for many generations. A number of countries had enacted policy barriers to nuclear new build or to close plants before the end of their economic lifetimes[3]. The recent earthquake in Japan has sent further alarm bells ringing. It is possible that some countries may return to nuclear technology in the future.

There are of course many other technologies to explore, including renewable, wind and solar power, and sequestration to remove CO_2 emissions (also involving burial underground or at sea, with further environmental concerns). Reduction in transport emissions, may depend partly on switching to electric power. Reforestation also offers the opportunity to take up CO_2 emissions. All of these technologies are likely to add significantly to the cost of providing energy, and subtract from possible GDP growth. Both IPCC and Stern make calculations as to the cost as a percent of GDP of programmes to reduce the effect of emissions on the climate. Ecological economics is fast becoming a major tool in shaping future progress, with the need to account for full waste/resource costs in any development.

IPCC and Stern indicate that CO_2 emissions must come down significantly over the future. The Stern report for example indicates that to stabilise at 550ppm by 2050, emissions would need by then to have been reduced to about a quarter of current levels. IPCC project that emissions of developed countries should fall 40%-95% below 1990 levels for a low to medium CO_2 stabilization level.

Table 2 sets out some illustrative positions *(**not** taken from IPCC or other source)*, based on *fossil fuel emissions only*, for emissions at 47% of those in 1990. Assumptions are displayed in red. Any number of combinations and sizes of reduction are possible, but to be meaningful they have to be consistent with what observers believe nations can achieve against trends achieved so far. The writer defers to the experts at IPCC, Stern and others on the probabilities of any scenario.

Table 2. Example projections of World Energy Consumption & GDP

		2000	**Projection 2050**				
Assumption			**A**	**B**	**C**	**D**	**E**
Population	*bn*	6.08	9.0	9.0	9.0	9.0	8.0
Emissions CO_2 #	*$GtCO_2$ pa.*	23.85	10.0	10.0	10.0	10.0	10.0
Energy Consumption	*bn toe pa.*	9.31	5.0	6.7	10.0	10.0	10.0
Emissions/Energy	*tCO_2/toe*	2.56	2.0	1.5	1.0	1.0	1.0
Energy per capita	*toe pa.*	1.53	0.56	0.74	1.11	1.11	1.33
Energy Intensity Kg/$	*KG/$*	0.19	0.15	0.10	0.10	0.05	0.05
GDP PPP (2000)	*$ trn*	$48.6	$33.3	$66.7	$100.0	$200.0	$200.0
GDP per capita	*$ 000*	$8.0	$3.7	$7.4	$11.1	$22.2	$25.0
Growth GDP/Hd 2000 - 2050			-1.5%	-0.2%	0.7%	2.0%	2.3%
(1980 - 2000 = 2.58% pa.)							

Assumed figures in red — *Source 2000 data: BP, EIA*

 # Emissions arising from fossil fuel use only.

On the assumptions given, all the illustrations indicate lower than historic growth in GDP per capita, with some going negative. To achieve scenario D, the emissions/energy consumption ratio is pitched at 39% of that in 2000 *(compared to the small 5% drop achieved from 1980 to 2004 illustrated at figure 4)*, and energy intensity at 0.05 kg oe/$ is nearly a quarter of 2000 levels *(well outside the range of the 39-year history illustrated at figure 3)*. Scenario E shows the effect of a reduction in population size. The alternative to the scenarios, is to accept a higher level of global warming than implied by a low to medium stabilization level.

3. Helm D. 'The New Energy Paradigm' (2007). *Oxford University Press.*

Economic

The studies of IPCC and Stern indicate that to reduce net carbon emissions requires a significant investment in technology. A part of this expenditure will be to replace ageing plant, but much of the rest serves not to increase or replace capacity, but to increase the net cost of producing cleaner and more efficient energy. What otherwise could have been channelled into consumption of other goods and services, raising GDP per capita, may now have to be channelled into 'safeguarding' expenditure. The economic potential of these technologies is set against a carbon price, at which it becomes profitable to invest in them.

A product of this process, however, will be to bend the curve of GDP/capital stock, illustrated at figure 1 of this paper, to the left, with growth in GDP per capita slowing down, against a net capital stock per capita still rising because of the increased cost of capital output. It is intuitively obvious that economic growth will likely slow down, until economies have been weaned off their use of carbon based fuels onto other technologies. We may thus enter a world of lower growth and reduced consumption, which potentially could be quite long-lasting.

International

The effect on the world economy may depend partly on agreements as to how much each country agrees to reduce their emissions. Table 3 summarises CO_2 output from consumption and flaring of fossil fuels in 2004. 169 countries ratified the Kyoto protocol, which runs to 2012. Notable exceptions included USA and Australia. India and China, although signed up, are not required to reduce carbon emissions. Currently, UK, Sweden, Germany, France and Netherlands appear to be on target to achieve their reduction *(EEA)*. Canada has abandoned its Kyoto target of a 6% reduction on 1990 levels; in 2004 its emissions were 30% above those of 1990. In June 2007 G8 leaders agreed to aim at least to reduce global CO_2 emissions by 2050. While it takes not too much effort to make a joint declaration, it is less likely that individual governments, mindful of their electorate and the short term consequences to their economy and sectional business interests, will move swiftly to enforce draconian policies that could seriously cut GDP. Some governments may choose to ignore the situation and carry on doing 'business as usual'. This may of course worsen the longer-term situation, and eventually antagonise others, politically and economically.

Objectives

The longer term requirement is for a cut in world emissions perhaps to less than half of 1990 levels, made worse by a forecast increase in world population to 2050 of up to 50%. It is of course for world governments to agree on a target, and what is equitable for each country, given their individual circumstances and state of development. Such agreed targets, however, would not be feasible unless strategies to reduce both emissions/energy consumption and energy intensity were viable (see figure 3 and figure 4).

Other Areas

Much interest and effort has been focussed on the implications for the world economy on climate change, and the need to reduce emissions of greenhouse gases to stabilize temperature rise. There are, however, other areas of concern for the future.

Table 3. CO2 output from consumption and flaring of fossil fuels 2004

	Population	*CO_2 Output*		*CO_2 per capita*
	mn	*mn tonnes pa.*	*%*	*tonnes pa.*
USA	293.0	5912.2	21.9	20.18
China	1298.9	4707.3	17.4	3.64
Russia	144.0	1684.8	6.2	11.70
Japan	127.3	1262.1	4.7	9.91
India	1065.1	1112.8	4.1	1.04
Germany	82.4	862.2	3.2	10.46
Canada	32.5	588.0	2.2	18.09
UK	60.3	579.7	2.1	9.62
South Korea	48.4	496.8	1.8	10.26
Italy	58.1	485.0	1.8	8.35
France	60.5	405.7	1.5	6.71
Australia	19.9	386.2	1.4	19.39
Mexico	105.0	385.5	1.4	3.67
Spain	40.3	361.9	1.3	8.98
Brazil	184.1	336.7	1.2	1.83
Rest of World	2752.9	7476.7	27.6	2.72
World	6372.7	27043.6	100.0	4.24

Source: EIA

A study carried out by the IFPR [4] on the world water and food position to 2025 indicates that the world is facing severe water scarcity, with severe impacts on food production, health, nutrition and the environment. The FAO [5] indicates that humanity faces a challenge on how to ensure sustainable use of fisheries resources when the level of demand has increased beyond what aquatic environments are able to supply, and appears set to continue. The UN [6] reports that by 2008 more than half the world's population (3.3bn) will be living in urban areas, and by 2030 this is expected to swell to 5bn. Many of the new urbanites will be poor.

Knowing our limits

All the forgoing analysis shows that in predicting the future, policymakers, managers and economists are increasingly having to take account of the impact of resource and waste factors on the world. Releasing unlimited CO_2 into the atmosphere is no longer an option, in terms of temperature rise and potential loss of land. Over-fishing the world's seas for food on behalf of a growing world population could be short-sighted. A part of the problem is the escalating size of the world population itself. Though overall this is now growing at a lower rate, for some countries, with large and densely-populated areas, future growth will present policy-makers with a difficult situation to deal with.

Over the next few decades humankind may have to get used to a low or nil growth GDP scenario, placing a limit on consumption and what this may mean in terms of the distribution of world wealth. A new economic age beckons.

4. World water and food position to 2025 International Food Policy Research Institute 2002.
5. Sustainability Issues, Fisheries and Acquaculture Department, UN Food & Agriculture Organisation.
6. State of the World Population 2007 UN Population Fund.

VOCAT
INTERNATIONAL LTD
Consultancy, Research and Expert Witness Services

Tavistock House
10 Falconers Field
Harpenden AL5 3ES
United Kingdom

Tel: +44 1582 462015
Fax: +44 1582 767459
E-mail: john.bryant@vocat.co.uk
Web: www.vocat.co.uk

Director: John Bryant BSc MSc CEng FIMechE FEWI