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ENTROPY MAN

John Bryant

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Contents

Preface

<i>1</i>	<i>Setting the Entropy Scene</i>	1
	Prologue	1
	Scene 1	2
	Scene 2	7
	Scene 3	10
	Scene 4	12
<i>2</i>	<i>A Short History of Human Development</i>	15
<i>3</i>	<i>Connecting to Economic Value</i>	27
	Productive Content	29
	The Source of Economic Value	32
<i>4</i>	<i>Economic Stocks and Flows</i>	37
	The Distribution of Income & Wealth	43
	Elasticity	46
	The First Law of Thermodynamics	47
	The Second Law of Thermodynamics	52
	Utility	57
<i>5</i>	<i>Production and Consumption</i>	64
	A Simple Production System	66
	The March of Entropy	76
<i>6</i>	<i>Money</i>	80
	Money Entropy	88
	Money Entropy and Interest Rates	90
<i>7</i>	<i>Labour and Unemployment</i>	98
<i>8</i>	<i>Resource Dynamics and the Economy</i>	105
	Non-Renewable Resource Dynamics	106
	Renewable Resource Dynamics	110
<i>9</i>	<i>Non-Renewable Resources</i>	115
	Energy in the Economy	115

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Oil and Natural Gas	117
Coal	125
Nuclear Power	128
Energy Return on Energy Invested	131
Metals and Minerals	132
Steel	133
Cement	135
Aluminium	136
10 Renewable Resources	138
Humankind	138
Water	141
Land and Soil	144
Human Dietary Trends	148
The Green Revolution and Yield	149
Cereal and Grain Production	151
Meat	152
Fish	153
Food Supply and Energy Consumption	155
Renewable Energy	156
Hydro-Electric Power	157
Wind	158
Solar	159
Other Renewable Energy	160
11 The Atmosphere, Oceans and Cryosphere	161
12 Economics, Entropy and a Sustainable World	179
Chapter Notes	188
Bibliography and References	196
List of Symbols	209
Index	210

Preface

The seeds for this book were sown in the 1970s, four decades ago, when I was then working as group economist for the engineering corporation Babcock International Plc. At that time the group employed about 30,000 people in subsidiaries spread all around the world, engaged in the design, manufacture and installation of capital plant for a variety of industries, including nuclear & conventional power generation, coal mining, gas, chemicals & petroleum, steel, automotive, cement, construction and environmental engineering. Prior to that, my formal university education had included a degree in engineering at University of Bath and a Masters in management science, allied to student sandwich experience with Amalgamated Power Engineering [*now a subsidiary of Rolls Royce*] and ASEA Brown Boveri, Switzerland, followed by working for SKF, the Swedish bearing manufacturer, often considered to be a bell-weather of world economic output.

From the 1980s onwards I worked as director of a consultancy, and subsequently also as an expert witness to the Courts, which roles I continue to the present day. These experiences have taught me to maintain an enquiring, dispassionate and impartial mind regarding the complex workings of human endeavour, the natural world and changes arising thereof.

My particular research interests in those early years concerned the parallels between the disciplines of economics and thermodynamics [*the science of energy & heat*] and how they relate to each other, as a result of which I published two peer-reviewed papers on the subject in *Energy Economics* [1979 & 1982]. Subsequent to these I gave presentations to international gatherings of government ministers, energy industry executives and academia.

Not being based at a university however, and with no research grant at my disposal, my main thrust had been to make a living from consultancy and therefore, until more recently, opportunities to spend time on research were few. Nevertheless, by the turn of the millennium I was able to find time to return to some research and published another peer-reviewed paper in the *International Journal of Exergy* [2007], followed up by several working papers on monetary aspects and energy models. Subsequently in 2009 I wrote a technical book on the subject, to bring together all the facets of the

work into a coherent whole: *‘Thermoeconomics – a thermodynamic approach to economics’*. The book was subsequently revised, corrected and added to, up to a third edition [2012], covering topics such as production and consumption processes, employment, money, interest rates and bonds, energy resources, climate change and sustainability, and including more up to date statistics. It has now been superseded by this book.

Whilst not being tied to a university, government agency, industrial enterprise or other organisation has disadvantages in terms of recognition and time available for research, it does nevertheless have the advantages of freedom to investigate and pursue a course of enquiry of one’s own choosing and of drawing conclusions independent of those that pay the piper or who may have pre-set agendas, however well-intentioned these may be.

The nature of the subject requires significant proof for economists and scientists to accept that similarities between thermodynamic and economic phenomena might imply more than just a passing analogy or isomorphism, and relations between the two disciplines have rarely been comfortable, with scientists sometimes having scant regard for the work of economists; and many economists believing that science has little to offer their discipline which, by its nature, can be thought of as anthropocentric rather than eco-centric. One eminent energy scientist advised me that he did not know of an economist who could follow a thermodynamic argument. Certainly a concept such as entropy means very little to most economists, still less to the man in the street – money is their language of communication. The latter is not, however, the language that Nature and the environment converse in.

This book is intended for a mixed readership of scientists, economists and those of an enquiring mind. It is a challenge therefore to convey the nub of the argument in terms that all can appreciate, with particular reference to the effects of potential problems such as ‘peak resources’, humankind’s effect on the ecosystem and the maelstrom that would ensue should resource failure or climate change ever come about to a significant degree.

While some chapters, notably chapters 4 through to 8, do contain some mathematical expressions, explanatory points are included to guide non-mathematicians onwards. Formal proofs and derivations have been relegated to the notes on each chapter.

Although economic man may currently have the ascendancy, he does not actually 'own' the Earth. He is there on sufferance, and the Earth would quickly forget him along the ecological timescale, should human civilisation fail or spoil the proceedings.

I am indebted to my wife Alison for all her support and for providing me with an atmosphere conducive to my research.

John Bryant

CHAPTER 9 NON-RENEWABLE RESOURCES

In this chapter we look at a range of non-renewable resources useful to humankind. They are all tied to energy use to a greater or lesser extent, and depending also upon the relative level of economic advancement, so it is appropriate to look at the energy sector first.

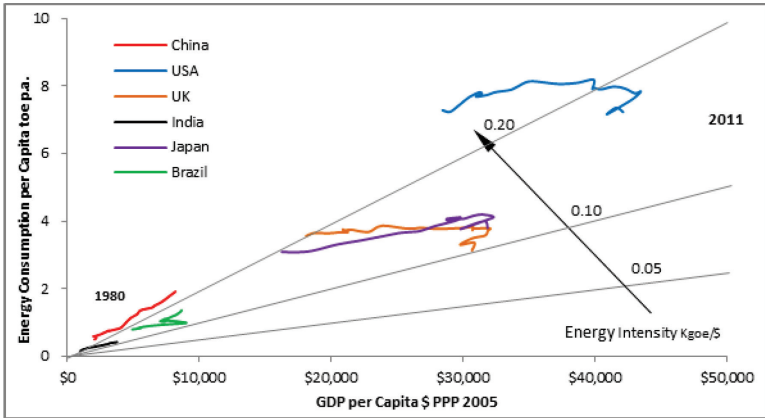
Energy in the Economy

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 2.3 at chapter 2 illustrates the inexorable rise in energy use, mostly based on non-renewable resources of coal, oil and natural gas, and table 2.4 sets out the range of human and industrial assets that currently require energy consumption in order to function fully.

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%.

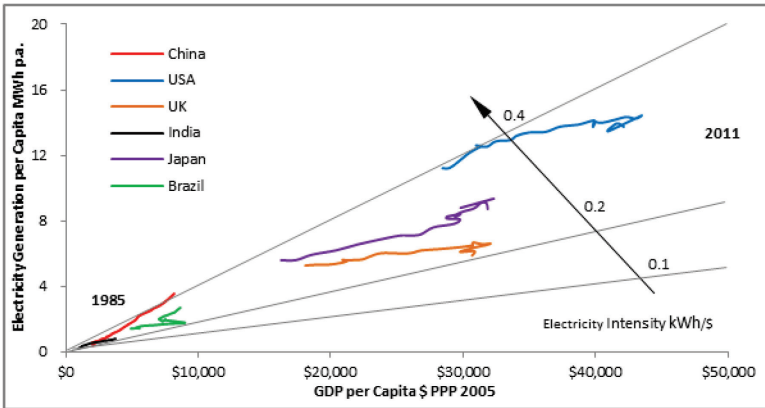
By common practice, the units used to measure energy production and consumption are those of weight [*tonnes of oil equivalent*], volume [*barrels of oil, billions cubic metres of gas (bcm)*] or the heat value of sources of energy

[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 9.1 and 9.2 summarise the development and relationship of primary energy consumption and electricity generation to GDP and population over several decades for some key countries.



Source: Penn World, BP Statistical Review

Figure 9.1 Primary Energy Consumption p.a. per capita, GDP per Capita (PPP 2005) and Energy Intensity. 1980 – 2011.



Source: Penn World, BP Statistical Review

Figure 9.2 Electricity Generation p.a. per capita, GDP per capita (PPP 2005) and Electricity Intensity. 1985 – 2011.

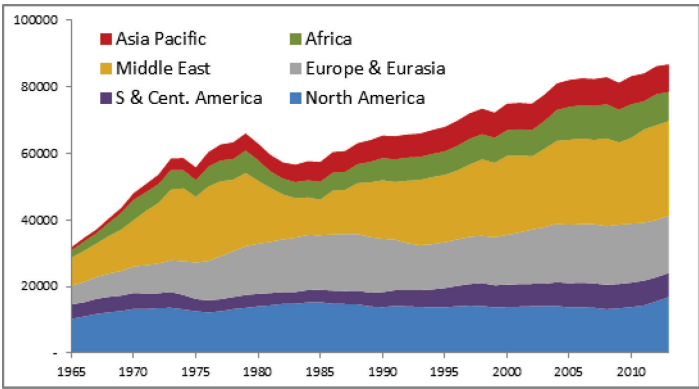
In some developed economies, energy consumption per capita has begun to level off, if not decline, indeed in the 2008 recession it declined

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.

Figures 9.1 and 9.2 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.

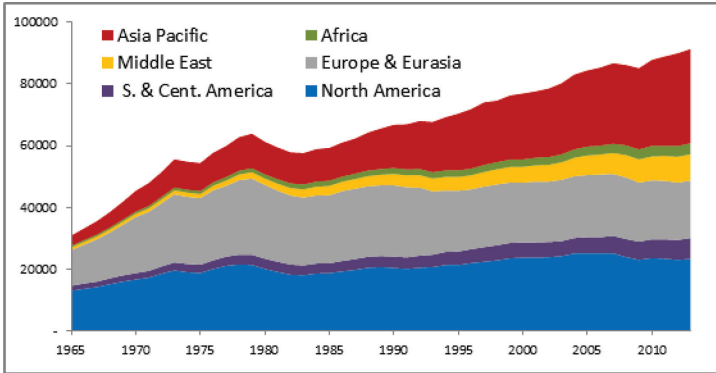
Oil and Natural Gas

Figures 9.3 – 9.6 set out charts of world production and consumption of conventional oil and natural gas.



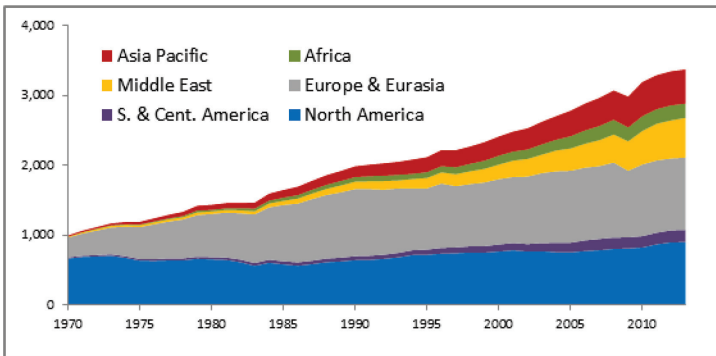
Source: BP Statistical Review

Figure 9.3 World Oil Production – 000's barrels/day.



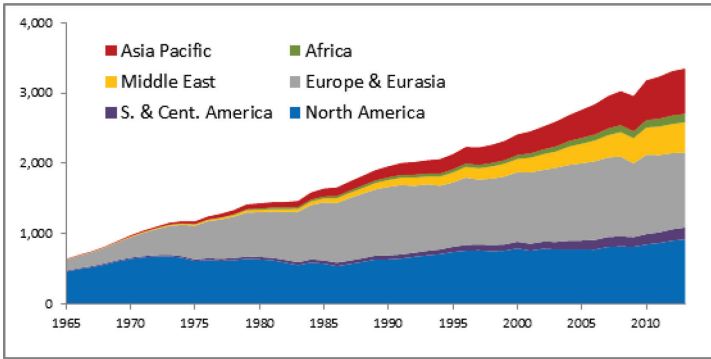
Source: BP Statistical Review

Figure 9.4 World Oil Consumption – 000's barrels/day.



Source: BP Statistical Review

Figure 9.5 World Natural Gas Production - bcm p.a.



Source: BP Statistical Review

Figure 9.6 World Natural Gas Consumption - bcm p.a.

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.

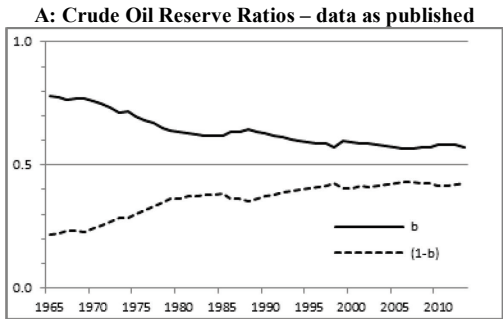
World natural gas production has expanded greatly, with the biggest growth occurring in Russia. Elsewhere, production has expanded in USA, Canada, the North Sea, Iran, Saudi Arabia, Algeria, Indonesia and Malaysia. Recent increases in US production are owing to the advent of shale gas production from 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 in chapter 8 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

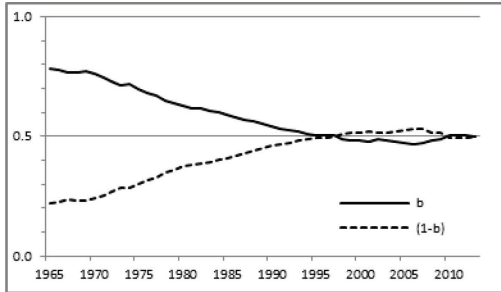
that no more discoveries will be forthcoming to increase the size of the net reserves remaining.

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 [*Laherrère, 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 9.7 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.



B: Ratios net of Canadian Tar Sands and OPEC amendments



Data sources: BP Statistical Review, OPEC

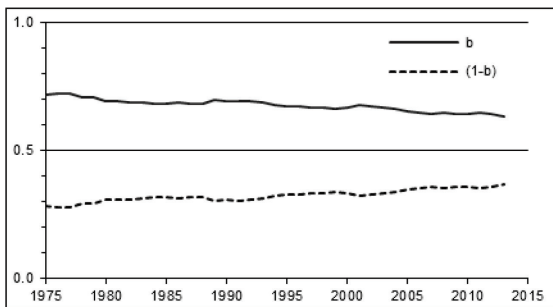
Figure 9.7 World Oil reserve ratios.

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 9.8 shows a similar set of ratios for world natural gas.



Data Source: BP Statistical Review.

Figure 9.8 World Natural Gas reserve ratios

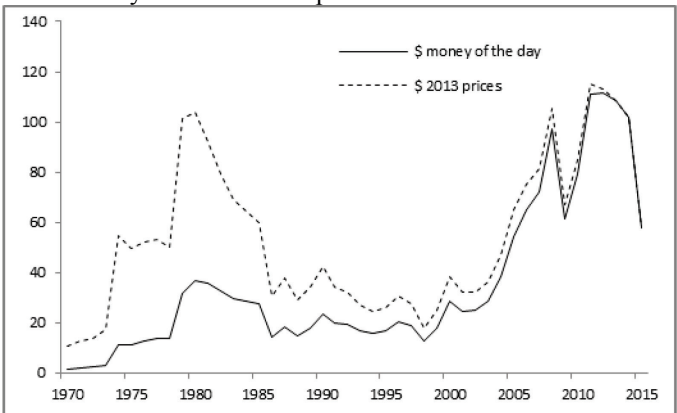
Ratio Net remaining reserves/Proven reserves [$b = N_R/R$] and Cumulative Production/Proven reserves [$(1-b) = N_C/R$].

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 in chapter 8. 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-)

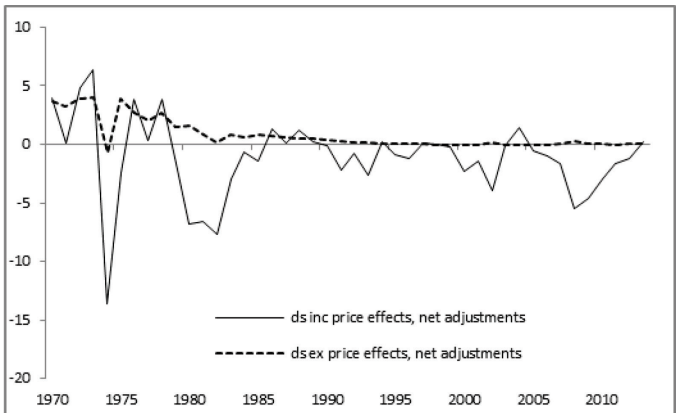
Figure 9.9 Crude Oil Price \$/barrel current and 2013 price base.

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.

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 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 9.10, 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 book.



Data Sources: BP Statistical Review, OPEC

Figure 9.10 Economic Entropy % change for changes in ratios of oil consumption/proven reserves and price 1970-2013.

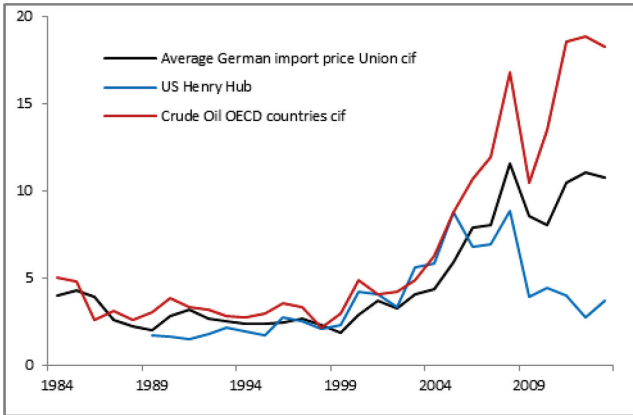
[Reserve adjustments constructed by Bryant for selected OPEC countries and Canadian tar sands, as per paper by Owen et al.]

In summary, however, the dashed line in the chart at figure 9.10 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 9.7, and accords also with the declining incremental change of entropy illustrated by the dashed line in the upper chart of figure 8.3. As yet the long-run oil entropy curve has not moved into negative territory. The solid line at figure 9.10, however, shows the variations introduced by the ups and down of world oil prices, impacting on elasticity and hence entropy/utility 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 8.2 and 8.3.

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.



Data Source: BP Statistical Review

Figure 9.11 World natural gas and oil prices US \$/million Btu.

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. 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.

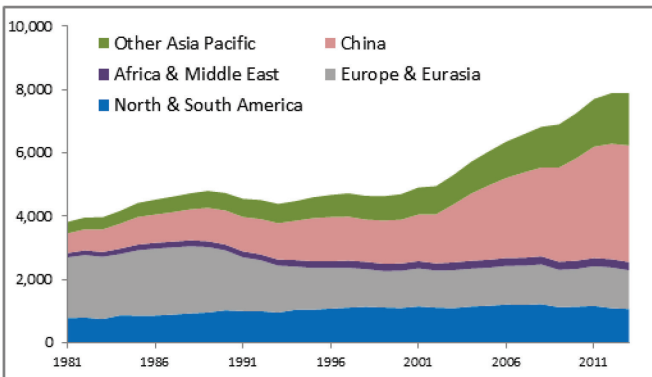
A potential longer-term source of energy is that of gas hydrates, effectively solid methane and other gas particles surrounded by frozen water. Geologists estimate that there are very large amounts situated around the world, in seafloor sediments and in permafrost sediments in the frozen tundra of Siberia. 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

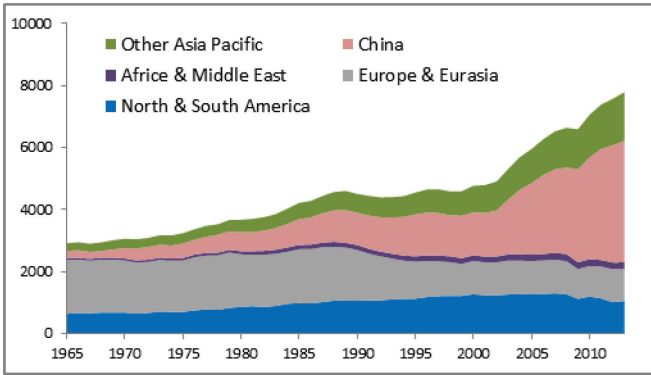
Besides oil and natural gas reserves, there is also some debate as to the extent of world coal reserves. According to the BP Statistical Review, total world remaining proven coal reserves at 2013 stood at 892 billion tonnes of coal; split 45% deep-mined bituminous/anthracite and 55% surface-mined lignite/sub-bituminous - 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 9.12 and 9.13 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

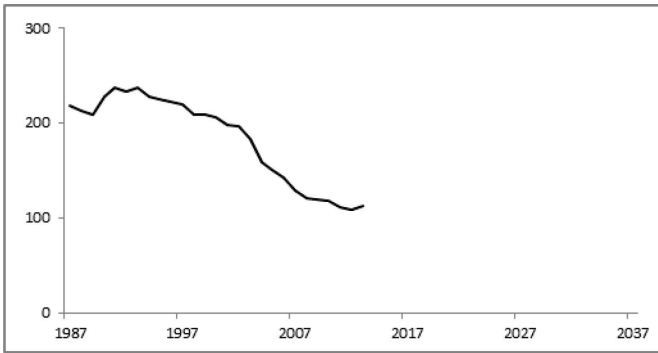
Figure 9.12 World coal production – Bituminous, Anthracite, Non-bituminous, Lignite M tonnes p.a.



Source: BP Statistical Review

Figure 9.13 World coal consumption – Bituminous, Anthracite, Non-bituminous, Lignite M tonnes p.a.

The chart at figure 9.14 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

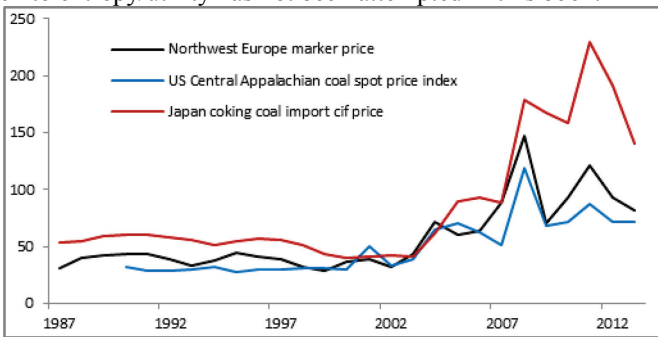
Figure 9.14 Ratio remaining reserves/current production rate – years.

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 9.14 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 9.15 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.

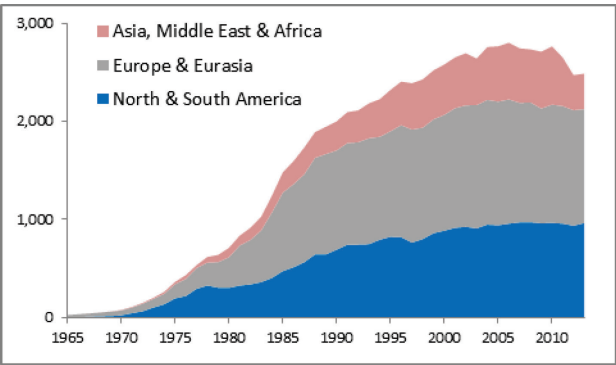


Source: BP Statistical Review

Figure 9.15 World coal prices US\$/tonne.

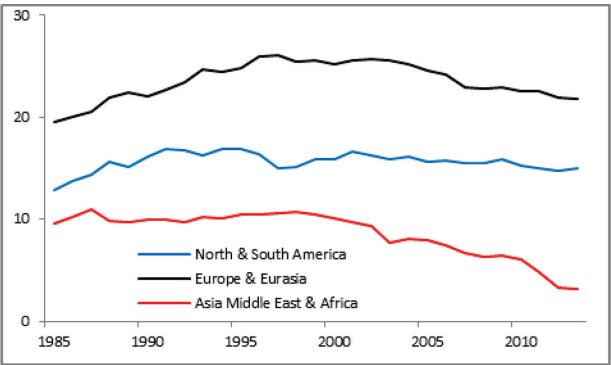
Nuclear Power

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 9.16 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 9.17 confirms that nuclear generated electricity has lost share to other capacity.



Source: BP Statistical Review

Figure 9.16 World electricity consumption from Nuclear capacity TWh p.a.



Source: BP Statistical Review

Figure 9.17 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 9.1 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 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.

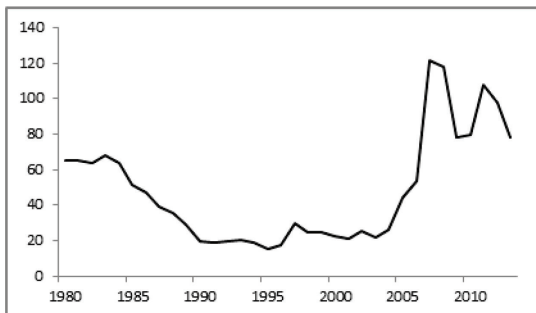
Figures of the Red book published by OECD and the International Atomic Energy Agency project world mine production capability rising from 73,405 tonnes p.a. in 2011 to 109,400 by 2035, with two-thirds of this coming from just three countries, Kazakhstan, Australia and Canada. Such a production level would meet a significant proportion of the WNA estimate of planned and proposed capacity set out in table 9.1.

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 9.14], 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 has reached a useful stage, and set against these 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 9.18 sets out a chart of uranium spot contracts €/kg.



Source: Euratom Supply Agency

Figure 9.18 Uranium spot contract €/kg.

The price index has followed to some extent the trend of world crude oil prices, shown at figure 9.9.

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.

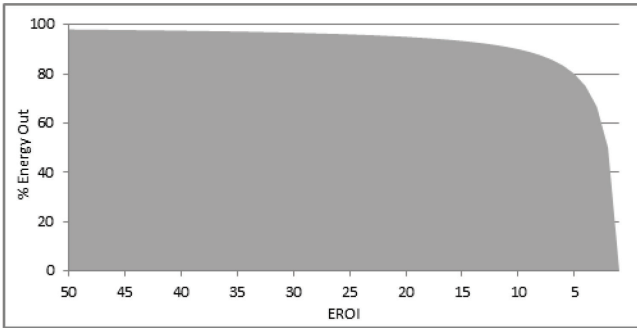


Figure 9.19 Energy Return on Energy Invested.

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 summing 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 chapter]* 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 chapter.

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 book: 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

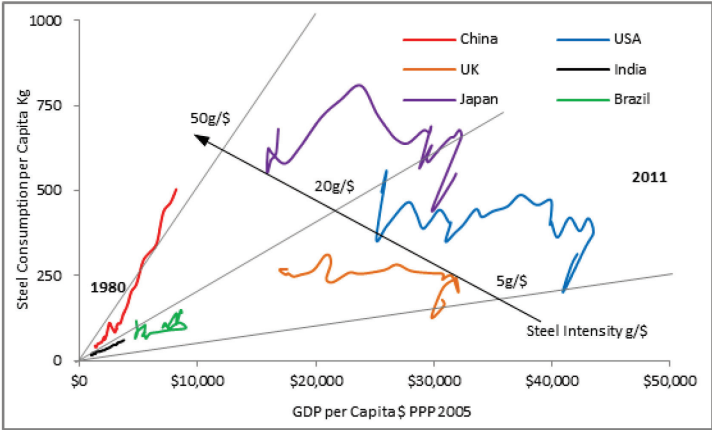
Steel consumption is one of the key inputs to becoming a developed country, though its use and the means of production depend upon the relative stage of industrialisation. During the early stages, the chief means of producing steel is by mining iron ore [*haematite*], which is then mixed with coke [*a 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 - 1900°C.

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 1200°C] 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 9.19 illustrates this effect.

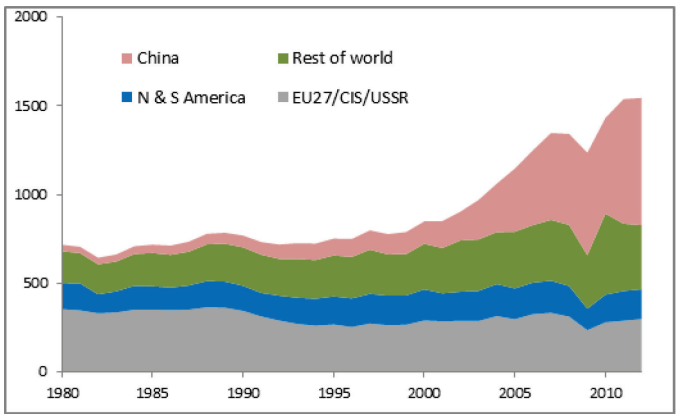


Sources: Penn World, World Steel Association

Figure 9.19 Steel consumption per capita versus GDP per capita. 1980 - 2011.

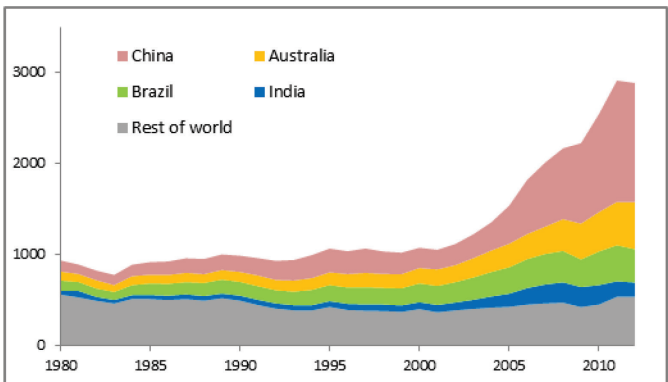
In China, growth of steel consumption per capita and steel intensity per unit of GDP is high, whereas, in the USA, UK and Japan, usage per head has levelled, and steel intensity is rapidly reducing, as these economies turn to other goals for economic affluence. To a significant extent this trend reflects also changes in primary energy intensity in an economy, as illustrated by figure 9.1.

Figure 9.20 illustrates the growth in world production of steel, and figure 9.21, the growth in world iron ore production.



Source: WSA

Figure 9.20 World steel production Mtonnes p.a.



Source: WSA

Figure 9.21 World iron ore production Mtonnes p.a.

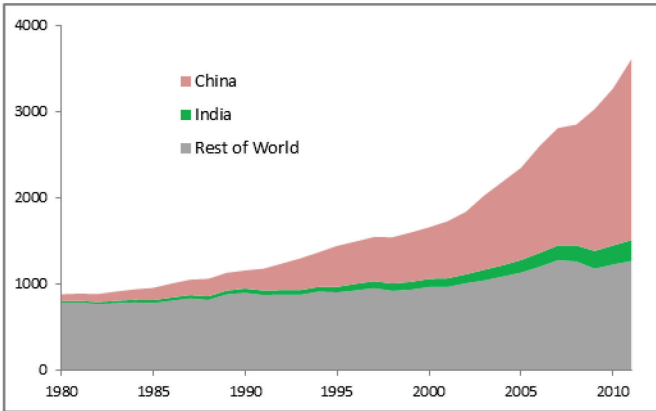
Steel production has doubled in the last decade, the rise mostly concentrated in China, accompanied to a lesser extent by other developing nations such as India. This has led to a tripling of world iron ore production. Readers should note also that a significant proportion of Australian iron ore production 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 1500°C. 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 9.19, 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 9.22 illustrates world production to date.



Source: USGS

Figure 9.22 World cement production M tonnes p.a.

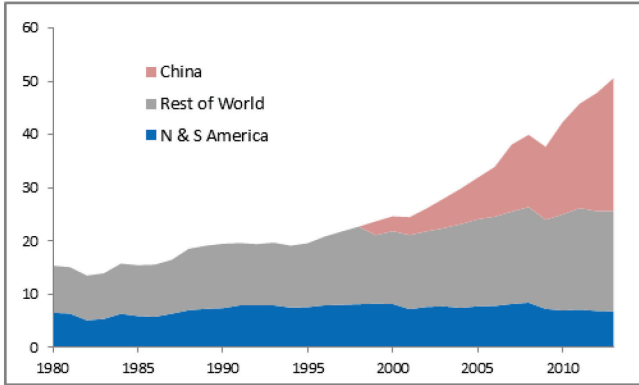
World production is dominated by China, which commands more than half of output, and rising.

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 1000°C. 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 9.23 summarises world production of aluminium.



Source: World Aluminium

Figure 9.23 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.