ENTROPY MAN

John Bryant

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Preface

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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 ascendency, 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 8 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.

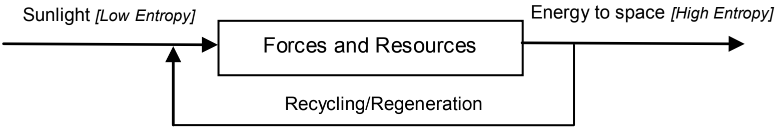

Figure 8.1 Pre-industrial Force and Resource Regeneration.

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 chapter is to set out some of the dynamics of resources; chapters 9 and 10 examine empirically world trends of some key non-renewable and renewable resources.

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, the costs of transport and development and the 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 8.2.

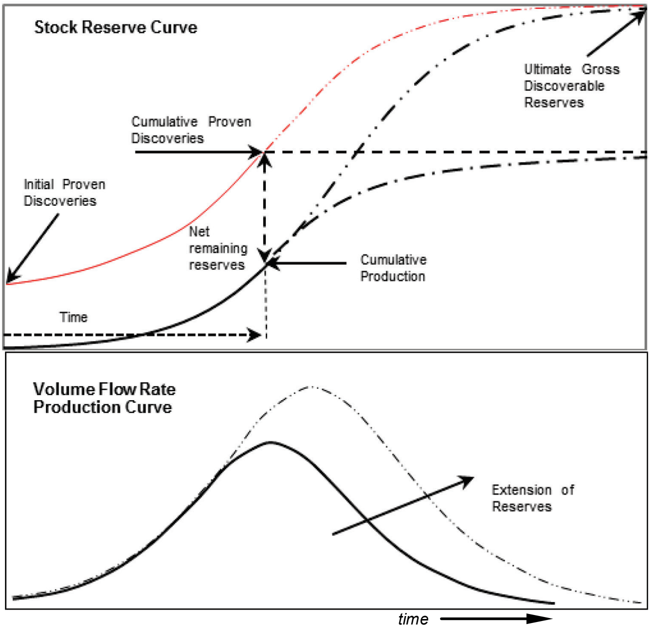

Figure 8.2 A Non-renewable resource reserve.

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 earlier in this book]*. And last, **R** is the total proven reserve, arithmetically equated to cumulative production over time plus net remaining reserves *[$\mathbf{R} = N_C + N_R$]*.

The solution to the above relationship is a logistic S-shaped path of reserve development, as shown in figures 8.2 and 8.3. For interested readers the mathematical formula is given in the notes to this chapter. 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:

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

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 the chapter. Figure 8.3 shows the loci of all the factors.

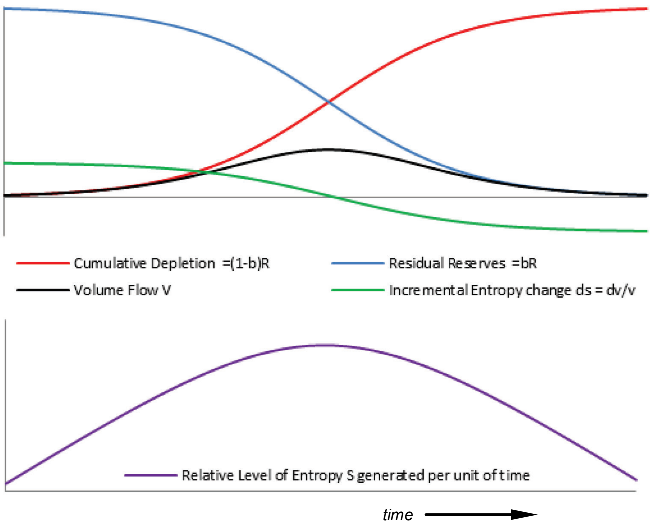

Figure 8.3 Loci of residual reserves $\mathbf{N_R}$ *[=bR], cumulative production or resource depletion* $\mathbf{N_C}$ *[=(1-b)R], volume flow **V**, incremental entropy change **dS [**assuming an elastic index **n=1]**, and the relative level of entropy generation **S** per unit of time over the life 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, 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.

A way forward perhaps is first to set out an ideal economic relationship similar to that developed in chapter 4, 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 before in this book, 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 entropy or utility generation change for a resource stock in *monetary terms* to our now familiar 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 8.1, 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. As set out in chapter 2, 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 8.4 illustrates the concept of the Lotka-Volterra model, with the trend of prey preceding that of predators.

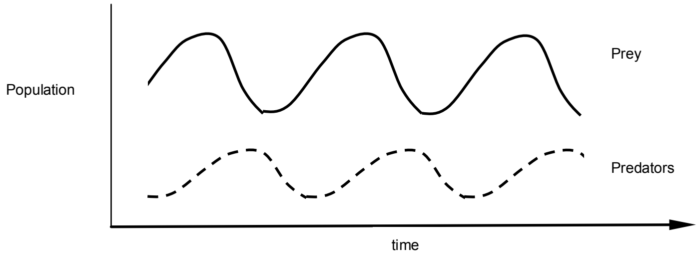

Figure 8.4 Lotka-Volterra Model - Population of predators & prey over time.

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 chapter.

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/utility 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.