Dale, Mr. Michael[1a], **Krumdieck, Prof. Susan[a]**, Bodger, Prof. Pat [b]

[1]Corresponding author: AEMSLab, Dept. Mechanical Engineering, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand. Tel.: +64 3 3642987; fax +64 3 364 2078; e-*mail*: michael.dale@pg.canterbury.ac.nz

[a]Advanced Energy and Material Systems (AEMS) Lab, Department of Mechanical Engineering, University of Canterbury, Christchurch 8041

[b]Department of Electrical and Computer Engineering, University of Canterbury, Christchurch 8041

Global Energy Modelling – A Biophysical Approach

Intended category: Limits to Growth

The standard economic approach to energy modelling is outlined and contrasted with energy models taking a biophysical approach. The latter incorporate thermodynamic and ecological principles and emphasise the importance of natural resources to the economic process. Neither the standard economic nor biophysical approach accounts for changing energy-returns-on-investment (EROI) due to declining resource-accessibility and technological learning, nor the capital intensive nature of renewable energy sources. These two factors will become increasingly important in the future as fossil fuel depletion continues and a transition to alternative sources occurs. A modelling methodology offering an extension to the biophysical approach is presented, which utilises a dynamic EROI function that explicitly incorporates both technological learning and declining resource accessibility. The methodology and main assumptions of the model are outlined and their validity is discussed. The model is calibrated using historical energy production data. Forecasts of future energy production from the model are presented and their policy implications are discussed.

1. Introduction

Modern society currently uses approximately 500 exajoules (EJ = 10^{18} J) of total primary energy supply (TPES) each year. This energy consumption has been increasing at roughly 2% per year for the past two hundred years (Etemad and Luciani 1991). TPES is currently dominated by three non-renewable energy sources: coal, oil and gas which, together with energy from nuclear fission of uranium, make up around 85% of the energy market(IEA 2008). According to the International Energy Agency's World Energy Outlook 2008 Reference Scenario (IEA 2008), total primary energy demand in 2030 will be 712 EJ, an increase of around 1.6% annually. This scenario projects that in 2030, non-renewable energy sources will still make up over 85% of TPES. A number of authors have begun to cast doubt such projections, instead predicting that production of some fuels, especially oil, may peak as soon as the next decade, if not earlier (Campbell and Laherrere 1998; Duncan and Youngquist 1999; ASPO 2001-2009; Bentley, Mannan et al. 2007).

Consumption of finite resources at a continuously growing rate is not sustainable in the long-term. A trend in policy direction is to seek a transition to renewable sources of energy The World Energy Assessment (WEA) scenario C1 projects a TPES of 880 EJ/yr in 2100, predominantly (over 80%) from renewable energy sources (WEA 2000). Such a transition raises some pertinent questions:

- What is the substitutability of renewable energy for fossil fuels?
- Can renewable energy sources supply these projected levels of demand?
- What would be the effect on the economy of a transition to an energy supply system run entirely on renewable energy sources?

2. Energy modelling

2.1. Standard economic approach to energy modelling

A number of energy-economy models have been developed since the ‘energy crises’ of the late seventies and early eighties. The most commonly used energy-economy models are:

- MESSAGE – Model for Energy Supply Systems And their General Environmental impact (Schrattenholzer 1981) developed by the International Institute of Applied Systems Analysis (IIASA)
- MARKAL – the MARKet ALlocation model (Regemorter and Goldstein 1998) developed as part of the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA)
- WEM – World Energy Model (IEA 2007; OECD/IEA 2009) also developed by the IEA to generate scenarios for their World Energy Outlook

The method common to all of these models is the determination of a Reference Energy System (RES) consisting of ‘energy chains’, linking primary energy resources, such as oil reserves or water in hydro reservoirs, via energy carriers (diesel fuel, electricity, etc.) to energy end-uses, such as transport or residential space heating (see Figure 1). Each of the processing stages within the energy chain is performed by a designated energy technology (oil rig and refinery, passenger train, hydro station, heat pump, etc.) with an associated financial cost. The only input required by the energy sector are sufficient monetary flows to cover the cost of energy processing.

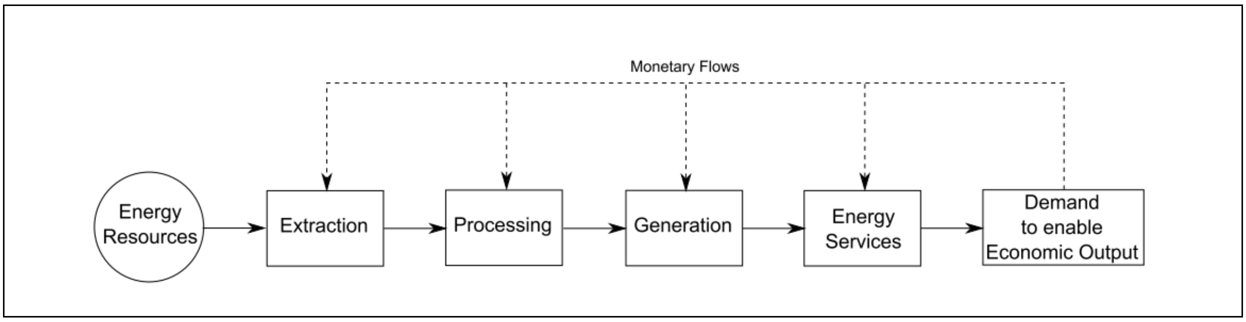

Figure 1. Diagram showing the relationship between the main economy and a simplified reference energy system (RES) based on (Seebregts, Goldstein et al. 2001). Solid arrows represent energy or material flows and dashed arrows represent monetary flows.

Demand for energy over the time horizon of the model may be generated using micro-economic factors, such as increasing population and per capita demand for energy services, or by macro-economic factors, such as economic growth, or by some combination of the two. Technology costs are often user-defined, although some MARKAL models have a technology-cost database built in. The RES is then optimised via minimisation of an economic objective function to find a least-cost combination of technologies that meets demand at each time-step. Issues of defining technology costs, particularly over time horizons of decades, may be summed up by a statement from the Executive Summary of the IEA World Energy Outlook 2008:

> “the sources of oil to meet rising demand, the cost of producing it and the prices that consumers will need to pay for it are *EXTREMELY UNCERTAIN*, perhaps more than ever” (IEA 2008, emphasis added)

In recent years, some authors have raised concerns, not only over constraints to available supply and rising energy prices, but also over declining EROI of energy resources and the negative effects this may have on the economy (Cleveland 1991; Peet 1992; Odum 1996;

Ayres 1998; Hall, Powers et al. 2008; Hall, Balogh et al. 2009). Standard economic approaches to energy modelling cannot capture the full implications of this decline without incorporating analysis of net energy yield (Peet 1986).

2.2.Biophysical energy-economy models

The *biophysical systems* perspective stems from the concepts and theories expounded within the physical and biological sciences. The biophysical economist believes that the laws of these sciences must constrain the choices available to an economic agent and hence they use "basic ecological and thermodynamic principles to analyze the economic process" (Cleveland 1987). Whereas standard economic models account only for gross production by the energy sector, J_5, energy analysis considers all energy flows between the energy sector and the rest of the economy (as depicted inFigure 2) in order to determine the *net energy yield* (the gross energy production less energy needs for extraction and processing), as in equation [1]. The ratio of net energy yield to the energy needed to obtain this yield, as in equation [2] , is known as the *net energy ratio* (NER) or *energy-return-on-investment* (EROI) (Baines and Peet 1983). The processes of the energy transformation sector necessitate the flow of energy back from the main economy; as the EROI of energy resources declines, so too does the net energy yield available to the economy. Many authors have begun questioning the effects that declining EROI values will have on the economy (Hall, Cleveland et al. 1986; Peet 1992; Cleveland 1993; Cleveland 2005; Hall, Powers et al. 2008).

$$J_5 - (J_2 + J_3 + J_4) \qquad [1]$$

$$\frac{J_5}{(J_2 + J_3 + J_4)} \qquad [2]$$

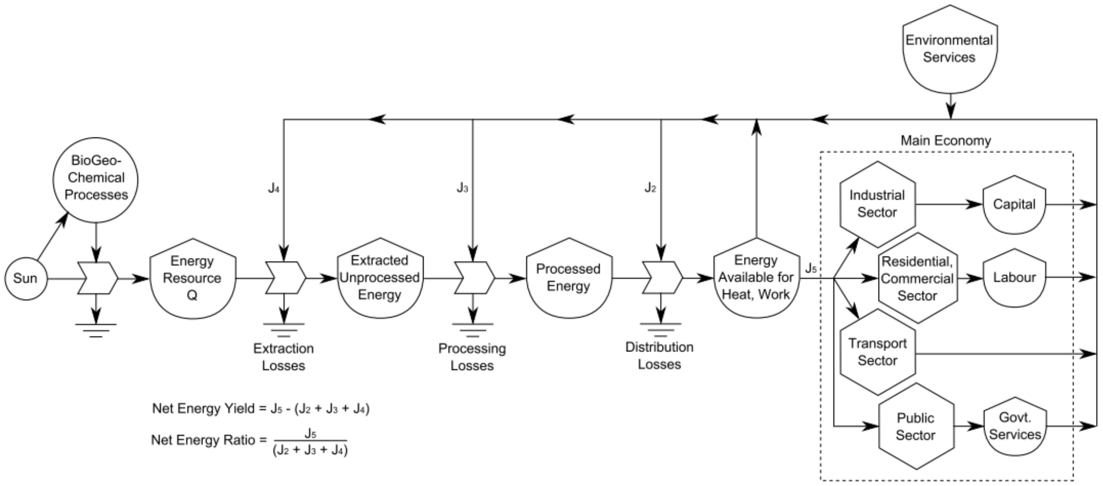

Figure 2. Diagram to show the relationship between the main economy and the energy sector from (Hall, Cleveland et al. 1986). All arrows represent energy flows (all material flows being 'embodied' as energy).

A number of energy-economy models based on physical material and energy flows have been developed since the advent of energy analysis as a policy instrument. The question "what is the instantaneous upper limit to global economic activity?" inspired the development of the System, Time, Energy and Resources (STER) global energy supply model (Hounam 1979). Consideration of 'whole-system' dynamics lay behind the famous World3 – "Limits to Growth" – model (Meadows, Meadows et al. 1972) and has also inspired other such models

(Baines and Peet 1983; Bodger and Baines 1988) The Energy and Capital Creation Options (ECCO) methodology (Slesser 1992) has been applied on a global scale (King and Slesser 1995) as well as to a number of national economies (Slesser, King et al. 1997) including European countries (Battjes 1999), New Zealand (Ryan 1995) and Australia (Foran and Crane 1998).

Although the issue of EROI of energy resources is represented in some of these models, the value of EROI for each energy source has sometimes been assumed to remain constant (Bodger and Baines 1988) or defined implicitly within the model with no reference to empirical data (Slesser 1992). In an attempt to rectify these issues a model of the energy-economy system has been developed that explicitly includes the EROI of energy resources as a dynamic function of energy production. This paper deals with the methodology employed in the development of the GEMBA model.

3. Methodology:

The energy-economy system is considered as a dynamic system. Dynamic systems are characterised by their complex nature, with many interacting causal and feedback loops. Due to the existence of feedback loops, complex dynamic systems cannot be fully understood analytically (Bertalanffy 1971; Forrester 1972; Hall and Day 1990), hence, these systems must be studied through numerical simulation.

The basic structure of the energy-economy system is pictured as an energy circuit diagram in Figure 3. The system is composed of two sectors: the energy and industrial sectors. The energy produced by the energy sector flows into the industrial sector where it is embodied as physical capital. Energy 'losses' from the industrial sector include any energy consumed in activities that do not directly contribute to the production of physical capital, such as residential heating, lighting or energy for cooking, as well as losses due to inefficiency. The energy sector is reliant on 'subsidies' from the main economy in the form of energy to run its processes, S_1, and physical capital, S_2. The size of these subsidies is dependent on the scale of energy production and the EROI.

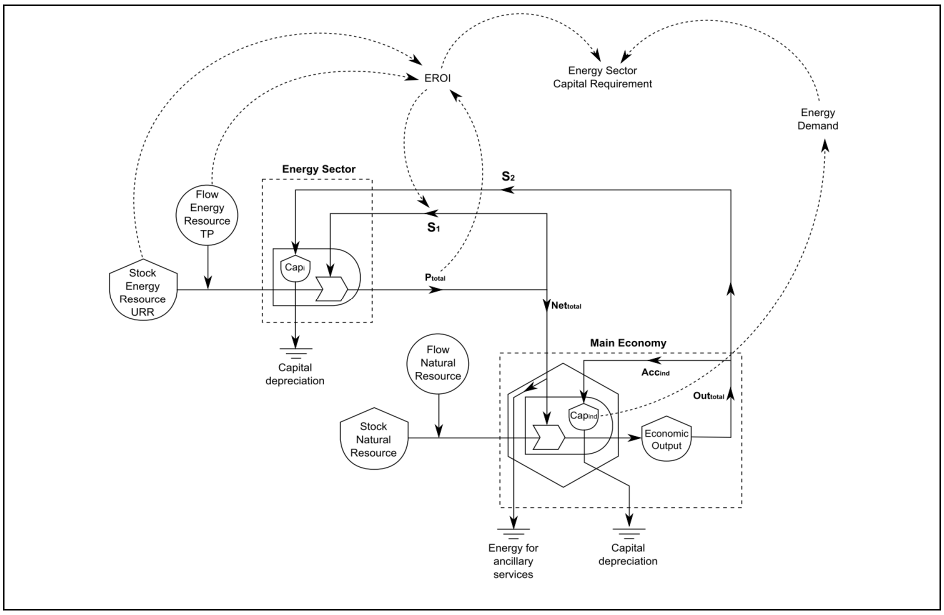

Figure 3. Structure of the GEMBA model as an energy circuit diagram. All stages of energy production have been collapsed into a single process. Feedback is introduced into the system due to the values of energy S_1 and capital S_2 subsidies changing as a function of energy production. Bold arrows represent energy flows with attendant losses 'to earth' as heat, etc and dashed arrows represent information flows.

Following the work of Bodger and Baines (1988), energy resources are characterised by three fundamental variables:

- **Incept date:** the year that the energy source first enters the market-place;
- **Availability:** how much of each energy source is still available
- **Accessibility:** the energy-return-on-investment (EROI) or energy yield ratio (EYR) offered by the energy source.

To these, the current authors have added another variable, *capital factor*, which describes the proportion of energy subsidy received by the energy sub-sector that is embodied as capital, as in equation [3].

$$capital\ factor = \frac{S_2}{S_1 + S_2} \qquad [3]$$

Following the work of Costanza and Cleveland (1983), EROI is characterised by a peaking function dependent on energy production history. The current authors hypothesise that this function is the product of a technological and a physical component (see Figure 4). Other assumptions are that: (1) energy sources are perfectly substitutable; (2) the capital needs of the energy sector take priority over those of the industrial sector; (3) energy capacity is always used fully and; (4) availability of energy is the only constraint on industrial output.

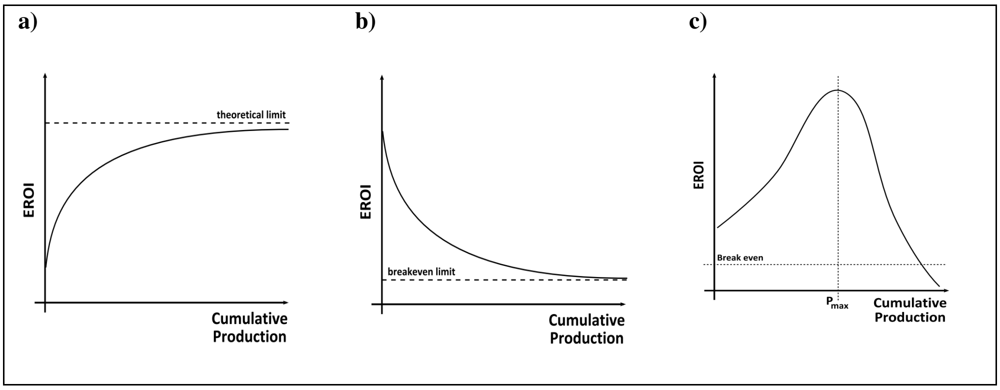

Figure 4. Energy returns a) increasing due to technological improvements, b) decreasing due to physical resource depletion and c) product as peaking function of production

4. Results:

The GEMBA model has been calibrated using historical data of energy production. The model output ‘total energy yield’ offers a good fit to the historical TPES data, with $R^2 = 0.987$. When this ‘baseline’ run is projected into the future TPES peaks around 2060 and thereafter declines to a level of around 200 EJ/yr in 2200. This peak aligns closely with the peak in ENERGY PRODUCTION$_{\text{NON-RENEWABLE}}$ (see Figure 5).

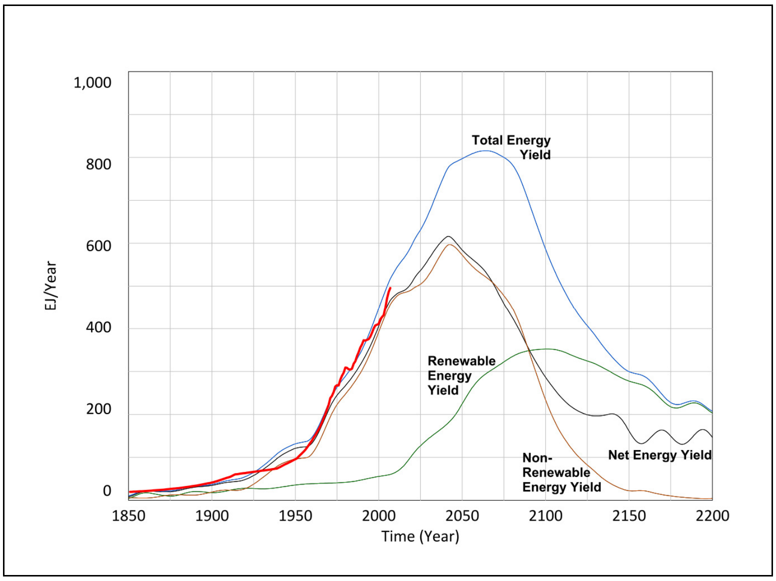

Figure 5. Historic data (red lines) compared with model outputs TOTAL ENERGY YIELD (blue line), NET ENERGY YIELD (black line), ENERGY PRODUCTION$_{\text{NON-RENEWABLE}}$ (orange line) and ENERGY PRODUCTION$_{\text{RENEWABLE}}$ (green line) of the baseline run

4.1.Sensitivity analysis

The output of TOTAL ENERGY YIELD was modelled when adjusting the model parameter TP$_{\text{RENEWABLE}}$. The result of the sensitivity analysis is plotted in Figure 6. Even if TP$_{\text{RENEWABLE}}$ is doubled, the baseline value for all renewable sources, TOTAL ENERGY YIELD peaks and declines to a level of 400 EJ/yr.

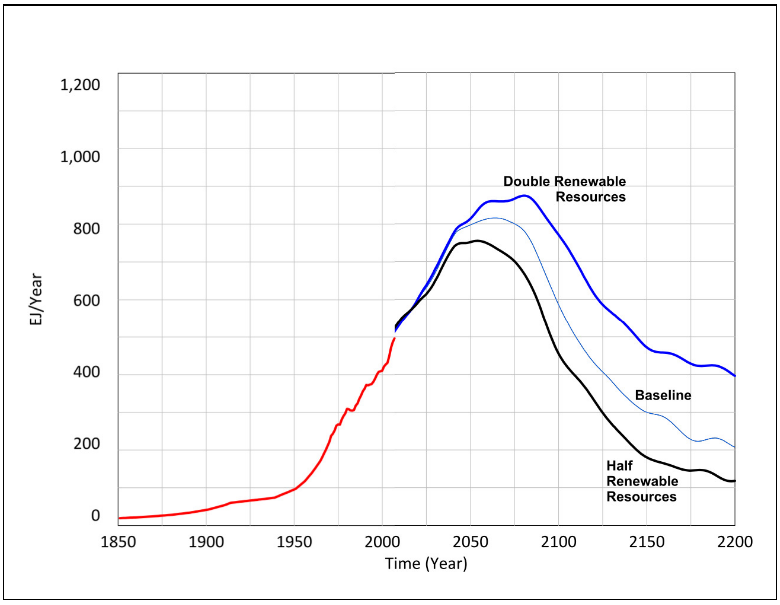

Figure 6. Sensitivity analysis of TOTAL ENERGY PRODUCTION to doubling (dark blue line) and halving (black line) TP$_{\text{RENEWABLE}}$ from the baseline value, historic compared with total energy production (red line).

The output of the model to changes in the parameter PEAK EROI$_{\text{RENEWABLE}}$ was analysed. The result is displayed in Figure 7 Doubling the parameter PEAK EROI$_{\text{RENEWABLE}}$ has the effect of reducing the peak of TOTAL ENERGY YIELD compared with the baseline run. This is most likely due to the way by which ENERGY DEMAND is allocated between ENERGY SOURCES. FAVOURABILITY$_{\text{k}}$ is proportional to PEAK EROI$_{\text{k}}$, hence increasing PEAK EROI$_{\text{RENEWABLE}}$ means that ENERGY PRODUCTION$_{\text{RENEWABLE}}$ increases, which draws capital from re-investment into the economy. However, despite the doubling in PEAK $\text{EROI}_{\text{RENEWABLE}}$, TOTAL ENERGY YIELD in 2200 is only 280 EJ/yr compared with a value of 200 in the baseline run.

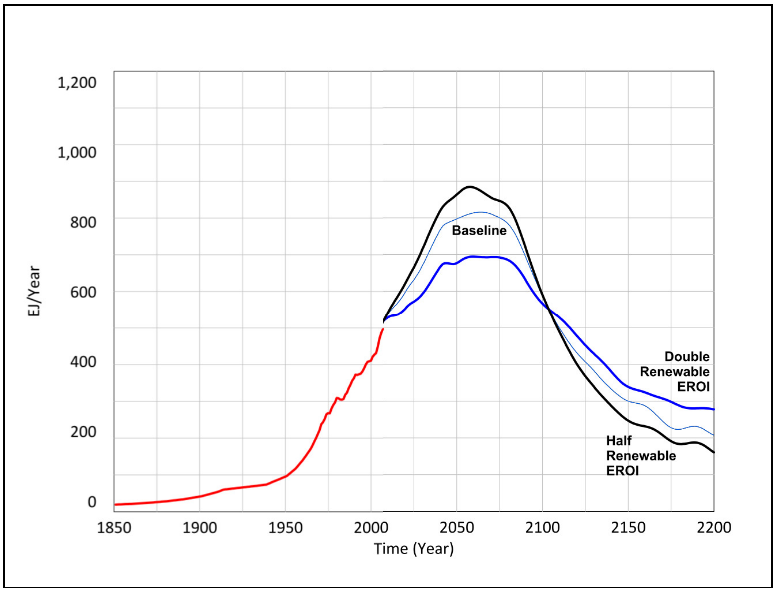

Figure 7. Sensitivity analysis of TOTAL ENERGY YIELD to doubling (dark blue line) and halving (black line) $\text{EROI}_{\text{RENEWABLE}}$ from the baseline value, compared with historic total energy production (red line).

5. Discussion:

The results of the sensitivity analyses made with the GEMBA model suggest that the model structure is incapable of supporting current energy consumption levels using only renewable energy sources. If it is accepted that the GEMBA model is an adequate model of the global energy-economy system, then these results have definite implications for both sustainable development and energy policy. Most current energy policies make little or no distinction between the behaviour of the energy-economy system under a regime utilising mainly non-renewable sources and that system running primarily on renewable energy sources. It is assumed that economic opportunities are the same within both system arrangements. Furthermore, most energy policies do not accept that renewable energy sources cannot support current levels of energy supply. It is simply assumed that renewable energy can be substituted for non-renewable energy sources so long as timely investment is made.

Recognition that current energy levels cannot be sustained using renewable energy sources might (hopefully) result in energy policies that would attempt to curb or even reverse the current trend of increasing energy demand. How this might be achieved is a matter of some considerable debate, given an increasing global population and an assumed increase in material living standards for all.

The validity of some of the assumptions behind the GEMBA model is now discussed.

5.1. Is the peaking function for accessibility valid?

Figure 8 shows empirical data for EROI for production of conventional oil which declined rapidly in the second half of the twentieth century, from a value of around 100 to around 20 at the start of the twenty-first century. Whether the energy return peaked before this time is an open question.

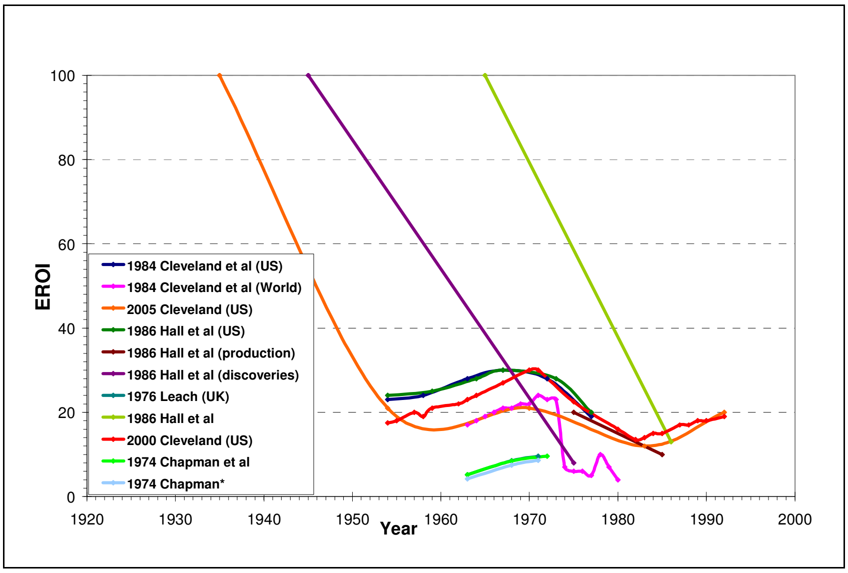

Figure 8. Dynamic estimates of EROI of conventional oil production from various sources (Cleveland, Costanza et al. 1984), (Cleveland 2005), (Hall, Cleveland et al. 1986), (Leach 1976), (Zucchetto 2004), (Hopkins 2008), (Cleveland, Kaufmann et al. 2000), (Chapman, Leach et al. 1974), and 1974 Chapman* data from (Boustead and Hancock 1979)

5.2.Are renewable energy sources more capital intensive?

A major assumption within the GEMBA model is that renewable energy sources are more capital intensive than non-renewable. The consequence of this assumption is that in the transition to a renewable energy system, there is less physical capital available for re-investment into the economy, hence energy demand decreases. Is this assumption valid?

Table 1 shows results from a number of recent studies regarding capital inputs into the energy production process. These studies show a large disparity between the capital intensity of renewable and non-renewable energy sources, offering strong support for the assumption that "renewable energy production is more capital intensive than non-renewable". Assuming that greenhouse gas emissions are a suitable proxy for energy consumption; in general, capital inputs into energy production from fossil fuels tend to be below 5% of their total energy inputs, for nuclear this figure is around 30%, and for hydro, wind and PV, it is at least 95%.

Table 1. Capital requirements into energy production process from various authors

Energy Source	*Capital Factor*
Coal	Hard coal – 0.8-1.8% of energy for capital requirements **(Frischknecht, Althaus et al. 2007)**
Oil	2.2% of energy for capital requirements **(Frischknecht, Althaus et al. 2007)**
Gas	Electricity from gas (standard) – 0.6-1.0% of energy for capital requirements**(Frischknecht, Althaus et al. 2007)**
Nuclear	Around 15% GHG emissions from construction, decommissioning and spent fuel storage **(Hondo 2005)**
Biomass	Electricity from wood (co-gen) – 27.3-33.9% of energy for capital requirements **(Frischknecht, Althaus et al. 2007)**
Hydro	82.8% GHG emissions from plant construction **(Hondo 2005)**
Geothermal	35.3% GHG emissions from plant construction, 30% from "exchange of equipment" **(Hondo 2005)**
Wind	97.6-98.5% of energy for capital requirements **(Frischknecht, Althaus et al. 2007)**
PV	95% of energy due to construction **(Meier 2002)**

5.3. *Is demand substitutable between energy sources?*

The condition that energy demand is homogeneous between energy sources assumes that energy sources are perfect substitutes. In the short-term this assumption may seem invalid; a car cannot run on coal, nor a laptop on petrol. However, in the long-term, there is evidence to suggest that this assumption has validity. Since 1800, energy for land transport has switched from biomass (in the form of horse-feed), to steam trains powered by coal, to automobiles powered by petroleum. Lighting and heating have undergone similar technology transformations in the same period.

This substitutability assumption acts to increase the flexibility of the GEMBA model, when compared with the real energy-economy system, which is severely constrained in options for substitution for certain energy sources. Within the GEMBA model, decline in the production of oil may easily be absorbed by increasing production of coal. Within the real energy-economy system, the ability to substitute between these two sources is low in the case of transport, which currently accounts for 60% of oil consumption worldwide (IEA 2008). The consequences of constraining the substitutability of energy resources could be explored in further development of the model.

6. Conclusion:

The underlying motivation for developing energy models and the standard economic approach taken by the main ‘contenders’ – MESSAGE, MARKAL and WEM – was given. Some of the limitations of such an approach have been outlined and other physical resource-based models, seeking to obviate these problems, have been identified. The model developed in this paper represents an extension on the alternative ‘biophysical’ approach. A number of the assumptions underlying the GEMBA methodology have been presented and their validity has been discussed.

The GEMBA model is used to explore the large-scale transition from non-renewable to renewable energy sources and the subsequent affects on the net energy yield from the energy sector to the rest of the economy. Two scenarios were investigated, in which the both the availability and EROI of renewable energy resources was changed from the baseline values. The model results from the baseline run and from the scenarios suggest that energy supply may be constrained in the future. This runs contrary to results from economic models, which predict ever increasing future energy demand. Results from the GEMBA model also suggest that the increasing capital requirements of a large scale shift to renewable forms of energy may stymie re-investment in other sectors of the economy. This will reduce demand for energy. The investment in physical capital required to deliver 500 EJ of energy from renewable sources may be greater than the economy can supply. This recognition has broad implications for current energy policies hoping to supply projected future energy demand with growth in renewables.

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