A review of EROEI-dynamics energy-transition models

Craig D. Rye⁎, Tim Jackson
Centre for the Understanding of Sustainable Prosperity (CUSP), University of Surrey, 388 Stag Hill, Guildford GU2 7XH, United Kingdom

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ABSTRACT
The need for an environmentally sustainable economy is indisputable but our understanding of the energy-economy interactions (dynamics) that will occur during the transition is insufficient. This raises fascinating questions on the future of economic growth, energy technology mix and energy availability. The crucial interactions between energy and economy systems can be usefully described in terms of the Energy Returned on Energy Invested (EROEI) metric (the energy cost of primary energy production). Multiple authors have used this metric to explore the behaviour of the economy over the transition to lower carbon energy sources. The following text is a review of energy-economy models that incorporate the EROEI metric. In particular, the EROEI-dynamics literature is found to describe a common set of dynamics associated with the transition to lower EROEI primary energy resources. These include: the rising resource-cost of primary energy production, the short-term misallocation of resources, the short-term overproduction of energy and the potential decline in economic stability. The literature can be divided into groups of related models. Following the review, a number of key areas for additional work are identified and discussed.

1. Introduction

The Energy Returned on Energy Invested (EROEI; aka efficiency) of primary energy production has declined markedly over recent decades (Murphy, 2014). Furthermore, the EROEI of primary production is projected to decline further in the early half of the current century, associated with the continuing depletion of fossil fuel reserves and the transition away from conventional fossil fuels (IPCC, 2014; Sterman, 1982; Gagnon et al., 2009; Grandell et al., 2011; Murphy and Hall, 2010). For example, Guilford et al., (2011) find that the EROEI for United States Oil and Gas has declined by around a half, between 1930 and present. The continuing decline of EROEI is a significant academic and political concern posing impacts on energy futures and the dynamics of the transition to a low carbon economy.

EROEI is estimated as the energy produced by an energy-gathering activity divided by the energy required for that production (Eq. (1)). The energy produced by energy gathering activity is referred to here as primary energy. Typical EROEI values are provided in Table 1. A similar useful metric of primary energy efficiency is Net Energy (NE), NE is estimated as the energy produced by primary energy minus the energy required for that production (Eq. (2)). Both the EROEI and NE metrics indicate the efficiency of energy production. EROEI is a particularly interesting term because its name explicitly refers to the energy that is ‘used up’ or ‘invested’ in the process of producing useful energy for society.

EROEI = \frac{\text{Energy Returned}}{\text{Energy Invested}} \quad (1)

NE = \text{Energy Returned} - \text{Energy Invested} \quad (2)

Many of the core insights of the EROEI (or NE) metric are intuitive but poorly accounted for. For example, an energy carrier (such as gasoline) must provide more energy when it is used than it requires in production. Otherwise, it would not make economic sense to produce it. The greater the energy return, or net energy, the greater the positive effect on the economy. Unfortunately, this kind of argument is often neglected. For example, green energy subsidies typically support biofuels and wind energy equally, however, wind power usually provides significantly greater energy and economic return. Therefore subsidies are often biased towards low EROEI renewables. EROEI provides a powerful approach for examining the efficiency of primary energy generation technologies.

Charles Hall and collaborators provide many early works on EROEI in economics (e.g. Hall and Cleveland, 1981; Cleveland et al., 1984; Hall et al., 2008; Hall et al., 2009). Notably, Murphy and Hall (2010) highlight that the relationship between Net Energy and the EROEI is exponential where NE declines rapidly as EROEI falls below approximately ~10:1. The relationship between EROEI and NE is commonly referred to as the ‘Net Energy cliff’ (see Fig. 1). This relationship...
suggests that advanced economies require EROEI values of at least 5 to maintain key infrastructure and avoid economic decline. From a similar argument, it is suggested that the Net Energy cliff could play a key role in the growth rate of an economy.

Following the work of Hall and Murphy, numerous authors have conducted empirical analyses of the relationship between EROEI and other economic indicators. For example, Heun and de Wit (2012) King and Hall (2011) and Brandt (2017) find interesting relationships between EROEI and energy prices. Heun and de Wit (2012) suggest that these relationships may break down as EROEI becomes small. Hall et al. (2008) suggest that during periods of energy shortage (i.e. low EROEI, such as the 1970s ‘energy crisis’ or the rising prices of 2000–2007) discretionary spending typically declines. Finally, Rubin (2012) and Hamilton (2009) use empirical analysis to argue that the rising energy prices (declining EROEI) of 2000–2007 contributed to the recent 2008 financial crisis. Empirical works therefore typically suggest an inverse relationship between EROEI and energy prices, and a link between EROEI and economic health.

Numerical models have been developed to explore the related set of system behaviours accompanying the transition towards lower EROEI (e.g. Sterman, 1982; Hounam, 1979; Baines and Peet, 1983; Bodger and Baines, 1988). These models typically simulate the behaviour of the energy-economy during a period of declining resource quality, or energy technology transition. The emergence, nuance, evolution and association of these EROEI-dynamics models are the subject of this review.

The structure of this review is as follows: Section 2 outlines the history of EROEI-Dynamics models. Section 2.1: discusses formative work (1970–1980). Section 2.2: covers a period of rapid development (1980–2000). Section 2.3: highlights the most recent literature (2000–2017). Section 3 outlines the closely related field of resource-curve models. Each model is described (typically in 3 paragraphs) in terms of its novelty, technical detail and main findings. Section 4 provides a discussion and Section 5 gives concluding remarks.

2. Numerical models of EROEI-dynamics

In this section, we review the history of energy-economy models that specifically explore EROEI dynamics. Emphasis is given to seminal works. There are unavoidably a number of limitations to this review. During the development of the literature, models are often documented inconsistently therefore it is challenging to provide a consistent outline of technical detail. Further, choosing the boundaries of the review is challenging. For example, this review does not explore the broader Integrated Assessment Modelling (IAM) literature. The accuracy of the IAM literature in simulating EROEI-dynamics is debated (e.g. Dale et al., 2013) and this discussion is beyond the scope of this review. However, some of the EROEI-dynamics models may be considered as belonging to the IAM literature and vice-versa. This review particularly emphasises research that directly refers to EROEI.


World3 is perhaps the earliest model to (implicitly) simulate EROEI dynamics (Meadows et al., 1972). It is associated with the Limits to Growth study (Meadows et al., 1972) and was designed to explore the integrated environmental challenges facing the global economy in the 21st century. The model was derived from the earlier work of Forester (1970) on Industrial Dynamics and has had a defining impact on the following energy-economy-environment debate.

The World3 model can be technically described as a globally aggregated, system dynamics framework, where well-chosen simplified equations are used to represent large complex systems. The model implicitly simulates EROEI-dynamics by assuming that the cost of extracting non-renewable resources increases as resources are depleted. Therefore as the model consumes non-renewable resources, their cost increases and this drives a downward pressure on economic growth. However, the model does not explicitly simulate energy systems.

The main results (or dynamics) of World3 are relatively consistent for a range of reasonable model parameters. The ‘standard run’ of World3 suggests that the current growth trend of the global economy is unsustainable; leading to the encroachment of environmental limits and ultimately ‘overshoot and collapse’ (Fig. 2). In this case, industrial output and food production peak around 2015 and decline thereafter. Population and pollution peak around 2030 and decline thereafter. The simulation stabilises around the beginning of the 22nd century with a global population of around a half of the peak value. However, accounting for the models’ uncertainty, its precise predictions are less important than the underlying dynamics (Jackson and Webster, 2016).

![Fig. 2. The distribution of core variables for the World3 ‘Standard Run’, taken from (Meadows et al., 1972).](image-url)
Shortly after publication World3 was heavily criticised (see Hall and Day, 2009; Bardi, 2011; Jackson and Webster, 2016 for more details). But the results of World3 were revisited by Turner (2008), who concluded that the behaviour of the global economy 1972–2008 agrees well with the ‘standard run’ scenario. Furthermore, World3 was recently re-calibrated by Pasqualino et al. (2015), who argue that recent improvements in pollution and food productivity may have delayed but not negated Meadows et al. (1972) prediction of ‘overshoot and collapse’.

Following World3, Roger Naill and collaborators (in association with the U.S. Department of Energy; Naill, 1973) developed a progression of five models, COAL 1 and 2, FOSSIL 1 and 2, and IDEAS. Unfortunately, these models are sparsely documented. However, these models are well cited and considered influential on following work (Sterman, 1982). FOSSIL and FOSSIL2 are perhaps the earliest System Dynamics models to incorporate energy market dynamics, investment time lags and price elasticities. Later iterations of the group, such as FOSSIL2 and IDEAS were used by the U.S. Department of Energy between 1973 and 1995, as policy design and testing tools (Qudrat-Ullah, 2013).

From a technical perspective, early iterations of COAL follow an aggregated (‘top-down’) approach similar to World3. However, later iterations of FOSSIL emphasise greater detail in primary energy production (‘bottom-up’ approach). FOSSIL 2 and IDEAS may be classed principally as bottom-up models (Qudrat-Ullah, 2013), where each sector, and often subsectors are described explicitly with individual behavioural equations.

Following World3, the COAL-FOSSIL studies, the STER (System, Time, Energy and Resources) model, documented by Hounam (1979), presents an innovative EROEI-dynamics approach. STER is one of the earliest models to explore the behaviour of the energy sector during a period of resource depletion, and therefore also one of the first to directly focus on EROEI-dynamics. It may also be one of the earliest examples of a ‘biophysical’ EROEI model, where all capital flows and production are defined in terms of energy. In addition, the research question posed by STER is novel; STER is designed to determine the maximum possible (resource constrained) growth rate that an economy can achieve in a given time period. In this regard, the model design avoids the uncertainty of many parameters by framing results in terms of the maximum economic potential. Unfortunately, STER is only documented by a single conference paper where it is described as a pilot study (Hounam, 1979).

It is difficult to discuss the technical detail of STER because of sparse documentation. The structure is shown in Fig. 3. STER is a simplified, aggregated, bottom-up model with a production function articulated in terms of energy, capital, labour, and technology. The model simulates EROEI dynamics by assuming that the demand for resources by the primary energy sector increases (i.e. the resource cost of primary energy production increases) as energy resources are depleted.

The results of STER suggest that, if energy use is held constant, the relative resource consumption of the energy sector must increase as resources are depleted, so as to keep up with demand. The rising cost of energy production then leads to the crowding out of (non-energy) industrial production and the growth of the energy sector relative to the non-energy industry (Fig. 4). This (relative) expansion of the energy sector during the transition to low EROEI is an important process discussed by the EROEI-dynamics literature.

Directly following World3 and the COAL-FOSSIL studies, John Sterman of the MIT System Dynamics group developed a seminal energy-economy model, referred to here as the Sterman model (e.g. Sterman, 1982). In line with STER, the Sterman model is one of the earliest models designed to specifically simulate the energy-economy dynamics associated with a transition from high to low EROEI primary energy. Furthermore, the model provides one of the earliest direct references to EROEI-dynamics (Sterman, 1982; Section 2.1 para. 8). A diagram of the structure of the Sterman model is shown in Fig. 5.

The Sterman model is a globally aggregated, top-down, system dynamics framework that uses a nested, constant elasticity of substitution production function in technology, capital, labour and energy. The model characterises the energy sector in terms of two aggregated technology groups, conventional and unconventional energy. This simplification supports the inclusion of complex economic detail and allows the examination of many interesting energy-economy dynamics. For example, the model includes inflation, monetary policy and international trade. It also provides a complex representation of investment and capital depreciation. Conversely, for simplicity, the model excludes many interesting factors that may play important roles in energy-transition dynamics, such as business inventories and environmental interactions.

The Sterman model simulates EROEI-dynamics using two key assumptions. In principle, it assumes that the cost of producing conventional energy increases as reserves are depleted (whereas the reserves of unconventional energy are infinite). Further, it assumes that the initial EROEI of conventional fossil fuels is greater than the EROEI of unconventional fossil fuels. Therefore, as the economy consumes conventional energy or transitions from conventional to unconventional energy, the resource cost of energy production increases. This increasing demand for resources by the energy sector ‘crowds out’ investment in the non-energy economy and provides a downward pressure on economic growth. It is noted that the EROEI-dynamics of the model follow from similar core assumptions made by the World3.

The conclusions of Sterman (1982) emphasises three key energy-economy dynamics:

1. As previously stated, the depletion of conventional energy leads to increasing resource requirements for the energy sector, leading to a downward pressure on economic growth by ‘crowding out’ investment in the non-energy economy.
2. Energy price increases are expected to drive an increase in economy-wide energy efficiency, however, it is argued that this will occur more slowly than investment in energy production. Therefore, in the short-term energy may be over-produced and capital misallocated. In the long run, the misallocation of capital will constitute inefficiency.
3. Due to the capital-intensity of energy production, significant investment will be required in the short-run at the start of the transition; the initial cost of transition will facilitate a short-term downward pressure on economic growth and may slow the transition.

1 The constant elasticity of substitution (CES) production function is a simple aggregate model of production (Solow, 1956). The function is characterised by constant elasticity’s for its factors (e.g. capital and labour) regardless of production scale. The role of energy in production is well discussed; authors such as Cantillon (1730) and Georgescu-Roegen (1971) make notable contributions. Early modelling studies that incorporate energy as a factor of production include: Tintner et al., 1974; Hudson and Jorgenson, 1974; Berndt and Wood, 1979).
The distribution of energy production over the transition as projected by Sterman is illustrated by Fig. 6. Sterman concludes: ‘the road to the economy freed from dependence on non-renewable energy sources is likely to be quite long and rocky’ (Sterman, 1982, page 352).

2.2. Intermediate models (~1980 to 2000)

Following the Sterman model and the STER model, Baines and Peet (1983), and Bodger and Baines (1988) developed a system dynamics model to explore the role of historical energy transitions (e.g. from biomass, to coal, to oil and gas) in long-run (inter-decadal) economic variability (e.g. Kondratieff, 1979). This is referred to here as the BPB model. A schematic of the BPB model and an illustration of the energy availability over recent energy transitions are shown in Figs. 7 and 8 respectively (Baines and Peet, 1983).

In a technical regard, the BPB model is a globally aggregated, top-down, biophysical approach that uses constant values for the EROEI of energy technologies. The model simulates historical energy transitions by assuming that the economy has a preference to consume the highest EROEI resources available. Therefore economies typically transition to higher EROEI resources as they become available. The model contains a similar level of energy production detail to the STER model. The BPB model was not thoroughly calibrated to historical data (Dale, et al., 2012). Furthermore, it does not appear to include a complex representation of the economy such as the Sterman model.

The results of the BPB model suggest that EROEI-dynamics have
played a plausible role in long-run (inter-decadal) economic variability, particularly in association with energy technology transitions. This argument is supported by the work of other notable authors, such as Schumpeter (e.g. Schumpeter, 1939), Sterman (1985) and King et al. (2015).

In the early 90s Malcolm Slesser and colleagues developed the Enhancement of Carrying Capacity Options (ECCO) modelling framework in association with UNESCO (e.g. Slesser, 1992). ECCO was originally developed to assist supply-side growth in low-GDP nations and has been applied to a range of economies including Kenya (Owino, 1991), China (Wenhua, 1991; Xiaohui, 1995) and the Netherlands (Noorman, 1990, 1995). ECCO is a biophysical system dynamics approach that draws directly from the approaches of World3, FOSSIL2, and STER (Gilliland, 1978). In particular, following STER, it is designed to determine the maximum growth potential of an economy as a function of its resource constraints.

The core ECCO model is a top-down aggregated simulation of a national economy. The structure of ECCO follows the Natural Capital Accounting methods of Slesser (1989). This basis leads to a strong emphasis on the efficiency of primary resource production, and therefore emphasis on EROEI. The model defines three types of natural capital, depletable (e.g. fossil fuels), recyclable (e.g. aluminum) and renewable (e.g. solar power). Similar to STER, ECCO is classed as a biophysical model and describes all the interactions in the economy in terms of energy. Following Dühr (1994), ECCO has a novel production function with factors in terms of operational energy and capital-embedded energy. The ECCO production function interestingly neglects the role of labour. Further, ECCO explicitly calculates the EROEI of multiple primary resources, including energy resources.

ECCO models typically incorporate an aggregated world model, referred to as CORECCO or GloBECCO. A diagram of the CORECCO structure is shown in Fig. 9. Similar to the ECCO national models, CORECCO explicitly simulates EROEI dynamics at an aggregate level.

The standard implementation of CORECCO suggests that industrial output of the global economy will peak in the early half of the current century and decline thereafter.

In the late 90s, Fiddaman (1997) developed the Feedback Rich Energy Economy model (FREE) in association with the MIT System Dynamics group that draws directly from World3 and the Sterman model (Fig. 10). FREE is designed to highlight the role of complex non-linear feedbacks in energy-economy systems, particularly over a period of energy transition. Furthermore, it is designed to explore the response of the energy-economy to policy proposals.

The FREE model simulates a large range of economy-energy-environment interactions, it therefore can be considered an Integrated Assessment Model, as well as an EROEI-dynamics model. The economy structure of FREE is derived from the highly cited DICE Integrated Assessment Model (Nordhaus, 1992). The energy systems and economy-energy coupling of FREE is derived from the Sterman model (e.g. Sterman, 1982). FREE uses a Cobb-Douglas production function with factors in Labour, Capital, Energy and Technology. Unlike the Sterman and World3 models, the population and total factor productivity are estimated exogenously. FREE explicitly accounts for EROEI dynamics and resource constraints, as well as climate interactions (Fiddaman, 1997, 1998).

The ‘business as usual’ results of the FREE model suggest that the net energy output of the global economy will decline between 2020 and 2045. However, unlike the Sterman or World3 models, the GDP of the economy does not appear to decline. This distinction for GDP highlights a potential rigidity in the model that may be associated with exogenous parameters, such as population or total factor productivity growth. Similar to Sterman (1982), Fiddaman argues: ‘Much of the harm from depletion actually arises from the difficult period of transition away from oil and gas, rather than from the long-run effects of losing the services of those fuels’. This is due to the cost of building new and retiring old energy systems (pg. 15, Fiddaman, 1997). Fiddaman therefore additionally supports Sterman (1982)’s emphasis on the role of the misallocation of capital during the transition, both in the energy industry and in the none-energy industry. Fiddaman argues ‘Depletion leads to suboptimal capacity utilization in the goods producing sector, because energy prices are far from the levels for which the capital stock was designed. In extreme scenarios, when depletion suddenly becomes severe, a near-shutdown of the economy is possible.’ (pg. 15, Fiddaman, 1997). Fiddaman argues that a depletion tax on oil and gas improves the economic stability of the transition by increasing the price of oil and gas earlier; therefore, by spreading the economic cost and risk of systemic failure.

2.3. Recent models (2000–2017)

Following from STER and ECCO, the Global Energy Modelling – a Biophysical Approach model (GEMBA; Dale et al., 2012) is a recent direct effort to explore EROEI dynamics over the renewable energy transition. GEMBA’s description of EROEI-dynamics is highly intuitive and engaging. Furthermore, GEMBA is notably well constructed for calibration with empirical data.

GEMBA can be technically described as a globally aggregated top-down, biophysical model that utilises a highly simplified economy model with a production function in terms of capital and a capital to output ratio (Fig. 11). In particular, GEMBA simulates a detailed range of production technologies, including coal, oil, gas, wind, hydro and solar. GEMBA estimates EROEI in terms of resource depletion and technological development (Dale et al., 2010).

The main results of the GEMBA model suggest that the relative capital requirement of the energy sector may increase over the energy transition to around half the capital in the economy (Fig. 12a; similar to STER and the Sterman model). Over the same period, the total available

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Fig. 7. A schematic showing the BPB model view of EROEI dynamics (Bodger and Baines, 1988).

Fig. 8. A schematic showing the distribution of capital between competing energy technologies over a series of transitions, as Envisioned by Bodger and Baines (1988), associated with the BPB Model.
Energy is suggested to peak mid-21st century, eventually stabilising at around half current values in 2200 (Fig. 12b).

Dale et al. (2013) compare the MESSAGE (common Integrated Assessment Model) projections, associated with the Special Report on Energy Scenarios (SRES, IPCC) with the GEMBA projections. GEMBA’s projections provide lower future estimates of energy availability than MESSAGE. It is argued that this is because GEMBA utilises more realistic primary resource estimates.

Fig. 9. Outline of CORECCO (Slesser, 1992) taken from Dale (2010).

Fig. 10. A schematic of the FREE model, taken from Fidderman (1997).
Finally, a recent work by Brandt (2017) focuses on the dynamics of the ‘Net Energy Cliff’. The Brandt approach is novel for the distinction that it makes between GDP and ‘material prosperity’. This emphasis on ‘material prosperity’ provides a strong link with the Biophysical approach, however, the Brandt model is not biophysical.

The Brandt model is a bottom-up globally aggregated model that uses a neoclassical production function, with factors in, capital, labour, energy and resources. The economy component of the Brandt model is derived from the KLEMS economy model (Van Ark et al., 2007) and its representation of energy production uses an input-output model of the energy industry. The Brandt model explicitly simulates EROEI-dynamics, where a decline in the EROEI of production is shown to drive a decline in the material prosperity of the economy.

The results of Brandt (2017) are used to explore the concept of a minimum EROEI. As suggested by Hall and Murphy (2011) Brandt finds a consistent behaviour in all runs, where below a specific level of EROEI, typically ~7, the material wealth of the economy declines rapidly.

3. Resource curve methods

In addition to the EROEI-dynamics models, a related body of literature utilises resource curve methods (e.g. Hubbert, 1956) to explore 21st century energy futures. Studies within this group include: Brecha (2008), Doose (2004), Nel and Cooper (2009), Macías and Matilla-García (2015). Resource curve methods simulate resource depletion but do not explicitly include EROEI-dynamics. The approach uses empirical observations of resource depletion and global geological data to estimate the future global depletion of resources. Resource curve methods typically apply these distributions as exogenous constraints. The resource curve literature is extensive and often overlaps with EROEI-dynamics models, it includes some influential studies that are well cited...
by the EROEI-dynamics modelling literature. The following section outlines a number of notable studies that use these methods.

Following World3, Capellán-Pérez and collaborators (e.g. Capellán-Pérez et al., 2014; Mediavilla et al., 2013) developed the World Limits Model (WoLiM). WoLiM is a biophysical system dynamics model that uses resource curve methods. WoLiM is designed to explore the feasibility of 20th century growth trends (Fig. 13).

WoLiM is a bottom-up model with notable detail in primary energy production (Fig. 14). The model is driven primarily by a group of GDP and population scenarios that are set externally (exogenous). Therefore EROEI decline is not able to influence GDP and the model is not able to properly simulate EROEI dynamics. The model simulates the depletion of resources with resource depletion curves (e.g. Mohr, 2012, Patzek and Croft, 2010). WoLiM’s results typically predict resource constraints in the early half of the 21st century. The majority of WoLiM runs exceed environmental limits leading to dangerous climate change. WoLiM may be thought of as a model that is designed to test for resource limitations as a result of optimistic 21st century growth projections.

Kumhof and Muir (2014) and Benes et al. (2015) provide related modelling studies that are more closely aligned with resource curve models then with the EROEI dynamics models. Kumhof and Muir (2014) use a top-down, Dynamic Stochastic General Equilibrium Model to explore the behaviour of the global economy responding to a decline in oil production. The model simulates energy scarcity using a resource depletion curve, which is expressed in terms of the oil price. Benes et al. (2015) use an econometric model of the global oil market to explore the response of the economy to a decline in oil production. The Benes model simulates EROEI dynamics through a rising oil price, associated with a depletion curve. The Kumhof model suggests that a realistic decline in the global oil production may drive a significant decline in the GDP growth rate of both importer and exporter countries. This decline is notable since the growth rates of the high GDP countries are currently declining and additional decline may constitute stagnation or decline (Summers 2011). The Benes model similarly predicts that resource depletion with drive oil prices to almost double over the coming decade. Benes notes that this scale of increase would have a dramatic impact on the global GDP, further supporting the arguments of Kumhof and Muir (2014) and the EROEI dynamics models.

Finally, Sgouris et al. (2016) developed the NETSET resource curve model. The NETSET model uses a novel inverse approach to simulate a range of feasible transition pathways. The framing of the approach is well illustrated by the title: ‘... quantifying the narrowing net-energy pathways to a global energy transition’ (Sgouris et al., 2016).

The NETSET model is a globally aggregated, top-down, biophysical simulation model. The model uses an exogenous projection of future population to estimate future energy demand. It then integrates backwards to estimate a range of transition pathways that satisfy emissions targets and minimum energy per capita requirements. NETSET uses three core pre-conditions. First, carbon emissions must not surpass levels chosen to limit global warming to 2 °C (between 510-1505 Gt CO2; IPCC, 2014). Second, energy availability must not decline below levels deemed as unrealistic (between 600 and 6000 Watts per person). Third, the rate of transition to low-carbon technologies should not exceed that which fully depletes non-renewable resources.

The results of the NETSET model suggest that there are a number of biophysically feasible pathways to transition to a low carbon economy (Fig. 15). Sgouris et al. (2016) uses a ‘feasibility indicator’ to determine which pathways are most likely. It intuitively suggests that the transition becomes more difficult if it is delayed, or if the carbon emission targets are relatively stringent. However, the model does not simulate macro-economic variables. The model, therefore, does not discuss the economic or social implications of the projected energy pathways.

4. Discussion

In the spirit of organizing our discussion, it is useful to present a historical synthesis of the models discussed in this paper. An overview of the key literature is shown in Fig. 16 and a summary table is shown in Appendix I. Four model groups are evident: the MIT System Dynamics group (red), the US department of energy group (blue), the BPB group (green), and the STER-ECCO group (orange). These four groups can be additionally linked. The red and blue groups are interconnected through the work of authors such as Sterman and Fidderman. The green and orange groups show strong association both through common authors and model design.

As previously stated, the World3 model is one of the earliest models to directly explore the inter-related global challenges associated with unsustainable 20th century growth trends, having a defining impact on following work. It is also perhaps one of the earliest models that implicitly simulates EROEI dynamics. It is important to note that World3 follows World2 and the formative work of Forrester in Industrial Dynamics (Forrester, 1970).

Following World3, the development of EROEI models can be described in terms of the MIT (red-blue) group and the Biophysical (orange-green) group. A divergence between the MIT and Biophysical groups occurs around 1980 associated with the STER model and the Sterman model. These models are perhaps the earliest to directly simulate EROEI dynamics; both make significant contributions to the literature.

The Sterman model signifies a more direct development of World3 but also draws influence from the COAL and FOSSIL models. The model has a stylised description of the energy sector and a more complex representation of the economy that provides a good platform for exploring energy-economy interactions. One may argue that many features of the Sterman model, such as the misallocation of capital, or the role of inflation and unemployment have been insufficiently explored following its publication. The Sterman model is followed by the FREE model, which integrates the Sterman approach with recent economic theory and explores a range of policy options.

At a similar time to the Sterman model, the STER model introduces multiple novel features to EROEI modelling, including the biophysical approach. It is unfortunate that the STER model is only documented by a brief preliminary paper. STER is followed by a series of biophysical models: BPB, ECCO and GEMBA (green and yellow). The BPB model uses a similar approach to STER but explores a distinctive question on the role of EROEI in historical inter-decadal energy transitions. The ECCO framework develops the STER approach and applies it to a range of national economies, with a particular interest in understanding the resource constraints of economic growth. Finally, GEMBA continues the approach of this group but returns to focus directly on the renewable energy transition and provides an intuitive structure that is well designed for calibration with empirical data. Of this group, the GEMBA model is perhaps the most directly interested in EROEI dynamics and provides a critique of the highly cited integrated assessment models.
that appear to neglect EROEI dynamics.

Following the progression of the MIT, and the biophysical modelling groups, a number of relatively independent models have made significant contributions. For example, WoLiM provides an alternative approach to the problem outlined by World3. It utilises more recent approaches to economic theory and highlights that current resource consumption growth trends are unsustainable, both in terms of resource and pollution limits.

Despite the diversity in the EROEI-dynamics literature, there are seven key arguments or dynamics that run through all material. These dynamics are listed below, along with the dates of their first documentation.

1. **EROEI declines during the low carbon transition** – during the transition to low carbon technology, primary energy production becomes less efficient (this is first implied by Meadows et al., 1972; this is fundamental to all models in this review except the BPB model).
2. **The energy sector outgrows the economy (aka. energy cannibalism)** - as the EROEI of primary energy production declines, the energy sector requires increasing resources (including energy) to maintain supply with demand (Hounam, 1979; Sterman, 1982; Slessor, 1992; Fiddaman, 1997; Dale, 2010; Capellán-Pérez et al., 2014; Kumhof and Muir, 2014; Benes, 2015).
3. **Short-term confusion** - during the transition to low-carbon technology, a short-term misallocation of capital and labour occurs due to imperfect information (Sterman, 1982; Fiddaman, 1997).
4. **Short-term over production** - energy scarcity drives both an increase in energy efficiency and investment in energy production. Sterman (1982) argues that this leads to a short-term overproduction of primary energy.
5. **Short-term scarcity** - a decline in EROEI is expected to drive scarcity and inflation (Sterman, 1982).
6. **Energy transition ‘long wave’** - ‘long wave’ (inter-decadal) economic variability may be associated with energy transitions and EROEI (Baines and Peet, 1983).
7. **‘Net Energy Cliff’** - economic systems become unstable as EROEI declines below 10:1 associated with the ‘Net Energy Cliff’ (Brandt, 2017; Murphy and Hall, 2010).

Fig. 14. Schematic illustration of the structure of the WoLiM model (Capellan-Perez et al., 2014) IB stands for Industrial Buildings sector. The WoLiM structure can be described as follows: GDP growth drives energy demand. Energy demand is divided into three categories. Demand drives production through a number of technology options. The optimal pathway for generation is a function of resource limits and environmental pollution.
These dynamics may be usefully re-framed into three groups: Scarcity (1, 2, 6), Instability (5, 6, 7) and Uncertainty (3, 4). From this view, ‘Scarcity’ encompasses the driving dynamics that lead to a decline in resource availability. Dynamics 1 and 2 of this group are the most consistent across the literature. ‘Instability’ encompasses potential systemic failures where systems are forced to sustain unanticipated resource constraints. Finally, ‘Uncertainty’ encompasses the period of change or adjustment, where unavoidable unknowns (imperfect information) lead to the misallocation of capital. Scarcity is the primary driver of Instability and Uncertainty, however, these dynamics are inter-related and constitute feedbacks that are difficult to simulate. From this framework, the issues of Instability and Uncertainty in energy-economy dynamics are notably poorly understood.

The issue of instability is an interesting topic of divergence in the literature. Multiple authors, particularly in the MIT group, suggest that the low carbon transition is likely to drive a period of instability (Sterman, 1982, Fiddaman, 1997). However, dedicated modelling studies such as Jackson and Victor (2015), Jackson (2017), suggest that the transition to a steady state or low carbon economy does not necessarily instate instability. Further work is required to explore the role of EROEI in systemic instability and the macro policy levers available to facilitate a stable energy transition.

In addition, the issue of late 21st century energy availability is an important topic in the literature. Models such as GEMBA and WoLiM predict a mid 21st century decline in energy availability (Dale, 2013; Capellán-Pérez et al., 2014). This behaviour is similar to the ‘system collapse’ described by World3 and CORECCO (Meadows et al., 1972; Slesser, 1992). However, models such as those of the Sterman (1982) and Fidderman (1997) predict short-term instability instead of long-run decline. Here, it is important to account for model design factors and consider the research questions being explored by given papers. For example, the Sterman model is highly idealised. It is not designed to predict future energy availability from empirical data. The models that are more directly designed to explore empirical estimates of resource constraints such as CORECCO, GEMBA and WoLiM typically predict a long-run decline in energy availability in the mid 21st century (Meadows et al., 1972; Slesser, 1992; Dale, 2013; Capellán-Pérez et al., 2014). Here it is argued that this issue requires further direct analyses of model code and empirical data.

Following models such as GEMBA and WoLiM, multiple authors have expressed concern that the highly cited Integrated Assessment Modelling or Energy-Economy modelling literature does not effectively simulate or discuss EROEI-dynamics (e.g. Dale et al., 2013) and therefore presents optimistic scenarios for future energy availability. Moreover, Keepin and Wynne (1984), Schneider (1997) and Schneider and Lane (2005) argue that the subcomponents of Integrated Assessment Models are often poorly coupled suggesting EROEI dynamics are poorly simulated. This concern is also crucial, requiring directed research and review. It is argued that it is beyond the scope of this review.

The Energy-Economy modelling literature is critiqued in general for documentation issues (Pindyck, 2015; Beck and Krueger, 2016; Pfenninger, 2017; Schneider, 1997). It is argued that the EROEI-dynamics literature could also benefit from improved documentation and archiving. For example, research papers (and/or manuals) for COAL, FOSSIL and STER are not readily accessible. However, these models are highly cited by later work. Model descriptions, terminology and schematics are often used inconsistently. For example, common challenging terms include, ‘Top-Down’, ‘Bottom-Up’, ‘Hybrid’, ‘Simulation’, ‘Optimisation’ and ‘General Equilibrium’. This issue is compounded by the concern that model code is rarely available for scrutiny, even decades after original research publications. It is further suggested that the literature may benefit greatly from an improved effort in review and synthesis.

Further research in energy-economy dynamics is vital, considering the urgency of the transition to a sustainable economy (IPCC, 2014; Svrdrup et al., 2015). Particularly considering that the current economic climate is characterised by declining economic growth rates (Summers, 2013), increasing instability (Rye and Jackson, 2016) and increasing uncertainty (Baker et al., 2016), all of which are plausibly related to EROEI dynamics. There is therefore a notable requirement for further empirical studies in EROEI-dynamics. For example, it may be possible to find signatures of EROEI dynamics in Secular Stagnation, or in international trade. Further work is required to provide an improved link between empirical work, such as Heun and de Wit (2012) and the modelling literature.

There are multiple a-priori EROEI dynamics identified by our discussion that are not discussed by the current literature. These provide interesting subjects for further research. Examples of these dynamics include:

- **The role of EROEI in financial instability** – e.g. As EROEI declines currently highly valued resources may become unprofitable to extract. A sudden loss in value would provide a significant destabilising perturbation to financial systems (e.g. stranded assets: Carbon Tracker, 2013).
- **The role of EROEI in Secular Stagnation** – Following e.g. Slesser (1992), EROEI plays a significant role in determining the growth rate of an economy. Therefore, the decline in EROEI over recent decades may have played a primary role in Secular Stagnation.
- **The role of international trade in global EROEI and global energy prices** – Resource exploitation and international trade strategies are likely to
change as EROEI declines and the nation state’s concerns of resource scarcity increase. It is possible that changes in trade may lead to a decline in oil price during a period of declining EROEI.

5. Concluding remarks

The literature discussed by this review is diverse and spans almost 50 years from the initial publications of the Limits to Growth study. It is possible to map the development of the EROEI-dynamics models over this period, to identify seminal works and provide a historical catalogue of blueprints for future work. Notable early works include: Meadows (1973), Hounam (1979) and Sterman (1982). The consistency of the key arguments stemming from these papers and running through the EROEI-dynamics literature is strongly supportive of their validity. The most widely established arguments suggest that geological resource constraints will drive a relative expansion of the energy sector in the coming century, and a downward pressure on material prosperity (arguments 1, 2, 3 and 5).

It is clear that considerable work is required to further our understanding of EROEI-dynamics. Perhaps the most significant concern following this review is the divergence in the literature, where the widely cited Integrated Assessment Modelling literature poorly cites EROEI-dynamics literature. It is possible that better integration of EROEI-dynamics could have a significant impact on the discussion of energy futures and therefore a significant impact on government policy.

Appendix I. Model Summary Table

Summary of models discussed by the review. The models are classified by the year of their first major publication as well as the development group assigned by this review. Red: MIT group. Blue: US government group. Orange: STER-ECCO group. Green: BPB group. Grey: no clear group. The models are also classified by the key dynamics. Further, by novel conclusions and their earliest reference.

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Year</th>
<th>R/2017 class</th>
<th>Model Design</th>
<th>Key Dynamics</th>
<th>Novel Conclusions</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>World3</td>
<td>1972</td>
<td>Red</td>
<td>Top-down, globally aggregated.</td>
<td>(1) Emphasises the argument: The global economy will eventually reach limits and the future will be uncertain.</td>
<td>Meadows et al. (1972)</td>
<td></td>
</tr>
<tr>
<td>COAL, FOSSIL &amp; IDEAS</td>
<td>1973-1995</td>
<td>Blue</td>
<td>Ranging from top-down to bottom-up</td>
<td>(7) Poorly documented.</td>
<td>Nail (1973)</td>
<td></td>
</tr>
<tr>
<td>STER</td>
<td>1979</td>
<td>Blue</td>
<td>Directly simulates EROEI-dynamics at a medium detail level.</td>
<td>(1-2) Emphasises the argument that a transition to lower EROEI will drive a prolonged recession.</td>
<td>Hounam (1979)</td>
<td></td>
</tr>
<tr>
<td>Sterman model</td>
<td>1982</td>
<td>Blue</td>
<td>Directly simulates EROEI-dynamics at a medium detail level.</td>
<td>(1-5) Emphasises the argument: ‘Leaving the ‘Long Wave’ (inter-decadal) economic variability is associated with energy transitions and EROEI.</td>
<td>Sterman (1982)</td>
<td></td>
</tr>
<tr>
<td>ECCO</td>
<td>1992</td>
<td>Orange</td>
<td>Directly simulates EROEI-dynamics at a medium detail level.</td>
<td>(1-2) Emphasises the argument: ‘Depletion leads to suboptimal capacity utilization...a near-collapse of the economy is possible.’ (pp. 15, Fiddament 1997)</td>
<td>Fiddament (1997)</td>
<td></td>
</tr>
<tr>
<td>FREE</td>
<td>1997</td>
<td>Orange</td>
<td>Top-down, globally aggregated.</td>
<td>(1-2) Emphasises the argument: ‘EROEI declines during the low carbon transition and the energy sector outgrows the economy.</td>
<td>Dale (2012)</td>
<td></td>
</tr>
<tr>
<td>GEMBA</td>
<td>2012</td>
<td>Orange</td>
<td>Directly simulates EROEI-dynamics at a medium detail level.</td>
<td>(1-2) Emphasises the argument: Economies become unstable as EROEI declines below 10 associated with the ‘Net Energy Cliff’</td>
<td>Brandt et al. (2012)</td>
<td></td>
</tr>
<tr>
<td>Brandt</td>
<td>2017</td>
<td>Orange</td>
<td>Directly simulates EROEI-dynamics at a medium detail level.</td>
<td>(1-2,7) Emphasises the argument: Economies become unstable as EROEI declines below 10 associated with the ‘Net Energy Cliff’</td>
<td>Brandt et al. (2012)</td>
<td></td>
</tr>
</tbody>
</table>

Greater research is required to explore this concern.

Regardless of this concern many of the immediate-term policy implications are consistent throughout the literature. These suggest that rapid investment in renewable energy and energy efficiency are required, some form of carbon or resource tax would be beneficial and delayed actions are likely to increase the chance of dangerous climate change. Further, there is a significant risk of systemic collapse. However, policy implications differ in the medium to long-term, where the EROEI-dynamics literature often advocates a low-growth or steady state economy. This is discussed both in terms of a mitigation strategy and a biophysical inevitability. It is clear that greater research is required to explore the dynamics of the steady state economy, as the EROEI-dynamics literature consistently projects that it may become a prominent feature of the current century.

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