https://doi.org/10.5194/esd-2020-59
Preprint. Discussion started: 13 August 2020

Earth System Dynamics
Discussions

ENERGETIC REGIMES OF THE GLOBAL ECONOMY - PAST, PRESENT AND FUTURE

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ABSTRACT

For centuries both engineers and economists have collaborated to attempt to raise economic productivity through efficiency improvements. Global primary energy use (*PEU*) and gross world product (*GWP*) data 1950 - 2018 reveal a the effects of aggregate energy efficiency (*AEE*) improvements since the 1950's have been characterised by two distinct behavioural regimes. Prior to the energy supply shocks in the 1970s the *AEE* of the global economy was remarkably constant such that *PEU* and *GWP* growth were fully coupled. We suggest this regime is associated with attempts to maximise growth in *GWP*. In contrast, in the 1970s the global economy transitioned to a lower growth regime that promoted maximising growth in *AEE* such that *GWP* growth is maximised while simultaneously attempting to minimise *PEU* growth, a regime that appears to persist to this day. Low carbon energy transition scenarios generally present the perceived ability to raise growth in *AEE* at least three fold from 2020 as a tactic to slow greenhouse gas emissions via lower *PEU* growth. Although the 1970s indicate rapid transitions in patterns of energy use are possible, our results suggest that any promise to reduce carbon emissions based on enhancing the rate of efficiency improvements could prove difficult to realise in practice because the growth rates of *AEE*, *PEU* and *GWP* do not evolve independently, but rather co-evolve in ways that reflect the underlying thermodynamic structure of the economy. (232)

INTRODUCTION

The debate over the role energy plays in the economy is long and contested (Stern, 2011). On the one hand there are those who emphasise the relatively small fraction of production costs imposed by energy (Dennison 1979; Newberry 2003; Grubb et al., 2018), whilst on the other there are those who emphasise how energy use necessarily underpins all activity, including that of economies (Ayres and Warr, 2005; Kümmel 2011; Garrett, 2011). Attempts to infer the role of energy from the relationship between economic output (e.g. Gross World Product; *GWP*) and Primary Energy Use (*PEU*) have been central to this debate, although no clear picture has yet emerged (Stern 2011, Kalimeris et al. 2014; Brockway et al., 2018). Resolving these uncertainties is critical to understanding whether the global economy can continue to prosecute current growth objectives whilst simultaneously decoupling from growth in resource use and environmental degradation. For example, most economic analyses assume that increasing energy efficiency plays a

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central role in reducing greenhouse gas emissions via reductions in *PEU* (Clarke et al., 2014). Some even argue efficiency should be the central focus of climate policy (Grübler et al., 2018). This assumes high levels of decoupling between these efficiency improvements and their subsequent effects on productivity, growth and the evolution of the economy. However, throughout the industrial era economic output has grown alongside the efficiency of most elements of the global economy (Csereklyei et al., 2016). It also appears economies have tended to increase the efficiency of primary energy conversion to counter the general tendency for all distribution networks to become less efficient as they expand (Jarvis, 2018). Thus, efficiency improvements appear central to maintaining economic returns and hence growth, and we might suspect that it is difficult to decouple the two in systems predicated on maintaining growth, especially in an environment of otherwise diminishing returns.

Although subjective judgements are deeply embedded throughout the accounting that underpins all *GWP* data, because *GWP* ultimately attempts to capture the annual production of real economic value, we might assume this is determined by physical activity, even if this activity is often highly dematerialised i.e. information rich. If so, we might assume *GWP* is akin to the rate useful work is done by the economy, i.e. the final useful energy per unit of *GWP* is somewhat constant (Warr and Ayres, 2010; Serrenho et al., 2016). If so, a possible thermodynamic relationship between *PEU* and *GWP* is given by $GWP \propto AEE \times PEU$, where *AEE* is the aggregate energy efficiency of the economy when converting primary energy flows into the physical activities judged to be useful. *AEE* parallels the more traditional energy intensity view of economic performance, *PEU/GWP*, although here *AEE*×*PEU* is specifically taken as the useful fraction of the energy flow powering valued economic activity, whilst (1-*AEE*)×*PEU* is the unvalued portion dissipated when realising this useful fraction.

The relationship $GWP \propto AEE \times PEU$ is not causal, but rather summarises the reconciliation of supply with demand. Traditionally in energy studies *PEU* might be partitioned into its useful and final useful components (Brockway et al, 2018) such that *AEE* represents the aggregate serial effects of the ability of the primary energy portfolio to do useful work, and the ability of economic structures to translate this into real value. Given the very substantial losses associated with relocating primary resources, Jarvis extends this view of *AEE* to explicitly include consideration of dissipative losses within the complex resource distribution networks linking primary resources to points of final use (Jarvis et al., 2015; Jarvis 2018). In this view, and as with all physical dissipative systems, we might see *AEE* as having three serial components: the efficiency of a given primary energy portfolio at doing any form of useful work; the efficiency of the distribution network when using useful energy to relocate material resources (including energy carriers and people) to form productive configurations; and finally the efficiency with which the residual useful energy fixes these configurations into structures so that they are able to provide returns over an array of timescales from seconds to millennia. We argue it is this creation of productive structure that is ultimately valued in *GWP*, even if some of these structures are often very short-lived.

Productive structures are necessarily low probability (lower entropy) configurations of matter made from higher probability configurations within the environment and, as a result, the dissipation of primary energy is reflected in the accumulation of information within systems. It is not surprising therefore that *GWP* is strongly associated with both material and informational elements in the economy. This framing does not negate orthodox representations of value production given inputs of labour, capital, and technology could each be viewed as determinants of productivity and hence *AEE* (Keen et al., 2019). We view this physical interpretation of the relationship between *GWP* and *PEU* as a null position which, if rejected, opens up alternative framings such as $GWP \propto PEU + x$, where x is measured value independent of any thermodynamic restrictions.

If $GWP \propto AEE \times PEU$ and the scaling from the rate of final useful work to value is stationary (Warr and Ayres, 2010; Serrenho et al., 2016) then, as in standard growth accounting, $r_{GWP} \approx r_{AEE} + r_{PEU}$, where $r_{GWP,AEE,PEU}$ are the relative growth rates of *PEU* ,*GWP* and AEE. This suggests we can explore the relationship between *GWP* and *PEU* in a thermodynamically consistent way through their relative growth rates. This also captures a critical element of the debate over the possibility for clean/green growth, because it suggests the possibility that growth in activities we value, r_{GWP}, could, in principle, be maintained through growth in the efficiency with which we use energy, r_{AEE}, whilst growth in energy use, r_{PEU}, could, in principle, be zero, or even negative (Sakai et al., 2019). For example, a significant proportion of the Nationally Determined Contributions (NDCs) toward emissions reduction currently pledged under the Paris Agreement are predicated on being able to trade reductions in r_{PEU} against increases in r_{AEE} independent of any adjustments in r_{GWP} (UNEP, 2018). This assumes a significant degree of decoupling between r_{PEU} and r_{AEE} is possible, albeit in economies currently in pursuit of positive economic growth objectives. Here we analyse the observed pattern of covariation between r_{PEU}, r_{GWP} and r_{AEE} within global *PEU* and *GWP* data to explore the past and present-day coupling among these three quantities in the context of global-scale socioeconomic behaviour. We then contrast this behaviour with that found in economic scenarios used to explore future actions believed to be required to avoid dangerous climate change. Our focus is necessarily global given both contemporary economic behaviour and climate change are both global phenomena.

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METHODS

Given the range of available *GWP* and *PEU* observations, and the sensitivity of regression results to the particulars of these data, we have elected to produce a single, homogeneous *PEU* and *GWP* series which blends the available mainstream series listed in Table 1. The eight global *GWP* series used in this study are a compilation of available, reputable inflation adjusted (constant) series. To reconcile the fact that these *GWP* data did not have a consistent base unit and compilation method, all *GWP* series were linearly scaled to the World Bank (WB) constant (2010) MER series. This only serves to homogenise units and has no effect on the relative scaling relationships explored in this paper. Similarly, the four global *PEU* series were linearly scaled to the International Energy Agency (IEA) data, again to reconcile only unit differences and methods of compilation. All analysis is based on the annual averages of the eight *GWP* and four *PEU* series listed in Table 1.

All estimates of the relative growth rate assume $r_{GWP,\,PEU} = \Delta \ln(GWP, PEU)$. Parameter estimation are as detailed in Figures 1 and 2. All uncertainties are reported as $\pm 1\sigma$ unless stated otherwise. All code and data are available on request from corresponding author.

135 **Table 1.** Global Primary Energy Use (*PEU*) and inflation adjusted Gross Domestic Product (*GWP*) data sources used in this study.

variable	**cover**	**source (as of 21/08/2019)**
GWP		
World Bank *GWP* (PPP 2011 USD)	1990 - 2018	https://data.worldbank.org/indicator/NY.GDP.MKTP.PP.KD
World Bank *GWP* (MER 2011 USD)	1960 - 2018	https://data.worldbank.org/indicator/ny.GDP.mktp.kd
United Nations (2010 USD)	1970 - 2017	https://unstats.un.org/unsd/amaapi/api/file/6
Penn World Tables (Expenditure PPP 2011 USD)	1950 - 2017	http://febpwt.webhosting.rug.nl/Dmn/Templates/Execute/53
Penn World Tables (Output PPP 2011 USD)	1950 - 2017	http://febpwt.webhosting.rug.nl/Dmn/Templates/Execute/54
Penn World Tables (National-accounts 2011 USD)	1950 - 2017	http://febpwt.webhosting.rug.nl/Dmn/Templates/Execute/47
Maddison (C*GWP* 2011 USD)	1950 - 2016	https://www.rug.nl/ggdc/historicaldevelopment/maddison/data/mpd2018.xlsx
Maddison (R*GWP* 2011 USD)	1950 - 2016	https://www.rug.nl/ggdc/historicaldevelopment/maddison/data/mpd2018.xlsx
PEU		
International Energy Agency (EJ yr^{-1})	1970 - 2016	https://webstore.iea.org/world-energy-balances-2018
British Petroleum (Mtoe yr^{-1})	1965 - 2018	https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/xlsx/energy-economics/statistical-review/bp-stats-review-2019-all-data.xlsx
International Institute Applied Systems Analysis (EJ yr^{-1})	1950 - 2014	http://www.iiasa.ac.at/web/home/research/researchPrograms/TransitionstoNewTechnologies/PFUDB.en.html
Energy Information Administration (TBtu yr^{-1})	1980 - 2016	https://www.eia.gov/totalenergy/data/browser/xls.php?tbl=T01.01

https://doi.org/10.5194/esd-2020-59
Preprint. Discussion started: 13 August 2020

RESULTS AND DISCUSSION

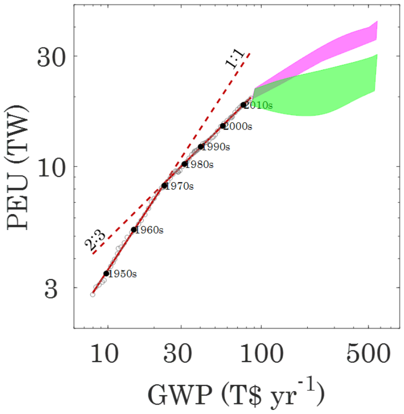

Figure 1. The relationship between gross world product (*GWP*) and Primary Energy Use (*PEU*) 1950 – 2018 (o). See Table 1 for data sources. The break point model $PEU = \min\{a_1 GWP^{b_1}; a_2 GWP^{b_2}\}$ has been fitted using nonlinear least squares. a_1 = 0.3527 (0.3382 – 0.3679); b_1 = 1.0070 (0.9910 – 1.0229); a_2 = 1.0483 (0.9928 – 1.1069); b_2 = 0.6610 (0.6464 – 0.6756); 95 % confidence. Also shown are the decadal mean values (●). The two shaded areas are the Business As Usual (BAU, 🟪) and <2 °C (🟩) Shared Socioeconomic Pathway 2 (SSP2) scenarios of Riahi et al., (2017) with *GWP* and *PEU* rescaled to correspond to the observed 2018 values.

Figure 1 shows the observed relationship between *GWP* and *PEU* 1950 - 2018 derived from the data listed in Table 1 (see Methods). Prior to the 1970's *PEU* scales linearly with *GWP* ($PEU \propto GWP^{b}$ [1], b = 1.01 (0.99 – 1.02), P <0.001). However, after the 1970's *PEU* scales 2:3 with *GWP* (b = 0.66 (0.65 – 0.68), P <0.001). This sub-linear scaling is a formal expression of the sixth stylised fact of the relationship between energy and the economy articulated by Csereklyei et al., (2016), and has been discussed at length in the context of the legacy of the 1970's energy crises (e.g., Huang et al., 2008).

The pattern of *PEU* versus *GWP* seen in Figure 1 can be described via the associated scaling exponent defined by the ratio of the corresponding average relative growth rates, $b = \bar{r}_{PEU} / \bar{r}_{GWP}$. From 1950 to 1970, *GWP* and *PEU* grew at, on average, 4.37 ± 1.19 and 4.35 ± 1.87 % yr^{-1}, i.e. $b \approx 1$, whereas from 1980 to 2018 *GWP* and *PEU* grew at, on average, 2.98 ± 1.47 and 1.92 ± 1.41 % yr^{-1}, i.e. $b \approx 2/3$ (see Figure 2 & 3).

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[1] In recognition of the fact that we do not view *PEU* as causally determining *GWP*, but rather view both as being co-evolutionary, here on we consider the relationship this way around simply to align with previous studies both in economics and biology.

The Pre-1970 regime

If $b = 1$ then *GWP* and *PEU* covary linearly and hence *AEE* is constant i.e. $PEU \propto GWP$. Given the significant scope for *AEE* to vary within the global economy in response to the myriad of factors affecting the pathway linking primary energy resources to rates of final useful work, this is a somewhat surprising observation for which we offer the following two possibilities. Growth in *GWP* could be exclusively demand limited at this time, hence being somewhat insensitive to energy supply restrictions. Under these circumstances the rate of increase in demand as determined by *GWP* growth sets the rate of increase of supply and hence *PEU* such that *AEE* appears somewhat constant as the system grows. Clearly significant amounts of energy were expended on capturing and distributing energy resources even in the 1950's and 60's, with De Sterke (2014) presenting data suggesting these were as high as ~40% of *PEU* at this time (Jarvis, 2018; Figure 1). We revisit this interpretation later when considering the overall development of *GWP*, *PEU* and *AEE* within the context of metabolic scaling theory.

An alternative although possibly related interpretation is offered by Jarvis (2018), who suggests that the efficiency of the pathway linking primary energy resources to final useful work is endogenously regulated in order to maintain the growth rate of the global economy at some nominal level. In this context we note that, before 1970, growth was the highest experienced over the last seven decades (Figure 2) and that the relationship between *PEU* and *GWP* growth shown in Figure 3 suggests *GWP* growth is close to a maximum relative to that for *PEU* at this time. This is re-enforced by the fact that growth rates above ~4.5 %/yr in either *PEU* or *GWP* tend to be associated with unstable inflationary regimes that do not persist. As a result we might conclude *GWP* growth is close to a maximum stable value. This line of evidence implies a system attempting to maximise *GWP* growth, which appears unsurprising given the prevalence of growth maximising objectives in the political and economic discourse post-Bretton Woods. What is perhaps surprising is that maximising *GWP* growth in this context is equivalent to maximising the flow of useful work into the creation of additional productive structure, and hence can be interpreted as a regime maximising the power output used in this structure creation.

The observed constancy of *AEE* supports the view that the power output into creating additional productive structure and hence *GWP* growth is being maximised. Rather than favouring increasing *AEE* as might initially be inferred from the relationship $GWP \propto AEE \times PEU$, in situations involving significant distributional losses like this, maximising some form of power output might favour a constant ratio of energy inputs to outputs and hence constant *AEE* (Odum and Pinkerton, 1955), particularly if mass flows are conserved in the system. In this situation raising *AEE* may actually reduce power output because the associated increasing mass flows in distribution networks can disproportionately increase dissipative energy losses. Here the maximum in power output is a trade off between increasing energy flows to points of final use set against the increasing dissipative losses of these flows (Odum and Pinkerton, 1955).

The constancy of *AEE* in this setting does not mean all elements of the efficiency pathway remain static. Growth increases mean path length of the distribution networks in the global economy, and hence the efficiency of this element necessarily falls even when network links are themselves optimised (Jarvis et al., 2015). This is one important explanation why economies invariably experience declining returns to scale, with ever bigger distribution networks consuming ever increasing proportions of primary energy inputs. If distribution efficiencies necessarily decline as the economy expands, maintaining constant *AEE* has to be the product of continual innovation on the usefulness of the primary energy portfolio itself, and the energy efficiency of the creation of new productive structure (Jarvis 2018), with the gains to be achieved through raising power output relative to input likely driving these dynamic adjustments to *AEE*.

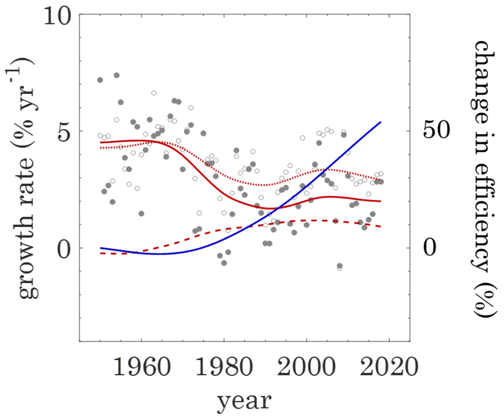

Figure 2. Annual time series and trends of the relative growth rates of *PEU* (●; —), *GWP* (○; ┈). Also shown is the trend in relative growth in *AEE* derived from the trends in *PEU* and GDP growth (- - -), along with the associated trend in the cumulative relative change in *AEE* (—).

The Post-1970 regime

Figures 2 & 3 suggest the the post-1970 regime was defined by two features. Firstly, growth in both *GWP* and *PEU* fell significantly (Figure 2). Secondly, the growth rate of *PEU* decreased more than the growth rate of *GWP* because growth in *AEE* increased from near zero in the 1950s and 60s to ~1 % yr^{-1} thereafter (Figure 2). If $b=\bar{r}_{PEU}/\bar{r}_{GWP}$, then a faster decline in *PEU* growth relative to that of *GWP* suggests some form of nonlinear behaviour in the relationship between the two. This nonlinearity, shown in Figure 3, is concaved, indicating that, across the dynamic range of growth rates experienced between 1950 - 2018, *PEU* tends on average to accelerate/decelerate faster than *GWP*. As a result, when growth fell in the 1970's, *PEU* growth fell faster than that for *GWP* and, more specifically, on average *PEU* decelerated at close to twice the rate of *GWP*.

One key observation from Figure 3 is that the nonlinearity in the relationship between *PEU* and *GWP* growth indicates a possible maximum in *AEE* growth relative to that for *GWP*. At this maximum in *AEE* growth the decoupling between *PEU* and *GWP* growth is locally maximised. So if the pre-1970 regime can be interpreted as one attempting to maximise the stable growth rate of *GWP*, the post-1970 state might be interpreted as one attempting to maximise the stable growth rate of *GWP* whilst simultaneously attempting to minimise the growth rate of *PEU*. Later we explore this behaviour in the context of metabolic scaling theory.

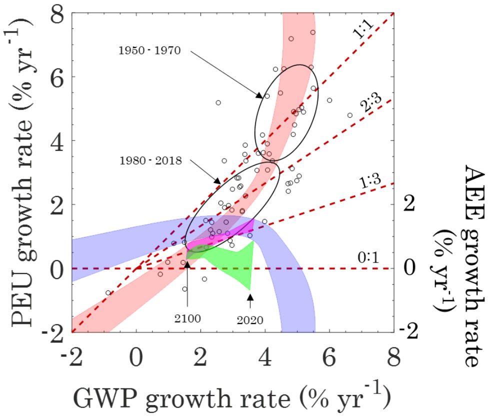

Figure 3. The relationship between the relative growth rates of *PEU*, *AEE* and *GWP*, 1950 – 2018 (o). Each ellipse is a one standard deviation covariation envelope for the identified time period. The two nonlinear models are i. (left axis) a three node cubic spline fitted to the *PEU* v GDP growth data (🟥; 95% confidence interval) ii. (right axis) the variations in *AEE* with *GWP* associated with the model in i (🟦; 95% confidence interval). Also shown is the ensemble of 2020 – 2100 pathways for the SSP2-BAU (🟪) and <2 °C (🟩) scenarios corresponding to Figure 1. Dashed lines are candidate scaling relationships for *PEU* v *GWP*.

The emergence of significant levels of *AEE* improvements and the resultant relative decoupling of *GWP* growth from *PEU* growth is an obvious response to the supply restrictions imposed by the energy crises in the 1970's, and we note the transition to this behaviour took approximately a decade to realise (Figure 2). However, we also observe that having transitioned to this region of the *AEE*-*PEU*-*GWP* phase space in the 1970's, the global economy appears to have remained in this b~2/3 regime ever since (Figure 1 & 3), suggesting that the effects of energy supply restrictions on the economy persist to this day.

Figure 3 shows that the observed maximum in *AEE* growth is relatively broad and hence the well of attraction about this optimum is shallow and somewhat poorly defined, making it difficult to 'find'. As a result, it would take something like a large disruption in the energy supply to provide the information on the potential gains associated with the relative decoupling between *PEU* and *GWP* growth that increasing *AEE* afforded. Prior to this disturbance, the effects of supply restrictions may well have been building, but the system had little or no information on the need or ability to address them. This explains why the transition between regimes was relatively rapid and distinct following the disturbance in supply, as opposed to being progressive.

To try and understand why there is a maximum in *AEE* growth relative to *GWP* growth we make the following observations. Firstly, raising the efficiency of a system requires increasing its structural complexity (Ruzzenenti & Basosi, 2008). This process is necessarily recursive given the need to build on existing structure, allied to the difficulty of identifying more productive, lower probability structural configurations. As a result, attempting to evolve productive structures too rapidly might lock out possible higher efficiency configurations, hence reducing long-term *AEE* growth through the contraction of the portfolio of available options going forward. We can articulate this shrinking opportunity for *AEE* improvements as the economy grows by recognising that $AEE \propto GWP^{(1-b)}$ which, for $0 < b < 1$ regimes, means that increases in *AEE* become progressively harder to realise as the economy gets bigger. Furthermore, changing the structure of the economy too rapidly leads to prematurely retiring productive capital, with a concomitant loss of expected returns. Both of these processes explain why *AEE* growth decreases as *GWP* growth increases above ~3 %/yr (Figure 3). Secondly, changes in *AEE* fundamentally rely on investment in innovation, and increasing *GWP* growth would be associated with increasing levels of available resource to invest in *AEE* improvement. This explains why, below *GWP* growth of ~3 %/yr, *AEE* and *GWP* growth increase together (Figure 3). We suggest the maximum growth rate of *AEE* is determined by the optimal trade off between these three processes.

The Pre and Post 1970 Regimes

Although we observe two distinct regimes pre and post 1970's, we also identify the following commonalities between the two from Figures 1-3 and our interpretation of these. i. The system organises in such a way as to attempt to maximise the flow of useful energy into stable growth. ii. The supply of energy to this growth process materially affects how the system evolves. iii. The transition between the two regimes is not progressive but discrete. iv. The scaling between *PEU* and *GWP*, i.e. $PEU \propto GWP^{b}$, does not increase, but rather decreases from $b \sim 1$ to $b < 1$ as the economy increases in size and complexity.

The lack of any obvious agent overseeing global systemic development along maximising trajectories leads us to assume this behaviour is the product of self-organisation and analogues for it exist in biological systems. Building on Banavar et al., (2010), Dalgaard and Strulik (2011) point out that the power output of an economy, as might be valued through output measures such as *GWP*, parallels cell-level metabolism, whereas primary energy inputs reflect the organism level metabolism. Here the difference between the inputs and outputs of energy principally reflect the effects of size-related distribution losses (Dalgaard and Strulik, 2011). If *GWP* does in some way reflect the final useful energy dissipation of so called 'terminal units' or 'control volumes' in the economy (Banavar et al., 2010; Dalgaard and Strulik, 2011), and the mass density of these volumes is conserved, *GWP* will also closely track the size and mass of the global economy. In contrast, *PEU* describes the overall metabolism of the economy, including all losses resulting from inefficiency. From this we might view the scaling relationship between *PEU* and *GWP* as mirroring that between metabolism and body mass that has been extensively studied in biological systems, with *PEU* mirroring metabolism and *GWP* mass and hence size (Brown et al., 2011). Indeed, body mass should more appropriately be viewed as a proxy for the rate of final useful work in these allometric scaling studies.

DeLong et al., (2010) show that metabolic scaling between mass and metabolism transitions from superlinear, through linear, to sublinear as the size and organisational complexity of the organism increases from prokaryotes to metazoans. The same is observed for individuals through their growth cycle. For example, fish embryos increase metabolism faster than mass whereas the opposite is the case for adults (Mueller et al, 2011; Clarke and Johnston, 1999) and tree saplings increase metabolism in proportion to mass, whereas for mature trees mass grows faster than metabolism (Mori et al., 2010). The reason for these observations appears to be that in immature organisms energy supply and demand are in relatively close proximity (Mori et al., 2010) and hence distributional losses are small comparatively. Whether the global economy in 1950's and 60's can be characterised in this way is questionable because distributional losses appear significant at this time (Jarvis 2018) as did the scale and development of the energy supply networks. This raises the spectre that the power maximising interpretation of the $b = 1$ and $b < 1$ regimes offered above proved an alternative and yet complementary interpretation of observed allometric scaling relationships in both biological and economic systems. That the post-1970 regime yields $b \sim 2/3$ scaling is intriguing in this context given it is also consistent with both geometric scaling in a 3d volume and optimal resource distribution on a 2d surface (Brown & West, 2000).

The analyses of both Fouquet (2014) and O'Connor and Cleveland (2014) (neglecting traditional biomass use) indicates that, over last 200 years, the energy intensity of Gross Domestic Product (GDP) of both the UK and US economies initially increases before later decreasing. If, as we have argued, energy intensity is inversely related to *AEE*, then such behaviour can again be associated with the transition from $b > 1$ to $b < 1$. Furthermore, the stock-flow consistent economic model of King (2020) exhibits this same rise and fall of energy intensity during the long-run development of the economy, even though no explicit account of distributional losses is taken into account in this framework. This suggests multiple yet complementary reasons behind the transition in scaling from $b > 1$ to $b < 1$ with a common theme being the dynamic balance between resource supply and demand during the ontogenic development of both organisms and economies.

The analysis of DeLong et al. (2010) also suggest that the transition from $b > 1$ to $b < 1$ does not change continuously in populations as a function of size, but rather there are three distinct classes of cellular complexity and organization each associated with $b > 1$, $b \sim 1$ and $b < 1$ regimes. For the economy we propose these regimes are discrete because they reflect different optimisation criteria, each the product of the evolving physical constraints associated with internal distribution losses as a system grows. This parallels the thinking of Galor (2011) who speculates the long run evolution of the economy is determined by the emergence and disappearance of discrete wells of attraction. We might observe these emergent states as a tendency for societies to follow persistent set practices (Shove et al., 2012), even when view of the physical boundary conditions would suggest alternative practices as being more appropriate. It is this over-reaching of a regime that would result in a rapid transition like that seen in the 1970's.

Possible Future Regimes

Here we contrast the behaviour of Integrated Assessment Models (IAMs) used to inform emissions reduction policy with that observed in Figures 1-3 to reflect on the nature of the proposed future energy transition designed to meet the terms of the Paris Agreement. These models invariably assign a significant role for enhanced energy efficiency improvements in the emissions reduction strategies they specify.

Figure 1 and 3 also show the Shared Socio Economic Pathway (SSP)2 Business As Usual (BAU) and < 2 ºC scenario ensembles, the latter being designed to keep warming below 2 ºC if economic trends were to otherwise continue (Riahi et al., 2017). From the SSP2-< 2 ºC scenario we see that, in the coming decade, the present day ~2 % yr^{-1} growth in *PEU* is near fully substituted by the introduction of an additional ~2 % yr^{-1} of enhanced *AEE* growth, such that *GWP* growth becomes near fully decoupled from *PEU* growth, hence temporarily halting the growth in emissions tied to *PEU*.

The transition in the global economy that occurred in the 1970's demonstrates that rapid systemic change is indeed possible. However, the SSP2 < 2 ºC scenario suggests the current constraints on *AEE* growth can be alleviated at will, which relies on the ability of the current economic actors to identify and implement improvements in *AEE* nearly three times faster than currently appears possible. In relation to the constraints on AEE growth discussed previously, it is not surprising that artificial intelligence is being proposed as an important component of realising the associated *AEE* improvements (Grübler et al., 2018) given it is possible that machines could, in the near future, identify more efficient economic configurations faster than their human counterparts. However, although the active decommissioning of carbon intensive capital assets is often discussed within the context of removing less efficient structures from the economy and replacing them with more efficient ones (Grübler et al., 2018), it is also strongly associated with stranded assets and the curtailing of returns on investment (Mercure et al., 2018).

Following the rapid introduction of this enhanced growth in *AEE*, the global economy is modelled to converge on both the historic and BAU relationship between *PEU* and *GWP* growth, albeit at radically lower levels of overall growth of near 0.5 and 1.5 % yr^{-1} respectively (Figure 3). One would imagine that, thermodynamic restrictions aside (see below), having learnt how to further decouple *GWP* growth from *PEU* growth, this behaviour would tend to persist as it did post 1970's, leading to a radically different economy in 2100 from the current one.

The SSP2 BAU scenario ensemble illustrates the forecast decrease in *GWP* growth through the 21st century that underpins the SSP's, a product of perceived emerging secular stagnation in, and convergence between, national economies (Dellink et al., 2017). This provides a significant tailwind to the SSP mitigation scenarios. From Figure 3 we see this decline in *GWP* growth is associated with proportional declines in *PEU* growth such that the system is predicted to evolve along a b~1/3 scaling pathway i.e. one that is not an extrapolation of the current, post-1970 trend. So even this BAU scenario would represent a significant transition in the global economy from a $b \sim 2/3$ to a $b \sim 1/3$ regime, where the *AEE* growth rate nearly doubles to 2 %/yr in the 2020's (Figure 3). This suggests the <2 ºC scenario significantly underestimates the effort required to realise its climate objectives through *AEE* improvements given the baseline against which it was designed itself represents represents a future economy that has already transitioned in a novel direction favourable to meeting these objectives.

Both the BAU scenario and its low carbon counterpart suggests a system ultimately evolving toward zero growth in *GWP*, *PEU* and *AEE* (Figure 3). Even though these scenarios were not explicitly constrained by physics, a zero growth state is equivalent to the global economy evolving toward and becoming constrained by thermodynamic limits on *AEE* in addition to and in association with material limits on extracting primary energy resources, with the SSP scenarios hinting the effects of this limit become material this century. An assumed decline in total factor productivity growth in an economic model is akin to declining growth in *AEE* (Ayres and Warr, 2005; Warr and Ayres, 2010). Thus, both orthodox and thermodynamic interpretations of the economy are consistent in asserting economic growth becomes further constrained by declines in *AEE* growth opportunities, despite offering apparently very different reasons for this. The difference between these two interpretations of the economy is that the orthodox (i.e. neoclassical) approach embedded in most IAMs ignores any thermodynamic limit on *AEE*. Furthermore, if it were possible to enhance the short term growth in *AEE*, this should feedback to accelerate the approach toward this limit.

Interestingly, the observed relationship between *PEU* and *GWP* growth in Figure 3 suggests transient absolute decoupling between the two is possible given, on extrapolation, ~1 % yr^{-1} growth in *GWP* appears associated with *AEE* growth alone. However, as with *GWP* growth above 4.5 %/yr, this low growth region of the phase space is characterised by highly unstable recessionary growth dynamics such as in 2009, and so is again is unlikely to be representative of stable growth regimes.

In the absence of knowing where the thermodynamic limits are, we note that *AEE* has increased by ~50 % since the 1970's and that its growth rate may have peaked around the year 2000 (Figure 2). The SSP2-BAU scenario ensemble predicts a further 130 to 190 % increase in energy efficiency from 2020 to 2100, whilst the SSP2-<2 ºC scenario ensemble requires an increase of 205 to 270 % over this interval. Such increases imply present-day *AEE* would have to be significantly less than 0.5 and 0.3 respectively to be physically tenable given $0 < AEE < 1$. Although current estimates of the components of *AEE* suggest significant headroom is available for future increases (Ayres and Warr 2005; Jarvis, 2018), as do the available portfolio of energy saving technologies (Grubler et al., 2018), it is important to again emphasise high growth rates in *AEE* simply act to accelerate the system toward this boundary. In addition, $AEE \propto GWP^{(1-b)}$; $b < 1$; again implies any future more complex configurations of the economy must be selected from a reduced portfolio of possibilities.

CONCLUSIONS

Overall, we interpret the pathway of the global economy through Figures 1 and 3 as follows. The relationship between *PEU* and *GWP* is always convexed and we have attempted to demonstrate this reflects similar patterns of behaviour in biological systems. However, this economic progression is not continuous, but rather occurs in regimes. We elucidate two observed regimes, with the 1950's to 1970's characterised by attempts to maximise output growth, followed by the 1970's to present day characterised by attempts to maximise output growth whilst minimising input growth. Independent of any consideration of climate change, we anticipate at least one future regime focused on maximising *AEE* itself, with progress to this end marked by ever decreasing levels of growth as more productive structural configurations become ever rarer.

In the context of avoiding significant threats to the global economy like anthropogenic climate change, it is reassuring to know rapid and significant transitions in patterns of energy use like that experienced in the 1970's are possible, and it is important to acknowledge the role of large acute shocks when alerting us to the possibilities. Covid-19, or a run of globally significant climate disasters, could be examples of the kind of stimulus needed to tip the economy into a new regime, just as the oil crisis did in the 1970's. However, the maximising behaviours we see either side of the 1970's energy transition warn us that the underlying calculus of the economy may well be underpinned by thermodynamic constraints and hence prove difficult to shape beyond this. For example, the data and reasoning of this paper support a conclusion that future enhancements in energy efficiency intended for emissions reduction are at significant risk of being co-opted to support *GWP* growth. This tendency could well become amplified in the era of declining *GWP* growth and stagnation we appear to be entering, where the battle to restore growth might become ever more pressing. To help assess this risk, the efficiency improvement components of the NDC's should be evaluated against national growth targets relative to trend. Planning in the knowledge the opportunities for growth will inevitably dry up could help us start to embrace alternative economic objectives and prepare for the next transition.

ACKNOWLEDGEMENTS

We would like to thank Cormac Lynch for expert assistance with compiling the *GWP* and *PEU* data sets and Paul Brockway for helpful feedback on earlier drafts of this paper. AJ is also grateful of financial support from the UK Economic and Social Research Council (ESRC) via the Rebuilding Macroeconomics Network, and the UK Natural and Environmental Research Council (NERC) via the AMDEG project.

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