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Discussions

Interactive comment on "Energetic regimes of the global economy – past, present and future" *by* Andrew Jarvis and Carey King

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We thank Prof. Hall for his useful review of our manuscript. We draw the following questions from his review and respond to them accordingly.

1. This kind of analysis has been done for at least the last 40 years so what is new? (our words)

We agree many studies have looked at the macroscopic relationship between GDP and PEU, Cleveland et al., (1984) being a good example of this, although we also note that rarely is this done at the global scale, which alone differentiates our paper enough (in our view). We attempted to include the relevant recent reviews of this area (e.g. Stern, 2000; Kalimeris et al., 2014; Csereklyei et al., 2016) to clarify the long-standing

nature of this critically important issue. The manuscript stated this as a long-standing and heavily debated issue from the opening lines of the Introduction. That said, we accept that reference to some seminal primary literature like Cleveland et al., (1984) should (and will) be included. However, despite this being a somewhat crowded space, we believe our work provides substantial new contributions to that debate. We show for the first time that a global scale meta-analysis of all credible GWP and PEU data indicate that observed PEU and GWP growth rates either side of the 1970's structural reorganisation scale as 1:1 (before 1970) and 2:3 (after 1970). This will be the first ever paper to point out that these scaling ratios, and the underlying efficiency dynamics they point to, can be accounted for by maximum power evolutionary trajectories, and that these states can be linked to metabolic scaling theory. Furthermore, Figure 3 is the first time global GWP and PEU data has been viewed through the relative growth rate phase space, and we show it is this space that both reveals the efficiency optimisation behaviour and properly highlights the inconsistencies in the speculated role of energy efficiency improvements in current IPCC scenarios.

2. That the PEU and GWP measure could be misleading. (our words)

PEU - In terms of energy quality, our statement in the manuscript is "the four global PEU series were linearly scaled to the International Energy Agency (IEA) data." In essence this means that we have scaled our energy data to the 'physical content method' that is used by the IEA. In this method, 1 kWh of hydro, PV, and wind are equated to 3.6 MJ of primary energy, which is the exact engineering conversion. The IEA assumes nuclear has a 33% conversion efficiency, such that 1 kWh of nuclear electricity translates to 10.8 MJ of primary energy (as heat). So nuclear electricity is not treated the same as hydro, PV, and wind electricity but rather has 3 fold higher primary energy quantity per kWh. So in this sense, we have accounted for quality of primary energy, but perhaps not in the way Prof. Hall is suggesting. This is because, like Kaufmann (2004), we see changes in the quality of the primary energy portfolio as being something the global economy innovates on and hence as necessarily being part of AEE

adjustments (Jarvis, 2018; King 2020). We believe that do date, either primary energy accounting convention produces practically the same relative growth rates (the focus of our manuscript) of PEU and GWP.

GWP - Table 1 shows we use 8 GWP series, all in constant dollar value and a mixture of both PPP and MER. We completely agree these data could be measuring things in addition to something proportional to useful work and leave the analysis open to that possibility (L91-94). In addition to the nonstationarity in the inflation adjustment Prof. Hall rightly articulates, these GDP measures also include an ever increasing valuation of financial services, especially post-1980, along with the cessation of fixed exchange rates and the convertability of the US dollar to gold with the end of the Bretton Woods era in 1971. So yes, the additional $\sim$1 %/yr growth in GWP over and above PEU post-1980 could be an artefact. Although like Prof. Hall we originally thought this to be the case, we now believe it to be real for four reasons. Firstly, as far as we are aware the inflation correction schemes used for GDP measures does not change suddenly in the 1970's, but rather any evolution in what is being valued, and how, is progressive. In contrast, the scaling relationship between PEU and GWP demonstrates a statistically unequivocal 'break' between the pre and post 1970 regimes. Secondly, the additional $\sim$1 %/yr growth we observe coincides with a maximum in the decoupling of GWP and PEU growth (see Figure 3). Thirdly, expanding biological systems appear to show the same behaviour as a necessary response to the dynamic evolution of the boundary conditions and the need to distribute resources within an increasingly large space. Fourthly, it is not unreasonable to assume that if GDP was measuring something useless this would be experienced over time and the scheme would be adjusted accordingly. The revised manuscript would certainly benefit from a fuller discussion of this important issue.

3. That Kaufmann's work in this area needs properly recognising. (our words)

We thank Prof. Hall for drawing our attention to Kaufmann's important contributions to this area and we will reference them where relevant. His and our work shares a

common theme of wanting to interpret observed changes in AEE using biophysics. However, there are important differences in our work. Kaufmann (1992) and (2004) focus on national economies and explaining changes in absolute values of GDP/PEU. In contrast, we look globally at the relative growth rates of GWP and PEU. This leads us to very different conclusions, with Kaufmann focusing on the role of changes in energy quality of PEU, whereas we focus on the role of maximising power flow and its relationship to size-dependent constraints on growth.

We also note in response to question 2 that Kaufman (1992 and 2004) does not consider in any way differences in the definition of GDP as part of an explanation for declining energy intensity (energy/GDP).

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