Response to Peter Haff

We place the reviewer comments in bold font and our response in normal font.

The arguments of this paper represent a conceptual break with standard views of the role of energy in modern society. As such, its claims are likely to be controversial. However, if the thesis of this paper holds up, it would stand as a significant advance in our understanding of the limits to human control of energy consumption by the global human-technology system (abbreviated in this review as the "world system"). In their explanations in the paper, and in author commentary on this site responding to reports of other reviewers, the authors' have defended their methods and conclusions to my satisfaction. I recommend publication of the paper following the authors' response to specific points and recommendations made at the end of this report.

We sincerely appreciate the supportive remarks.

The authors' conclusions, based on their analysis of economic time series, imply that global energy consumption cannot be manipulated at will, at least not without radical disturbance of the modern world system. This should not be unexpected since energy is not like other commodities, but plays a special role in any dynamic system. Thus, for the world system, the energy slice of the economic pie, perhaps totaling to 10%, is unique, in that it pervades and powers every other sector. Removing half of a 10% energy sector would not be a 5% overall economic effect, but more like a 50% effect, or larger, somewhat like the consequence for a person of the removal of one half of their rather small volume of blood. The authors report the counterintuitive result that the current rate of energy consumption by the world system is proportional to world economic production ("GDP") summed over all past years. This implies that current energy consumption is driven not just by recent economic activity, where human influence on energy use is most obvious, but also by activity performed in the distant past, whose consequences remain with us today.

We agree with the reviewer's summary of the article.

One obvious criticism of this claim of historical determinism is the observation that physical devices and systems of long past years that no longer function, or that no longer even exist, cannot continue to consume energy today and thus cannot contribute to current energy use. The authors' explanation of the enduring influence of past production on current energy consumption is that individual system components existing today, together with their potential energy demands, are generated not just through recent production but also in consequence of many years of prior production. This seems to me a reasonable argument. Thus, the magnitude of current energy use (i.e., the system's metabolic rate) depends on the total value of production achieved along the specific trajectory of the system's historical development, because that production necessarily generated incremental additions to past metabolic base rate that made possible the existence and performance of those populations, cultures, plans, patterns of organization, tools, inventions, wars, and other factors that did in fact elevate consumption over time to the level seen today. That is, construction of the system, a result of chronic non-zero GDP, represents more than accretion and organization of material into a complex growing edifice, but also requires a continuous and dedicated flow of energy to support what has been created. Thus, a suitable and growing metabolic base rate E has to be maintained at all times in the system's history. In the simplest model the background energy demand that sustains this construct—the world system–would simply be proportional to the total production. Although old material construction disappears with time and technology becomes more efficient, complexity and size of the system continue to increase, suggesting that energy demand of these latter factors outweigh what is lost through decay and increased efficiency of specific devices and systems.

The wording employed here is superb. We hope to include a modified form of the phrasing in a revised manuscript.

Another general critique that might be raised is that the authors emphasize physical principles in their analysis of large-scale societal energy-use rather than turning to more standard tools of economics. However, an approach informed by physical requirements that are applicable to any dynamic system may be more suitable for broad, global analyses where smaller-scale details fade away, than methods based on economic assumptions and models calibrated to influences of national or local markets and to cultural behaviors. Thus, for example, the law of energy conservation, the 2nd law of thermodynamics and the requirements of dimensional consistency in equations and variables reveal their utility when applied at global scale. Models that employ non-scalable relations or manipulate quantities that cannot be clearly connected to basic physical variables may be useful tools for specific applications where careful calibration is possible, but these approaches will generally be less useful for questions that require extrapolation outside the restricted problem-space for which they were designed.

We agree. It works both ways. The simplicity of the approach presented here makes it less well adapted, at least a priori, for studies of economic sectors or nations. The reverse is also likely to be true, that traditional economic models are less able to address world-scale economic behaviors that are constrained by such key issues as resource availability.

The conclusions of the paper, if they stand up to future criticism, have substantial implications for future human well-being. They point to a fundamental challenge facing efforts to manage world energy consumption. The proportionality of current energy use to total past production suggests the difficulty of redesigning a system when the past holds sway, a point illustrated in microcosm by the expense, disruption and political resistance that often accompanies attempts to renew or replace urban infrastructure in long established cities. Change, by contrast, can be much easier to effect when it occurs as growth, i.e., a positive GDP—in the above example perhaps outward expansion of the city—rather than as a reconstruction of legacy systems which, through lack of access to other sources of energy, are forced to disrupt and cannibalize the extant metabolic energy flows that sustain their existence.

Two main points I take away from the paper are: 1. That the influence of the past infuses an intrinsic conservatism into the dynamics of the world system, according to which it tends to resist change; and 2. In such a physically enforced conservative environment, significant change and the production of novelty are made possible only by injecting energy into the world system faster than it is dissipated by its underlying metabolic processes, i.e., by increasing the rate of world energy consumption and in the process adding to total past consumption.

This is well worded.

Title: I would change the title of the paper to something more compelling. Many in the ESD community who might be interested in its arguments may pass over what may appear as a discussion of the minutiae of economic production. For example: "Lotka's wheel and the long arm of history: how old technology and forgotten ideas determine the value of today's global rate of energy consumption", or, perhaps: " 'The past isn't dead. It's not even past': how old technology...". (Faulkner).

These are excellent suggestions. We adopted the following modified version of the first one: "Lotka's Wheel and the long arm of history: how does the distant past determine today's global rate of energy consumption?".

I might also suggest adding a sentence or two emphasizing (as per the urban infrastructure example above) that change and novelty ride on the back of dE/dt, not E, the latter of which supports business as usual.

We have added the text: *that is the innovation of something newly consumptive over and beyond the business-as-usual scenario that would have energy consumption rates stay constant.*

Line 30: "wit units". There are a few typos in the text. These should be removed using a fine tooth comb; they indicate momentary lapses of attention, a condition which leads to doubts in readers' minds about bigger issues

We have carefully reviewed the text.

Line 31: The paper states that it focuses only on global quantities, but use of "Gross Domestic Product" or "GDP" with no qualifier may cause confusion. Perhaps settle on uniform use of "Gross World Product" or "global Gross Domestic Product" instead?

We have added the qualifier "world" in several places prior to GDP. GWP turns out to have its own problems due to the potential confusion with Global Warming Potential.

Line 57: Clarify explanation of why the relation between W and E is not simply one of correlation.

The text has now been rewritten to better explain the intended points.

The relationship between W and E does not appear to be one only of correlation between two quantities, as for example has been noted for E and Y (Jarvis, 2018). Instead the two quantities have maintained a linear scaling over the half century period for which widely published data are available. A least-squares fit to the logarithms of W and E yields the relationship $W = 5.47E^{1.00}$ Calculated instead as a linear fit, the relevant expression is $W = 5.67E - 66$. Note the intercept of the fit where $E = 0$ is equivalent to $W = -66$ trillion 2019 USD. This value is just -1.9% of the 2019 value for W_i of 3547 trillion 2019 USD, and so sufficiently small as to plausibly approximate the origin. By contrast, the linear fit for world GDP and energy is $Y = 0.17E - 21$. So, while Y and E are correlated, they do not scale since the intercept corresponding with zero energy demands is $Y = -21$ trillion 2019 USD, or -25% of the 2019 value.

Line 73: "non-integer exponent of E". Perhaps expand discussion here slightly to illustrate the problem of scaling with variables or exponents that have been determined simply by familiarity and/or calibration rather than by relation to actual physical process. This can also help emphasize the value, where it is appropriate, of a physical framework in place of traditional, non-physical models. In general this paper is a good venue to expand the argument for treating (some) economic problems in a framework that manifestly respects, or at least does not contradict, physical law.

The text has been revised to read

Expressing economic production as related to a change in energy demands, that is its derivative with respect to time, differs significantly from prior approaches. These most usually employ production functions that ignore the role of energy altogether. In the few studies where production functions do appeal to energetic demands, the functional dependence is to some non-unity exponent of E (Ayres et al., 2003; Keen et al., 2019), which physically and dimensionally is nonsensical. While it is certainly possible to obtain through fitting a non-unity exponent relating two quantities, it cannot be presumed the fit expresses something fundamental about the system unless the appropriate units for physical quantities are maintained.

Line 127: "provided the system is in its phase of growth". This caveat may not be needed. Thus, using a biological example, mature organisms whose growth has stopped nonetheless still consume energy at a steady rate, E, determined by their size (total production), but their "GDP" is zero. For such systems where E is nominally a constant (no growth), minor wear and tear might be fixable by the system, but accumulating insults to functionality with age, or more catastrophic impacts which the system is ill equipped to combat using already spoken for metabolic energy supplies, may eventually make it impossible for the system to survive (maintain its metabolic rate) in the absence of access to increased sources of external energy. The constraint of a constant metabolic rate makes organismal longevity a challenge, and in the end a losing battle (as in the case of an organism). The results of the present paper suggest that a continuing increase in energy consumption is a necessary condition for the long term survival of world civilization. Of course it is not a sufficient condition. A state of chronic acceleration cannot last forever and limiting effects that are outside the scope of this paper will eventually have their impact.

Point taken. The text has been reworded slightly to read:

But, in all cases past consumption is a primary determinant of the system's current energetic demands.

Finally, the other reviewers raise interesting points that together with the responses of the author help to clarify the arguments of the present paper. I believe the authors can further improve their paper by incorporating into it some portion of their written responses to these reviewer/commenter suggestions. I hope my own review is similarly serviceable, and that, after manuscript revision, which I believe does not need to involve a major rewrite, ESD will proceed to publication of the manuscript.

Our sincere appreciation for a thoughtful review.

References

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