We thank Reviewers 1 and 2 for constructive comments and the effort put into reviewing the paper.

Response to Reviewer 1

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

(1). I object to arbitrarily introducing a new production function (equation 3) without serious discussion. The discussion in the text, based on curves in Figure 1 is not nearly sufficient to justify equation 3. The standard Cobb-Douglas production function was introduced in 1928 for a good reason and the other production functions economists have introduced and tested since 1928, have histories also. I am not defending any of them, but the reasoning behind equation 3 cannot simply be based on the data represented by the curves in Figure 1.

We agree that Equation 3 is not a production function in the same sense as e.g. the Cobb-Douglas or Leontieff production functions, namely a function that calculates the output of economic production Y on the basis of inputs, or factors of production, typically capital K and labour L. As mentioned in the first paragraph, such "production functions" (deliberately put in quotation marks on line 16), grossly underestimate the role of energy in production by treating the energy sector as just one of many other sectors in the economy. By contrast, we are interested in the direct relationship between primary energy consumption and economic output, without going through the route of a production function in the economic sense. For this reason, we termed Equation 3 an "inflation-adjusted production relation" on line 67 (immediately before Equation 3), but regrettably used the term "production function" on line 72 (immediately after Equation 3). This reference is now removed.

Having said that, the result expressed in Equation 3 is a direct consequence of the 50 years of data in Figure 1 supporting a nearly fixed relationship between historically cumulative GDP and current energy consumption as given by $W(t) = \int_0^t Y(t')dt' = wE(t)$. Namely, we first *define* W as the integral of production Y in Equation 1 and then *observe* in Equation 2 that this quantity is related to energy E through a nearly constant ratio w over a period during which the GDP increased by a factor of 4.5. Equation 3 then follows purely mathematically from Equations 1 and 2 (namely by taking derivatives and assuming that w is constant), that is, $Y(t) = wdE/dt$. Equation 4 then further validates this relation by estimating w as the ratio between Y and dE/dt, with a value similar to the one found in Equation 2.

The physical arguments supporting why might the relationship hold are as described by Lotka (1922) in the introduction and elaborated upon in the discussion. It is not clear from the comment why empirical evidence and physical reasoning is considered "arbitrary" as the basis for establishing a link between economic production and growth in energy consumption.

(2). In another place, the authors note that the usual relationship for capital growth is [dK/dt = Y-C minus delta (capital depreciation)], where delta (the depreciation rate) is constant and C = cY where c also is assumed to be a constant. The last assumption is wrong. The ratio c = C/Y (the fraction consumed) may leave a significant surplus for capital investment now (and for the past 50 years) but 200+ years ago c was practically unity while the depreciation rate was smaller than it is now – the surplus for investment or saving back then was virtually zero, and what surplus there was came from coal mines. In other words, until very recently almost everybody needed every bit of their income to buy consumables, mainly food and fuel (for light and heat). So, in the long run c is not a constant; it can (and will) decrease. Neither is the depreciation rate constant, by the way. Most people will spend their time playing computer games.

Nowhere in the article is it stated as the reviewer claims that depreciation or the ratio of consumption to production c is constant. See lines 100 to 105 which in fact point to the opposite. Average rates are provided, but this is stated by acknowledging that the instantaneous rates have changed during the period under consideration. The point being made is that whatever new that is produced is either consumed or depreciates at a rate that appears too rapid to allow for societal contributions from the more distant past.

Also (3) the curve shown for capital stock K in Figure 1 is presumably based on prior work by Garrett but – being central for the rest of the argument – the underlying data also needs explanation and justification, especially since Garret's earlier work in this field has not been widely accepted. (That is not a criticism). The underlying capital stock K data for Figure 1 should be published.

The underlying capital stock data are from the Penn World Tables and are referenced, as are all other quantities. See the Appendix for methods.

Response to Reviewer 2

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. Also, we have slightly modified the beginning of the Results section to read "To avoid complications associated with the details of trade, or interactions between economic sectors, this study is focused only on global quantities as described in the Materials and Methods below."

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 have adjusted the conlusions to include the statement "The result suggests that humanity has metabolic needs that are independent of the economy as is typically quantified financially by the current GDP. "

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: *The result suggests that humanity's current metabolic needs are independent of the current economy as typically quantified financially by the GDP. Instead, cumulative production is better considered as an emergent property of a system that boot-straps itself to its current state through past technological creation that allows more to be produced with less Haff (2014); Garrett et al. (2020).*

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.

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