Response to Professor Herrmann-Pillath

We thank Professor Herrmann-Pillath for the time reading the manuscript and the thought put into the review. Our response is outlined below.

GDP is often defined as a measure of production, but that is misleading, as is well known. 'Production' means 'economic value added', hence represents the classical distinction between productive and unproductive activity. If one compares this measure with energy consumption, this mixes entirely different categories, as energy consumption relates to material production (even making Bitcoins is 'material', in the sense of producing certain processes on computers). Material production as a category is much larger than GDP. For GDP, it is necessary to subtract all intermediary production because these are just costs that do not add value. But for considering energy throughput, of course all production matters. That means, I think that the appropriate measure would be gross production, but not GDP. This comes closer to modern approaches of Material Flow Analysis than GDP. Hence, I think the authors should switch to that measure. To avoid misunderstanding: Gross production or output (covered by Input-Output tables in national accounts) is not 'material' in the sense of MFA but is also measured in value terms. The point is that the notion of 'production', in my view, must include all productive activities, hence also intermediate stages, when exploring regularities in energy flows through the economy. Beyond that, there is much productive activity that is not covered by national accounts, well recognized for long, such as shadow economy and household production. Again, for considering material and energy flows one would need the full picture of economic activity.

We are aware of the distinction between gross production and the GDP or "value added". However, the article is not attempting to illustrate a relationship between gross production and energy flows, as seems to be suggested by the reviewer: "for considering energy throughput, of course all production matters.". Instead, the focus on "value added" is meant to avoid double-counting, rather than ignore intermediate steps. For example, if the primary cost of extracting wood from a forest to build a shed is $10,000 and this wood is then sold to Home Depot for $12,000, which then sells to my contractor for $15,000, who then charges $20,000 for the shed, the correct accounting for the final product is indeed $20,000, and *not* the sum of all transactions, namely $10,000 + $12,000 + $15,000 + $20,000 = $57,000, as this would be a tremendous overestimate of the original cost of extracting the wood, counted here 4 times. In other words, the "value added" by the timber company is $2,000 (which corresponds to other costs not necessarily the wood itself, such as machinery and labour), that of Home Depot is $3,000 (again, only taking into account previously unaccounted costs such as the staff in the store, etc), and the value added by the contractor is $5,000 (say his labour and equipment).

Thus, the argument being made is that the GDP – precisely as a measure of the addition to economic value – is tied to the *increase* in energy consumption, not to energy consumption itself. This was already stated in Section 3 of the article:

> *Eq. 3 expresses economic production as proportional to an increase in energy demands, that is its derivative with respect to time.*

Regarding the role of e.g. housework, this too is already discussed:

> *By way of explanation, consider the circulations within our bodies, brains, and machines, and our activities such as housework, transport to and from work and the grocery store, and even conversation among family and friends, that all of these require current energy consumption in some form. Each one of these may involve a financial transaction at some prior stage, for cleaning products, gasoline, or food, yet no financially quantifiable purchase is made at the point at which the energy is consumed.*

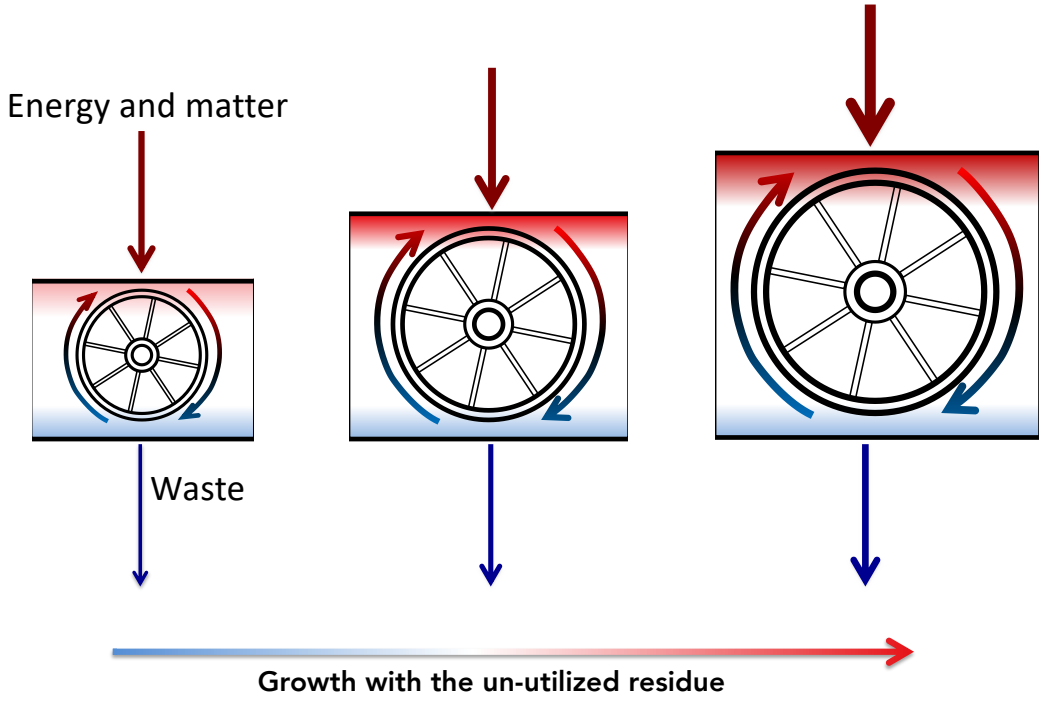

Figure 1. Representation of Lotka's view on the thermodynamic mechanisms governing system growth, involving a wheel that enlarges and accelerates using an "un-utilized residue" of energy and matter

Seeing the connection between past, current, and future consumption is critical. Civilization, as an open thermodynamic system, must consume and dissipate energy to sustain all its activities, insofar as they have developed from the past, whether or not they are tallied in yearly national accounts. Final production, or value added – otherwise termed the GDP – is argued here to depend on an imbalance, whereby consumption exceeds dissipation, allowing civilization to grow to consume more in the future as it becomes embedded in the structure of the network of civilization. The daily imbalance can be quite small, about 0.01% of daily consumption (Garrett et al. 2020), yet still lead to a doubling of thermodynamic demands in about 50 years. Thus, strictly, the inference from a fixed relationships between E and W is that there is a fixed relationship between the GDP and the rate of energy consumption *growth*.

We have attempted throughout the manuscript to further clarify this argument, including an additional quote from Lotka's paper in the introduction:

> *Lotka emphasized that "In every instance considered, natural selection will so operate as to increase the total mass of the organic system, to increase the rate of circulation of matter through the system, and to increase the total energy flux through the system,* so long as there is presented an un-utilized residue of matter and available energy.*" (our italics).*

This is accompanied by a new figure illustrating Lotka's point, Figure 1.

and a figure illustrating our point (Figure 2):

We have also written such statements as:

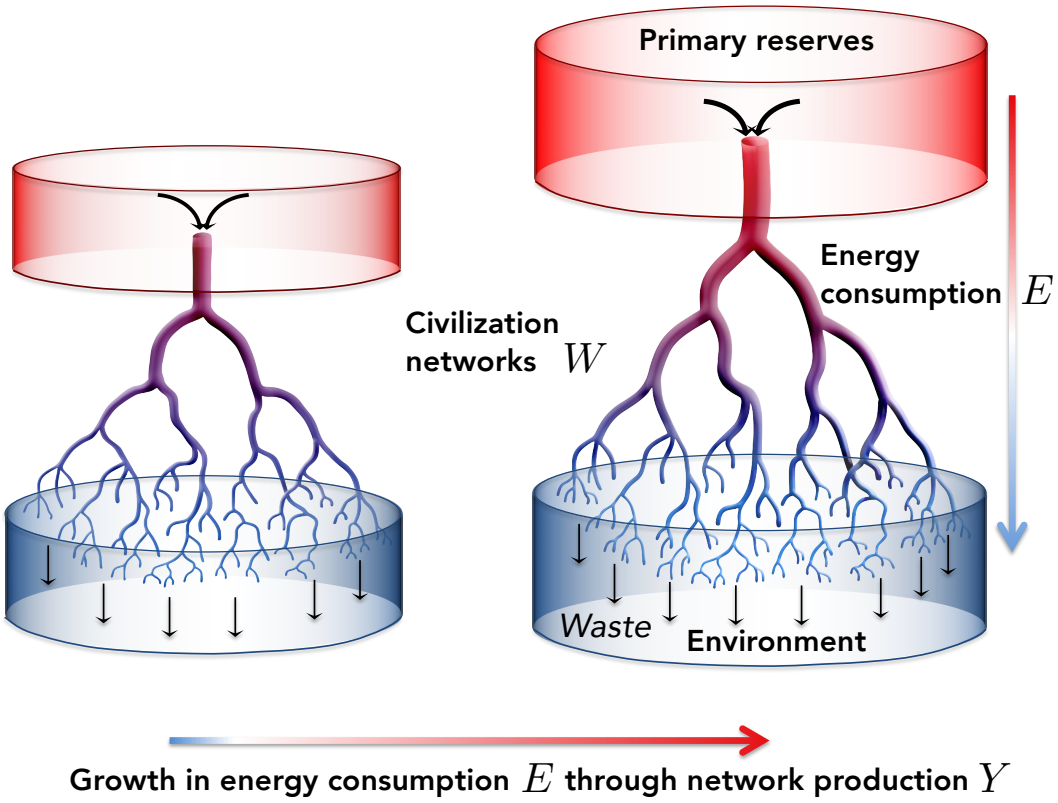

Figure 2. Elaboration on Lotka's Wheel. Civilization growth related to increases in its power at rate dE/dt as tied to network production through the inflation-adjusted GDP Y. Current power E is thus tied to the historically cumulative GDP through $W = \int_0^t Y\,(t)\,dt' = w\int_0^t (dE/dt)\,dt' = wE$

.

> *A consequence of the relationship is that inflation-adjusted economic production is more closely related to a surplus of energy – or the "un-utilized residue" using Lotkas's words – than the rate of energy consumption itself*
>
> *So, it is only with an excess or "un-utilized residue" of available energy that an effective phase change becomes possible whereby raw materials are converted through economic production into newly created civilization networks, and societal movements can be accelerated along them.*

The other problem is the cumulation of these values. This makes even less sense for GDP than for gross production. The justification forwarded by the authors simply does not apply for value added. If one uses GDP, the only reasonable approach would be capital formation, which could be conceived as 'embodied energy'. For gross production, one might possibly argue that this is somehow becoming embodied in many forms, as the authors try to explain for GDP. But that needs more detailed analysis.

If the GDP represents "value added" tallied over the (somewhat arbitrarily chosen) course of one year, we are simply using the mathematical property of addition to tally over all of history, making a key downward adjustment for inflation. The interpretation is effectively that the real GDP represents an addition to pre-existing societal networks. But, regardless of

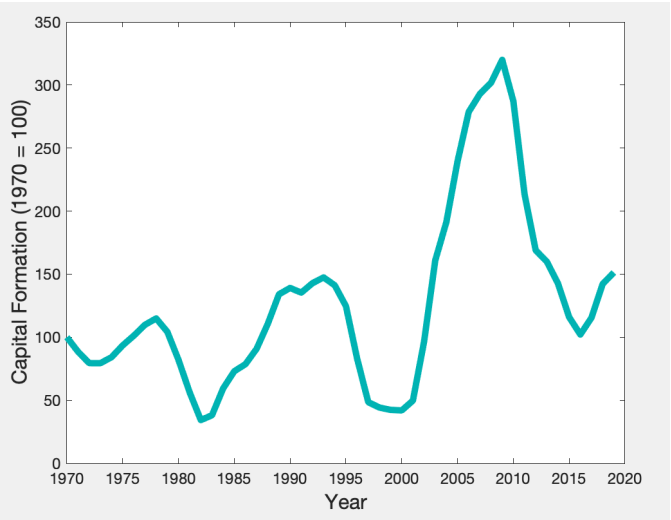

Figure 3. The ratio of capital formation values dK/dt to annual energy consumption, setting the ratio in 1970 to 100.

interpretation, or beliefs to the contrary, the data presented here should speak for itself. No criticism has been made by the reviewer (or any other reviewer) of how the analysis was done. As is clear from the figure here, there is no correspondence between energy consumption rates and capital formation as suggested by the reviewer (see Figure 3), only to the historically cumulative world inflation-adjusted GDP as already argued in the article.

We have included the following in the article:

> *A related quantity, the rate of capital formation, dK/dt, is not shown because it is implicit in the curve for K, however its value varied considerably. While it increased by a factor of 1.5 between 1970 and 2019, the relative increase was 3.2 in 2009 and 0.34 in 1982.*

That being said, the empirical regularity is worth noting. But I do not think that it can be directly extrapolated as long one uses GDP. I do not defend simplistic decoupling theories, yet it is true that 'value added' has no direct material interpretation but depends on how we measure consumption and production and what specifically is valued on the marketplace. For example, if people start to value playing the flute, they will spend money for buying one flute, perhaps even in their lifetime. Otherwise, they pay for a teacher who does not need any other equipment than her skills and knowledge. This would indeed reduce material and energy flows going along with GDP generation, unless owning many flutes becomes a marker of status, so that people would spend much money on collecting large collections of flutes. Indeed, these flutes accumulate, but they do not only embody value added, but all matterenergy throughputs that are necessary to make them.

We appreciate that the reviewer feels the result is worth noting. Our argument is that, if it applies for 50 years of civilization growth, it can be reasonably expected to be able to be extrapolated to the future. After all, the "empirical regularity" was first published in 2009 based on 36 years of data, and it has held since to now encompass 50 years.

As for the flute argument, we do not follow. It appears to be conjecture and largely unrelated to the global analysis we perform here. That said, for the sake of argument, flutes, as part of our global culture, do facilitate material and energetic flows

associated with civilization as a whole, a *r*ate that is independent of the *amount* of energy that went into their manufacture, integrals and integrands being orthogonal quantities. An argument could be made that flutes and their performance are valued according to their relative thermodynamic role in civilization, and that flutes will continue to be valued accordingly given their millennia of cultural importance. Because of path-dependence, it is very unlikely that flutes will arbitrarily become much more valuable than everything else in a short time, hence the role for inertia we discuss. Unfortunately, we lack the data to test any flute-related hypothesis.

Response to the editor

Minor word-smithing was done throughout the document for style and typos.

As a note in response to an editorial suggestion we have added the text:

> *Systems may even undergo quite dramatic changes in character while maintaining at all stages a dependence on previously consumptive states, such as with the succession of species that occurs during development of new forest following a major disturbance (Oliver, 1980)*

We also added an elaboration to the quote by Piketty:

> *Like "dark-matter" in astronomy that cannot be seen but is known to be the bulk of our universe, there appears also to be "dark-value" in economics, something that is described well by Piketty, "All wealth creation depends on the social division of labor and on the intellectual capital accumulated over the entire course of human history," continuing "the total value of public and private capital, evaluated in terms of market prices for national accounting purposes, constitutes only a tiny part of what humanity actually values - namely, the part that the community had chosen (rightly or wrongly) to exploit through economic transactions in the marketplace"*