Review by Peter Haff

I am greatly appreciative of Prof. Haff's thoughtful review of the paper and his helpful summary of its contents. There were a few questions in the review that are addressed below.

Possible points that may profit from more discussion in Garrett's paper include the observed constancy of the proportionality factor between power usage and accumulated wealth of civilization. A general correlation between these two quantities is not surprising, but the reasons for a rigid constancy are less clear.

A more detailed discussion of the physical motivation for presuming the relationship between a and C is outlined in Section 2 and Appendix A (of the revised document, Part 2.1 of the discussion document), and in much more detail in Part I. The basic interpretation is that wealth is a manifestation of reversible circulations within civilization, and these are sustained by a proportionate degree of energy consumption. Of course, this does not provide a mechanistic explanation for how our neurological perception of financial worth relates to a capacity to dissipate energy. This is an interesting challenge that may form a line of future work. The interpretation that is provided might be debated. What matters most is that wealth *as defined* has a fixed relationship to energy consumption that is supported by available data.

A second point that might be developed in more detail is the assumption that each unit of reserve energy consumed by civilization will be used to expand civilization's "boundary" with the source of such reserves. Garrett does not provide a physical argument for this assumption, but the suggestion seems to be that even "nonproductive" consumption of energy, like playing video games (my example), increases the highly filigreed contact boundary, in this case as expressed in an increased number of energy-using play stations and other gaming hardware. In any case, a short explanation would be in order here.

The physical argument that is provided is that energy consumption only goes towards expanding the boundary if there is an imbalance in the energetic flows as described in Appendix A (Part 2.1 of the current document). In this case energy consumption is faster than energy dissipation. Nearly all of energy consumption is required to sustain wealth, or the magnitude of civilization circulations that has previously been accumulated through a past energetic imbalance driving material growth. A much smaller fraction goes towards further expansion, currently at a rate of about 2.2% per year. The text now includes the following paragraph

From Part 1, and as illustrated in Fig. 2, civilization can be thought of as a heat engine where energetic and material flows are coupled. Increasing energy consumption in Eq. 3 arises where civilization is able to incorporate matter into its structure faster than it decays. Civilization is made of matter not energy, but as it grows it increases a material interface with available energy reserves. In the material growth phase it also consumes more energy with time.

Finally, it would also be useful to compare the basic datum used here that, as a function of time, global energy usage is proportional to accumulated GWP, to the results of Brown et al (listed in Garrett's references) that per capita energy usage is proportional to a power (roughly 3/4) of per capita GDP as calculated from a time average of data for individual countries.

Yes, this is certainly an intriguing result. One aspect of this work that remains to be developed further is the relationship of macroscopic economic variables to more internal quantities such as people. It is beyond the scope of this particular paper but the goal is to address it in future development of the implications of underlying theory.

Review by C. Herrmann-Pillath

Prof. Herrmann-Pillath's constructive review of this paper and prior papers have contributed greatly to their improvement. The effort is much appreciated. Some specific comments are addressed below.

This approach has the great advantage that it does not need to disaggregate the economic system, which is normally done by IAM models. These models have to introduce certain assumptions about economic variables which are highly problematic, therefore rendering predictions almost arbitrary, as has been stated clearly in a recent assessment by a leading economist working in this field (see Pyndick 2013). Therefore, Garrett's approach is highly welcome.

Thank you for the positive comments and in particular for the reference to **?** which is now added to the introduction.

In my earlier review, I already questioned the definition of wealth. It comes close to the economic notion of 'capital', but uses gross values of production that do not include depreciation. However, depreciation is introduced in section 2.4 as a 'decay parameter'. I think that this should be considered also in the definition of wealth, in order to be exact in the economics. In other words, I think that Garrett now includes physical decay, but not economic depreciation (in other contributions, this is related to inflation, which I think is bad economics). So, I have the impression that the two parts are not consistent, because including decay was one of the improvements that I noticed in the new model.

In my view, one of the rather elegant results that comes from λ being a constant is that physical decay is equivalent to either economic depreciation *or* inflation. The difference between the nominal and inflation-adjusted GDP, or the GDP deflator, is implicitly a representation of physical decay. The way to think about it, I think, is that wealth is purely an energetic representation of the capacity to enable reversible circulations at any given instant within the economic system. Economic production, the GDP, or the addition to wealth, is more explicitly tied to the material growth of the system. Civilization is made of matter not energy, so it's growth is material. Therefore, physical decay is best ascribed to production not wealth – it is the matter that is decaying. As is described in greater detail in Part I, it follows quite naturally from λ that the magnitude of the decay rate is related to the GDP deflator. If there is zero decay, all of the nominal GDP is the real GDP. Otherwise, some fraction is lost to inflation.

As for the measure of wealth, that would imply using NWP Net World Product in the original time series. Further, Garrett states that the physical manifestation of wealth is networks, both technological and human. This perspective is essential for arguing that in measuring global production, it is not necessary to distinguish between investment and consumption, as we can conceive of consumption as producing and maintaining the human network. Obviously, this presupposes a fully-fledged materialist theory of human consumption activity (such as in the arts, fashion etc.) in relating all this to the energetics of the economy. I think that this is possible (see my own work, Herrmann- Pillath 2013). However, this also means that using the GWP as a measure may be problematic because the GDP data do not include the production of public goods by political entities funded by taxes. This is a well-known limitation of national accounts and certainly is highly relevant for Garrett's argument. For example, roads, airports, harbours or power stations as essential parts of the 'hardware' of the economy would be left out of Garrett's measure of wealth also pertinent for the analysis of innovation, which in New Growth Theories is treated as a positive externality (so, by definition is excluded from national accounts).

The argument that government funded infrastructure development is not tallied in the GDP is surprising to me. I help run a company that sells meteorological instrumentation. All sales thus far have been directly or indirectly funded by the governments of the United States or Switzerland. The company builds instruments through acquisition of parts and construction equipment from other companies, all labor payments are reported to the IRS by company employees, and company profits are themselves reported and taxed. I am quite sure that all these expenditures get included in GDP calculations, independent of the original funding source.

As an aside, one frustration of using GWP data is that the United Nations reports the global statistic to the *dime* (i.e. thirteen significant digits), while providing no estimate of the measurement uncertainty in the statistic. I agree that all measurements are problematic to some degree. However, it is critical to assess the extent. Unfortunately, this does not appear to be standard practice for this particular statistic.

Another technical problem is the use of market exchange rates for measuring GWP which Garrett simply imports with the data base that he uses. I think that only purchasing power parities make sense, given the focus on energetics. As is well known, market exchange rates distort the measurement of the true standard of living. Especially for less-developed countries. However, it is this 'real' level of economic activity that drives energy transformations. So, I think PPP conversions should be used.

PPP measures are focused on the standard of living of people. From a strictly energetic or physical standpoint, people seem a rather arbitrary choice. The energy consumption by human bodies is only about 4% of the global total. The issue of PPP versus MER currency was addressed in more detail in the Supporting Material section of Part I http://onlinelibrary.wiley.com/store/10.1002/2013EF000171/asset/supinfo/eft223-sup-0004-SupportingInfo-text.pdf?v=1&s=817db4a862fea11bc0dc6e4f38f77583522b03afwhere it is stated that:

*"It might be argued that MER valuations are misleading and that PPP dollars should be used instead (**?**). PPP dollars are adjusted from MER dollars on the premise that market exchange rates do not accurately reflect the price of equivalent baskets of goods in differing countries. In principle, the theory presumes that equivalent baskets should be worth the same after adjusting for the exchange rate, and that any disequilibria should be expected to diminish over time. Discrepancies between PPP and MER valuations have been used as a tool to assess whether currencies are overvalued. Criticisms of the approach have included the difficulty of establishing an equivalent basket of goods between disparate cultures, and the observation that disequilibria diminish rather slowly with a half life of three to five years, perhaps due to the competing effects of international and domestic markets on the pricing of goods (**?**).*

The work here addresses different questions than those where PPP valuations would be relevant. It is not concerned with short-term inequalities or with nations. What is considered instead is only the sum of all human activities within the global economy, including all components, with an eye to variability in the long run. No specific resolution is made of people or their baskets of goods, nor even of nations, nor of the economic evolution of parameters that have doubling times of anything less than decades.

Effectively, the economics described here considers only one "basket of goods", and that is civilization as a whole, including all its composite networks, both social and physical. Purchasing power parity calculations are not obviously applicable in this situation. And, in any case, if they were performed according to theoretical expectations, the disequilibria between nations would be theoretically expected to damp out more quickly than the timescales of interest in this study."

Accordingly the following text is now added

MER units are used rather than purchasing power parity units (PPP) since the focus is not on short-term inequalities between people and nations but rather the sum of all activities within the global economy with an eye to variability in the long run.

Considering my arguments an on necessary modifications of the fundamental quantities, the questions arises whether the empirical regularity of a fixed ratio between wealth and energy use would survive the statistical corrections. I have no preconceived opinion on this, but of course the challenge is that we cannot implement those corrections, especially we cannot measure the stock of public goods over longer time periods. Therefore I advise that Garrett should present some reasons why he regards his measure as a good approximation.

It is true that a different definition of wealth would be unlikely to have a fixed relationship to rates of energy consumption in the statistics. But the definition of wealth that is used is mathematically very precise, and is the one that is used. To give an analogous example, the energy of a photon has a fixed linear relationship to its frequency. One could make the argument that Planck got it wrong because the energy of an ocean wave doesn't have a fixed linear relationship to it's frequency: amplitude also factors in. But, that doesn't matter. Ocean waves aren't photons. The fundamental basis for quantum mechanics remains robust.

Garrett's work concurs with views such as articulated in Ayres and Warr (2009) that innovation is tantamount to improvements in energetic conversions, in his words, the rate of return. I agree with this view, but want to point out that this also means that an essential driver of economic growth remains unexplained, just as in the earlier neoclassical growth models that Garrett briefly sketches in the appendix. So, the question is whether this is also a weakness for a physical model advocated by Garrett. In his narrative, technological progress happens because of both technology and availability of reserves. Thus, one would guess that a standard economic model of resource extraction with technological change would be a proper complement. However, as has been shown by authors such as Kmmel (2013), this approach would probably commit the mistake to assume that technology is a full substitute for energy. So, at this point a step towards further disaggregation of the physical model seems unavoidable.

I'm sorry. I'm not sure I understand. What is the essential driver of economic growth that is missed? Building from theoretical thermodynamic arguments, this paper identifies three forces for improvements in technological change at global scales: increased longevity, discovering energy reserves faster than they are depleted, and improved energy efficiency of raw material extraction. Technology and energy are not substitutes in any physically meaningful sense.

To sum up, Garrett's work is highly productive in opening up new ways of thinking about the human economy in the Earth System context. He tries to see the forest, whereas much modelling practice is busy with counting the trees.

Review by Andrew Jarvis

This thoughtful, critical review has been extremely helpful at refining the manuscript. I am greatly appreciative of the effort that went into it.

Garrett's work on conceptualising the growth of industrial society from a thermodynamic perspective has influenced my work in this area significantly. This particular contribution reveals his evolving thinking on this very important subject. Much of what he presents is characteristically insightful and illuminating. However, I take issue with some aspects of the work as detailed below. My main concerns are as follows:

1. As with all our attempts to pitch into this area we feel the need to pay due respect to the current macroeconomic calculus. This is understandable, but I find there are certain areas where this paper abandons the original refreshing 'it's physics stupid' perspective and starts to become quite macroeconomic itself. Perhaps that's no bad thing if aiding communication is the intended goal, but I think this needs to be made clear rather than attempting to give the impression it is all first principles natural science (see specific comments below).

The point is that, because λ appears to be a constant, the macroeconomics is simply an expression of the physics. It is more than just a matter of communication (although that effort is part of the exposition). The beginning of Section 2 now states this more clearly

The basis for a model linking economics to physics is a fundamental identity that relates a monetary expression for wealth to how fast civilization as a whole is able to dissipate energy.

2. The paper focuses on evaluating the framework against GWP data specifically from 1950 to 2010. My first issue with this is that the thermodynamic framing should tend to favour the global primary energy use data, and if not why not? My second issue is that from my understanding of the data 1950 – 2010 represents one cycle of a wave and hence rather than being truly long-run as suggested by the title, the analysis is of a single wave of innovation.

The thermodynamic framework does employ the global primary energy use data for the establishment of λ for the period from 1970 to 2010 since this is the period for which the global primary energy use data from the EIA are available and for which concurrent statistics of GWP are available from the UN. I appreciate the semantic argument over what counts as "long". 1950 to 2010 could be seen as a wave of innovation, although not of growth since civilization growth has occurred for thousands of years, albeit at varying rates. The reason for choosing the word long-run is to make a connection to some of the language used in macroeconomics where the decadal timescales that are discussed would certainly be considered long.

3. The balance of the paper needs changing slightly. Data need careful introduction as does the estimation of the various quantities. Repetition of material also in Garrett (2014) needs to be kept to a minimum.

Much of the ground work, both theoretical and with regards to the datasets was established in Garrett (2014). The point of separating the work into parts was to establish the theoretical and empirical edifice first (Part I), test the dynamic model (Part II), and make predictions (Part III to come). Part I was in fact where much of the data introduction was made, with added material in the appendix

I apologies in advance for the now 9 pages of comments, but this is important material and I find it fascinating. Please forgive any misunderstandings below. I very much want to see this work in print and I hope my review helps refine the paper to maximise its impact.

p657 "It tends to be the slowest and largest aspects of current variability that are the most powerful and least responsive." It's not clear what you mean by "current variability".

The paragraph is now rewritten and hopefully more clear

What this might suggest is that the human system has inertia, much like physical systems. Current variability reflects an accumulation of prior events, so persistent forces from the past tend to have the greatest influence on the present. Such large-scale trends tend to continue to persist into the future because they are the least responsive to current small-

scale rapid forces that become diluted in the history of actions that preceded them (Hasselman 1976). One reason that it may appear so difficult to wean ourselves from fossil fuels today is that we have spent at least a century accumulating a large global infrastructure for their consumption. It is not that current efforts to move civilization towards renewables cannot change this trajectory of carbon dependency, but rather that it will take considerable effort and time.

p657 "Part 1 of this study describes a physical model that provides expressions for making long-range economic forecasts of civilization evolution (Garrett, 2014)." Need to be clear that Garrett (2014) is to be referred to as 'Part 1' hereafter.

Done

p657 "The model differs from IAMs by including no explicit role for human decisions; the physics does not allow for mathematical expressions of policy. Rather, economic innovation and growth is treated primarily as a geophysical phenomenon, in other words as an emergent response to available reserves of raw materials and energy supplies." I think this is not entirely accurate. Human agents are still required to act such that the geophysical behaviours emerge and I think it would be helpful for the reader to make this clear.

To clarify this issue the text now reads. "*Rather, economic innovation and growth is treated primarily as a geophysical phenomenon, in other words the totality of civilization is expressed as an emergent response to available reserves of raw materials and energy supplies. "*

p658 "In the period following World War II, an economic "front" passed that propelled civilization towards unprecedented levels of prosperity and, by proxy, greenhouse gas emissions. This paper examines whether the theoretical model introduced in Part 1 can explain the evolution of this front." Taken as a whole, far more time/space is dedicated to re-introducing Garrett (2014) than to a rigorous evaluation against data. If the paper is to retain this focus then I think this balance needs addressing. For example, more effort could be dedicated to detailing the exact data sources to be used and why, and following through the uncertainties. Similarly, the introduction of

the model could be trimmed back to the essentials given they are reported in detail in Garrett (2014). For example, section 2.1 is largely redundant in this context. The estimation of the various quantities needs explaining clearly in the main text.

The paper already tries to trim things back to essentials given that there is no lengthly derivation of the underlying terms for economic innovation and growth. What we have done is to move Section 2.1 to an appendix and shorten the conclusions section.

p662 "Within civilization, wealth is due to the connections between and among ourselves and our "physical capital"". I don't see the need for the direct quotes here. Also, this is speculation and needs expressing as such.

I used quotes since "physical capital" since the expression is used in the traditional economics sense, not a physical one. The justification for the statement is elaborated upon in Part I, as mentioned, but the text is now added

Within civilization, wealth is due to the connections between and among ourselves and our "physical capital", from the circulations along transportation, telecommunications, and social networks.

p662 "All aspects of civilization, whether social or material, compete for globally available potential energy. Financial expressions of any element's value reflect the relative extent to which its connections enable civilization to sustain global scale circulations and wealth." This statement passes almost unnoticed and yet, for me, is probably one of the most important in the entire paper, especially when trying to help the reader appreciate the links between what they perceive and the analysis being presented. I suggest this is developed a little more here and revisited in the Conclusions. That said, given you are trying to describe 'wealth' you can't use 'wealth' in the definition. Also, it is difficult to properly appreciate why the instantaneous circulations within societies networks (driven by energy use) relate to accumulated GWP rather than GWP. In all your writing I have yet to hear this argument absolutely nailed. I appreciate this was the central discussion of your last ESDD paper (Garrett, 2011) but there is an opportunity here to really help the reader. I have read this section many times and still feel there is an unnecessary sleight of hand.

p662 "Wealth emerges from the past through prior production of these connections. Value added to civilization through the construction of a house decades ago still con- tributes to value today, provided the house remains part of a network [which] ties it to the remainder of civilization. Even with no one home and all the utilities turned off, a house maintains its value for as long as it can be perceived by other active members of the global economy." I understand the point you are trying to illustrate here. However, in relation to the preceding paragraph, by removing the inhabitants and unplugging the house it is not sustaining any material/energy flows at that point in time and hence under your physical definition of 'value' it's value should drop dramatically. In effect it is being unplugged from the physical network. The alternative you allude to here is that there is a psychological dimension to 'wealth' partially decoupled from material/energy flows. It is as if the potential to support flows is as important as actually supporting flows. Clearly this is not traditional thermodynamics as you use it and is more like traditional economics, which needs spelling out.

p662 "Even with no one home and all the utilities turned off, a house maintains its value for as long as it can be perceived [as useful (or similar)] by other active members of the global economy."

The above three points are addressed now with revised text that reads

Financial expressions of any element's value reflect the relative extent to which its connections enable civilization to irreversibly consume potential energy in order to sustain the reversible circulations of the global economy.

So while energy consumption is required to economically produce and grow, a generally much greater amount is required to sustain circulations within the network of connections that has been accumulated from prior production in the past. An analog is an adult human body since it is also a network of connections that has grown through childhood and adolescence. Far more of current daily food consumption goes towards maintaining life than to any extra weight gain. Here, value added to civilization through the construction of a~house decades ago still contributes to value today, provided the house remains part of *a~network that supports civilization by supporting its inhabitants. Part of such value may be only psychological since, even with no one home and all the utilities turned off, a~house still maintains some worth for as long as it can be perceived as potentially being useful by other active members of the global economy.*

p663 "the model is strictly thermodynamic". I'm not entirely convinced. Although equation 1 makes a strong appeal to thermodynamics, and the energy use component is described as a thermodynamic growth process in Garrett (2011), it is necessarily derivative, exploiting some empirical arguments not least because it invokes economic measures such as GWP. There is also clearly a perceived quality to 'wealth' as you illustrate (see above).

Once λ is established it is strictly thermodynamic as there are no further relations that are derived from empirical fits. The rest is just physics.

p663 "in which case no requirement exists for dimensionally inconsistent fits to prior economic data that are dependent on the time and place that is considered. The model does not rest upon any statistical correlation between energy consumption and economic production. . ." But this is exactly how lambda is derived! Admittedly it is far less prone than it's classical macroeconomic counterparts, but I think it is important to state clearly the true similarities and differences.

This point is made more clear in the text which now reads

The constant λ is not derived from a correlation analysis (something that has has been erroneously claimed by others **??**), but instead it is obtained from the observation that the ratio of C to a does not change even though C and a do. This is much like the basic expression of quantum mechanics where it was initially assumed and then validated with measurements that a photon's energy E and its frequency ν are linked through Planck's constant h. The interpretation is that, for the purposes of understanding the physics, the two quantities are interchangeable. The theoretical and empirical support for λ being effectively a constant is the basis for interpreting real global economic wealth, as it is defined, to be more fundamentally a representation of how civilization's circulations are sustained by a dissipation of primary energy.

p663 "and Y in units of 2005 MER US dollars per second". Picking up on an earlier discussion with you about PPP and noting Herrmann-Pillath's concerns about whether MER is the best measure, I think as a minimum there needs to be a discussion here about the data used to estimate lambda as there is for the evaluations presented later on. This discussion needs to articulate the uncertainties too.

The text currently states *What was shown in Table S2 of Garrett (2014), and in graphical form in Fig. 3 is that, for the period 1970 to 2010 for which global statistics for power consumption are available, the mean value of* λ *is 7.1 milliwatts per 2005 US dollar. GWP more than tripled over this time period.*

p664 "The basic reason is that, from Eq. (1), the [relative] growth rate of civilization. . ."

Changed

p664 "Since 1970, average rates of return for a and C have been [$\sim$]1.90% per year (Fig. 3)".

Changed

p664 "So, the current rate of return is tied to [the] past. . ."

p664 "The rate of change of civilization's rate of return can be referred to as an "innovation rate"". It is incongruous to specify the return rate as something that is changing at this stage because up until now you've been convincing the reader it is constant (1.9 %/yr). This needs some introduction.

To clarify a possible source of confusion, the text now reads

Since 1970, rates of return for a and C have varied, but have both averaged $\sim$1.90 % per year (Fig. 3).

p665 "Since λ is a constant, increases in the production efficiency (or inverse energy intensity) Y/a are equivalent to the expression for innovation dlneta/dt." I can see how the previous argument indicates your definition of 'the return rate' can increase because Y is growing faster than a but it is not clear how this supports eq. 7 explicitly. As you say, the introduction of eq. 7 is "a bit arbitrary" and I was surprised

to see it defended from a heuristic economic perspective. As discussed above, this clearly is not a purely thermodynamic framing hereon.

If feel the mathematical and physical justification is already summarized in the text, although I have added the phrase “it follows that” to make it clearer that a derivation is implied.

p665 “Innovation is a driving force for economic growth since it follows directly from Eqs. (4) and (5) that the real GWP [relative] growth rate is governed by. . .”.

Changed

p665 “GWP [relative] growth = rate of return + innovation rate”. Also by now the term ‘return rate’ is becoming very ambiguous. Previously it related to energy use and wealth because you argue it is common to both. But we are now also thinking about the return rate on GWP and eta too. I suggest return rates and/or relative growth rates are stated explicitly from the outset.

The rate of return is defined explicitly with equation 4. Wealth and energy consumption are not the only things that grow, yes, but the rate of return is not used as an expression to describe other dynamic quantities.

p665 “The implication here is that current rates of GWP growth. . .” I understand that in an economic framing GWP growth is important, but for me it’s as if the paper is losing it’s thermodynamic roots. I think you need to keep reminding the reader what GWP represents in the thermodynamic setting.

The physical forces for the innovation that drives GWP are elaborated upon a bit later in the section now slightly renamed to emphasize this point “Physical forces for innovation”.

p665 “Accordingly, current GWP growth rates will tend to persist; new technological advances will always struggle to replace older advances that are already in place (Haff, 2014).” These are two separate issues that need discussing separately. The second one is really interesting and important and worth expanding on.

The text is now rewritten slightly to read

The first term implies that current GWP growth rates will tend to persist because past innovation is carried to the present; the second term implies that new technological advances will always struggle to replace older advances that are already in place

The elaboration is already exists in the following sentence.

p665 "Figure 4 shows how rates of return, innovation rates, and GWP growth..." Again 'return rate' and 'GWP growth' is very confusing as they are both relative growth rates. Also, my estimates of the return rate on global primary energy doesn't look at all like this (see http://www.earth-syst-dynam-discuss.net/5/1143/2014/esdd-5- 1143-2014.html), but rather looks much more like your estimates of innovation and GWP growth. I can only assume it is estimated from the time integrated (and hence smoothed) GWP data. If you used the global primary energy use data (which you ought to given this paper espouses thermodynamic principles) you would get a very different answer indeed. The data sources and estimation methods need to be put into this paper so the reader can see how this was done. "See Garrett, 2014" is not helpful.

Yes, there are relative growth rates for differing quantities, but they are named consistently. The paper referred to is currently in review, and my own review of that paper raised concerns about the completeness of the primary energy data sets that were used. They omitted key sources of renewable energy like wind and gravity that likely played critical roles in the past. As for presenting analyses based on referenced datasets, this is common practice.

p666 "Meanwhile, innovation rates have declined." When looking at the long-run evolution of global primary energy use you will see this decline is transient, similar to what was seen in the 1930's. Given the papers title I would be much more cautious in offering these interpretations of Figure 4.

Yes, the decline is transient, but the nature of the evolutionary behavior is what is shown to be consistent with some underlying theoretical principles. A similar analysis could be done for the 1930s, but with more caution since naturally short term fluctuations become more uncertain the further back in time one goes.

p666 "From Eq. (8), GWP growth. . ." This paragraph needs much more hedging. If it were related solely to Eq. 8 it would be fine, but it is also offering an interpreta-

tion of past/observed events. Also, it slips into discussing GDP (undefined) which is something different.

GDP is now changed to GWP since that was merely an oversight. The discussion is based only the statistics in Figure 4.

p666 "Rather, they increase when new reserves of energy or matter are discovered and they decrease when there is is[delete] accelerated decay."

Changed

p667 "Here, NS represents the accumulated material size of civilization due to past production. delta is a decay parameter that accounts for how rapidly NS falls apart due to natural causes." You need to be clearer what you mean by 'size'. Is it a mass or some kind of dimension? Clearly this affects what decay means.

The text is now rewritten to read

Here, N_S represents the amount of matter or mass within civilization. N_S grows from a positive imbalance between civilization's incorporation of raw materials from the environment and civilization's material decay.

p667 "Building on the identity a = lambdaC, it was argued" By Garrett (2014)?

Yes. The reference is added.

p667 – 668 "In our case, our bodies are a complex network of nerves, veins, gastrointestinal tracts and pulmonary tubes. We use this network so that we can interact with a network of electrical circuits, communication lines, plumbing, roads, shipping lanes and aviation routes (van Dijk, 2012). Such networks have been built from a net accu- mulation of matter. So, as civilization grows, any given addition becomes increasingly incremental." van Dijk 2012 only relates to social/information networks. You need to cite and discuss this section in the context of Jarvis et al (2015) (http://www.earth-syst- dynam-discuss.net/6/133/2015/esdd-6-133-2015.html). I'm slightly frustrated I have to point this out to you given you reviewed that work and were sent earlier versions of the same back in 2013.

The paper referred to is still in review.

p668 “That economic growth has been sustained over the past 150 years is a testament to to[delete] the importance. . .”

p668 “technological change = improved longevity+net reserve discovery +extraction efficiency gains”. The impression given here is that these fall naturally out of the analysis. However, I am left thinking that is because these are the things we think are important in this context and hence we fashion the analysis accordingly. This is fine, but needs to be made clear which.

No, fashioning the analysis that was would be a bad approach that runs counter to the intent of this work. Each term falls naturally out of the thermodynamics. Of course I tried to give the terms sensible sounding names that help to convey what the thermodynamics represents. But that’s no different than labelling something a force or a pressure.

p668 “there would be no offset to new network growth.” Why network growth? Networks are not an explicit consideration of this research.

It comes from Part I where growth is expressed in terms of a length density. Nonetheless the work network is no replaced with material.

p669 “increased longevity, corresponds with declining inflation and faster real GWP growth”. I think it is interesting to reflect on why therefore short-termism is so prevalent in many innovations. We argue it’s because the stock of society has to evolve at a certain rate.

I’m not sure I understand the relationship to short-termism within this context.

p669 “It represents a technological advance because there is reduced competition for available resources.” Why?

The text is now added

From 10, larger reserves enable higher rates of return on the relative growth of wealth and energy consumption.

p670 “An initial exponential growth phase yields to diminishing returns where growth rates stabilize (Fig. 5).” Again, long-run global primary energy use data suggest long-run relative growth rates are persistent (Jarvis and Hewitt, 2015) and there is no sign of it tailing off yet. This needs to be discussed here.

The physics and data support a picture of evolving growth rates for civilization, common with other organic systems like plants and animals, and inorganic systems like snow flakes. As described in the text, even historical examinations of past civilizations support a logistic growth curve (**?**), not one of fixed growth.

p670 "This is in fact precisely the behaviour that has been observed in the past few decades." See earlier discussion on long-run behaviour of global primary energy use in relation to Fig. 4.

See the associated response.

p671 "the long-run evolution of the global economy." Would prefer something broader/more thermodynamic than the 'global economy'.

The phrase "*and its resource consumption"* has now been added.

p671 "Figure 6 shows the relationship between innovation rates and rates of return over the past three centuries (see Part 1 for associated statistics)." Again, we need data sources including in the caption for Figure 6.

The data sources are Part I. They are published nowhere else. However, more explanation is now provided.

p671 "For the period since 1950 where statistical reconstructions of GWP are yearly and presumably most reliable Maddison (2003), Fig. 6 shows that the past 60 years have been characterized by a least-squares fit relationship between innovation rates dlnηdt and rates of return (with 95% uncertainty bounds) given by...". Some reason for the observations not conforming to this behaviour pre 1950 needs to be given beyond 'the data are crap'.

To avoid confusion as to the intent here, the text now reads

Focussing on the period since 1950 where statistical reconstructions of GWP are yearly and presumably most reliable.

In the paragraph prior it is already acknowledged that the data point to periods of both rising and falling innovation. Given the sparsity of the data provided by Maddison prior to 1950, it simply did not seem warranted to make too much of the precise relationship between $d\ln\eta/dt$ and η.

p673 "Coal power production expanded steadily at a rate of about 2% per year. Oil reserves, on the other hand, expanded at an average 3.6% per year between 1950 and 1970 but shrunk at an average 0.7% per year between 1990 and 2010. The amount of energy required to access key raw materials such as cement, wood, copper and steel, dropped by an average 3.5% per year between 1950 and 1970 implying rapid efficiency gains. Since then, energy consumption and raw material consumption have grown at nearly equivalent rates." All these stats need citations.

These statistics were calculated for this paper based on the statistical sources cited in Appendix (now) C. This is mentioned already in this section.

p674 "As a consequence of being a constant, calculated rates of return are similar whether they are calculated from available energy statistics using Eq. (4) or from GWP statistics using Eq. (6)." I'd like to see this as I don't think this is true, or if it is it must depend on which data are used given my experience is very different.

As mentioned, these statistics are described in Table 3.

p674 "Civilization has seen waves of logistic or sigmoidal growth throughout its history where an initial phase of exponential growth was followed by slower rates of expansion." If they are "waves" then the framework proposed here only describes what is happening within a wave and does not capture the wider long-run systemic features of the growth of civilisation.

I'm not sure I understand the distinction.

p679 "As a side note, since eta is also equal to the rate of growth in energy consumption (Eq. 4) [t]his yields. . ."