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Discussions

Interactive comment on "Long-run evolution of the global economy: 2. Hindcasts of innovation and growth" *by* T. J. Garrett

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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).

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.

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.

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".

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.

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.

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.

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.

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 contributes 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.”

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).

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.

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.

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

p664 “Since 1970, average rates of return for a and C have been [∼]1.90% per year (Fig. 3)”.

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.

p665 “Since I 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.

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. . .”.

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.

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.

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.

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.

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.

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

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

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.

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

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 accumulation 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.

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 e_ciency 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.

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

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.

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

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.

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.

p671 “the long-run evolution of the global economy.” Would prefer something broader/more thermodynamic than the ‘global economy’.

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.

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 dln_=dt and rates of return (with 95% uncertainty bounds) given by. . .”. Some rea-

son for the observations not conforming to this behaviour pre 1950 needs to be given beyond 'the data are crap'.

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.

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.

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.

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

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