

## ***Interactive comment on “Revolutions in energy input and material cycling in Earth history and human history” by T. M. Lenton et al.***

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I really enjoyed reviewing this paper both for its subject and for its comprehensive approach and in-depth scholarship, plus I got a chance to present my own views to those reading this online journal. This paper should be a valuable source for researchers, while the culminating section on a solar powered recycling revolution should be an inspiration to both scientists and activists around the world, a call to make this other world that is possible come into being, before our children and grandchildren are plunged into the abyss of climate catastrophe. Wind and solar power are potentially the energy source of a 21st century industrial revolution, a reprise of the role of coal in the 18th century apparently a result of capital's drive to control labor power versus using its alternative water mills (Malm, 2016).

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The paper's underlying theme is the succession of revolutions in Earth history, following Lenton and Watson's (2011) earlier invocation of this concept (see e.g., my review, Schwartzman, 2014a). The authors brilliantly illuminate each revolution, focusing on the stepwise increase in capture of energy by the biosphere (see their Figure 1). But not examined in this paper is whether these revolutions were essentially inevitable products of biospheric evolution, roughly deterministic or rather unique to Earth history. This question is of intense interest to the astrobiology community and its critics. For example, is the emergence of oxygenic photosynthesis very likely, given the likely abundance of water on Earth-like planets around Sun-like stars? I side with the determinists, play the tape again, pretty close to the same outcome (Schwartzman, 1999, 2002; 2015c), a hypothesis likely to be tested in the next few decades by the exoplanetary research program. Further, in view of the order of magnitude billion year lag times in these revolutions, culminating in the very condensed outcomes in human history, were there constraints responsible for holding them back for so long or was this timing simply a matter of chance as Lenton and Watson (2011) argue?

I have pointed out the constraint commonly ignored, the climatic temperature history of the geologic past. While still under debate, I find the oxygen isotope record in sedimentary chert and the compelling case for a near constant isotopic oxygen composition of seawater over geologic time supporting thermophilic surface temperatures prevailing in the Archean. A cold Archean is hard to explain given the likely higher outgassing rates of carbon dioxide, significantly smaller land areas and weaker biotic enhancement of weathering than present in the context of the long-term carbon cycle, taking into account the fainter Archean sun in climate modeling. This evidence points to an important conclusion regarding biological evolution, namely to the critical role of a temperature constraint holding back the emergence of major organismal groups, starting with phototrophs, culminating with metazoans in the latest Precambrian. As a result of the co-evolution of life and its abiotic environment, the evolution of Earth's biosphere is close to being deterministic, i.e., its origin and history and the general pattern of biotic evolution are very probable, given the same initial conditions, potentially a model for

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Earth-like planets around Sun-like stars (Schwartzman, 1999, 2002; 2015a).

Briefly mentioned is the role of biotic enhancement of weathering (BEW) in triggering snow ball Earth episodes in the late Proterozoic (lines 274-275 citing Lenton and Watson, 2004). But evidence for the progressive increase in the BEW over geologic time has profound implications for the coevolution of the biosphere and its biota, since BEW represents a powerful catalytic factor in the long-term carbon cycle (Schwartzman and Volk, 1989; Schwartzman, 1999, 2002; 2015b). The Archean (and Hadean) was likely near abiotic with respect to BEW, so this factor must be taken into account in modeling the long-term carbon cycle in the context of abiotic drivers, namely rising solar luminosity, continental area and decreasing volcanic outgassing over geologic time to the present.

Now for revolutions in human history.

Line 567. “The correlation between energy use and human development appears to be highly non-linear. At low levels of human development relatively small increases in energy input have large positive effects, while at high levels of human development large increase in energy input have little or no effect on further increases in standards of living (Steinberger and Roberts, 2010).”

Nevertheless, supplying the rough minimum of 3.5 kilowatt per person to the energy-deprived global South could dramatically increase life expectancies, arguably a robust measure of quality of life (Schwartzman and Schwartzman, 2011; 2013).

Line 570. “Forward look: A solar powered recycling revolution” is a welcome end section to this paper. I have long been advocating the same approach, recognizing that besides avoiding the well-know negative impacts of fossil fuels and and more contentiously nuclear power, high efficiency collection of solar radiation with wind and solar technologies has the capacity to do the work required for recycling. The energy base of the global physical economy is critical: global wind/solar power will pay its “entropic debt” to space as non-incremental waste heat, unlike its unsustainable alternatives

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(Schwartzman, 1996, 2008, 2009).

Line 580-590. “A sustainable energy system is challenging but feasible from a purely technological point of view. The technical potential for renewable energy (RE) technologies exceeds current and future global primary energy demand by several orders of magnitude (GEA, 2012). However, the rate of de-carbonization of the global energy system is constrained by a number of economic (e.g. economic viability of RE technologies, large up-front investments, devaluation of investments in existing energy infrastructure), socio-cultural (e.g. public acceptance of large scale infrastructure projects, food security and various other competing land uses), and technological (e.g. issues of transmission, integration and storage) factors (Fischedick et al., 2011). Current assessments of global development scenarios with ambitious climate mitigation targets put the supply of RE between 250-500 EJ yr<sup>-1</sup> in 2050 (GEA, 2012; Fischedick et al., 2011; Clarke et al., 2014). Depending on assumptions this corresponds to 25%-75% of global primary energy demand.”

I find the authors being too conservative in their assessment given the challenges humanity is facing in this century. Going beyond business-as-usual modeling being cited here is imperative. Radical changes in global political economy are likely necessary to implement a timely and robust energy transition to wind/solar power coupled with the elimination of fossil fuels. In thirty years or less this transition could deliver two times the global primary energy consumption level of 551 EJ yr<sup>-1</sup> in 2014 (BP, 2015), equivalent to 35 Tera Watts, even with present efficiencies in collection which will increase in this time frame (Schwartzman and Schwartzman, 2011; Schwartzman, 2014). Assuming modest population growth by 2050 corresponding to roughly 9 billion, this level will be needed to terminate energy poverty in the global South, insuring state-of-the-science life expectancy for all of humanity, as well as to generate the incremental energy required for carbon-sequestration from the atmosphere and climate adaptation.

We are now a Type I civilization in Kardashev’s scale of cosmic civilizations (Kardeshev, 1964), at a bifurcation, an imminent choice between the collapse of civilization or the

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emergence of a truly planetary civilization mobilizing our star's fusion energy for human and nature's needs instead of our present reality of perpetual war on both entities. I submit that an approximate doubling of global energy consumption using this energy source is a necessary condition for the better choice.

Lines 641-644. "An outstanding task therefore is to formulate a steady-state "Earth system economics" that supports long-term human and planetary well-being. One of the most difficult problems to be solved along the way will be to find out how a steady-state society can find new ways to organize a just distribution of wealth in an economy that functions physically as a zero sum game."

Commonly "steady-state" is taken as referring to a no-growth economy. However, the qualitative versus quantitative aspects of economic growth should be distinguished, with the concept of economic growth being deconstructed, particularly with respect to ecological and health impacts. Growth of what are we speaking, weapons of mass destruction, unnecessary commodities, SUVs versus bicycles, culture, information, pollution ? Instead, advocates of global degrowth with their goal of reaching a zero growth steady-state economy commonly lump all growth into a homogenous outcome of the physical and political economy (Schwartzman, 2009, 2012). A zero growth economy is an unwelcome prescription for the immediate challenges posed by the threat of catastrophic climate change as well the undeniable lack of material consumption enjoyed by the majority of humanity living in the global South, the lack of adequate nutrition, housing, education and provision for health services, but most critically, their state of energy poverty. A sustainable growth phase, beginning in capitalism itself, must necessarily have a different quality than capitalist economic growth as measured by the GNP, namely not only requiring global growth in the wind and solar power infrastructure, but also in the agroecological sector. Sustainable economic growth would include global solarization of energy supplies, demilitarization and ecosystem repair (Schwartzman 2009).

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Line 89. Update: evidence for biogenic carbon in 4.1 Ga zircons (Bell et al., 2015).  
Line 131-139. The authors are correct to point out the ambiguity of the sedimentary isotopic record of carbon; also see my discussion in Schwartzman (1999, 2002), p. 26-31. A higher volcanic outgassing rate of carbon in the Archean was balanced by a more intense silicate weathering sink on smaller continents and oceanic islands, plausibly releasing a higher flux of nutrients to the ocean (Schwartzman, 1999, 2002; 2015b). Hence marine biotic productivity may have been enhanced, and biospheric energy capture in the Precambrian may be underestimated. Line 276. Modern desert microbial crust productivity is not a good model for Proterozoic or early Phanerozoic terrestrial biota. Line 416. Even earlier agriculture in Peru, dating back to 10,000 BP is argued by Dillehay et al. (2007).

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