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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 is an innovative attempt to apply principles of thermodynamics to understanding certain key features of the world economy. Such an approach from outside the cannon of classical economics can be understood in the following way. The set of assumptions that form the basis for standard economic analysis are based on empirical observations about the behavior of humans and human institutions that were encoded before the world had entered an epoch of profound change in its physical state. When systems are forced to operate in novel environments, it is always useful to look beyond empiricism alone to fundamental physical principles to help avoid surprises. These may not be able to resolve details of system behavior, and do not necessarily aim to disclaim existing methods of analysis, but can sometimes provide guidelines for dealing

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with changed conditions. For example it is a known principle, for a closed dynamical system where mass cannot be added or removed, that the waste products produced by that system must eventually be recycled to maintain system function. This is a consequence of the second law of thermodynamics, and of the observation that maintenance of mass and energy flows in any dynamic system requires suitable gradients. Mass and energy pollution tend to destroy these gradients. Prior to the present level of resource consumption, natural capital provided sufficient recycling services to the economy, which therefore did not operate as a closed system. However, today's global economy is overwhelming the recycling capabilities of nature; it operates in effect as a closed system, and the limitations defined by physics loom ahead, independent of the details of how the economy actually works. The economy at the most basic level is driven not only by human ingenuity and intention, although these are necessary ingredients, but by pre-existing energy gradients that nature provides and that are the source of forces without which no thought, keystroke, or policy may be initiated. Similarly, the economy must eventually recycle its own wastes, not because humans demand it, but because physics demands it. In sum, economics is a discipline that, like all others, must work within the limitations of the laws of physics. The utility of economics within its accustomed sphere notwithstanding, when physical stressors to an economic system become sufficiently severe, as in the Anthropocene today, it is useful to ask what can be learned from looking at underlying physical principles. This is what Garrett has done.

Main features of Garrett's model are as follows. He identifies a proportionality relation between the current rate of global energy use (watts) and the time-integrated value of past economic production in constant dollars (which he calls the accumulated wealth of civilization). He shows that the proportionality factor is in fact very close to a constant over the period of time (from 1970) that adequate statistics are available. The only empirical data used in the development of the model at this stage is in determination of the value of this quantity. However, this is enough to derive a range of interesting quantities that can be interpreted in physical terms having plausible economic analogs, such as innovation rate and rate of technological change. To make further progress requires constitutive assumptions about how the rate of return on accumulated wealth, i.e., the rate of change of energy usage, depends on quantities such as size of available energy reservoirs, the physical size of the world's infrastructure (which delivers the energy to end users), how effectively that energy contributes to growth, and the decay rate of infrastructure. These constitutive assumptions are not fundamental attributes of the basic model, but are working hypotheses about how the model applies to specific situations. For example one could manipulate these assumptions to test the effect of discovery of new energy resources. The present paper provides a test of the basic model, and of a set of particular constitutive assumptions, through, for example, hindcasting to relate relative changes in rate of return on accumulated wealth and innovation rate, behavior that it captures with high positive skill.

In summary, Garrett's work demonstrates how basic physical laws can constrain economic function. These constraints do not arise from within economic analysis but are imposed from the outside, a necessary consequence of the fact that the economic system is now big enough to come up against physical constraints whose origins have nothing to do with human economic behavior, and thus whose effects are not captured by the principles of economics. This is not a special limitation on the allowable practice of economic empiricism alone, but on the practice of all fields that derive from considerations that are less general than the basic physics that enables and defines the limits of their function.

This paper may be controversial. Garrett's model does not distinguish labor from capital, and its pays no explicit heed to relations such as supply and demand that are basic to the language of classical economics, nor does it separate out sectors such as manufacturing, services and so on. There are no people or institutions or decisions visible in the basic physical description. This is the nature of emergence, where fine grain substructure, essential as it is to overall system function, effectively fades out at large enough scale. In a similar way, the dynamics of water waves does not refer to constituent water molecules. In the present case, physics does not displace economics, but conditions its application. It provides a framework within which economics-under-high-stress can be applied, as a wave defines the universe in which the water molecule moves.

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 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. 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.

In any case, the present work is an effectively argued physical model of certain fundamental processes in the Anthropocene. It deserves publication, subject to consideration of the points outlined in the preceding paragraph, and even to be highlighted as a possible new approach for studying key questions, or at least asking key questions, about the Anthropocene as they relate to energy use, the role of technology (innovation), effects of climate change (decay), and other factors that affect economic growth and thus human well-being.

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