Response to Richard Rosen

We place the reviewer comments in bold font and our response in normal font.

It has been long known that the ratio of energy consumption to annual GDP has been falling at somewhere between 1-2% per year, depending on the year. This implies that energy consumption will slowly fall with respect to cumulative production as well. But this is merely a matter of math and not a cause and effect relationship, since the technologies used for production many decades ago can not affect energy consumption today, except to the extent that a few of such technologies still consume energy. Whatever the lifetime is for old energy consuming technologies, this fact would say little about how fast energy consumption could be made to drop each year in the future. With strong energy efficiency policies in place, energy usage could be made to drop much faster in the future than it has averaged in the past. For example, all electric vehicles which are good for mitigating climate change are far most energy efficient than the currently fleet of vehicles. All electric vehicles could be phased in within 20 years. Similarly, old buildings could be rapidly renovated to reduce their energy consumption. The authors demonstrate that there is a lot of "momentum" built into the energy/economic system, with a fairly constant "velocity" in the past. With enough policy "force" applied to the system, this velocity could be greatly slowed down, as we all hope will happen as climate change is rapidly mitigated, to use a Newtonian metaphor! Thus, the world is not constrained by past energy consumption trends.

As stated in the paper, the ratio of energy consumption to annual GDP has been falling at a rate of 1.00% per year (line 46). There is no mention of “momentum" or “force" in the paper, as it is not clear that these are well-suited concepts for description of an open thermodynamic system such as the global economy. That said, it follows from Equation 3 that increasing energy productivity Y/E leads to increased energy consumption. Namely, dividing Equation 3 by E leads to

$$\frac{Y}{E} = w\frac{1}{E}\frac{dE}{dt} \quad (1)$$

where $w = W/E$ was found to be nearly a constant for the 50 year period of growth considered. If Y/E increases, due for example more efficient vehicles or buildings, energy demands would also increase. Production grows the system, in which case energy consumption must adjust to sustain this addition in civilization size, as quantifiable through the link to historically cumulative past production given by Equation 2.

Again, as I indicate in my other comment, the culprit that determines all the energy consumption trends is the type of technologies invested in each year over the past, which consumes somewhat varying amounts of energy from year to year, but which has a finite lifetime. Given the typical rate of global growth over the past decades, the typical energy consuming technology might only be 10-20 years into a 50 year lifetime, to use rough but illustrative numbers. This could be a piece of industrial equipment, a power plant, or a building heating system. Energy consuming vehicles tend to turn over at a faster rate, of course, than once every 50 years. That implies that typically if no new policies are introduced by governments to phase out existing energy consuming technologies, or if market forces do not lead to existing energy consuming technologies being abandoned prior to their normal lifetime, the well-known slow but steady 1-2 percent per year declining trend of total energy use in a given year per dollar of GDP will continue unabated. This is the rough trend that these authors show, however it is precisely expressed. Overall, macroeconomic production functions have little to do with these consumption trends for energy technologies. This argument applies to both fossil fuel consuming technologies as well as to renewable energy consuming technologies. The fairly steady ratio that the authors find between annual energy consumption and cumulative GDP is mostly a coincidence, and a simple product of these slow long term trends for the very slow turnover of energy consuming technologies. Obviously, in terms of cause and effect, only the fraction of any year's GDP that is directly invested in energy consuming technologies cause a fraction of future year's energy consumption until that piece of technology is retired. Thus, macroeconomic arguments alone can never explain these trends. Once either the governments of the world or market forces cause more efficient energy

consuming technologies to be invested in more rapidly than typically happened in the past, then this fairly constant ratio can change. The author's analysis shows that this has not yet happened in the past. But if this article is to be published, it must be completely revised so that it focuses on the types and rates of investment in energy consuming technologies in each year in the past compared to total GDP in each year. This will allow the authors to explain the trends they find by disaggregating the causes and effects of the trend in terms of technology and not abstract arguments.

The relationship given by Equation 2 covers a period during which energy consumption E increased by nearly a factor of 3, and economic production by over a factor of 4. However the term “coincidence" is meant to be used in the comment above, a great deal happened in society over this 50-year time period, including a 60$\%$ increase in production efficiency, during which the ratio between energy consumption E and historically cumulative production W did not change.

It is difficult to see how to meaningfully disaggregate components of the global system for global scale questions, those most relevant to e.g. discussions of anthropogenic carbon dioxide emissions. No person, machine, or economic sector can be meaningfully disconnected from the global economy as a whole, or even from any time in history, as all are connected through either current networks or temporal causality. The reviewer argues that some fraction of the GDP going towards “energy consuming technologies" while (presumably) the remainder of the GDP goes to production of goods and services that do not require energy. Thermodynamically speaking, this argument is peculiar as nothing can happen production-wise, of whatever sort, without energy having been consumed to convert raw materials into the makeup of civilization, or to make something move faster. And once civilization is grown through production Y, more energy E is required to sustain circulations within the previously accumulated internal civilization networks connecting people and their machines W. This is even more the case if the production was done efficiently leading to faster growth in W. If there is an alternative conclusion that can be drawn from the data presented in Figure 1, it should be presented through consideration of the human system as a whole not by disaggregation into its parts.