Why the energy transition is not enough

Benjamin Leiva (bnleiva@uvg.edu.gt)
Universidad del Valle de Guatemala https://orcid.org/0000-0002-2312-2532
John Schramski
University of Georgia https://orcid.org/0000-0003-4294-7692

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Abstract

Efforts to accommodate the growth in global energy consumption within a fragile biosphere are primarily focused on managing the transition towards a low-carbon energy mix. We show evidence that a more fundamental problem exists through a scaling relation, akin to Kleiber's Law, between society's energy consumption and material stocks. Humanity's energy consumption scales at 0.78 of its material stocks, which implies predictable environmental pressure regardless of the energy mix. If true, future global energy scenarios imply vast amounts of materials and corresponding environmental degradation, which have not been adequately acknowledged. Thus, limits to energy consumption are needed regardless of the energy mix to stabilize human intervention in the biosphere.

Introduction

Humanity's rate of energy consumption (i.e., power) of 16.1 TW in 2010 is projected to increase by 94 – 247% by 2050, with a reference scenario at 140% given by SSP2 and RCP 4.5 (van Ruijven et al., 2019). On track with these expectations, humanity reached 18.9 TW in 2018 - a yearly 2% growth since 2010. Such growth is confronted by the well-documented realities of climate change (Tong et al., 2019), persistent 80% share of fossil fuels in the global energy mix (IEA, 2019), and declining quantity and quality of fossil fuel reserves (Chapman, 2014; Mohr et al., 2015). These issues have highlighted the need for an energy transition towards low-carbon energy sources (Grubler, 2012; Smil, 2016; Sovacool, 2016) such as renewables and nuclear (Moriarty & Honnery, 2016; World Nuclear Association, 2019). The main obstacles for such transition discussed in the literature have been slow deployment (Moriarty & Honnery, 2009), low energy return over investment (Murphy, 2014; Rye & Jackson, 2018), and the material requirements of new energy technologies, specifically metals such as cobalt and lithium (Giurco et al., 2019; Moreau et al., 2019; Valero et al., 2018).

We show evidence that the continued increase of energy throughput faces a more fundamental problem. The use of energy requires prime movers such as people, engines, computers, etc. that are built from materials found originally in nature. Moreover, the use of energy inevitably rearranges materials in the environment. This posits a problem that goes beyond the carbon content and specific material requirements of given technologies, and thus cannot be solved through substitution. Higher power rates need and provoke more materials (metals and others) being rearranged from otherwise healthy ecosystems into social structures such as firms, cities, and governments and into goods such as furniture, electronics, and food. In fact, the 20th century witnessed a 9-fold increase in humanity's power alongside a 16-fold increase in its material stocks (Krausmann et al., 2017). We contend that the ecosystem degradation (MEA, 2005), biodiversity loss (IPBES, 2019), and dangerous human intervention in the Earth system (Steffen et al., 2015) that followed from such harvesting of the biosphere could have only partially been avoided with a low-carbon energy mix.

We evaluate what we believe is the first preliminary evidence of a coupling, akin to Kleiber's Law in biological organisms, between power and the material stocks of social systems. Previous social allometric scaling relationships have not related power to mass, but power to birthrate and child mortality (Burger et al., 2011), and power to GDP/capita (Brown et al, 2011). Moreover, material constraints to the energy transition have been pointed out for specific materials (Giurco et al., 2019; Moreau et al., 2019; Valero et al., 2018), but not in a general approach as allowed through allometric scaling. We use a newly compiled dataset from published estimates of power and material stocks of Human civilization between 1900-2010 and the USA and Japan between 1980 and 2005. Like Kleiber's Law, we use ordinary least squares on the logarithms of these variables to estimate the scaling parameter between them and then compare the resemblance to relationships found in biological organisms.

If true, this relation implies a strict limit to power growth that cannot be addressed with low-carbon energy sources. Using our results, we demonstrate that current projections of energy consumption and population growth imply unsustainable levels of material stocks as they imply considerable additional harvesting of the biosphere. We then suggest that current material stocks can be maintained while accommodating population growth through 2050 if a 2.0 kW/capita limit is established. Although this limit has been shown to be enough for a dignified life, it implies a considerable degrowth in more than half of the world´s countries.

Results

Extended Kleiber's Law

Biological organisms use foodstuff through mitochondria, cells, and muscles to rearrange carbon, hydrogen, and other elements into the components of a functional body and use that body to intervene in the world. Macroecological theory and Kleiber's Law in particular show that a biological organisms' power (P) is allometrically proportional to its mass (M) such that with and for intraspecific and interspecific species, respectively (Feldman & McMahon, 1983; Heusner, 1982; Kleiber, 1961).

Similarly, social systems act as super-organisms that also use energy to rearrange mass into living support structures, and then use those structures to modify the environment (Fig. 1) (Haberl et al., 2019; Krausmann et al., 2017; Rees, 2012). *In a very real sense both animals and economies have "metabolisms". Both consume, transform, and allocate energy to maintain complex adaptive systems far from thermodynamic equilibrium"* (Brown et al., 2011). The main difference is that social systems use more types of energy sources (e.g., foodstuff, biomass, fossil fuels, electricity), through a broader set of prime movers (e.g., people, gas turbines, computers) to rearrange a wider set of materials (e.g., biomass, gravel, iron, silicon) into the components of a functional society (e.g., people, products, buildings, infrastructure).

Our data shows that power and material stocks in social systems seem to be related in a manner consistent with Kleiber's Law in the USA [0.67 (95% CI 0.58-0.75, 95)], Japan [0.61 (95% CI 0.54-0.69, 94.3)], and globally [0.78 (95% CI 0.76-0.80, 98.6)] (Fig. 2.A). We combine these three super organisms with a sample of biological ones to relate power and material stocks over 14 and 17 orders of magnitude respectively and obtain 0.86 (95% CI 0.85-0.86, 99.9) (Fig. 2.B). This higher-than-expected exponent is a numerical artifact due to the different y-intercepts of the individual series' best-fit curves. Independently centering each series eliminates the regression constants and yields 0.74 (95% CI 0.71-0.77, R^2 = 96.7) (Fig. 2.C). Whereas the results for the USA and Japan corresponds to biological intraspecific scaling (0.67 and 0.61 versus 0.67), Humanity's scaling corresponds to biological interspecific scaling (0.78 versus 0.75), and the combined social and biological scaling is identical to Kleiber's original result in 1961 (i.e., 0.74).

Considerations

Why do social systems´ power and mass scale this way? One idea is based on fractal geometry (West et al., 1999), where the invariant "length" could be given by the individual person. Brown et al. (2011) use this idea arguing that "*The energy and other resources that sustain these systems [animals and economies] are supplied by hierarchically branching networks, such as the blood vessels and lungs of mammals and the oil pipelines, power grids, and transportation networks of nations. Models of these networks suggest that three-quarter-power scaling optimizes distribution of resources*". Another idea is based on size-dependent limitation of resource storage (Maino et al., 2014; Thommen et al., 2019), where the role of macromolecules could be played by energy goods. A third idea is based on the interaction of physiological features with environmental conditions (Koziowski & Weiner, 1997), where growth and reproduction could be given by an economy´s aggregate investment and consumption. In any case, noting that the theoretical basis of Kleiber's Law remains controversial after 80 years of research (Escala, 2019; Hulbert, 2014), finding a theoretical explanation for an extended Kleiber´s Law remains as future research that may become foundational science towards Humankind´s sustainability. In the meantime, further data on mass and energy of nations is important to broaden the empirical basis of this relationship.

The main implication of this proposal is that, regardless of the energy mix, future energy growth scenarios are fundamentally proportional to the rearrangement of prodigious amounts of materials given . For a projected population of 9.7 billion and per capita power consumption of 4 kW/capita, the resulting global power growth of 140% between 2010 and 2050 will result in Humanity´s material stocks increasing by 1109 Gt (95% CI 959 – 1271 Gt). The actual amount of raw materials taken from nature would be higher because more than one ton of materials must be extracted from nature per ton of materials included in civilization (Krausmann et al., 2018). Given that Humanity's current material stock is roughly 800 Gt, how can an increase by 1109 Gt to 1909 Gt take place while maintaining the biosphere's integrity? Estimates of Earth's green matter, for example, vary from 268 to 901Gt C with 500-800 Gt C being the generally accepted range.

Trivially, the Extended Kleiber´s Law implies that material stocks simultaneously scale with per capita power and population growth (yellow plane, Figure 3A). The levels of growth in material stocks are shown in 50-year intervals (black, gray, blue, and red planes). The level of material stocks in 1950 (gray) coincide with the onset of the Great Acceleration. The increasing distances between the material-stock planes at 50-year durations depicts the changing speed in material use of the Great Acceleration.

The maximum sustainable level of material stock is currently unknown and undefined. It is likely that 1901 Gt (projected 2050 level) is unsustainable and dangerous, while 81 Gt (1950 level, just before the Great Acceleration) is likely sustainable and safe. The 2010 level of 792 Gt might already be unsustainable, considering that by then humanity had trespassed at least two planetary boundaries, yet it may could be sustainable if ecosystem protection, greener agriculture and low-carbon energy sources were implemented. In any case, setting that year´s material stocks as the maximum sustainable level helps begin the discussion of tradeoffs between per capita power and population. If the Extended Kleiber's Law is true, the balance of these tradeoffs is foundational for sustainability science. For example, a goal to maintain material stocks in 2050 at the 2010 level (792 Gt) with a projected population of 9.7 billion would require no more than 2.0 kW/capita (Figure 3B, dotted line, red marker).

These results include technological progress and thus the tradeoffs cannot be avoided through it. For example, during the 20th century Humanity's power scaled at 0.78 and not proportionally to mass at 1 because, for example, the energy cost of ammonia dropped from over 100 to 33 MJ/kg (Smil, 2001), of iron from over 50 to 10 MJ/kg (Smil, 2008), of aluminum from 50 to 13 MJ/kg (Smil, 2005), light bulbs' efficiency improved from less than 25 to more than 175 lumen/W (Smil, 2003), and engines reduced their mass-to-power ratios from 90 to less than 1 g/W (Smil, 2005). Without these and other technological achievements power would have scaled proportionally to mass, and with 1 humanity's 2010 material stock level would have been associated with power 8,000 times higher. If social systems obey an extended Kleiber's Law as suggested, this relation between power and mass becomes a constraint for social metabolism as fundamental as in animal metabolism (West & Brown, 2005), and technological innovation plays a role in the former as important as evolution has played in the latter.

If population reductions are not an option, the most reasonable response would be a worldwide 2.0 kW/capita limit. The implementation of such limit poses gargantuan technical and political challenges. Given the difficulty and invasiveness of individual measurements of energy consumption, how could a country enforce it? And thus, how could a community of countries do so? Moreover, even if technically possible, it is unlikely that any country would willingly reduce its average per capita power (Smil, 2008). Historically this has only happened under extreme circumstances such as the fall of the Roman Empire and the breakdown of the Soviet Union. A peaceful and ordered lowering to 2.0 kW/capita would be unprecedented in medium-high-powered countries with 3.0 kW/capita (e.g., China, Chile), let alone in very-high-powered countries with more than 10.0 kW/capita (e.g., USA, Australia). In all, 53% of the 151 countries with data in 2014 had more than 2.0 kW/capita. In 2019 such percentage rises to 78% between the 80 countries with data, due to the growth in per capita power and selection bias among countries with most updated information.

Although unprecedented, we contend that such reduction of per capita power is needed regardless of the energy mix given the relation of mass and energy found here. Failing to do so risks disrupting the biophysical foundations of human civilization, and triggering waves of civil unrest and violent conflict in the process (Ahmed, 2017). Fortunately, there is extensive literature documenting asymptotic social returns to power for the Human Development Index (HDI) (Annila & Kuismanen, 2009; Arto et al., 2016;

Lambert et al., 2014; Martínez & Ebenhack, 2008) and other indicators such as political freedom and improved water access (Arto et al., 2016; Goldemberg et al., 1985; Pasten & Santamarina, 2012; Schulz et al., 2008; Smil, 2008). Intuitively, while at low levels of per capita power (e.g., < 1.0 kW/capita) more power helps secure the necessities of life, over a certain threshold (e.g., > 5.0 kW/capita) the data shows such necessities have already been satisfied. Historically, early hunter-gatherers used just enough energy to satisfy their metabolic needs of ~0.1 kW/capita. Power per capita increased throughout the agricultural and successive industrial revolutions such that the current global average is ~2.3 kW/capita and surpasses 10kW/capita in some high-income countries. A specific limit at 2.0 kW/capita has been proposed by the 2000-watt society since 1998 based on the per capita power of western Europe during the 60s and the dignified life it enabled, and according to our results, it is coincidentally the value required to maintain material stocks in check below 800 Gt globally by 2050 given expected population levels.

Moreover, radical increases in resource productivity as outlined in Grubler et al. (2018) and Circular Economy proposals (e.g., Ellen MacArthur Foundation (2013)) could enable some growth in per capita consumption without more energy and material throughput, or their reduction without sacrificing living standards. In any case, such approach must be accompanied by strict limits to aggregate energy use and material stocks to avoid the rebound effect (e.g., Jevons paradox) that has prevented previous efficiency gains to translate into lower environmental pressure. Another approach would be to directly reduce working time and per capita consumption of good and services, which could be welfare-enhancing in high-powered societies (Pullinger, 2014) but would require a profound paradigm shift (Brand-Correa & Steinberger, 2017; Daly, 2014; Kuhn, 1962; Schmelzer, 2015; Vanhulst & Beling, 2014). Perhaps such shift, characterized by a voluntary reduction of overconsumption and the goal of a simpler life, is more critical than the energy transition for Humankind´s sustainability (Wiedman et. al, 2020).

Materials And Methods

All codes and data are available as supplementary information.

Humanity’s material stocks come from Krausmann et al. (2017) and those of the USA and Japan from Fishman et al. (2014)(Fishman et al., 2014). Both sources contain roughly the same non-human types of mass. A human type of mass was included by multiplying yearly population by yearly average weight. This type of mass accounts for virtually 0% of total material stocks. More detail is available upon request.

Humanity’s power comes from Smil (2017) and BP (2019). Data between 1900 and 1910 was linearly extrapolated. Power for the USA and Japan comes from U.S. Energy Information Administration (2019). Mass and power for biological organisms comes from Ramsey & Schafer (2013).

The Extended Kleiber’s Law model was estimated with Ordinary Least Squares using Eicker–Huber–White standard errors. Fig. 2A was obtained by independently regressing the series for Humanity, the USA and Japan; Fig. 2B by regressing those three series together alongside the series with biological organisms; and Fig. 2C by regressing these four series together after demeaning them independently.

The mass associated with future power levels was estimated with the inverse of the Extended Kleiber´s Law, i.e. with . The range of additional material stocks was estimated with the lower bound of the conservative future power prediction and the upper bound of the generous future power prediction.

The mass associated with different population levels at 2.0 kW/capita and with current projections were estimated with the inverse of the Extended Kleiber´s Law. This equation is also used to obtain the three-dimensional graphs depicting the relation between a continuum of materials, population, and per capita power levels.

Declarations

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Supplementary Information

Supplementary Information was not provided with this version of the manuscript.

Figures

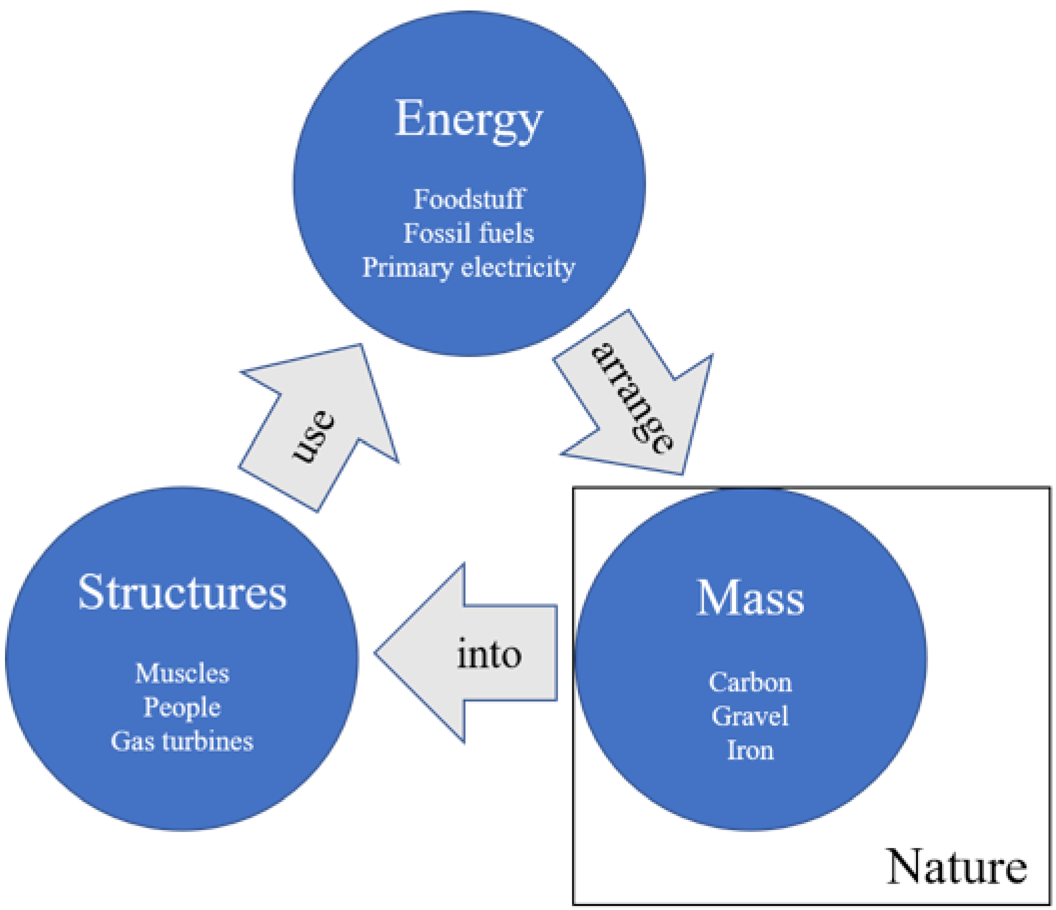

Figure 1

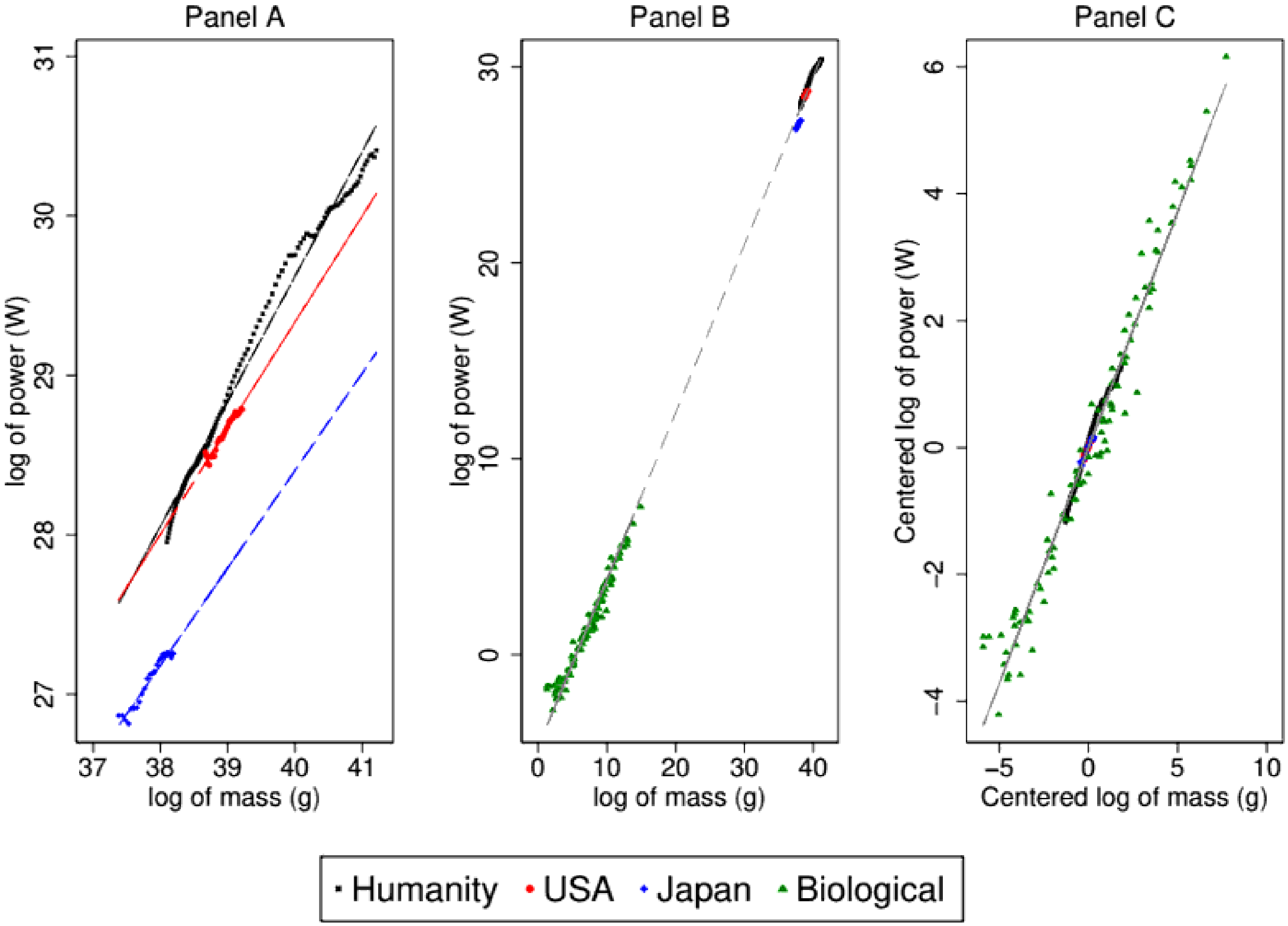

Figure 2

The relation between material stocks and energy. Panel A shows the scatter plot for Japan in blue (n=26), the USA in red (n=26), and globally in black (n=111). Lines are the individual Ordinary Least Squares (OLS) best fit curve. Panel B depicts the information from Panel A in the top right with a sample of biological ones in the bottom left (n=95). The line is the OLS best fit curve for all data (n=258). Panel C shows the same scatter plot but demeaning the series independently. The line is the OLS best fit curve for all the demeaned data. Data available in S.I.

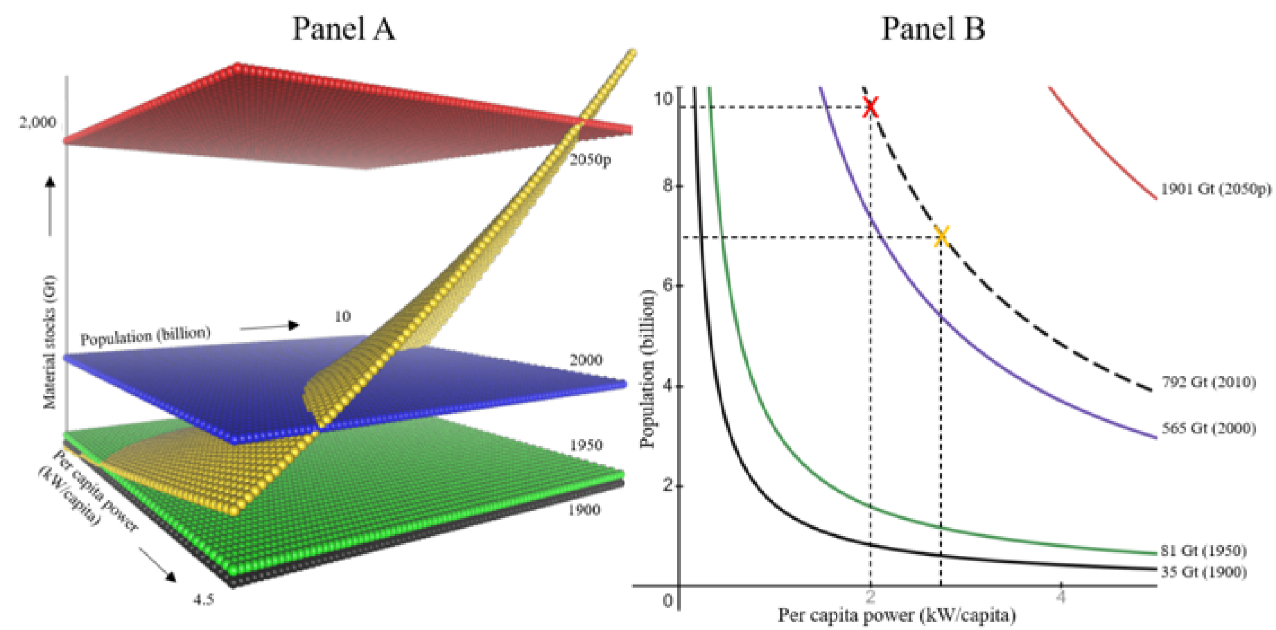

Figure 3

Panel A depicts Extended-Kleiber's Law relation between per capita power, population, and material stocks. The yellow plane shows the 0.78 scaling of material stocks as a function of per capita power and population. In 1900, a population of 1.6 billion people averaging 0.8 kW/capita implied material stocks of 35 Gt (black plane). In 1950, a population of 2.5 billion averaging 1.3 kW/capita implied materials stocks of 81Gt (green plane). In 2000, a population of 6.1 billion people averaging 2.1 kW/capita implied material stocks of 565 Gt (blue plane). In 2050, a projected 9.7 billion people averaging 4.0 kW/capita implies material stocks of 1901 G (red plane). The rapidly increasing distance between the material stock planes at equal 50-year intervals depicts the Great Acceleration. Panel B shows the intersections of the yellow plane at each material stock plane of Panel A to depict iso-material stock curves: the compensation between population and per capita power to maintain the respective material stock levels. Note that these curves only show point estimates of the Extended Kleiber´s Law and therefore need not show the exact historical values of population and per capita power. The dashed-black line in Panel B shows the 2010 iso-material stock curve (2010 level not shown in Panel A). The line depicts 792 Gt of material stocks with 6.9 billion people averaging 2.8 kW/capita (orange marker, actual data for 2010 is 6.9 billion people averaging 2.3 kW/capita). The dashed-black line implies that maintaining Humanity's materials stock at 792 Gt while growing to 9.7 billion people requires 2.0 kW/capita (red marker).