Lotka's Wheel and the long arm of history: how does the distant past determine today's global rate of energy consumption?

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Abstract. Global economic production ~~, or –~~ – the world GDP ~~, has risen –~~ – is rising steadily relative to world primary energy demands, ~~suggesting~~ which suggests that technological change is driving a gradual decoupling of society from its resource needs and associated environmental pollution. Here we ~~show~~ present a contrasting argument, showing that in each of the 50 years following 1970 for which reliable data are available, one Exajoule of world energy was consumed to sustain each 5.50 ± 0.21 trillion constant 2019 US dollars of running cumulative production summed over human history, ~~a scaling that notably does not apply to~~ while no similar scaling applied to the more familiar quantities of yearly production or physical capital. The half-century for which this fixed ratio ~~holds~~ has held covers two thirds of historical growth in energy demands, ~~so the implication is that society is not in fact decoupling from~~ implying that society may be fundamentally coupled to its resource needs. ~~Rather, assuming persistence of the scaling~~ Assuming the scaling continues to persist, it can be expected that future environmental impacts will ~~be more strongly guided by pastactivities, or inertia~~remain strongly anchored to society's unchangeable past, ~~than is generally~~ or by inertia, much more so than has generally been permitted within economic and climate modeling prescriptions that allow for policy to spur more rapid change.

1 Introduction

Alfred J. Lotka regarded the "life-struggle" as a competition for available energy whereby the role of any physical system, subject to external constraints, is to maximize the energy flux through it. "The influence of man, as the most successful species in the competitive struggle, seems to have been to accelerate the circulation of matter through the life cycle, both by 'enlarging the wheel', and by causing it to "spin faster" (Lotka, 1922).

~~While physical constraints may seem an inevitability for~~ In Lotka's view, physical constraints are an inevitability component of any societal action, ~~their consideration nonetheless~~ yet their consideration remains a fringe view ~~relative to the traditional~~ in the economic treatments most widely used to guide economic and climate policy (Tol, 2018; Nordhaus, 2017). There, "production functions" consider resource extraction as just one sector of the economy, no more significant than the services sector, for instance. ~~Such an~~ The approach permits consideration of ~~whether, through technological change and efficiency gains , human prosperity can continue to grow~~ technological change through efficiency gains as able to lift human prosperity while limiting adverse impacts from resource depletion and environmental degradation through waste production (Victor, 2010; Deutch, 2017).

Here we extend our past work ~~that has~~ where we described a new macroeconomic quantity – historically cumulative production – ~~which can be shown~~ that we demonstrated to have had a quantifiable constant relationship with primary energy resource demands (Garrett, 2011, 2012; Garrett et al., 2020). By using a longer available data set, the relationship is demonstrated to hold over a half-century of global growth. Other, more traditional economic quantities such as the world GDP, or economic capital, are not found to exhibit this scaling law, so the result suggests that time series for historically cumulative production may be used to provide a "top-down" guide for facilitating long-run dynamic predictions of future interactions between society, natural resource depletion and discovery, and climate change.

2 Results

To avoid complications associated with the details of trade, ~~or~~ interactions between economic sectors, or distinctions between energy types, this study is focused only on global quantities, as described in the Materials and Methods below. Annual ~~energy demands~~ primary energy sources, those that are available to drive civilization activities of whatever type, are consumed and ultimately dissipated as waste heat at a rate that can be expressed as an instantaneous quantity E ~~with units of power~~ (e.g., Terawatts) or a ~~yearly~~ yearly-averaged quantity E_i with units of ~~energy~~ power (e.g., ~~Exajoules)~~either Terawatts or Exajoules per year) (Garrett et al., 2020). For example, $E_{2019} = 609$ means that humanity ~~in~~ over the course of 2019 was powered by 609 Exajoules or at a rate of 19.3 Terawatts. Annual economic production (Gross Domestic Product) or output is defined monetarily as the sum of tallied financial exchanges made to acquire final goods and services within a given year. After adjusting for inflation, we denote this quantity as Y_i, expressed in units of constant 2019 USD ~~, or as an~~ per year, effectively a yearly average of the instantaneous rate Y ~~as~~ in 2019 USD per year.

Given that humanity's billions emerged from the past, the magnitude of civilization's annual energy demands might be thought to be tied to an economic quantity that is not a rate – as for Y – but rather has accumulated through time and has units of currency. The first candidate we consider for such an accumulated quantity is economic capital K_i, one of the primary factors of production. The second is a time integral of production, not just over one year – as is done in calculation of Y_i – but over the entirety of history, what we term the world historically cumulative production $W_i = \sum_{j=1}^{i} Y_j$, or expressed in continuous form as

$$W(t) = \int_0^t Y(t')\,dt' \tag{1}$$

The contribution of depreciation to W is addressed later.

Time series for Y_i, K_i, W_i and E_i are shown in Figure 1 covering a 50 year period between 1970 and 2019. Global energy consumption E increased by a factor of 2.8, production Y increased by a factor of 4.5, and economic capital K increased by a factor of 7.9. The ratio $y = Y/E$, sometimes termed the energy productivity, has trended steadily upward. Defining growth rates in quantity X as $R_X = (1/X)dX/dt = d\ln X/dt$, a least-squares fit to the data gives $R_y = 1.00\%$ per year. Meanwhile, the ratio $k = K/E$ grew at rate $R_k = 1.96\,\%$ per year, nearly twice as fast as y, or a doubling time of 35 years. The economy appears to be becoming rapidly less energy intensive, suggesting that technological innovation is enabling more to be done with less (Sorrell, 2014).

It would ~~seem~~ be natural to infer from increasing Y/E that technology is allowing the global economy to undergo a long-term decoupling from resource constraints. However, a comparison between W_i and E_i suggests otherwise. Relative to Y_i and K_i, cumulative production W_i increased more slowly ~~,~~ by a factor of 2.7, ~~similar to the factor~~ a similar increase as found for E_i. Expressed (for simplicity) as a continuous function, the ratio $w = W/E$ has fluctuated to some degree, but the average tendency has been $R_w = -0.02\,\%$ per year, far less than the tendencies of either Y/E or K/E. The average value of the ratio is:

$$w = \frac{W}{E} = 5.50 \pm 0.21 \tag{2}$$

in units of trillion 2019 USD of cumulative production per Exajoule of energy consumed each year.

~~Thus, the~~ This relationship between W and E does not appear to be one only of correlation between two quantities, as for example has been noted for E and Y (Jarvis, 2018). Instead the two quantities have maintained a linear scaling over the half century period for which widely published data are available. A least-squares fit to the logarithms of W and E yields the relationship $W = 5.47E^{1.00}$ Calculated instead as a linear fit, the relevant expression is $W = 5.67E - 66$. Note the intercept of the fit where $E = 0$ is equivalent to $W = -66$ trillion 2019 USD. This value is just -1.9% of the 2019 value for W_i of 3547 trillion 2019 USD, and so sufficiently small as to plausibly approximate the origin. By contrast, the linear fit for world GDP and energy is $Y = 0.17E - 21$. So, while Y and E are correlated, they do not scale~~since~~: the intercept corresponding with zero energy demands is $Y = -21$ trillion 2019 USD, or -25% of the 2019 value.

3 Discussion

~~A~~ We interpret the quantity identified here as the historically cumulative global production W ~~appears to be~~ as an economic expression of the rotational power of Lotka's Wheel, that is the capacity to drive the collective to-and-from of civilization's circulations through the relationship $W = wE$, where w is nearly a constant. Certainly, an objection might be raised that the past 50 years is too short relative to the time span of humanity to draw meaningful conclusions about the relationship of cumulative production to energy demands. Measured in units of years, this may be true. However, the ~~period covers roughly~~ last half-century covers a remarkable two-thirds of humanity's growth in its energy consumptive demands, or 1.5 doublings in E, during which ~~clearly~~ a great deal changed in humanity's social and technological makeup.

With respect to an inflation-adjusted production relation, taking the first derivative of Eq. 1, and assuming $W = wE$ for constant w, yields

$$Y = \frac{dW}{dt} = w\frac{dE}{dt} \tag{3}$$

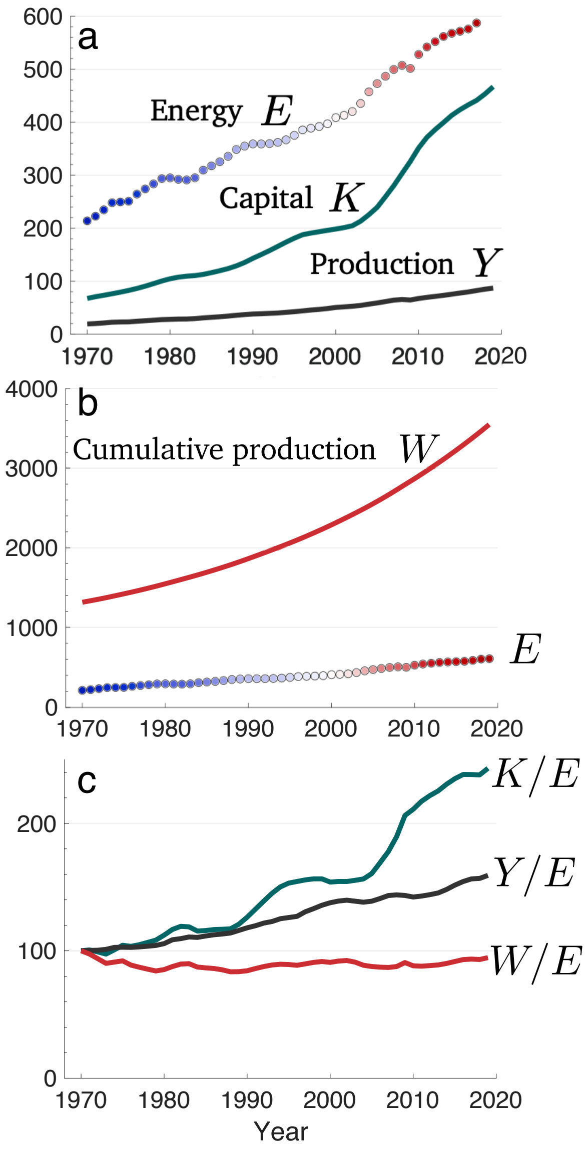

Figure 1. a: Time series for the period 1970 to 2019 of global yearly annual primary energy consumption E_i in Exajoules per year, the world annual GDP Y_i in yearly currency~~per year~~, and the total value of physical capital capital stock K_i in units of currency. b: Energy in Exajoules per year and historically cumulative production W_i in currency. c: The ratio of economic values to annual energy consumption, setting the ratio in 1970 to 100. All currency units are in trillion 2019 USD

~~Expressing economic productionas related to a change~~ In the hypothetical limiting case of $dE/dt = 0$, the world attains a sort of metabolic steady-state characterized by a balance between energetic and material inputs and outputs. Energy consumption maintains a fixed rate, but also there is no *real* economic production. Nominal production may remain, but it is completely eroded by inflation. This hypothetical case of economic collapse may not be survivable. If so, the point at which $dE/dt = 0$ may only represent a temporary marker on a pathway to more complete thermodynamic collapse with the steady-state condition of $E = 0$. A distinction must be made with the quite different steady-state condition where $dY/dt = 0$, namely one of constant inflation-adjusted economic *production* Y, or zero GDP growth, as this would imply continued expansion of energy demands at rate Y/w. In the constant GDP growth case with fixed $d\ln Y/dt$, energy consumption accelerates.

Eq. 3 expresses economic production as proportional to an increase in energy demands, that is its derivative with respect to time, ~~does differ significantly~~ which differs from prior approaches that ~~most usually employ production functions ignoring~~ tend to ignore any explicit mention of the role of energy~~altogether. In the few studies where production functions do appeal to energetic demands, the functional dependence is to some non-unity exponent of E (Ayres et al., 2003; Keen et al., 2019), which is physically and dimensionally nonsensical. While it is certainly possible to obtain through fitting a non-unity exponent relating two quantities, it~~. Where energetic demands are considered, the production functions are complex, and the dimensions of the problem are not considered. Rather than starting with the constraint that the factors of economic production, of whatever combination, must tally dimensionally to units of currency per time, quantities such as dimensionless capital, labor, and useful work are set to non-integer exponents, or are themselves placed in exponents (Ayres et al., 2003; Ayres and Warr, 2009; Lindenberger and K While the functions can be shown to reproduce past behaviors for specific nations, it is only by way of specifying coefficients, or "output elasticities", that are themselves determined from past economic conditions, and that vary according to the time period considered. The production functions become moving targets, and therefore cannot be presumed ~~the fit expresses~~ to express something fundamental about the ~~system unless the appropriate units for physical quantities are maintained.~~ economic system. As attributed by E. Fermi to J. von Neumman "with four parameters I can fit an elephant, and with five I can make him wiggle his trunk."

Here, by contrast, Eq. 3 is simple, dimensionally reasoned, and assumes that w is a constant, so it can be readily refuted (or supported) with data. It does nonetheless have limitations. Note that the quantity of cumulative inflation-adjusted economic production W is highly smoothed because it is a summation, or integration, over history and the global economy. Thus, even given a strong apparent relationship of E to W, variability in E cannot as easily be related to national economic production evaluated on scales of years. Nonetheless, calculated as a running decadal mean, the average ratio of ~~production to change~~ global production to yearly changes in energy consumption is

$$\widehat{w} = \frac{Y}{dE/dt} = 5.9 \pm 2.2 \tag{4}$$

in units of trillion 2019 USD per Exajoule consumed each year, a very similar value to Eq. 2 although more noisy being a differential. Implicitly, ~~our~~ the collective societal assessment of the final inflation-adjusted value of goods and services Y appears to correspond with "enlarging the wheel" or enabling it to "spin faster", that is the technological innovation of a larger human system, one that is newly consumptive over and beyond the scenario where energy consumption rates stay constant.

Current energy demands sustain the wheel's rotation against dissipation. ~~With~~ So, it is only with an excess of available energy ~~,~~ that an effective phase change is enabled to convert raw materials via economic production to newly created components of civilization, and to accelerate societal circulations so that they include them. In fact there is some suggestion ~~of a near equal~~ that the division between changes in size and speed as two independent modes of variability is nearly equal. A linear scaling has been noted between the magnitude of a city's population and how fast its inhabitants walk (Bettencourt et al., 2007). More globally, over the 50 year period considered, world population – as a measure of size – increased at an average rate of 1.46% per year. Meanwhile, per capita world GDP – as a plausible metric for speed – increased at the nearly equivalent rate of 1.55% per year.

At some level, the empirical nature of Eq. 2 stands on its own. Nonetheless, its simplicity may come across as counter-intuitive, especially considering that W is not directly tied to any current economic transaction, only to the past. By way of explanation, consider the circulations within our bodies, brains, and machines, and our activities such as housework, transport to and from work and the grocery store, and even conversation among family and friends, that all of these require ~~energy~~ current energy consumption in some form. ~~While each one of them may indirectly~~ Each one may involve a financial transaction at some prior stage, for cleaning products, gasoline, or food, yet no financially quantifiable purchase is ~~in fact~~ made at the point at which the energy is consumed.

A possible counterargument is that historically distant production cannot linger to contribute to current energy demands~~. Fig~~ , considering that fig trees grown for the enjoyment of Ancient Greeks ~~would~~ seemingly have nothing to do with the power consumption of internet servers today. ~~In~~ The way the problem is approached in traditional economic accounting ~~,~~ is to consider that current capital is formed through economic production Y after subtracting both depreciation at rate δ and consumption C of goods and services, that is $dK/dt = (Y - C) - \delta K$. Expressing consumption as $C = cY$ and adopting a simplified production function of form $Y = \beta K$ where $\beta = Y/K$ is the production efficiency (or the inverse of the capital-to-output ratio), it follows that

$$\frac{dK}{dt} = (\beta - \delta')K, \tag{5}$$

so that the capital exponential growth rate is $R_K = (\beta - \delta')$ where $\delta' = \delta + c\beta$~~and~~ ; consumption itself can be viewed as a form of depreciation of very short-lived capital. From data for Y_i and K_i, the value of β over the past 50 years has steadily declined at an average rate of 0.95% per year ~~but the average value is~~ with an average value of approximately 0.24 or 24%. ~~So, considering how~~ Considering that capital grew at an average annual rate of 4.0% over the same period, the implication is that the annual rate δ' at which capital has been devalued is approximately $24\% - 4\% = 20\%$, that is capital value in traditional accounting has a halving time of just 3.5 years. Well-known concerns may be raised about any comparison of rates of capital formation with capital valuation, and with how valuations of varied capital stocks should be aggregated (Samuelson, 1966; Sraffa, 1975). Nonetheless, the benefits of past productivity clearly persist for much longer. We may no longer use the personal computers of the 1980s, but current devices are derived from that seminal transformation. Ancient Greek fig trees died over 2000 years ago, but important aspects of the culture of fig-eating Ancient Greeks have lasted to today.

The crux of this valuation problem appears to be that the long-distant contributions of past civilizations to politics, science, athletics, architecture, and language are ignored in traditional accounting because they cannot be monetized on an open market, even though without them the bulk of our modern infrastructure for wealth-generation would disappear. As noted by Piketty, “All wealth creation depends on the social division of labor and on the intellectual capital accumulated over the entire course of human history,” continuing “the total value of public and private capital, evaluated in terms of market prices for national accounting purposes, constitutes only a tiny part of what humanity actually values - namely, the part that the community had chosen (rightly or wrongly) to exploit through economic transactions in the marketplace” (Piketty, 2020). Capital K, as valued by curent markets, is an order of magnitude smaller than the more abstract quantity of historically cumulative production W. The scaling between W and E then suggests that energy is required not just to sustain that which we believe potentially available to be sold today, but also the unspoken utility of that which has previously been produced. Civilization was not built in a day.

There are important analogs in the biological and physical world that may provide a ~~guide~~useful guide to economic growth theory. The energy of a wheel’s rotation is the product of its mass and the square of its radius and rotational frequency, all quantities that increase through a prior history of material and energetic increments. In a cloud, a snow crystal grows through the diffusion of vapor molecules~~. Current~~ ; current vapor consumption depends on the reach of the crystal branches into the surrounding vapor field, insofar as the branches have built upon a prior accumulation of condensed vapor residing within the unexposed crystal interior (Lamb and Verlinde, 2011). The leaves of a deciduous tree enable photosynthesis that fuels fluid circulations through the exterior sapwood~~. Leaves~~ ; the leaves die seasonally as the sapwood turns into heartwood that, while not actively connected to a larger rejuvenated leaf crown in the following year, structurally supports it (Shinozaki et al., 1964; Oohata and Shinozaki, 1979). Inevitably there are loss processes, such as friction for a wheel, moments of evaporation or breakup for a snow crystal, or disease and predation for a tree. But, in all cases even quite distant past consumption is the primary determinant of the system’s current energetic demands.

Conclusions

We have identified a nearly constant relationship between world historically cumulative inflation-adjusted economic production and current energy demands~~that~~ . The scaling has held for the past half-century, a period during which resource consumptive demands nearly tripled~~. The result suggests~~ , suggesting that humanity’s current metabolic needs are ~~independent of the current economy as typically quantified financially by the GDP. Instead, cumulative production is better considered as an emergent property of a system that boot-strapped itself to its current state through past technological creation that has allowed more to be produced with less Haff (2014); Garrett et al. (2020). Whatever the explanation, the~~ best considered as emerging from past innovations that allowed for surplus Haff (2014); Garrett et al. (2020). The relationship’s persistence ~~would appear~~ appears to place substantial bounds on humanity’s future interactions with its environment. ~~For one, it~~ It implies that present sustenance cannot be decoupled from past growth, ~~implying~~ or that inertia plays a much greater role ~~for inertia~~ in societal trajectories than has been broadly assumed, for example ~~,~~ in the integrated assessment models used to evaluate the coupling between humanity and climate (Nordhaus, 2017). Even if world GDP growth falls to zero from its recent levels close to 3% per year, the long-term decadal-scale growth in resource demands and waste production ~~would~~ will continue to accelerate. ~~More worryingly, the result~~ The scaling suggests that it is only by way of collapse of ~~the~~ previous growth that led to the wealth we enjoy today, effectively by shrinking Lotka's Wheel, ~~that~~ will our resource demands and waste production ~~can~~ decline. Eq. 1 offers no direct mathematical approach for such an event to occur, except perhaps through hyper-inflation~~, as~~ . In economic accounting, this would lead to high values of the GDP deflator ~~that in economic accounting yield values of~~ so that the inflation-adjusted ~~GDP~~ real GDP would be much lower than the nominal GDP. Historically, hyper-inflation has been associated with periods of societal contraction (Zhang et al., 2007) ~~suggesting~~ pointing to a possible link of inflation to decay (Garrett, 2012).

On the topic of climate policy, a constant value of w ~~implies that economic production can be~~ permits economic production to become decoupled from carbon dioxide emissions, but only provided a rapid switch from carbon to renewables or nuclear energy. ~~All~~ Simply to stabilize carbon emissions, any newly added energy production would need to be emissions free, which based on recent consumption growth rates works out to about 1 Gigawatt per day. Alternatively, or concurrently, some means would need to be devised for decoupling W from E by increasing the value of w. Given the value of w has varied little ~~while society has changed tremendously~~ over the last 50 years while society has changed tremendously, it is difficult to conceive how this would be managed. That said, adjusting w upward could be seen as a new target for mitigating future climate damages.

Appendix A: Methods

Yearly statistics for world primary energy E_i are available for both consumption and production from the Energy Information Administration (EIA) of the U.S. Department of Energy (DOE) for the period 1980 through 2018, and for consumption from British Petroleum (BP) for the years 1965 through 2019 (DOE, 2020; Bri, 2020). A yearly composite of E_i in units of Exajoules per year for the years 1970 to 2019 is created from the average of the three datasets while using single sources where only one is available. The difference between the values in the BP and EIA data sets is significant, $8.5 \pm 1.5\%$, but it is steady, and small relative to the 180% increase in energy consumption over the 50-year time period considered here. Economic production is tallied and averaged using World Bank (WB) and United Nations (UN) statistics for the years 1970 to 2019 (The World Bank, 2019; UNs, 2020) and expressed here in units of trillions of market exchange rate, inflation-adjusted "real" year 2019 dollars. Statistics for the aggregated capital stock of 180 countries K_i are available from the Penn World Tables ~~(Feenstra et al., 2015)~~(PWT) (Feenstra et al., 2015). Uncertainties in UN, WB and PWT economic values are not published. They are assumed here, as with the energy estimates, to be small compared to the many factor increase in their sizes.

The world historically cumulative production $W_i = \sum_{j=1}^{i} Y_j$ requires for its calculation yearly estimates of Y_j prior to 1970, for which we apply a cubic spline fit to the Maddison Database (Maddison, 2003) for years after 1 C.E. Adjustments are made to the Maddison dataset to account for the chosen inflation-adjusted year of the dataset and to convert from currency expressed in purchasing power parity dollars rather to market exchange units using as a basis the time period between 1970 and 1992 for which concurrent MER and PPP statistics are available. The value for cumulative production in 1 C.E. $W(1)$ is obtained by assuming that the population and W were growing equally fast at that time. Population data from 1.C.E and one century before and after show that global population was 170 million and growing at 0.059 % per year (United States Census Bureau, 2021). While there are inevitable uncertainties in the reconstruction of W as with any other, the yearly values of W since 1970 that are emphasized here cover two-thirds of total growth and so the calculations are more strongly weighted by recent data that is presumably most accurate. Thus, calculation of W, most particularly the conclusion that w is nearly a constant, can be shown to be relatively insensitive to uncertainty in the older statistics (Garrett et al., 2020).

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References

BP statistical review of world energy 2020, https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html, 2020.

United Nations Statistical Databases, https://unstats.un.org/unsd/snaama/Basic, (last access: November 2020), 2020.

Ayres, R. U. and Warr, B.: The economic growth engine, Edward Elgar, Cheltenham, UK, 2009.

Ayres, R. U., Ayres, L. W., and Warr, B.: Exergy, power and work in the US economy, 1900-1998, Energy, 28, 219–273, https://doi.org/10.1016/S0360-5442(02)00089-0, 2003.

Bettencourt, L. M. A., Lobo, J., Helbing, D., Kühnert, C., and West, G. B.: Growth, innovation, scaling, and the pace of life in cities, Proc. Nat. Acad. Sci., 104, 7301–7306, 2007.

Deutch, J.: Decoupling Economic Growth and Carbon Emissions, Joule, 1, 3–5, https://doi.org/https://doi.org/10.1016/j.joule.2017.08.011, 2017.

DOE: Annual Energy Review, Tech. rep., Department of Energy, Energy Information Administration, https://www.eia.gov/international/data/world/total-energy/total-energy-production, (last access: November 2020), 2020.

Feenstra, R. C., Inklaar, R., and Timmer, M. P.: The next generation of the Penn World Table, American economic review, 105, 3150–82, 2015.

Garrett, T. J.: Are there basic physical constraints on future anthropogenic emissions of carbon dioxide?, Clim. Change, 3, 437–455, https://doi.org/10.1007/s10584-009-9717-9, 2011.

Garrett, T. J.: No way out? The double-bind in seeking global prosperity alongside mitigated climate change, Earth Sys. Dynam., 3, 1–17, https://doi.org/10.5194/esd-3-1-2012, 2012.

Garrett, T. J., Grasselli, M. R., and Keen, S.: Past world economic production constrains current energy demands: Persistent scaling with implications for economic growth and climate change mitigation., PLoS One, 15, 2020.

Haff, P.: Technology as a geological phenomenon: implications for human well-being, Geological Society, London, Special Publications, 395, 301–309, 2014.

Jarvis, A.: Energy Returns and The Long-run Growth of Global Industrial Society, Ecological Economics, 146, 722 – 729, https://doi.org/https://doi.org/10.1016/j.ecolecon.2017.11.005, 2018.

Keen, S., Ayres, R. U., and Standish, R.: A Note on the Role of Energy in Production, Ecological Economics, 157, 40–46, 2019.

Lamb, D. and Verlinde, J.: Physics and chemistry of clouds, Cambridge University Press, 2011.

Lindenberger, D. and Kümmel, R.: Energy and the state of nations, Energy, 36, 6010–6018, https://doi.org/https://doi.org/10.1016/j.energy.2011.08.014, 2011.

Lotka, A. J.: Contribution to the energetics of evolution, Proc. Nat. Acad. Sci., 8, 147–151, 1922.

Maddison, A.: The World Economy: Historical Statistics, OECD, (last access: April 2010), 2003.

Nordhaus, W. D.: Revisiting the social cost of carbon, Proceedings of the National Academy of Sciences, 114, 1518–1523, https://doi.org/10.1073/pnas.1609244114, 2017.

Oohata, S.-i. and Shinozaki, K.: A statical model of plant form-Further analysis of the pipe model theory, Japanese Journal of Ecology, 29, 323–335, 1979.

Piketty, T.: Capital and ideology, Harvard University Press, 2020.

Samuelson, P. A.: A summing up, Quart. J. Econ., 80, 568–583, 1966.

Shinozaki, K., Yoda, K., Hozumi, K., and Kira, T.: A quantitative analysis of plant form-the pipe model theory: II. Further evidence of the theory and its application in forest ecology, Japanese Journal of Ecology, 14, 133–139, 1964.

Sorrell, S.: Energy Substitution, Technical Change and Rebound Effects, Energies, 7, 2850–2873, https://doi.org/10.3390/en7052850, 2014.

Sraffa, P.: Production of commodities by means of commodities: Prelude to a critique of economic theory, CUP Archive, 1975.

The World Bank: DataBank, https://databank.worldbank.org, 2019.

Tol, R. S. J.: The Economic Impacts of Climate Change, Review of Environmental Economics and Policy, 12, 4–25, https://doi.org/10.1093/reep/rex027, 2018.

United States Census Bureau: Historical Estimates of World Population International Data Base, Tech. rep., https://www.census.gov/data/tables/time-series/demo/international-programs/historical-est-worldpop.html, 2021.

Victor, P.: Questioning economic growth, Nature, 468, 370–371, https://doi.org/10.1038/468370a, 2010.

Zhang, D. D., Brecke, P., Lee, H. F., He, Y.-Q., and Zhang, J.: Global climate change, war, and population decline in recent human history, Proceedings of the National Academy of Sciences, 104, 19 214–19 219, https://doi.org/10.1073/pnas.0703073104, 2007.