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Garrett relation

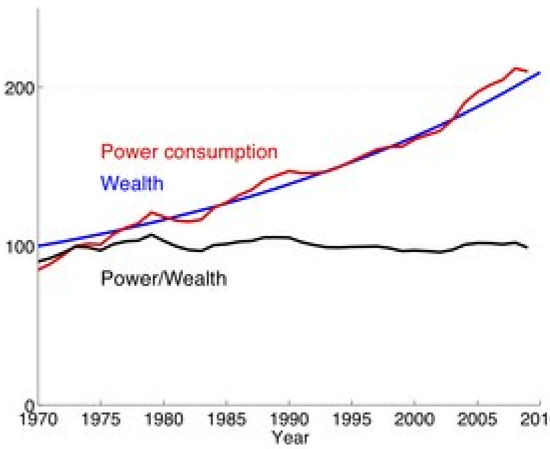
The **Garrett Relation** postulates that there exists a fixed relationship between the world inflation-adjusted Gross Domestic Product, accumulated over all of history, and the current rate of global energy consumption. It was first identified in 2009 in a study of the forces controlling the evolution of world carbon dioxide emissions.[1]

Contents

Observational evidence

The Garrett Relation applies to global quantities, not to individual countries or economic sectors due to the imbalances created by trade.[2] Tabulating global economic production as the world real annual GDP, the sum of GDP over all years (with index i) is termed the cumulative production C: [3]

$$C = \sum_i GDP_i$$



Indexed changes in the rate of global energy consumption (power) and wealth C relative to 1970. The ratio has been invariant to within observational uncertainty.

The current rate of global primary energy consumption E can be related to cumulative production C through a coefficient λ:

$$E = \lambda C = \lambda \sum_i GDP_i$$

The hypothesized scaling defining the Garrett Relation is that the value of λ is a constant that is independent of the year that is considered.

Economic statistics from the Maddison database,[4] the United Nations (https://web.archive.org/web/20170505195258/https://unstats.un.org/unsd/databases.htm), and the U.S. Energy Information Administration (https://www.eia.gov/beta/international/data/browser/) show that the value of $\lambda = E/C$ is 7.1 milliwatts of current power consumption per inflation adjusted year 2005 United States dollar (USD) for each year since 1970, the period for which concurrent statistics for annual global GDP and global primary energy consumption have been published. The year to year standard deviation of λ has been 3% over a time period when GDP increased by 238% and C increased by 111%.[5]

The Garrett Relation can also be expressed as a continuous function. Supposing that $Y\left(t'\right)$ is the inflation-adjusted economic production for the world estimated at each point in history t', its integral over time has a relationship to the current rate of energy consumption $E\left(t\right)$ through a parameter λ

$$E\left(t\right) = \lambda \int_0^t Y(t')dt'$$

Thermodynamic justification

Civilization is an open thermodynamic system. It uses external sources of primary energy and raw materials and dissipates waste heat and materials. The historical accumulation of real economic production is assumed to reside in the capacity to use energy to sustain civilization by enabling flows of communication and materials along networks connecting people to people, and people to capital and the physical environment. Real GDP represents added value by growing networks. As part of a dissipative system, a continuous expenditure of energy is tied to the historically accumulated real production of civilization's networks.[5][6]

In traditional economic treatments capital is believed to be a physical quantity that possesses value independent of energy constraints. The Garrett Relation implies that an individual capital element has no value without an associated consumption of primary energy to actively connect it to other civilization elements. From this perspective, a very generalized metric of wealth lies in active networks of people and infrastructure rather than specific physical capital elements. Civilization has no value without energy consumption. In this way, if global energy consumption were to cease entirely, the value of civilization would rapidly tend towards zero. Not only current GDP would go to zero, but so would the inflation adjusted value of all past production go to zero. This is perhaps the most direct available way to see the connection of power consumption to not just current real GDP, but all past GDP summed as well.

A corollary of the Garrett Relation is that the global GDP is linked to the amount of physical work done to grow civilization's networks. For a net positive GDP, work must be sufficient to overcome natural network decay. The magnitude of decay in reducing real GDP is implicit in the Garrett Relation through the inflationary adjustment from nominal to real GDP, accounted for by the GDP deflator.[5]

Economic implications

Traditional economic growth models represent capital growing due to economic production less consumption and depreciation. In these models, economic production is a consequence of the combined contributions of labor, capital and economic productivity. The GDP grows in response to increasing quantities of each.

On a purely mathematical basis, the Garrett Relation implies an alternative economic growth model. Taking the first derivative of the Garrett Relation with respect to time leads to:

$$\frac{dC}{dt} = Y = \frac{1}{\lambda}\frac{dE}{dt}$$

Inflation-adjusted global economic production adds to global cumulative production. For real production (*i.e.* production beyond that needed merely to maintain existing civilization elements against decay) to exist, what is required is increasing global power consumption capacity.

Dividing by the Garrett Relation $E = \lambda C$gives the growth rate of energy consumption η

$$\eta = \frac{1}{E}\frac{dE}{dt} = \frac{1}{\lambda}\frac{Y}{E}$$

This equation describes how a global economy with a higher energy efficiency Y/E (or equivalently a lower energy intensity E/Y) has a higher value of η and therefore more rapid growth of its energy demands. As long as the Garrett Relation continues to hold, increasing energy efficiency is essential for real global economic growth.

The Garrett Relation is consistent with the **Generalized Jevons' Paradox**;[7][8] a wider more explicitly thermodynamic interpretation of the classic Jevons' Paradox, and also known as the Khazoom-Brookes Postulate.[9] William Stanley Jevons observed that improving the energy efficiency of coal driven steam engines would lead to increased coal consumption as it would facilitate a stronger economy and enable mining coal at a faster rate. The Generalized Jevons' Paradox says that any improved civilization efficiencies will result in savings - savings which can and will be used to enable economic output elsewhere in the economy - and the additional output encumbers new energy consumption to support the new growth enabled[7] reflected as higher total values of . From a thermodynamic perspective, with lower energy intensity of production, civilization is able to incorporate new raw materials to grow its networks at a faster rate. A larger civilization is able to increase its access to energy resources and therefore its ability to consume them.[1][2]

Energy efficiency, population, and some other traditional measures included as independent variables in standard economic models are, in this new view, seen to be dependent variables. [3] The ruling paradigm is the optimization of economic growth on an individual as well as national and global scale. We invest in energy efficiencies to the level current economic conditions allow. We grow population at a rate allowed by fundamental energy availability, and hence wealth constraints. Political constraints may inhibit such growth, but these will not violate the Garrett Relation as they are reflected in lowered total time integrated real GDP as well.[10][8]

Implications for sustainability and climate change

The Garrett Relation ties economic growth to the discovery, access, and increased use of energy and raw materials. In general, larger civilizations are better able to discover and utilize new energy resources. However, limits to growth are imposed by resource depletion and accelerating network decay due to higher environmental destruction and pollution.[5]

The rate of global energy consumption is closely coupled to emissions of the long-lived greenhouse gas carbon dioxide (CO_2) due to the large fossil fuel component of the energy supply. CO_2 is a long-lived gas in the atmosphere. The Garrett Relation implies that current rates of energy consumption are attributable to the historical accumulation of civilization cumulative production due to past economic activity. Thus, even if future CO_2 emissions rates stabilize, continued accumulation of CO_2 in the atmosphere can be expected to be "locked in" by past fossil fuel infrastructure development.[2]

A dynamic model based on the Garrett Relation has been used to argue that there is no 21st century scenario consistent with stabilized atmospheric CO_2 concentrations without a combination of an unrealistically rapid switch away from fossil fuels together with a low resilience of society to the climate damages that would correspond with economic collapse.[11]

Decreasing the energy intensity of the economy has been suggested as a strategy for dealing with both limits to growth and rising CO_2 emissions.[12] The Garrett Relation shows this is problematic. It follows from the Garrett Relation (Nolthenius (2018, p 262-264[10]) that

$$1/\lambda = \partial f/\partial t + (f/Y)\partial Y/\partial t$$

where $f = E/Y$ is the energy intensity of GDP, plotted on Figure 1 with historical data. Historically, λ , f, and Y are all positive. Thus, a prolonged global degrowth or recession with $\partial Y/\partial t < 0$ implies increasing energy intensity.[7] If the Garrett Relation remains true (*i.e.* λ remains constant), then decreasing the energy intensity of the economy is, in fact, incongruent with long-term economic degrowth.

The Garrett Relation implies that civilization accesses energy to the maximum extent possible given existing societal and resource constraints, subject to thermodynamic constraints.[5] Most strategies for climate change mitigation assume that civilization can stabilize climate by increasing energy efficiency and choosing not to access energy at the highest rate and efficiency possible. However, this behavior would be in stark contrast to the observed behavior of biological systems generally. Civilization, considered as a living organism, behaves as an "optimal forager". It makes maximum efficient use of past production to support its current size and to power future growth.[7][13][14][15][16][8] Realistic climate projections, and the Garrett Relation, indicate that maximizing economic growth is incompatible with stabilizing global climate.[12][17]

Criticisms

Application of thermodynamics to human systems

It has been argued that complex human systems are not deterministic physical systems.[18][19] Human systems exhibit highly complex behavioral changes in response to market forces that in turn alter markets. Such non-linear behaviors are not generally present in physical systems.

However, non-linear systems are observed throughout the physical universe and are not precluded by the Garrett Relation. Even if people exhibit learning and emergent behavior within evolving legal strictures and can be argued to exhibit free will, humanity is also subject to thermodynamic laws that constrain aggregate behaviors on global scales.

Relationship of energy to GDP

The relationship of global energy consumption to GDP has changed over time as the energy intensity of the economy has steadily declined (*i.e.* energy efficiency has steadily improved). [18][19] However, the Garrett Relation relates global accumulated global GDP - not current global GDP - to rates of energy consumption. The annual GDP growth rate peaked at 6% in the 1960s whereas the maximum annual growth rate of cumulative GDP peaked in the past decade at 2.4%.[4]

Accuracy of economic statistics

Inflation measures: Decay in past economic production is implicitly accounted for by the adjustment from nominal to real GDP in historical statistics. Politically motivated biases may cause officially reported consumer price inflation (CPI[20], a major component of the GDP price deflator[21]) to be lower than actual.[10][22][23] For many policy and economic purposes, a desired inflation measure should correct nominal prices for changes in price levels of the changing goods and services in the economy. For example, trends in the U.S. economy show static or declining wages for most Americans, forcing substitution in consumption downward in the quality scale. Improper substitution procedures, it is argued, artificially bias CPI to be low.[24][25] Correcting for this bias may make the historical Garrett Relation more constant than official data would suggest.[10] However, a predictive model based on the Garrett Relation does not account for actions by Central Banks that may arbitrarily raise or lower inflation due to arbitrary policy decisions unrelated to actual cumulative production.[10][8]

GDP as a measure of total production: Calculation of cumulative production is based on officially reported GDP. Unreported transactions that are part of a "shadow economy" are not included in the GDP. The thermodynamic validity of the Garrett Relation implies that a proper measure of C should include these. If unreported transactions remain proportional to the reported GDP, then the constancy of the Garrett Relation still holds, with the value of λ being lower. The shadow economy was measured using proxies by Elgin and Oztunali[26] to be as large as 26% of official GDP in the 1960s, but quickly declining to about 22% during recent decades. Incorporating the shadow economy into the Garrett Relation, however, actually makes the resulting trend over time of the ratio of integrated C to current power consumption more nearly constant, and thus supports more strongly the thermodynamic connections and validity of the Garrett Relation[10] [8].

Use of Market Exchange Rate rather than Purchasing Power Parity currency conversion: In converting published national GDP values to a unified currency, two principal methods have been used; "Purchasing Power Parity" (PPP[27]) uses the prices of a sample of nearly identical products between countries to convert between currencies, while "market exchange rates" (MER) uses real world market-driven currency exchange rates averaged over the relevant year. The Garrett Relation is based on MER accounting, but it has been argued that PPP accounting is more suitable.[19] MER accounting is used to calculate the Garrett Relation because PPP accounting is not adapted for an integrated global context focused on energy consumption where comparisons between people in various countries are not considered. Market exchange rates implicitly include estimated future value of purchases to the currency value via standard discount methods employed by traders, while PPP was designed to focus instead on present currency equivalence. Since the Garrett Relation connects past economic production to current power consumption and thus current production to future power consumption, MER accounting has been judged most appropriate.[5][7]

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