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The Key Role of Energy in Economic Growth

Robert U. Ayres, Paul E. Brockway, Emmanuel Aramendia

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Introduction

Most articles on *energy and economics* focus on aspects such as the price of petroleum, the cost of electric power, or the demand for domestic air conditioning or industrial heat. Those topics are about the factors driving producers to invest in different sources of supply, and the factors affecting demand. Instead, this article is about how energy acts as a crucial factor of production and as a driver of, or barrier to, economic growth. It also explains how it happens that conventional economic theory neglects the role of energy, and discusses the implications of that neglect in terms of explaining past economic developments and forecasting the future. This article presents the key thermodynamic-based concepts for studying the relationships between energy and the economy, and finds that upcoming energetic constraints mean the neo-classical illusion of a global, perpetual economic growth machine will fail, and most likely sometime soon.

General Overviews

The role of energy in economic growth requires understanding from various strands. First, on the side of energy, Smil 2017 provides a very good starting point for understanding energy use in a global, historical context. Related to the concept of energy, Sciubba and Wall 2007 provides an excellent explanation of the second thermodynamic law and the definition and historical use of the term exergy (as potential work). Second, on the side of economics, Coyle 2015 provides a good history of the development and use of economic output, specifically gross domestic product (GDP). The statistical linkage between energy and economic growth is well reported, for instance in Csereklyei, et al 2016. A brief history of the development and use of production functions—used by mainstream economists to add up economic growth—is given by Mishra 2010. The flaws in mainstream economics is well laid out by Keen 2011 in the author's classic book *Debunking Economics*. Third, on the side of the impacts of energy use, the IPCC 2014 provides the most comprehensive report on the impacts of rising greenhouse gas emissions, which occur mainly from fossil fuel burning. The economic impacts of energy-related greenhouse gas emissions is best covered in Stern 2006. Last, bringing these strands together, few comprehensive summaries of the thermodynamic (exergy) based role of energy in economic growth exist as books. The two most relevant are Foxon 2017 and Ayres and Warr 2010.

Ayres, R. U., and B. Warr. 2010. *The economic growth engine: How energy and work drive material prosperity*. Cheltenham, UK: Edward Elgar.

This books present a theory of growth based on energy, measured most precisely as useful exergy, namely the energy available for producing work within an economy. It is shown that such a theory of growth can account for 20th-century economic growth in both the United States and Japan, without resorting to exogenous technological progress, conversely to neoclassical growth theory.

Coyle, D. 2015. *GDP: A brief but affectionate history—Revised and expanded edition*. Princeton, NJ: Princeton Univ. Press.

This book recounts the history of GDP indicator, from its invention in the 1940s and its evolution until current times. The strengths and weaknesses of this indicator are discussed, and it is concluded that although GDP might have been an appropriate indicator in the 20th century, it is proving increasingly inappropriate.

Csereklyei, Z., M. Rubio, and D. I. Stern. 2016. Energy and economic growth: The stylized facts. *Energy Journal* 37.2: 223–255.

In this article energy and GDP data from 1971 to 2010 for a panel of ninety-nine countries are reviewed. It is found that there is long-term evidence of relationship between energy use per capita and GDP per capita, and that the energy use per capita has tended to decrease in countries that have become richer, but not in other countries. Other findings include that energy use per capita has tended to rise and that the energy quality has tended to increase.

Foxon, T. J. 2017. *Energy and economic growth: Why we need a new pathway to prosperity*. London: Routledge.

This book provides a review of the role of energy in economic growth and in the waves of industrial change. The history of energy sources and technologies is presented, as well as the ecological challenges associated with the current economic growth paradigm, and the needed low carbon energy transition is discussed.

IPCC. 2014. IPCC Fifth Assessment Report: Climate change. Cambridge, UK: Cambridge Univ. Press.

IPCC reports are a comprehensive review of the most recent scientific literature related to climate change. The First Assessment Report (FAR) was published in 1990, the Second Assessment Report (SAR) in 1995, Third Assessment Report (TAR) in 2001, Fourth Assessment Report (AR4) in 2007, and most recently the Fifth assessment Report (AR5) was published in 2014.

Keen, S. 2011. *Debunking economics: The naked emperor dethroned?* London and New York: Zed Books

In this book, mainstream economic theory is sternly questioned, as numerous flaws and inconsistencies are presented and discussed. Keen discusses the reasons of the recent economic crisis and what ought to be done in order to better the economy's situation.

Mishra, S. K. 2010. A brief history of production functions. *IUP Journal of Managerial Economics* 8.4: 6.

In this work, the history of production functions and aggregate production functions is presented. This includes notably the beginning of the concept, the different functional forms that were suggested as the early Cobb-Douglas proved limited, and attempts to include energy flows in APFs. The main limits and criticisms addressed to the aggregate production function approach are equally presented, including the Cambridge Capital Controversies and the underlying identity criticism.

Sciubba, E., and G. Wall. 2007. A brief commented history of exergy from the beginnings to 2004. *International Journal of Thermodynamics* 10.1: 1–26.

This article presents a comprehensive review of the exergy concept. The historical development of the concept is described, as well as its main applications, which includes very diverse fields such as engineering, complex systems analysis, life cycle analysis, and societal systems analysis.

Smil, V. 2017. *Energy and civilization: A history*. Cambridge, MA: MIT Press.

This book provides a historical review of the relationship between energy and society, and of how energy has shaped society across the ages, from foraging societies to the current fossil fuel–based industrial society.

Stern, N. 2006. *The economics of climate change*. London: Cambridge Univ. Press for H. M. Treasury U.K.

This book, also known as "The Stern Review," represents the most extended and well-known work discussing the economic impacts of climate change. Available for purchase online.

Fundamentals of Thermodynamics and Energy

This first section summarizes the key thermodynamic laws and their application to energy use and conversion. This is covered in two historical periods: the key developments in the 19th century, and next the 20th century onward.

19th-Century Foundations

Before the key insights of the relationship between energy use and economic growth are viewed, it is worth introducing the fundamentals of thermodynamics and energy. Indeed, thermodynamic laws are paramount in understanding these relationships, as the first law accounts for the fact that energy can change from one form to another but is always conserved, and second law for the fact that energy canot be completely converted into physical work. Thermodynamics can reasonably be called the essence of physics. It is about the relationships between heat and other forms of energy (as the name implies) and more generally about relationships between all the forms of energy. Types of energy come in various forms, including chemical, electrical, mechanical, thermal, nuclear, and gravitational. The relationship between energy use and physical work and the development of the laws of thermodynamics were established in the 19th century. The obvious start date is 1824, when Carnot 1824 published his treatise *Reflections on the Motive Power of Fire*, where he stated "the work that can be extracted of a heat engine is proportional to the temperature difference between the hot and the cold reservoir." Clausius 1867 and Thomson 1849 published simultaneously definitions of the two laws of thermodynamics. Later, Clausius 1867 introduced the concept of entropy (as a measure of the unavailabilty of energy in the universe to do physical work), and restated the first law (the energy of the universe is constant) and second law (the entropy of the universe tends to a maximum). Of particular importance in relation to energy conversion and end use is the second law. Noting that not all energy can be converted into work, Gibbs 1873 introduced the concept of "available energy" (later called Gibbs free energy), to define the maximum amount of mechanical work that could be extracted from an energy source. A decade later, the part of energy that can perform physical work was first described as *useful work* by Anderson 1887.

Anderson, W. 1887. *On the conversion of heat into work: A practical handbook on heat-engines*. London: Whittaker.

This textbook, aimed at students and practical engineers of the day, presents the principles of how heat-engines turn heat into physical work, with supporting examples. Notably the book also contains possibly a first written reference of the term *useful work*, which predates by nearly eighty years Rant's *exergy* term.

Carnot, N. L. S. 1824. *Réflections sur la puissance motrice du feu et sur les machines propres a développer cette puissance*. Paris: Bachelier.

Carnot's work is regarded as the onset of modern thermodynamics. Carnot firstly describes what will come to be known as the second law of thermodynamics, later formalized by Clausius. He also introduces the ideal thermodynamic machine, which is still currently used as a reference for diverse thermodynamic cycles. Reprint. Edited by R. Fox. Libraire Philosophique J. Vrin, Paris, 1978.

Clausius R. 1867. *The mechanical theory of heat: With its applications to the steam-engine and to the physical properties of bodies*. London: John van voorst.

In this landmark book, which combines Clausius's earlier works, the second law of thermodynamics and the entropy concept are formalized. It is therefore a work of key influence in the development of modern thermodynamics.

Gibbs, J. W. 1873. *Collected works*. New Haven, CT: Yale Univ. Press.

In this work Gibbs's concept of free energy is introduced. This concept is key as it predates the exergy concept. Although these two concepts are not thermodynamically equivalent, they both account for the fact that only a portion of energy is available to produce work. Therefore the concept of free energy can be regarded as part of the development of the modern exergy concept. Originally published in *Transactions of the Connecticut Academy of Arts and Sciences*. Vol. 2 (1948): 382–404.

Thomson, W. 1849. XXXVI.—An account of Carnot's theory of the motive power of heat; with numerical results deduced from Regnault's experiments on steam. *Earth and Environmental Science Transactions of The Royal Society of Edinburgh* 16.5: 541–574.

The two laws of thermodynamics are formally presented in this early work. Alongside Clausius's formulations, these are the first formal formulations, hence the relevance for later thermodynamic applications.

Into the 20th Century: Introducing Exergy

The concept of useful work as the component of energy that can perform work was translated as a new term, "exergy," by Rant 1956. A general definition was given by Baehr 1965, which later Wall 1977 restated as "the maximum theoretical useful work obtained if a system S is brought into thermodynamic equilibrium with the environment by means of processes in which the S interacts only with this environment." Thus, we know from the first law that energy is conserved in every physical process, but the second law states that the energy available to perform work, that is, *exergy*, decreases as its useless counterpart, *anergy*—which is the component of energy that cannot do work—increases. Later, Szargut, et al. 1988 defined exergy for different energy sources. Consequently, some kinds of energy are more useful than others, as they have a greater ability to perform work. The term *work* in thermodynamics refers to force transferring useful energy (measured as useful exergy) to cause a physical action, such as acceleration of a vehicle, overcoming gravity, or friction. Examples of useful thermodynamic work (i.e., useful exergy) include raising pyramids, driving locomotives, cutting trees, plowing a field, reducing ores to their elements, manufacturing ammonia from natural gas. or operating a computer. Of key note is that electricity – which is an energy carrier not energy source – is pure exergy. It is important to distinguish between first and second law energy efficiency, as firstly evidenced in Carnahan, et al. 1975. First law efficiency is the ratio between (useful) energy output to energy input of a given process, such as a gas heater. It is calculated by dividing the heat content of the air, water, or steam by the heat content of the input fuel. The higher the ratio, the greater the first law efficiency. The second law (exergy) efficiency is defined in exergy terms, as the ratio between the minimum theoretical exergy input to a process divided by the actual exergy input. In general, second law efficiencies are much lower than first law efficiencies, which can be quite misleading, as defended in Winter 2007. For example, take the case of low temperature heating, where first law boiler efficiencies are typically above 80 percent, compared to second law efficiencies of ~5 percent. So, we have learned that energy conversion and use must obey thermodynamic laws, by definition. These have key implications for economics, as we shall see later.

Baehr, H. D. 1965. *Energie und Exergie*. Dusseldorf, Germany: VDI.

Baehr provides an early definition of the exergy concept, which makes this work of historical interest.

Carnahan, Walter, Kenneth W. Ford, Andrea Prosperetti, et al. 1975. *Efficient use of energy: A physics perspective*. New York: American Physical Society.

This report, issued after the 1973 oil crisis, was a first attempt to draw scientists' and engineers' attention to the issues of energy efficiency. The difference between first and second law efficiency was evidenced as it enabled widening first law energy analysis.

Rant, Z. 1956. Exergie, ein neues Wort für "technische Arbeitsfähigkeit." *Forsch. im Ingenieurwesen* 22:36–37.

Rant's linguistic essay discusses international equivalent names for the term *exergy* (he proposed *exergie* in French and German, *exergia* in Spanish, *essergia* in Italian, and *eksergija* in Slavic languages).

Szargut, J., D. R. Morris, and F. R. Steward. 1988. *Exergy analysis of thermal, chemical, and metallurgical processes*. New York: Hemisphere Publishing.

This book presents the concept of exergy, what the exergy value of different substances is, then it carries out the exergy analysis of different processes, and demonstrates different applications of the exergy analysis field, notably thermoeconomic and ecological applications.

Wall, G. 1977. *Exergy – A useful concept within resource accounting*, Report No. 77–42. Gothenburg, Sweden: Institute of Theoretical Physics, Chalmers Univ. Technology.

This reports defends the usefulness of the exergy concept for resources accounting and presents the results of an exergy based resource accounting of the 1975 Swedish economy. This study is of key interest as it is the first of an extended literature of exergy accounting studies, i.e., resource accounting studies based on resources' exergy content. Available online.

Winter, C. J. 2007. Energy efficiency, no: It's exergy efficiency! *International Journal of Hydrogen Energy* 32.17: 4109–4111.

In this article, the author defends exergy—or second law efficiency—versus energy efficiency. Indeed it is argued that exergy efficiency enables one to think out of a given energy system, while energy efficiency limits the scope to within a particular energy system.

Fossil Fuel-Driven Exponential Economic Growth

From the thermodynamic platform, the next section covers how fossil fuels have provided the energetic inputs to fuel the industrial revolution. The first part explores the historical period of energy use and technological development since the 18th century, and how energy use and economic growth are causally linked. Second, the deleterious planetary impacts of global fossil fuel combustion is summarized.

Energy Use and the Industrial Revolution

Economics has been called "the dismal science" (by Thomas Carlyle), because of the Malthusian argument, which stems from Malthus 1798 that human population will always grow faster than food supply, whence the future of mankind was destined to be constrained by poverty and starvation. That didn't happen during the following two centuries and hasn't happened yet. In fact, overproduction seems to be a greater problem (in the developed world) than underproduction. The basic reason why Malthus's forecast missed the mark is simple. He didn't allow for the rapid increase in economic productivity that was achieved in Western countries, starting in the 18th century. That increase in productivity was due to exploitation of coal (and subsequently other hydrocarbons) to drive so-called "heat engines" capable of doing thermodynamic work. Watt's steam engines arrived (mainly in coal mines) only a few decades before Malthus, in the 18th century. Their first application to transportation and manufacturing came later. Those crude steam engines and their descendants are now ubiquitous. They range from stationary steam turbines utilizing coal (or nuclear heat) and gas turbines for electric power generation to mobile gasoline or diesel engines that drive vehicles (cars, trucks, aircraft) or other mobile equipment. Internal combustion engines depend upon liquid or gaseous hydrocarbons. In fact, modern mobility systems—excluding electrified rail—are currently almost entirely dependent on the availability of liquid hydrocarbons, such as gasoline, kerosene, and diesel oil, with ethanol (from sugar cane or corn) as an exceptional alternative. In the early 19th century, Dupin 1827 counted the animals and machines. He concluded that they multiplied the work done directly by human muscles by a factor of five in that year. Food and feed are still an important input for human workers and animals. But the energy (exergy) consumed by machines today comes mainly from fossil fuels—photosynthesis-derived "buried sunshine," as described by Dukes 2003, from biota that lived hundreds of millions of years ago (hence "fossil" fuels). The tight coupling between the exponential growth of fossil fuel (energy) use and economic growth is unequivocal, as shown by Belke, et al. 2011 and Stern and Kander 2012.

Belke, A., F. Dobnik, and C. Dreger. 2011. Energy consumption and economic growth: New insights into the cointegration relationship. *Energy Economics* 33.5: 782–789.

This study finds that international developments are key in explaining energy demand in OECD countries. It also points out that energy consumption is relatively price-inelastic, hence energy consumption is seen as a necessity. Causality tests carried out suggest that energy consumption and economic growth act to mutually cause one another.

Dukes, J. 2003. Burning buried sunshine: Human consumption of ancient solar energy. *Climate Change* 61:31–44.

This paper constitutes a first attempt to estimate the amount of ancient solar energy that was photosynthetically fixed and stored as fossil-fuel carbon. Calculations suggest producing coal from plants is less than 10 percent efficient, while oil and gas from photoplankton is less than 0.01 percent efficient. The author suggests replacing fossil fuels with modern biomass would require a 50 percent increase in the appropriation of biota for human energetic use. Available for purchase.

Dupin, C. 1827. *Forces Poductives et Commerciales de la France*. Paris: Bachelier.

This book provides an overview of the French industrial and commercial strengths and of how these could be improved. There is a particular focus on the counties of northern France.

Malthus, T. R. 1798. An essay on the principle of population.

Malthus's seminal work described the idea that population would grow faster than food supply, resulting in famine and starvation, unless preventive measures were adopted.

Stern, D., and A. Kander. 2012. The role of energy in the industrial revolution and modern economic growth. *Energy Journal* 33.3: 125–152.

In this study, the authors use an extended Solow growth model, in which energy is included alongside labor and capital, in order to investigate two hundred years of Swedish economic growth. Findings imply that a scarcity in energy services considerably constrain economic growth and result in a steady-state economy. The increase in energy services is found to be a major driver of economic growth.

Impacts of Fossil Fuel Use

Consumption of hydrocarbons is thus closely related to overall economic activity. However, the waste products of fossil fuel consumption—mainly carbon dioxide (CO_2), but also methane, sulfur and nitrogen oxides, and particulates—are now known to be directly harmful to human health. CO_2 and methane are also known as "greenhouse gases" (GHGs) because they absorb thermal radiation from the Earth and re-radiate it back to the Earth, raising the surface temperature, as noted by Arrhenius 1896. GHGs must either accumulate in the Earth's atmosphere or be dissolved in the oceans (making them more acidic). McKibben 2011 describes how this atmospheric buildup of GHGs tends to cause climate changes, such as increased storm frequency and violence as well as ocean warming. The warming is already evident in the Arctic and Antarctic regions, where average temperatures have already risen by several degrees Celsius and sea ice is becoming thinner and melting earlier. Mountain glaciers are also melting, resulting in more rapid spring runoff and flooding. The IPCC 2014 evidences that CO_2 emissions from energy-related combustion of fossil fuels accounts for the majority of global GHG emissions. Steffen, et al. 2015 demonstrates how such physical impacts are but part of exceeding a wider set of planetary boundaries. Besides physical impacts, climate change has damaging economic implications, both due to adverse consequences to agriculture per se and indirectly due to increased storm damage and rising sea levels, which has been studied by Nordhaus 1991 and Stern 2006. Shifting temperature-rainfall patterns will also affect agriculture and enable fast reproducing pests to overcome slower reproducing livestock and wildlife. These changes, if allowed to proceed too far or too fast, could ultimately bring economic growth—or even human life on Earth—to an end. Therefore, the IPCC 2018 recognizes that fossil fuels must be phased out during the next fifty years (or sooner) if very serious climatic changes are to be avoided.

Arrhenius, Svante. 1896. On the influence of carbonic acid in the air on the temperature on the ground. *Philosophical Transactions of the Royal Society* 41:237–276.

This work represents the first statement that anthropogenic greenhouse gases emissions would result in a significant increase in the Earth's temperature. Although the quantification carried out is not seen as accurate, this paper is the first historical attempt to quantify the temperature increase related to greenhouse gases emissions.

IPCC. 2014. IPCC Fifth Assessment Report: Climate change. Cambridge, UK: Cambridge Univ. Press.

The Fifth Assessment Report (AR5) is divided in three volumes: physics of climate and climate change, impacts of climate change, adaptation and vulnerability, and climate change mitigation.

IPCC. 2018. IPCC Special Report 15: Global warming of 1.5°C. Cambridge, UK: Cambridge Univ. Press.

An IPCC special report on the impacts of global warming of 1.5°C above preindustrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.

McKibben, B. 2011. *The global warming reader*. New York: OR Books.

This book provides more than thirty-five opinions about the issues that the planet is facing. Ideas from the 19th century to the present are presented, such as the ones of Al Gore, Naomi Klein, and Vandana Shivam. It therefore provides a comprehensive view of the different visions of the current environmental issues.

Nordhaus, W. D. 1991. A sketch of the economics of the greenhouse effect. *The American Economic Review* 81:146–150.

This paper attempts to assess the costs and benefits of different levels of greenhouse gases abatement. In order to do so, it estimates both the damage caused by climate change and the costs of greenhouse gas reduction.

Steffen, W., K. Richardson, J. Rockström, et al. 2015. Planetary boundaries: Guiding human development on a changing planet. *Science* 347.6223: 1259855.

This study updates the planetary boundaries framework introduced in 2009 by the same authors, and shows that three of these boundaries have been already exceeded with a high risk, while two other boundaries are in an increasing risk situation. Other limits, such as freshwater use or stratospheric ozone depletion, remain at safe levels.

Stern, N. 2006. *The economics of climate change*. London: Cambridge Univ. Press for H. M. Treasury U.K.

According to the report, the climate change is the largest market failure ever seen, and by controversially adopting a very low (1.4 percent) social discounting rate, the author suggested it was more cost-effective to take action now to limit climate change damages. Available for purchase online.

Mainstream Ignorance of Energy's Role in Economic Growth

The historical perspective of how economics largely discounts the role of energy is presented in the first section. The second section proposes that this is an important omission, as the laws of thermodynamics cannot in reality be ignored.

It Wasn't Always Thus

The evolution of the prevailing economic theories deserves attention. In the 18th century, Physiocrats such as the author of Cantillon 1755, considered that "land is the source or matter from whence all wealth is produced." As the land took the energy from sun to make agricultural produce, Physiocrats considered (pre-fossil fuel) energy as instrumental to creating economic output. Later, however, classical economics took a different view. For example, Smith 1846 in the book *Wealth of Nations* (1776) argued that growth in economic outputs stemmed not from energy or land but from the proper division of labor. Following in these footsteps, today's dominant neoclassical school ignores energy as being important in economic growth on a cost-share basis: the cost of energy as a fraction of GDP is small, therefore its role must also be small. This argument is questioned by Kümmel 2013. Mainstream (neoclassical) economists view economic growth through an "aggregate production function" (APF), which defines the relationship between the economy's inputs (labor and capital) and outputs, meaning the total production of goods and services, usually measured as aggregate GDP. Neoclassical economics thus consider that physical materials are intermediate goods, provided (i.e., extracted from nature and transformed) by human labor, with the help of tools or other kinds of capital. The neoclassical relationship between these two factors of production can be mathematicized by defining the inputs labor (L) and capital (K) and economic outputs (Y), and relating them via an APF functional form, i.e., Y = F(K,L). However, Solow 1957, in his landmark empirical US study, found only a minority of economic growth was attributable to labor and capital inputs, with the "Solow Residual" remainder assigned to exogenous "technical progress," also known as total factor productivity (TFP). Thus the "science" of growth accounting was born, where economists such as Denison 1979 allocated the Solow residual to improvements in capital utilization and labor quality, but not energy. Aside from the empirical concern of excluding energy and only explaining a minority of economic growth, there are deep and wide-ranging conceptual arguments about the validity of the APF. These include the HUMBUG critique developed in Shaikh 1974 and the Cambridge capital controversy, by for instance Robinson 1953 and Robinson 1971. Works such as Felipe and McCombie 2010 continue the sustained attacks on the APF. Despite this, the APF approach survived, and prospered, and became an indispensable notion in modern economics.

Cantillon, R. 1755. Essai sur la Nature du Commerce en Général (Essay on the Nature of Trade in General). Translated by Henry Higgs. London: Macmillan.

This early essay discusses numerous aspects of economic theory, including population growth, wages, interests, prices, and entrepreneurship. It was designated by Jevons as "the cradle of political economy."

Denison, E. 1979. Explanations of declining productivity growth. *Survey of Current Business* 59.II (August): 1–24.

In this article, Denison provides an explanation for the US decline of productivity and slowdown in economic growth. It is rejected that this slowdown can be largely ascribed to the rise of energy prices on the basis of a cost-share reasoning: energy expenditures are low in national accounts, hence the contribution of energy to national aggregate economic output cannot be crucial.

Felipe, J., and J. S. L. McCombie. 2010. What is wrong with aggregate production functions. On Temple's "aggregate production functions and growth economics." *International Review of Applied Economics* 24.6: 665–684.

In this answer to Temple 2006, the authors present arguments against the use of aggregate production functions, and particularly detail the underlying accounting identity criticism. According to these, aggregate production functions give statistically significant fits to real GDP because of the underlying identity, which consequently impedes drawing any economic meaningful interpretation.

Kümmel, R. 2013. Why energy's economic weight is much larger than its cost share. *Environmental Innovation and Societal Transitions* 9:33–37.

This article was published as part of a special issue in honor of the lifetime contributions of Robert Ayres. The paper summarizes the results of work undertaken by Ayres, Kümmel, and others, who included energy (alongside labor and capital) in aggregate production functions, and found Solow Residuals are largely or wholly eliminated.

Robinson, J. 1953. The production function and the theory of capital. *Review of Economic Studies* 21:81–106.

In this article Robinson questions the aggregate production function approach, notably by discussing the notion of capital and showcasing that this approach comes with issues in aggregation and definition of capital. The rate of profit on capital is thereafter discussed based on a theoretical argumentation.

Robinson, J. 1971. The measure of capital: The end of the controversy. *The Economic Journal* 81.323: 597–602.

The author summarizes different recent discussions about the concept of capital. Then, showcasing that Cobb-Douglas functions fit any time series with fairly constant share wages in total output, Robinson underlines how the marginal productivity of capital seems a meaningless expression. This article aims at closing a long series of discussions on capital.

Shaikh, A. 1974. Laws of production and laws of algebra: The humbug production function. The *Review of Economics and Statistics* 56.1: 115–120.

In this stern criticism of Solow's paper, Shaikh demonstrates how the goodness of fit obtained by Solow is purely a consequence of an underlying accounting identity and of the laws of algebra (Solow 1957). He shows this by fitting the same functional form that Solow used on a dummy dataset (which is graphically represented as the word "HUMBUG") and keeping the same almost constant profit shares as Solow.

Smith, A. 1846. *An inquiry into the nature and causes of the wealth of nations*. Edinburgh: A. & C. Black, and W. Tait.

This seminal work discusses numerous aspects of economic theory, from a classical economics standpoint. Although it is often referred to as the cradle of modern capitalism and liberalism, it is worth noting that Smith was considerably distrustful toward uncontrolled capital and wealth accumulation, and not as liberal as some like to believe.

Solow, R. M. 1957. Technical change and the aggregate production function. *The Review of Economics and Statistics* 39.3: 312–320.

Perhaps the most seminal of all papers which consider the aggregate production function. Solow produces an empirical case study of the United States for the capital-labor Cobb-Douglas production function. The key finding is that most of US economic growth is attributable not to labor or capital inputs, but to "technical progress." This later became known as the *Solow Residual*. Available for purchase online.

Temple, Jonathan. 2006. Aggregate production functions and growth economics. *International Review of Applied Economics* 20.3: 301–317.

Temple considers the role of aggregate production functions in macroeconomics. It offers a defence to their use in models that are "parables"—suggesting they have value even if their assumptions are unrealistic and cannot be formally justified.

Importance of Thermodynamic Laws

We now consider economists' ignorance of the laws of thermodynamics and their implications for economics. All kinds of physical work are subject to the laws of thermodynamics. As well as the well-known first law (energy conservation), perhaps more important is the second law of thermodynamics, known as *the entropy law*. We recall this means every spontaneous process in a closed system (or in the universe) is irreversible. Every process converts global order (low entropy) into global disorder (high entropy). This means that economic processes that seem to produce local order (e.g., information) do so only by increasing global disorder, as discussed in Georgescu-Roegen 1975 and Prigogine and Stengers 1984. It also means that perfection, in terms of impurity elimination (e.g., metal refining) or "recycling" wastes, is impossible in practice. The "circular economy" is a modern version of perpetual motion; it is theoretically impossible. This means that "zero waste" and the "circular economy" are far distant goals that can never be fully achieved, rather than practical objectives. Besides, economics dictates that costs of reducing impurity content of crude metals or recycled wastes needs to be balanced against the market value of the higher purity that is achieved. To put it more simply: most scarce elements are underpriced from the perspective of a circular economy. Mainstream economists see it differently. They foresee a "cornucopian" doctrine of perpetual growth driven by unending innovation and unlimited substitution, as described in Simon 1994 and Goeller and Weinberg 1976. The fallacy of these two central tenets of neoclassical economics is laid bare by the second law of thermodynamics. Unending growth is not possible with diminishing natural resources. In fact, the issue is likely to become paramount in the foreseeable future. An early warning was the classical essay of Boulding 1966, and this issue has been further theorized, for instance in Valero and Valero 2015 or Calvo, et al. 2017. To make matters worse, mainstream neoclassical economics have ignored the fact that there are resources for which there is no substitute. For example, fresh air and fresh water cannot be substituted. Some minerals also fall into this category—a more definitive example is the element phosphorus, which is needed by every living organism, is essential in agriculture for fertilizer, is not recycled in nature, and is being mined today from ores of biological origin. However, the most important of the non-substitutable resources is useful exergy.

Boulding, K. E. 1966. The economics of the coming spaceship Earth. In *Environmental quality in a growing economy*. Edited by H. Jarrett, 3–14. Baltimore: Published for Resources for the Future by the Johns Hopkins Press.

This seminal conceptual essay first considers human existence and resource consumption on Earth as a *cowboy economy*, where there was always a new frontier of resources (e.g. land, food, shelter) to move to. In this world, maximization of resource throughputs is desirable. Second, with the Earth approaching full utilization, the future is akin to a spaceship economy, where maintenance of stock matters most, and resource throughputs are best minimized.

Calvo, G., A. Valero, and A. Valero. 2017. Assessing maximum production peak and resource availability of non-fuel mineral resources: Analyzing the influence of extractable global resources. *Resources, Conservation and Recycling* 125:208–217.

The authors estimate the peak of production for forty-seven non-fuel mineral resources. It is found that the peak of extraction of most of these resources, although it depends on a few parameters, is likely to happen within this century. A few peaks are likely to happen within the forthcoming fifty years, and a couple of them already occurred.

Georgescu-Roegen, N. 1975. Energy and economic myths. *Southern Economic Journal* 41.3: 347–381.

This articles examines the economic implications of thermodynamic laws and rejects some of the dominant economic ideas based on this energetic analysis. Among other things, it rejects the possibility of a complete recycling process, and states that the amount of accessible energy is finite, as well as the amount of mineral resources.

Goeller, H. E., and A. M. Weinberg. 1976. The age of substitutability. *Science* 191.4228: 683–689.

This paper argues the possibility for human societies, in the long term, to reach a thriving state where the use of material and energy non-renewable resources has been progressively replaced by renewable resources.

Prigogine, Ilya, and I. Stengers. 1984. *Order out of chaos: Man's new dialogue with nature*. London: Bantam Books.

This book, based on insights from thermodynamics, defies the usual Occidental mindset of splitting and reducing complex problems into simpler ones.

Simon, J. L. 1994. More people, greater wealth, more resources, healthier environment. *Economic Affairs* 14.3: 22–29.

This articles states that wealth, natural resources availability, environmental quality, life expectance, etc, have been considerably increasing over the last two hundred years, alongside human population. As such, it optimistically concludes that this trend will continue, and that more population will drive further improvements. Conversely, our main concern should be about "unsound social regulations" of economic activities, that hinder imagination and freedom.

Valero, A. C., and A. D. Valero. 2015. *Thanatia: The destiny of the Earth's mineral resources*. Singapore: World Scientific.

This book showcases a cradle-to-cradle view of the Earth's abiotic resources based on the second law of thermodynamics, thereby emphasizing the dissipation and loss of quality of both materials and energy. Therefore it focuses on the exergy of resources and describes the difficulties related to extend the resources' life cycle. It raises the question of whether the Earth is becoming Thanatia, an exhausted planet, and when that might happen.

Insights from Exergy Economics

This section presents relevant insights from the field of exergy economics. First, key studies in economy-wide exergy accounting are summarized. Second, the main insights gained into the role of energy in economic growth from exergy economics are considered.

Economy-Wide Exergy Accounting

The foundations for insights from the field of thermodynamics and economics (thermo-economics), also called exergy economics, are based on economy-wide exergy accounting studies. Reistad 1975—stimulated by the 1973 oil crisis—produced the first economy-wide, published exergy accounting study, for the United States. The methodology mapped primary energy (e.g., extracted coal, oil, gas) to final energy (e.g., electricity, petrol) to useful energy (e.g., lighting, heating, motion), measured in exergy terms. Over time the system of national exergy accounting has been extended to cover a wide group of countries including Brazil in Schaeffer and Wirtshafter 1992 and Portugal in Serrenho, et al. 2016, Sweden in Wall 1987, as well as economic sectors including industry in Ayres, et al. 2011 and transport in Byers, et al. 2015. A review of different societal exergy analyses is provided by Ertesvåg 2001. Exergy accounting has also been applied to mass balance, as the quantity of wastes from a process, or a factory, or a company, or a city, can be calculated from the masses of inputs and useful outputs. This “mass-balance principle” is a useful accounting tool for government regulators as well as business leaders, which is described in Ayres and Ayres 1998. Advances in exergy accounting methodology—including those set out by Rocco, et al. 2014 and Miller, et al. 2016—have laid the platform for more sophisticated understanding of energy systems and the interaction with the economy, as we shall see later.

Ayres, R. U., and L. W. Ayres. 1998. *Accounting for resources 1: Economy-wide applications of mass-balance principles to materials and waste*. Cheltenham, UK, and Lyme MA: Edward Elgar.

This books presents methods and principles in order to account for the use and flows of resources, as well as the production and dispersion of waste. It shows how Material Flow Accounting methods, based on the mass-balance principle, can be used both at the material and process level.

Ayres, R. U., L. Talens Peiró, and G. Villalba Méndez. 2011. Exergy efficiency in industry: Where do we stand? *Environmental Science & Technology* 45.24 (15 December): 10634–10641.

This paper defines second-law industry efficiency as “useful exergy output divided by total exergy inputs,” and estimates values for the US chemical industry in 1991–1993 and US all-industry in 1991. The authors note their values (~35–40 percent) are much lower than the first-law US industry efficiency (~80 percent) published by the US Energy Information Agency, and suggest this gives significant room for efficiency improvement.

Byers, E. A., A. Gasparatos, A. C. Serrenho. 2015. A framework for the exergy analysis of future transport pathways: Application for the United Kingdom transport system 2010–2050. *Energy* 88 (August): 849–862.

This paper’s key novelty is to develop an exergy-based analytical framework for studying future transport pathways. Taking the United Kingdom as a case study for the period 2010–2050, they input UK government scenarios of transport modes and fuel sources, including electrification. Importantly—in the context of upcoming renewables-based energy transitions—they find renewables-based electrified transport as the most exergy-efficient system.

Ertesvåg, I. S. 2001. Society exergy analysis: A comparison of different societies. *Energy* 26.3: 253–270.

This article provides a review of different societal exergy analysis conducted for different countries. It importantly differentiates studies that focus on energy carriers and those that include the exergy content of other resources. It is found that assumptions somewhat vary between studies, although cross country structural differences are of higher importance. Societal exergy analysis is presented as an appropriate tool for studying the evolution of societies.

Miller, J., T. Foxon, and S. Sorrell. 2016. Exergy accounting: A quantitative comparison of methods and implications for energy-economy analysis. *Energies* 9.11: 947.

This paper contributes to ongoing efforts to develop a consistent methodological framework for economy-wide exergy analysis. The study examines different alternatives for key aspects of exergy analysis, including renewables-based electricity, vehicle-based mechanical drive, and industrial heat applications. Importantly, they test the effects of each option on a case study country: the United Kingdom, 1960–2012.

Reistad G. 1975. Available energy conversion and utilization in the United States. ASME Transactions Series. *Journal of Engineering for Power* 97:429–434.

This paper provides a societal-level exergy analysis of the United States for 1971. This seminal work is the first known study at an economy-wide scale of *available energy* (i.e., *exergy*). Importantly, the paper also provides first and second law efficiencies for a wide range of end-use applications (e.g. light bulbs, cars) and sectors (e.g. residential, transport), and uses Sankey diagrams to show flows of *available energy* through the US economy.

Rocco, M. V., E. Colombo, and E. Sciubba. 2014. Advances in exergy analysis: A novel assessment of the Extended Exergy Accounting method. *Applied Energy* 113:1405–1420.

This paper describes societal exergy analysis theoretical foundations and presents different methods for extended exergy accounting, i.e., exergy accounting that includes the exergy content of natural resources. It shown how societal exergy analysis can be used both as a resource quantifier and as way to clarify operative potential.

Schaeffer, R., and R. M. Wirtshafter. 1992. An exergy analysis of the Brazilian economy: From energy production to final energy use. *Energy* 17.9: 841–855.

A Brazilian societal exergy analysis is carried out for the year 1987 in this article, and it is demonstrated that the exergy approach enables to identify mismatches between the quality of the energy carries provided to the end users and the quality required by these. The exergy approach therefore enables to identify additional room for improvement.

Serrenho, A. C., B. Warr, T. Sousa, and R. U. Ayres. 2016. Structure and dynamics of useful work along the agriculture-industry-services transition: Portugal from 1856 to 2009. *Structural Change and Economic Dynamics* 36:1–21.

This study provides the Portuguese societal exergy analysis for a particularly long-term period covering the full agricultural-industrial-services transitions. Some important methodological advances are presented, and a main finding of the study is that the Portuguese useful exergy intensity has remained strikingly constant over the whole time period covered, conversely to final exergy intensity.

Wall, G. 1987. Exergy conversion in the Swedish society. *Resources and Energy* 9:55–73.

A societal extended exergy accounting is presented for Sweden in 1980. The efficiency of the conversion of energy and materials throughout the Swedish society is assessed with this methodology.

Insights from Exergy Economics

Various key insights of the importance and role of energy in economic growth have followed from the exergy economics field. The first insight relates to growth accounting: energy (measured as exergy) has been identified as a key factor of production—much more important than suggested by the cost-share theorem—alongside labor and capital. Kümmel, et al. 1985 and Ayres and Warr 2005 pioneered the approach of inserting energy (in exergy terms) into aggregate production functions, which served to virtually eliminate the previously unexplained Solow Residual. More recently, Santos, et al. 2018 applies a cointegration technique for Portugal, whereby it is found that cost-share theorem can be respected while ascribing a key role to energy consumption. Second, decomposition methods have been applied to unpick the drivers of changes in useful exergy consumption and thus economic growth. Examples include Serrenho, et al. 2014 and later Voudouris, et al. 2015 which conclude that mechanical drive and electricity-based useful exergy uses have more impact on economic growth than other end uses. Brockway, et al. 2015 applies a log mean decomposition index (LMDI) method to identify that efficiency gains have driven most of China's useful exergy growth. Third, empirical analysis suggests that useful exergy intensities (e.g., useful exergy consumed per unit of GDP) have decreased less than final or primary energy intensities, and have even been remarkably constant for specific countries, as illustrated by Serrenho, et al. 2014. Fourth, the role of exergy efficiency gains in economic growth has been evidenced. Indeed, Sakai, et al. 2019 finds that a quarter of UK economic growth stems from gains in final-to-useful exergy efficiency. The implication, as Ayres and Warr 2005 suggest, is that future constraints to economic growth due to slowing efficiency gains are to be expected. Fifth, the possibility of decoupling energy consumption from economic growth has been discussed through an exergy based technique in Heun and Brockway 2019, whose authors find that decoupling energy consumption from economic growth will be very difficult to achieve.

Ayres, R. U., and B. Warr. 2005. Accounting for growth: The role of physical work. *Structural Change and Economic Dynamics* 16:181–209.

In this study, a linear-exponential (Linex) aggregate production function is used in order to account for economic growth in the United States during the whole 20th century. It is found that using a Linex function, the combination of energy, capital, and labor can successfully be used in order to account for economic growth, and that the need for an exogenous technological progress factor is removed.

Brockway, P. E., J. K. Steinberger, J. R. Barrett, T. J. Foxon. 2015. Understanding China's past and future energy demand: An exergy efficiency and decomposition analysis. *Applied Energy* 155:892–903.

This paper undertakes a rare, economy-wide exergy analysis for China, the world's largest energy consuming nation. Over the period 1971–2010, aggregate exergy efficiency more than doubled (5 to 12.5 percent), and the study uses a novel application of decomposition analysis to find structural change is the key driver of efficiency gains. Last, they estimate 25 percent higher primary energy demand for China by 2030 using novel exergy-based methods versus conventional techniques.

Heun, K. M., P. E. Brockway. 2019. Meeting 2030 primary energy and economic growth goals: Mission impossible? *Applied Energy* 251.

This paper completes a societal exergy analysis of Ghana and the United Kingdom. The results suggest that efficiency gains are correlated to economic growth. Importantly this suggests that Ghana has efficiency headroom for rapid economic growth in contrast to the United Kingdom, where slowing efficiency gains could offer an alternative causation for slowing economic growth (secular stagnation).

Kümmel, R., W. Strassl, A. Gossner, and W. Eichhorn. 1985. Technical progress and energy dependent production functions. Zeitschrift Für Nationalökonomie *Journal of Economics* 45.3: 285–311.

In this work, the author introduces the Linear Exponential (LINEX) aggregate production function and applies it to Western Germany's and to the US industrial sector. It is found that such a function can successfully account for economic output for the time period considered. Conceptual issues of neoclassical theory are equally discussed, including the neglect of energy, the exogenous technological change—considered endogenous in Kümmel's approach—and aggregation issues.

Sakai, M., P. E. Brockway, J. R. Barrett, and P. G. Taylor. 2019. Thermodynamic efficiency gains and their role as a key 'engine of economic growth.' *Energies* 12.110.

This article includes thermodynamic (energy) efficiency gains as an independent variable within an econometric based energy-economy model. By constraining previous efficiency, the effect of historical efficiency gains is revealed to be a quarter of UK economic growth in the period 1971–2013 analyzed.

Santos, J., T. Domingos, T. Sousa, and M. St. Aubyn. 2018. Useful exergy is key in obtaining plausible aggregate production functions and recognizing the role of energy in economic growth: Portugal 1960–2009. *Ecological Economics* 148 (January): 103–120.

This important paper proposes a novel approach, grounded on cointegration analysis, to identify statistically significant and economically plausible macroeconomic aggregate production functions linking output with capital, labor, and useful exergy. Applied to Portugal, over the period 1960–2009, the key findings of this work are that useful exergy has a positive causal impact on economic growth, and the aggregate production function developed is able to reproduce output without the need for a Solow residual term.

Serrenho, A. C., T. Sousa, B. Warr, R. U. Ayres, and T. Domingos. 2014. Decomposition of useful work intensity: The EU (European Union)-15 countries from 1960 to 2009. *Energy* 76 (November):704–715.

This important paper provides a rare multi-country, national-level exergy study of fifteen countries in the European Union, covering the 1960–2009 period. Useful exergy economic intensities are calculated for each country and the aggregate EU-15, where decomposition analysis finds variations mostly attributable to changes in industrial high temperature heat usage and residential energy uses.

Voudouris, V., R. Ayres, A. C. Serrenho, and D. Kiose. 2015. The economic growth enigma revisited: The EU-15 since the 1970s. *Energy Policy* 86:812–832.

This article applies semi-parametric production functions to the EU-15 since 1971. It is found that the marginal products of the considered factors of production (capital, labor, and useful exergy) are variable, conversely to what is usually implied in macro-economic models. Mechanical drive and electrical useful exergy uses have more impact on economic growth than other end uses.

Energetic Constraints to Future Economic Growth

This section summarizes evidence of upcoming energetic constraints, which in turn will affect economic growth. First, key studies which suggest that fossil fuel availability is declining are presented. Second, the slowdown of energy conversion efficiency gains is considered.

Declining Fossil Fuel Availability

Two looming fossil fuel constraints provide us with further food for thought. The first is fossil fuel resource depletion. Indeed, as reserves of fossil fuel resources are finite, the extraction of these must, physically, go through a peak and then diminish until reaching a null extraction state. The prime example is “peak oil,” where declining availability of proven oil resources means that there exists a maximum rate of oil extraction, after which it enters terminal rate of decline. This was first suggested by Hubbert 1971, and may be with us already, as some believe, and appears very likely to occur before 2030, as defended in Sorrell, et al. 2009 and Madureira 2014. Notwithstanding most economists, who assume that there is always a substitute for anything that looks scarce, cheap, high quality oil is running out *and there is no low cost substitute*. Canadian tar sands, tight oil, and deep sea drilling are a lot more costly and less efficient. Other fossil fuels, such as coal and gas, shall also go through the same kind of peak, though as with oil, their respective peak dates remain uncertain. The second upcoming energetic constraint is declining net energy returns to the economy. This is conceptualized through the notion of energy-return-on-investment (EROI), that is, the ratio of energy extracted to energy invested. An early pioneer was Gilliland 1975, though it was Hall and Cleveland who popularized the EROI term, for instance in Cleveland, et al. 1984. Hall, et al. 2014 and Gagnon, et al. 2009 suggest that declining EROI values may soon act as a serious constraint to the global economy. More recently Brockway, et al. 2019 suggests that EROI ratios for fossil fuels at the final energy (finishes fuel) stage are much lower (~6:1) and nearer to a “net energy cliff” than thought, where available energy could decline rapidly. These two energy resource constraints will have economic impacts. Energy prices will rise as a consequence of this availability decline (entailed by both fossil fuel depletion and declining EROI), thereby choking growth, unless energy conversion device final-to-useful efficiency gains are fast enough to over-compensate for declining primary resource availability. Court and Fizaine 2017 suggests that there is no evidence, so far, that this is happening.

Brockway, P. E., A. Owen, L. I. Brand-Correa, and L. Hardt. 2019. Estimation of global final stage energy-return-on-investment for fossil fuels with comparison to renewable energy sources. *Nature Energy* 4:612–621.

This paper's key contribution is to estimate global fossil fuel energy-return-on-investment ratios for fossil fuels at the final energy stage (finished fuels). By including a wider set of energy production sectors and supply chain energy, the EROI ratios are suggested to be around 6:1, much lower than the ~30:1 estimated for the primary energy stage of fossil fuel extraction.

Cleveland, C. J., R. Costanza, C. A. Hall, and R. Kaufmann. 1984. Energy and the US economy: A biophysical perspective. *Science* 225.4665: 890–897.

Different hypothesis about the relationship between national energy use and national economic activity are presented and discussed for the United States over a nearly one-hundred-year period. The concept of energy return on investment (EROI) is notably introduced as a main driver of the US economy, and data showcasing a marked decrease in the EROI of principal fuels is provided.

Court, V., and F. Fizaine. 2017. Long-term estimates of the energy-return-on-investment (EROI) of coal, oil, and gas global productions. *Ecological Economics* 138:145–159.

Estimates for global fossil fuel based EROI are rare, and had only been estimated for several decades at most. This paper therefore makes an important contribution through price-based long-run estimates of EROI for oil, coal, and gas from the 1800s to 2012. The authors suggest EROI for oil and gas are in decline, while coal is still rising.

Gagnon, N., C. A. S. Hall, and L. Brinker. 2009. A preliminary investigation of energy return on energy investment for global oil and gas production. *Energies* 2.3: 490–503.

EROI time series are constructed for the world's most important fossil fuels, and it is showed that the EROI of oil started decreasing after reaching a peak. The general conclusion is that the EROI of the most important fuels is decreasing over time.

Gilliland, M. W. 1975. Energy analysis and public policy. *Science* 189.4208 (26 September): 1051–1056.

This paper presents an early contribution to the field of net energy analysis, and whose key novelty was to set out how net energy analysis could be applied to public energy policy.

Hall, C. A. S., J. Lambert, and S. B. Balogh. 2014. EROI of different fuels and the implications for society. *Energy Policy* 64:141–152.

This paper assesses the evolution of fossil fuel's EROI for different nations, and draws the conclusion that most of these EROIs are declining. It then shows that most renewable energies have considerably lower EROI than traditional fossil fuels. Subsequently it underlines the large and adverse impacts that a decrease in future energy sources' EROIs is likely to have on economies.

Hubbert, M. K. 1971. The energy resources of the Earth. *Scientific American* 225.3: 61–70.

Hubbert curves predicting the dates of, e.g., *peak oil* are of course synonymous with his name. Though Hubbert first presented his ideas in the 1950s, this 1971 article in *Scientific American* illustrates how the concept was gaining exposure to a public audience, just ahead of the 1970s oil crises.

Madureira, N. L. 2014. *Oil reserves and peak oil. Key concepts in energy*. London: Springer International.

This book chapter reviews one of the most turbulent subjects in the energy field: oil resources. The historical development of the debate is recounted, including the different arguments and misunderstandings, and a review of the current state of the art of the debate is provided. See pp. 125–126.

Sorrell, S., J. Speirs, A. R. Brandt, R. Miller, and R. W. Bentley. 2009. *Global oil depletion: An assessment of the evidence for a near-term peak in global oil production*. London: Energy Research Centre.

This article presents a review of the evidence of depletion of conventional oil. A large literature, different supply forecasts, and industry databases are reviewed. A key conclusion is that the peak of production of conventional oil is likely to occur before 2030 and may even occur before 2020.

Declining Efficiency Gains

In fact, a third future energetic constraint points to the opposite: gains in aggregate thermodynamic exergy conversion efficiency (primary-to-useful) are slowing, which may act to constrain economic growth, as described in Warr and Ayres 2006. As energy resources are limited—in terms of land and material requirements for renewables, and in terms of resources for fossil fuels, as defended in Arrobas, et al. 2017 and Capellán-Pérez, et al. 2017—the useful exergy provided to the economy depends a great deal on *efficiency* (the ratio of useful output to input) at every stage from discovery to end use. The 1973 oil crisis focused attention—particularly in the United States—on the problem of high oil prices. Increasing energy efficiency was seen as the solution: use less energy and save money. Engineers and energy analysts were thrust into the limelight—much to the chagrin of mainstream economists such as Webb and Pearce 1975 and Common 1976. Carnahan, et al. 1975, in the American Physical Society report "*Efficient Use of Energy: A Physics Perspective*" was a pioneer study in this field. It importantly distinguished between "first law" and "second law" efficiency. The report estimated average "second law" efficiency of automobiles at around 10–12 percent. In recent years, cars have become somewhat more efficient, due to lower air-resistance, lightweighting, and a few other changes, but spark-ignition engine efficiency has not changed much. Regarding energy efficiency in industry, International Institute for Applied Systems Analysis 2012 and Ayres, et al. 2011 find the second law efficiency of major energy-consuming industries (cement, iron and steel, aluminum, petrochemicals, etc.) are in the 30 percent range. At an economy-wide level, Brockway, et al. 2014 found the second law US exergy efficiency is now about 13 percent. Japan and western Europe are more efficient (around 20 percent) because they have more compact cities with more public transportation and less air-conditioning. However, Williams, et al. 2008 and Brockway, et al. 2014 suggest efficiency gains are slowing due to "efficiency dilution," for example, more cars, bigger houses, and more air-conditioning. Considering that most efficiency improvements have already been done in developed countries, and that less efficient services are spreading within societies, slowing gains in aggregate energy efficiency are expected. If economic growth is driven by useful exergy—which is the product of primary energy (exergy) input to the economy times the efficiency with which it is converted to work—slowing efficiency gains will act as a drag on economic growth.

Arrobas, D. L. P., K. L. Hund, M. S. McCormick, J. Ningthoujam, and J. R. Drexhage. 2017. *The growing role of minerals and metals for a low carbon future*. Washington, DC: The World Bank.

This report from the World Bank evidences the growing need in mineral resources that a massive renewable energy transition would entail. Specific minerals for which the demand is likely to increase considerably, such as cobalt, copper, lithium, or rare earth metals, are identified. The link between the energy transition and mineral requirements is thus showcased in this report, which aims at engendering a broader dialogue on this critical issue.

Ayres, R. U., L. Talens Peiró, and G. Villalba Méndez. 2011. Exergy efficiency in industry: Where do we stand? *Environmental Science & Technology* 45.24 (15 December): 10634–10641.

This paper defines second-law industry efficiency as "useful exergy output divided by total exergy inputs," and estimates values for the US chemical industry in 1991–1993 and US all-industry in 1991. The authors note their values (~35–40 percent) are much lower than the first-law US industry efficiency (~80 percent) published by the US Energy Information Agency, and suggest this gives significant room for efficiency improvement.

Brockway, P. E., J. R. Barrett, T. J. Foxon, and J. K. Steinberger. 2014. Divergence of trends in US and UK aggregate exergy efficiencies 1960–2010. *Environmental Science & Technology* 48:9874−9881.

This paper made key advances in exergy accounting methodology, in particular mechanical drive, electricity end-uses. A second contribution was to identify that US aggregate efficiency had stagnated due to *efficiency dilution*, caused by the greater use of less efficient processes, e.g., air-conditioning.

Capellán-Pérez, I., C. de Castro, and I. Arto. 2017. Assessing vulnerabilities and limits in the transition to renewable energies: Land requirements under 100 percent solar energy scenarios. *Renewable and Sustainable Energy Reviews* 77:760–782.

This study focuses on the land requirements of a large transition toward renewable energies by taking the particular example of solar energy. It is concluded that such a transition has the potential to intensify pressure on land in terms of food security and biodiversity conservation.

Carnahan, W., K. W. Ford, A. Prosperetti, et al. 1975. *Efficient use of energy: A physics perspective*. New York: American Physical Society.

This report, issued after the 1973 oil crisis, was a first attempt to draw scientists' and engineers' attention to the issues of energy efficiency. The difference between first and second law efficiency was evidenced as it enables to widen first law energy analysis.

Common, M. 1976. The economics of energy analysis reconsidered. *Energy Policy* 4.2: 158–165.

This article is an answer to Webb and Pearce's earlier criticism of energy analysis. It is argued that Webb and Pearce's idea that energy analysis is useless as it does not add any information to traditional economic analysis is unfounded and premature.

International Institute for Applied Systems Analysis. 2012. *GEA, Global energy assessment*, 2012. Edited by Nebojsa Nakicenovic. Laxenburg, Austria: International Institute for Applied Systems Analysis.

This report analyzes connections between major challenges and energy, and the possibilities for reaching a sustainable energy future, in terms of technologies, resources, energy systems structures, and policies and measures. Available online.

Warr, B., and R. Ayres. 2006. REXS: A forecasting model for assessing the impact of natural resource consumption and technological change on economic growth. *Structural Change and Economic Dynamics* 17.3 (September): 329–378.

This paper marks a first attempt to use economy-wide exergy analysis to produce forecasts for future energy demands and economic growth. Their case study was the United States from 2000 to 2050. Their key finding was to show how declining gains in future exergy efficiency acted as a key constraint to future economic growth. Available online.

Webb, M., and D. Pearce. 1975. The economics of energy analysis. *Energy Policy* (December): 318–331.

This paper is notable for two key reasons. First, it marks an important date in the mid-1970s, when energy accounting was evolving to become the field of energy analysis that we know today. Second, it shows the opposition to this formed by leading economists, who felt that economics was a superior discipline, to which energy analysis could not add value.

Williams, E., B. Warr, and R. U. Ayres. 2008. Efficiency dilution: Long-term exergy conversion trends in Japan. *Environmental Science & Technology* 42.13: 4964–4970.

This paper was the first to define and use the term *efficiency dilution*, to explain how Japan's overall efficiency had declined, through the introduction of less exergy-efficient technologies.

The Illusion of the Perpetual Growth Machine

Last, the under-recognized role of energy and implications for future economic growth are considered. First, the mainstream economics' pursuit of endless economic growth is presented. Second, studies which present the case for the end of economic growth are summarized.

Mainstream Pursuit of Economic Growth

Keynes 2010 argued that because of growing economies, "our grandchildren will be much richer than we are." The accounting of economic output that we know today as Gross Domestic Product (GDP) was developed by Kuznets 1934 in response to the Great Depression of the 1930s. Though at the time, Kuznets 1955 noted that "The welfare of a nation can scarcely be inferred from a measurement of national income," later he noted the impact on income inequality. GDP has translated into the single most important economic metric in our world today. Every government and every company nowadays wants, and demands, faster economic growth. Mainstream economists including those at the World Bank 2018, Organisation for Economic Co-operation and Development (OECD), and the International Monetary Fund (IMF) continue to assure us that growth is both desirable and automatic, given reasonable government tax and other policies. Despite this, there are growing voices—such as Jackson 2009 and Raworth 2017—who are asserting that GDP is the wrong metric and should be replaced, to better account for other socio-environmental factors, such as the Genuine Progress Indicator described in Kubiszewski, et al. 2013. But what is the source of this economic growth that mainstream economists are so confident of? Standard economic theory says that it is due to the accumulation of qualified labor and capital plus "technological progress." However, aside from the domain of information technology, the insights from exergy economics research tells us that technological progress elsewhere, measured in terms of energy efficiency from supply to end use, has largely peaked. The reality is that economic growth in recent years has instead been driven by increasing consumption. The consumption has been partly paid for by borrowing against future income from economic growth. In short, a lot of countries—especially (but not only) the United States—have been spending money not yet earned. This borrowing has been permitted by governments, based on the assumption by politicians, based on advice from economists, that future growth, due to automatic technological progress, is assured. Standard economic "growth theory" supports this risky assumption, but only because the growth models in use do not allow for declines. However, the post-2008 world continues to be in secular stagnation of low economic growth. There is a healthy debate by economists about its causes and solution. For instance, Gordon 2015 supports a secular stagnation theory, the validity of which is questioned in Mokyr 2014.

Gordon, R. J. 2015. Secular stagnation: A supply-side view. *American Economic Review: Papers & Proceedings* 105.5: 54–59.

Gordon defends in this article that there is evidence of secular stagnation in the five previous years of US economic performance, and that stagnation may stay with us for a while. The secular stagnation approach, that relies upon feedbacks between supply and demand, is described.

Jackson, T. 2009. *Prosperity without growth: Economics for a finite planet*. Abingdon, UK, and New York: Routledge.

In this book the need and desirability of further economic growth is questioned, both on the ground of environmental impacts and human fulfilment. The author suggests to redefine prosperity, and based on that, introduces different steps for bringing about a prosperous society within environmental limits.

Keynes, J. M. 2010. Economic possibilities for our grandchildren. In *Essays in persuasion*. London: Palgrave Macmillan.

In this essay, Keynes gives his vision of the economic future likely for future generations. His essay is optimistic, as according to him, further growth will enable future generations to live a comfortable life and to be free to enjoy leisure activities.

Kubiszewski, I., R. Costanza, C. Franco, et al. 2013. Beyond GDP: Measuring and achieving global genuine progress. *Ecological Economics* 93:57–68.

This article showcases that conversely to GDP, the Genuine Progress Indicator (GPI) peaked in 1978 and has been decreasing ever since. It shows that the GPI/capita increases until a GDP/capita of $7000/capita, and does not increase with further economic growth. It is therefore suggested that a better repartition of wealth would enable a greater GPI worldwide and that policies that focus on welfare instead of mere GDP are needed.

Kuznets, S. 1934. *National income, 1929–1932. National Bureau of Economic Research Bulletins 49*. New York: National Bureau of Economic Research.

This bulletin presents the results of a study for the US Department of Commerce whose target was the quantification of national incomes estimates for the period 1929–1931. This study is of key importance as it resulted in the GDP indicator.

Kuznets, S. 1955. Economic growth and income inequality. *The American Economic Review* 45.1: 1–28.

This article discusses linkages between economic growth and inequality. It is pointed out that growth may occur alongside a widening gap in income inequality.

Mokyr, J. 2014. Secular stagnation? Not in your life. Geneva Reports on the World Economy, August 2014.

In this work, Mokyr replies to economists that believe that stagnation is to be expected for a long period. He argues that technological progress will solve the situation and bring widespread benefits. Pp. 83–98.

Raworth, K. 2017. *Doughnut economics: Seven ways to think like a 21st-century economist*. White River Junction, VT: Chelsea Green Publishing.

The main flaws of mainstream economics are presented in this book which aims to be a manual for 21st-century economists. Seven concepts reckoned of primary importance for new economics are introduced and extensively described.

World Bank. 2018. Global Economic Prospects Turning of the Tide? A World Bank Group Flagship Report. Washington, DC.

In this report, the World's Bank prospects for economic growth over the world for the forthcoming years are described. The report states the need and desirability for further economic growth as perceived by the World Bank.

The End of Growth

We face a global convergence of three powerful, unsustainable trends that together constitute a crisis that threatens civilization itself. The first trend is the habit of borrowing against future growth that is no longer assured. Keen 2009 describes the mountain of debt—private, corporate, municipal, and sovereign—that was somehow invisible until recently. The only possible escapes from the debt problem are (i) printing money, which eventually results in hyper-inflation, (ii) large-scale debt repudiation by governments and widespread bankruptcy by borrowers, or (iii) accelerated economic growth. And all these escapes will be very hard to achieve because of the next two unsustainable trends. The second trend is decreasing energy costs, upon which historical economic growth has depended. Useful exergy in its various forms has declined dramatically in cost during the industrial revolution. But those halcyon days are over. King 2016 suggests that we have gone past the lowest point of energy (and food) costs. Constraints due to fossil fuels resources depletion, to the declining energy-return-on-investment (EROI) of main fuels, and to the slowdown of efficiency gains, as described in the previous sections, are likely to considerably hamper economic growth and to entail rising energy prices. Bashmakov 2007 discusses how increases to energy costs have significant negative impacts on economic growth above 10 percent of GDP costs. The third trend is the atmospheric accumulation of greenhouse gases (GHGs), mainly from fossil fuel combustion. The benign climate that will have enabled our global population to rise to over nine billion by 2050 is at risk. A global temperature rise of 2°C may be survivable (with difficulty) but a rise of up to 8°C would make large parts of the Earth uninhabitable. The 2008 global financial crisis taught us our economic systems don't cope with slow or no growth. However, the laws of thermodynamics must be obeyed, which, coupled to the three unsustainable trends, mean we will have to adjust to a steady state or degrowth-based economy sooner than we think. Although such a degrowing economy is advocated by a few scholars, such as Kallis 2018, this is falling on deaf ears, as economists pursue their fool's gold: the fallacy of a perpetual growth machine. Diamond 2005 describes how civilizations that were not able to take appropriate action when their environment was seriously damaged collapsed. *Will we be able to take appropriate action in time?*

Bashmakov, I. 2007. Three laws of energy transitions. *Energy Policy* 35.7 (July): 3583–3594.

This paper's most important proposition is that there exists a stable energy "cost-share" ratio of ~8–11 percent of total GDP. Below that ratio and economic growth accerates unsustainably, while above that level and economies head toward recession. This result is important, as it suggests that the role of energy in the economy is greater that its low cost-share would suggest.

Diamond, J. 2005. *Collapse: How societies choose to fail or survive*. New York: Penguin Books.

This seminal book looks at the collapse of previous civilizations including those at Easter Island and the Mayan empire, and finds common factors such as environmental damage, climate change, population growth, and poor decision making. This is an important book, since all of the factors identified are present in today's globalized planet.

Kallis, G. 2018. *Degrowth*. Newcastle-upon-Tyne, UK: Agenda Publishing.

The aim of the book is to summarize the core elements of degrowth as an interdisciplinary theory that formulates its critiques and propositions by bringing together different schools of thought, such as ecological economics and other heterodox schools of economics.

Keen, S. 2009. Household debt: The final stage in an artificially extended Ponzi bubble. *Australian Economic Review* 42.3: 347–357.

The article explores the history of the Australian private debt. It elucidates its composition, magnitude, and purposes. It also seeks to explain the drivers of the private debt bubble. It uses a dynamic model to describe speculative finance, and concludes that the depression could have been milder if it had not been forestalled rescuing markets.

King, C. W. 2016. Information theory to assess relations between energy and structure of the U.S. economy over time. *BioPhysical Economics and Resource Quality* 1.2: 10.

The article describes a decreasing food and energy cost share in the US economy from 1946 to its lowest point at 2002, and uses network theory to examine the trade-off between efficiency and redundancy of network flows in the economic system.

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