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Are there biophysical limits to technical change?

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Are there biophysical limits to technical change?

A review of societal exergy analysis and ecological macroeconomics

Simon Furse

Abstract:

This paper examines two literatures that try to understand the biophysical constraints placed on the economy and economic growth. Firstly, exergy economics uses the second law of thermodynamics to examine the aggregate exergy conversion process to the useful stage. This shows the dependency of the economy on physical laws and highlights the limits to continued productivity growth. I argue that exergy economics provides a vital contribution to economics, but previous attempts to integrate it into an economic framework are undermined by a reliance on the neoclassical production function. Secondly, ecological macroeconomics examines biophysical constraints to the economy using heterodox economic theory and models. My review of this literature shows that productivity growth is often modelled as unconnected to energy and materials and able to increase exponentially into the future despite biophysical constraints. The paper argues that biophysical limits to productivity growth need to be considered alongside the more commonly modelled damage functions and limits to resource availability and quality in ecological macroeconomics.

Keywords: Exergy, Energy, Societal Exergy Analysis, Ecological Macroeconomics, Technical Change, Production Functions, Limits to Growth

JEL codes: E12, O44, Q43, Q57

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1 Introduction

Economic theory, whether mainstream, heterodox, or even ecological, overwhelmingly assumes that productivity will grow exponentially indefinitely into the future. This applies whether productivity growth is seen as endogenous or exogenous, across a huge range of different economic theories and modelling techniques. However, a brief examination of the trajectory of labour productivity in high income countries shows that productivity growth is declining and has been doing so for some time. Figure 1.1 shows the development of labour productivity in a selection of high-income countries, with projections based on productivity growth each decade. Productivity today is 73%, 30%, and 15% less than an extrapolation of 1960s, 1970s, and 1990s rates respectively, with the growth continuing to decline in the following decades.

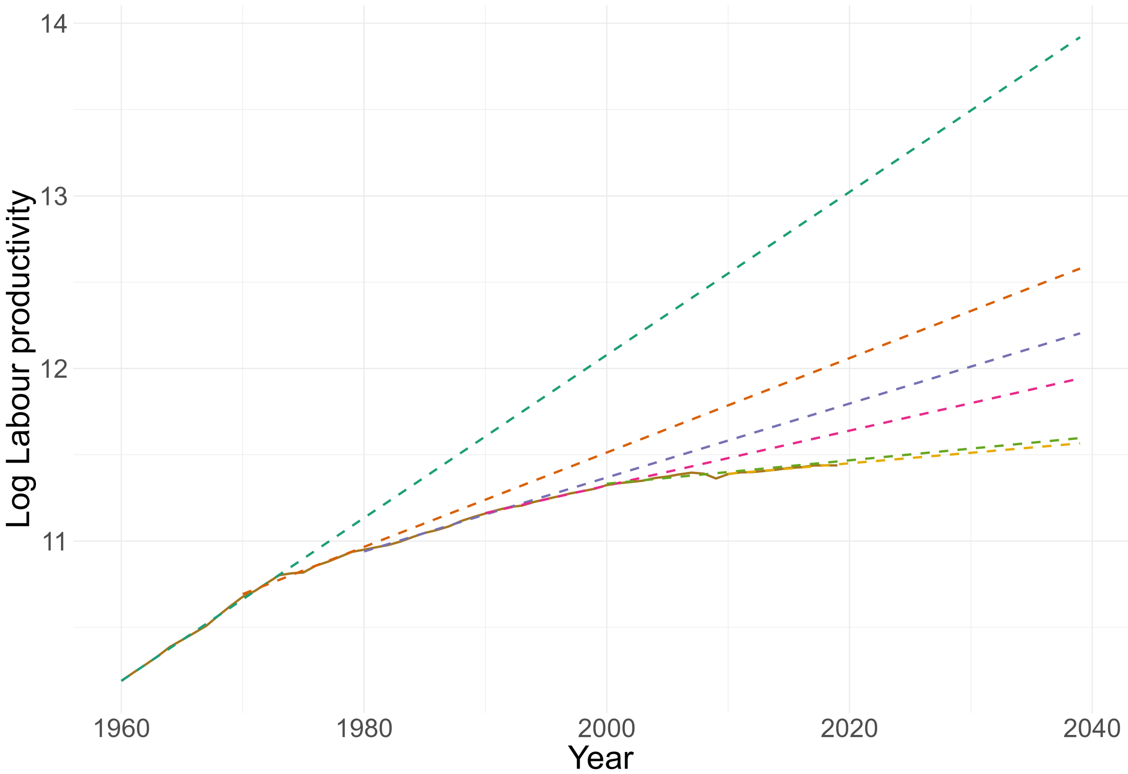
This deceleration has spawned a huge literature in economics, positing a variety of different explanations for the slowdown (see e.g. Gordon, 2016; Tavani and Zamparelli, 2018; Kleinknecht, 2020; Goldin et al., 2024). However, the explanations are generally internal to the economic process and do not examine the possibility of biophysical limits to growth. Even in ecological economics, where biophysical limits are central, productivity growth is often modelled as unconnected to energy or material inputs (subsection 4.3). This paper examines the extent to which there are biophysical limits to technical change, focusing on the role of energy and energy conversion efficiency. To investigate this question, I examine two literatures: the work on Societal Exergy Analysis (SEA) and exergy economics pioneered by Ayres and Warr (2009), and the development of ecological macroeconomic models (Hardt & O'Neill, 2017).

SEA is a technique that examines the efficiency with which societies convert energy inputs (coal, gas renewables, etc.) into useful outputs (heat, light, mechanical work, etc.) and can give the aggregate efficiency for a society across all processes. Exergy economics then incorporates SEA into an economic model using a neoclassical production function. This literature highlights the role of energy in productivity growth and shows that efficiency improvements have been a key driver of growth (Ayres & Warr, 2009; Haberl et al., 2020; Serrenho et al., 2014). However, efficiency improvements cannot continue forever, as the maximum theoretical value is 100% and feasible thresholds are much lower. This raises important questions for our understanding of growth and technical change, and suggests that productivity growth will face biophysical limits. The field of ecological macroeconomics aims to integrate the insights and modelling approaches of post-Keynesianism while overcoming its traditional neglect of biophysical limits (Fontana & Sawyer, 2013). However, despite its focus on ecological constraints, most ecological macroeconomic models do not see any constraints to technical change and project permanent exponential productivity growth (subsection 4.3).

This paper has two primary goals. Firstly, it argues that previous attempts to integrate the insights of SEA have been undermined by reliance on the neoclassical production function. Neoclassical theory argues, in direct contradiction of the second law of thermodynamics, that production is possible with infinitesimal amounts of energy (or any other natural resource), as its marginal product will approach infinity as its supply approaches zero. Ayres and Warr (2009) attempt to rescue the production function by including useful exergy, but this leads to a series of contradictions (section 3). The paper argues that these contradictions are inevitable because SEA is based on the second law of thermodynamics, but the production function is based on a physics that pre-exists this law. This leads to ontological contradictions, as fundamental features of a world with an entropy law violate the principles of neoclassical theory (subsection 3.4). SEA fits better into a heterodox economic framework, as central tenants of the heterodox ontology require a world with an entropy law (subsection 4.1). In addition, the use of a post-Keynesian framework adds a consistent demand perspective to the supply-side framework of exergy economics and can theorise the interactions between a demand-determined economy and supply constraints (subsection 4.2).

Secondly, the paper argues that SEA can make an important contribution to the emergent field of ecological macroeconomics. SEA has been developed in a rich literature by scientists, but has been largely ignored by economics. The idea that energy is an important factor in explaining growth is far from new. It is at the heart of ecological economics (Stern, 2011), and has even been argued by some neoclassical authors (Berndt, 1990). What is distinctive about SEA is its ability to parsimoniously track energy through its conversion stages and provide a theory of efficiency gains consistent with the laws of thermodynamics. This provides three key insights for ecological macroeconomics: the tracking of energy further through its conversion stages than conventional metrics, the relationship between energy and technical progress, and the likelihood of technical progress facing a declining rate. These points highlight gaps in the ecological macroeconomics literature, which often models technical change using a constant-rate exponential function, without an explicit link between energy and productivity (subsection 4.3). I argue that limits to technical change should be considered as a third form of biophysical limit, alongside the more commonly modelled environmental damages and declining resource quality/availability.

Figure 1.1: Productivity growth in high income countries



Source: Author's calculation from data in (Marquetti et al., 2021)
Notes: Dotted lines are projections based on the growth rate for each decade. Selection of high income countries with data going back to 1960 (see subsection A for details)

Following this introduction, the second section introduces exergy and SEA, and argues that this has important implications for economics. The third, examines the incorporation of SEA into a neoclassical production function. It criticises the arguments given in favour of using the neoclassical production function, outlines the contradictions that result, and shows the roots of these contradictions in the neoclassical adoption of classical physics. The fourth chapter argues that a heterodox framework can overcome these contradictions, as key features of its ontology require an entropy law. It then outlines the benefits of using a post-Keynesian framework for ecological modelling, before examining assumptions about biophysical limits, energy, and technical change in existing ecological macro models. The final section concludes.

2 Societal Exergy Analyis and Exergy Economics

This section begins by outlining the foundational concepts of societal exergy analysis (SEA). It then examines the relationship of exergy to economics and answers some possible critiques.

2.1 Thermodynamics, Energy and Exergy

The concept of exergy[1] derives from the first and second laws of thermodynamics. The first law of thermodynamics states that: 'energy, including the energy equivalent of mass, is a conserved quantity. It can be neither created nor destroyed.' (Kümmel, 2011, p. 35). Applying this law to energy conversion processes, this means that the input of energy always equals the output of energy plus any waste energy emitted. Using the example of a car, the chemical energy of the fuel exactly equals the kinetic energy of the car plus waste heat emitted as friction and air resistance, and energy used to power subsystems (such as air conditioning).

One way of thinking about the second law of thermodynamics is to recognise that energy has not only a quantity, but also a quality. Higher quality energy has a greater ability to perform useful work[2]. The ocean has enormous amounts of heat energy, but very little of this energy can be used. By contrast, electricity is a very high quality energy, as it can be converted into almost any kind of work with minimal losses. The total energy of a system can be divided into two components: exergy and anergy (Wettstein, 2023). Exergy refers to available energy, or that component of the energy that can perform useful work, while anergy is the component that cannot. The second law of thermodynamics states that in any irreversible process, the amount of exergy always decreases and the anergy increases. Many common ways of discussing energy relate more to exergy than to total energy. For example, we cannot properly speak about the consumption of energy, as energy is always

[1] The ideas underlying the concept comes from 19th and early 20th century thermodynamics, but the term exergy is first used by Rant (1956).

[2] Work is defined here in the manner of physics. It was originally defined for lifting weights against gravity, but the same concept can apply to many other forms of work where energy is applied to achieve some change in a subsystem.

conserved. In fact, it is exergy that is consumed in an economic process.

In equations, the first law of thermodynamics states that total energy, equal to exergy plus anergy, is always conserved:

$$Energy = Exergy + Anergy = Constant \tag{1}$$

While the second law states that in any non-reversible process, the exergy (E) of the system always decreases (anergy increases).

$$\frac{dE}{dt} \leq 0 \tag{2}$$

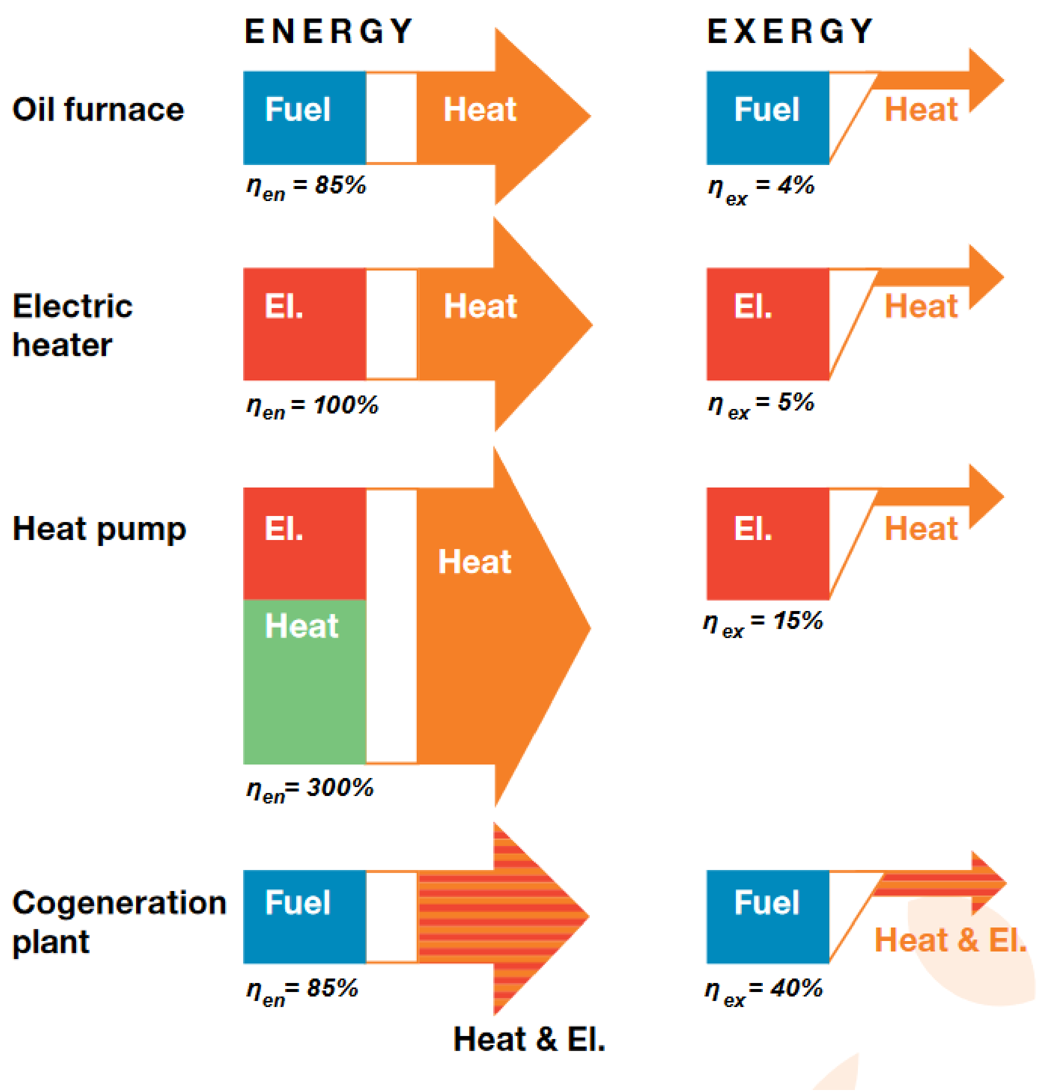
Another way of thinking about the second law of thermodynamics is in terms of gradients. For example, a large temperature difference between two systems can be used to do work as heat flows from the hotter to the colder system[3]. However, this reduces the gradient, brings the system closer to thermodynamic equilibrium, and reduces the system's ability to do work (reduces its exergy.). The heat energy of the ocean has little exergy because it is in, or close to, equilibrium with its surroundings. This shows the link between the second law as a decrease of exergy and the more common formulation as an increase of entropy (Dincer, 2020). Entropy is an abstract state variable that increases as the system approaches thermodynamic equilibrium and becomes more mixed or disordered. As a system approaches thermodynamic equilibrium, it therefore loses exergy and gains entropy.

2.2 Exergy Efficiency

The first and second laws of thermodynamics entail different efficiency metrics that can be used to assess the efficiency of an energy conversion process. Energy (first law) efficiency measures the percentage of energy applied to a process (the energy in a fuel, electricity, etc.) that is used in the process (is not wasted). This is the efficiency metric that is most commonly reported. For example, an oil furnace with an (energy) efficiency rating of 85% means that 85% of the fuel energy is used to heat, while 15% is wasted. The problem with this efficiency metric is that it does not take into account energy quality. The process of

[3] The situation is essentialy the same with other gradients, such as chemical or electrical

Figure 2.1: Energy and exergy efficiency for heating

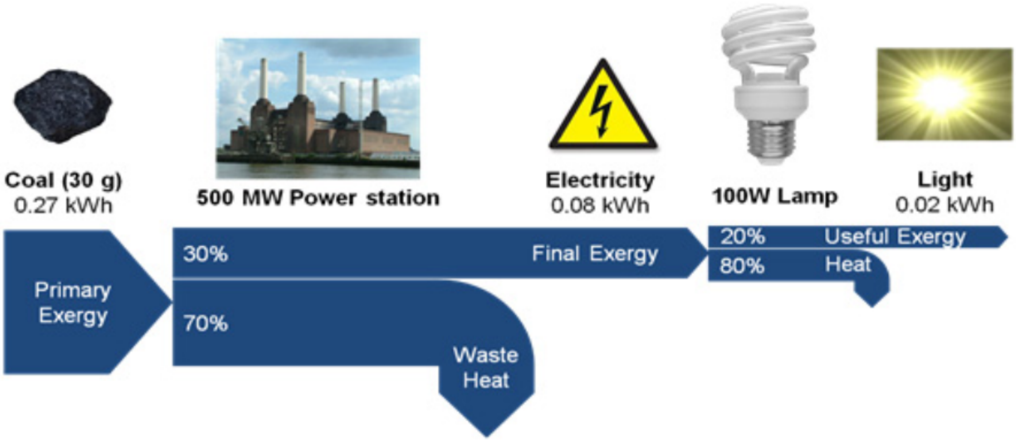


Source: (Wall, 2010 cf Dewulf et al., 2015, p. 9)
Notes: EL. is Electricity

burning oil for space heating converts a very high exergy heat potential (fuel oil burns at around $2000°C$) into low-temperature heat. This matters because the same resource could be used to provide just as much heat to the home, while also producing significant other useful work. For example, to generate electricity in a co-generation plant (Ayres, 2016, chap. 10). The difference between energy and exergy efficiency for different types of heating can be seen in Figure 2.1.

Energy (first law) efficiency can therefore be misleading, as processes with a very high energy efficiency rating can still be substantially improved. It is also very process-specific, meaning that it is difficult to compare the energy efficiency of two different processes. For

Figure 2.2: Exergy conversion stages



Source: (Brockway et al., 2017, p. 4)

example, the cogeneration plant in Figure 2.1 has the same energy efficiency as the oil furnace despite producing the same amount of heat and also generating electricity. Using the metric of exergy (second law) efficiency overcomes these shortcomings by explicitly taking account of the changes in energy quality in energy transformations. The value of exergy analysis for understanding societal energy flows has been recognised by several prominent scientific organisations (APS, 2008; Brockway et al., 2016).

The definition of different energy conversion stages can be seen in Figure 2.2, with the example of a coal power station that powers a lightbulb. The exergy goes through three stages. The primary stage (E_p) refers to the energy source in its original form (coal, crude oil, uranium, etc.), the final stage (E_f) refers to the exergy as sold to the consumer (electricity, petrol, piped gas, etc.), and the useful stage (U) refers the useful output (heat, light, motion, etc.) At each step of the process exergy is lost. Exergy efficiency is defined as the ratio between the exergy at two different stages. Using the example from Figure 2.2, the primary to useful exergy efficiency ($\eta_{pu} = U/E_p$) is 0.02/0.27 = 7.4% while final to useful efficiency ($\eta_{fu} = U/E_f$) is 0.02/0.08 = 25%. Because exergy efficiency is comparable between processes, the aggregate exergy efficiency of a sector or economy can also be defined as the ratio between the aggregated values for each stage. When carried out at the level of a country, this is known as societal exergy analysis (SEA) (Brockway et al., 2014; Sousa et al., 2017). Exergy efficiency has a theoretical maximum of 1, which implies a fully reversible process, but feasible process limits are much lower (Rosen, 2015).

The idea of conducting a societal exergy analysis goes back to the 1970s (Carnahan et al., 1975; Reistad, 1975; Sousa et al., 2017) but the widespread creation of aggregate country level exergy efficiency time series and their use in economics is relatively recent. This was pioneered by Ayres, Warr, and colleagues (Ayres et al., 2003; Ayres & Warr, 2005, 2009; Warr et al., 2010; Serrenho et al., 2014). They proposed a methodology for splitting up the uses of exergy in the economy by fuel type, sector, and use, and calculating the second law efficiency for each of these subcategories from estimates of thermodynamic production efficiencies. This allows the creation of sectoral and aggregate times series of exergy and efficiency at the different stages.

2.3 Exergy efficiency and the economy

Ayres and Warr (2009) argue that exergy efficiency is the best measure of technical progress, as it reflects the physical efficiency of an economy in converting inputs to outputs in physical terms. Implicit in their theory is the idea that the economy, and therefore technical progress, is materially based, that is, economic growth and technical change come essentially from a greater material output. In this respect, the ideas of Ayres and Warr, as well as those of many others who have written about the relationship between energy and growth (Smil, 2018; Ayres & Warr, 2009; Kümmel, 2011), are closer to classical political economy, which put production at the centre of its theory, than to neoclassical economics, which centres exchange. If one accepts that the economy and technical change are (at least primarily) materially founded, this entails a central place for exergy. Economic growth requires greater production, which in turn requires more useful exergy. This can only come about through higher exergy inputs or through greater efficiency. SEA shows that efficiency gains cannot continue forever because it is a bounded variable, and further gains become increasingly hard to sustain. This adds to the problem of declining quality of exergy resources to give us two barriers to the production of useful work (Brockway et al., 2019).

We can examine the implications of this, and the contrast to most economic theory, by using an equation that I think of as a general theory of technical change. This expresses technical change ($\hat{y}$) as a function of a vector of explanatory variables (X).

$$\hat{y} = f(X) \tag{3}$$

Taking a specific view on which variables should be included in X is beyond the scope of this paper. In the literature a variety of variables have been proposed, including the capital stock, R&D investment, number of patents, GDP growth, or the wage share (Storm and Naastepad, 2012, chap. 4; Tavani and Zamparelli, 2018; Howitt, 2018). However, f(X) is almost always modelled as a linear function, which means constant returns to $\hat{y}$ in terms of X ($f''(X) = 0$). Exergy economics effectively inserts useful work per worker (u) between productivity and its explanatory variables so that Equation 4 becomes:

$$\begin{aligned} y &= f(u) \\ \hat{u} &= g(X) \end{aligned} \tag{4}$$

More X produces more useful work ($g'(X) \geq 0$), but the declining quality of energy resources and limits to efficiency mean that more X is required to produce additional U ($g''(X) \leq 0$). With the additional assumption that the relationship between useful work and output is linear (Keen et al., 2019) this means that there is also dimishing returns to productivity growth in terms of X. This argument can be used to explain the decline of productivity growth rates. Growth in the input of energy and in the efficiency of the conversion to useful work have been important preconditions of the spectacular economic growth of the last two centuries (Ayres & Warr, 2009; Smil, 2018). The influence of both of these factors has begun to slow down, and this has put a downward pressure on both productivity and economic growth.

2.4 Implications for productivity growth

The idea of exponential growth is so central to economic theory and models that an economist reading this is likely to have several objections to the idea that productivity growth is constrained by natural laws. Using SEA we can see that there are three ways to increase productivity: (1) increasing final exergy per worker, (2) increasing exergy efficiency, and (3) decoupling growth from useful work [4]. This can be seen from the identity splitting productivity into three ratios: final exergy per worker ($\epsilon = E_f/L$), exergy efficiency

[4] A more fundamental critique of SEA can be formulated by using the work of Mirowski (1988), who questions whether energy can be aggregated at all. His work is useful in highlighting that aggregation is an abstraction that obscures the differences between, for example, a joule of petrol and a joule of electricity. In response, however, we might argue that such abstractions are necessary for understanding the world and the aggregation of energy obscures less than standard constructions in economics such as GDP.

($\eta_{fu} = U/E_f$), and useful work productivity ($y_U = Y/U$)

$$y_L = \epsilon \cdot \eta \cdot y_U \tag{5}$$

The growth rate of labour productivity is then the sum of the growth rates of the components:

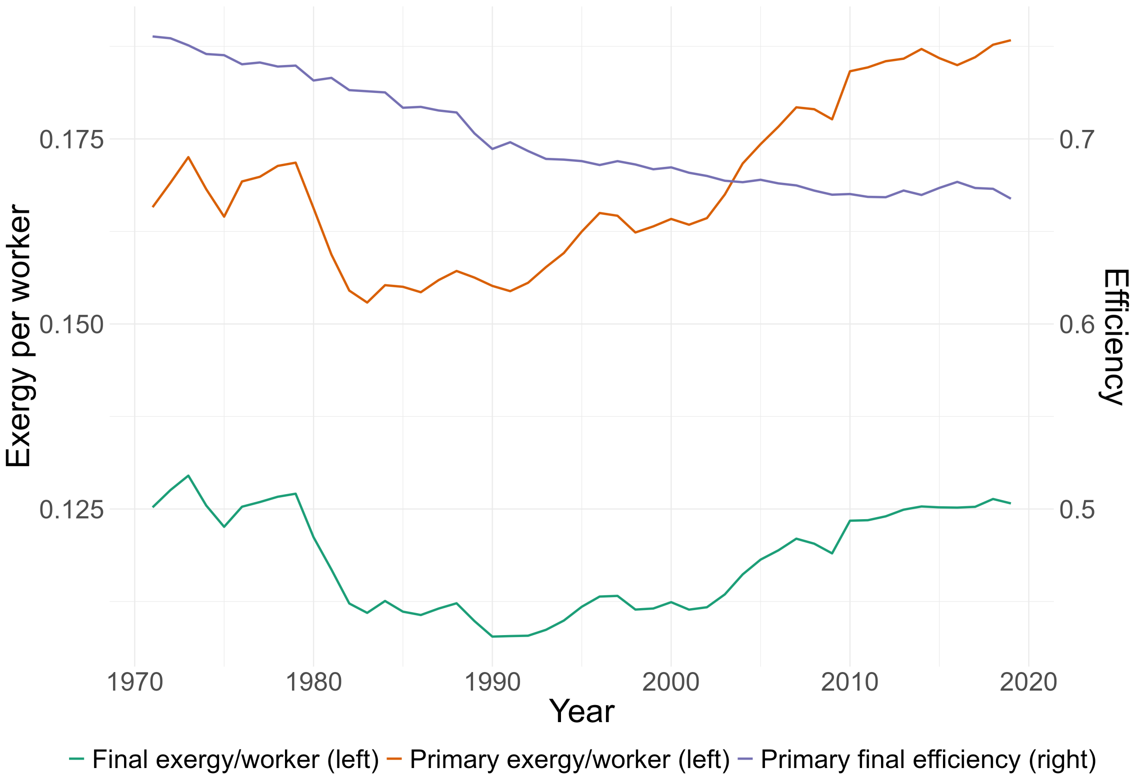
$$\hat{y_L} = \hat{\epsilon} + \hat{\eta} + \hat{y_U} \tag{6}$$

The maintenance of a constant rate of productivity growth therefore requires that any decrease in one of the component gorwth rates is met by a compensating increase in the others. I will argue that while there is possiblities for growth in each of these compenents to continue to greater or lesser extent, the long-run trajectory is likely to be a continued downward trend in productivity growth.

Increases in final exergy

The first possibility is that while efficiency gains may be limited, there is nothing to prevent final exergy from continuing to increase and drive productivity growth. While fossil energy may be limited by stocks and the necessity to reduce emissions, there is no limit to renewables. Perhaps we can even discover some radically new technology, such as nuclear fusion or orbital solar farms, which will completely remove energy scarcity. In response, we should first note that the issue is not just the absolute availability of energy sources, but also their quality or return. This is often captured in the literature through the concept of Energy Return on Investment (EROI), which measures the return on energy sources relative to that used in their extraction. The energy sources with the highest EROI are likely to be exploited first, leading to a Ricardian dynamic of declining returns from energy over time (Brockway et al., 2019, Figure 2.3). This tendency can be offset, for exammple, by increases in productivity of the manufacturing of the extraction equipment. However, if these increases are themselves dependent on efficiency gains subject to diminishing returns, the first tendency will eventually assert itself. The argument applies not only to fossil fuels but also to renewables (Jacques et al., 2023). The cheapest and

Figure 2.3: Primary and final exergy per worker and primary to final efficiency



Source: Author's calculation from (Marquetti et al., 2021; Marshall et al., 2024)
Notes: EPW in Megajoules (MJ) per worker

best renewable energy sites are likely to be exploited first, and this puts limits on their economic expansion.

Figure 2.3 shows the development of the final Exergy per worker ratio (ϵ) at the world level, split into primary exergy per worker (E_P/L) and primary to final exergy efficiency (E/E_P). This shows that ϵ has been largely stable since the 1970s, but this has required increasing primary exergy per worker to offset the diminished quality of energy resources (Brockway et al., 2019). This increased amount of primary energy to maintain the same final energy per worker means creates an upward pressure on energy costs and disincentivising energy intensive production.

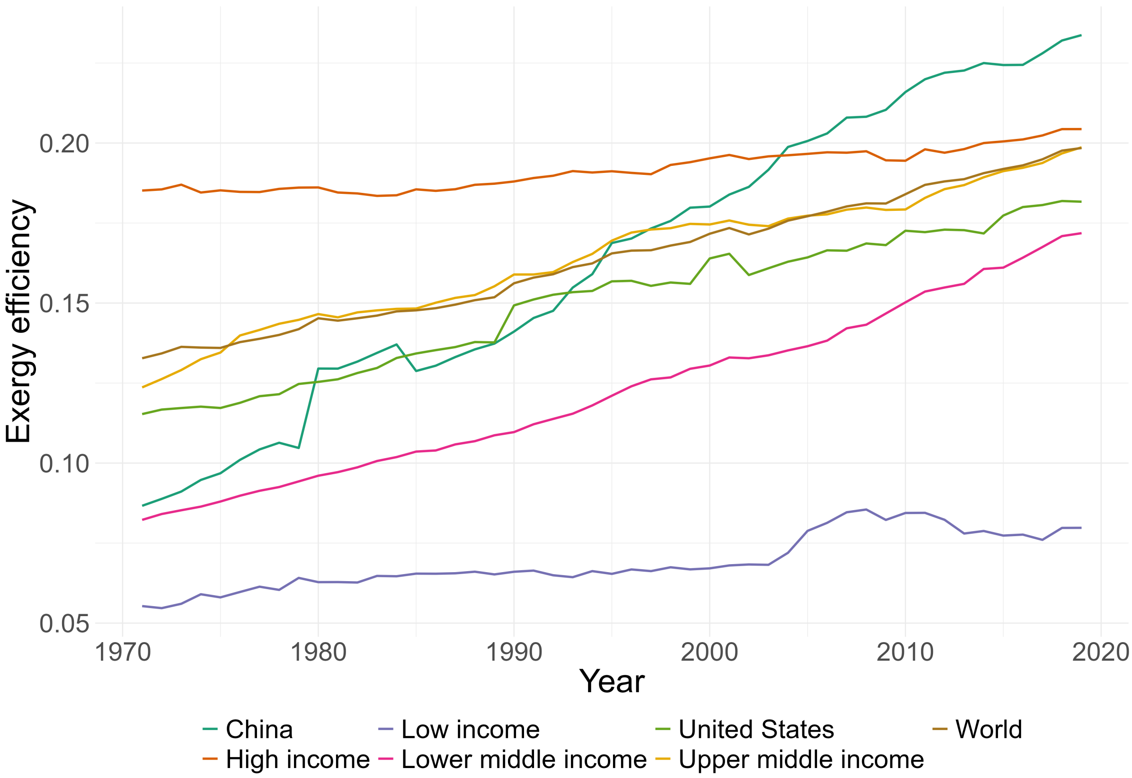
Secondly, renewable energy is not free of environmental impact. It requires materials which must be extracted and also become scarcer, decrease in quality, and require more energy to extract; and it requires land that then cannot be used for other purposes (such as a natural carbon sink). While the land constraint might not seem that significant, exponentially growing renewable energy at historical trends would require the entire surface of the earth in a couple of centuries (Murphy, 2021). Thirdly, it is as yet unclear the cost of running modern societies on an exclusively renewable basis. Despite huge increases in renewables, world energy systems remain hugely dependent on fossil fuels, and there is some doubt about the cost, and speed with which, this dependence can be broken (Smil, 2022; Christophers, 2024).

Although we cannot rule out a deus ex machina technology, such as nuclear fusion, its development in time to solve all our energy problems seems unlikely. In any case, a technology that allowed further exponential increases in exergy would only push the limits to new terrains. All exergy that is used in the economy ultimately ends up as waste heat. At the moment, the effect of this 'anthropogenic heat emission' is quite small, about 1% of the radiative forcing of anthropogenic climate change in 2015 (Berg et al., 2015). But with continued exponential increases in exergy production, it would quickly become significant. Murphy (2021) calculates that with current levels of the greenhouse effect and annual exponential growth of energy at 2.3%, atmospheric temperatures would reach boiling point in 373 years. The upshot is that, while we cannot rule out increases in energy driving increased productivity in the short to medium term, it's continued exponential increase into the future is impossible.

Continued efficiency increases

A second possibility is to accept constraints to energy efficiency, but argue that we are far from hitting these constraints.Depending on the country and context, this critique has some truth. In many countries exergy efficiency is decelerating under the current set of institutional arrangements; however, this does not mean that the limit could not be pushed higher. Renewable energy and electrification are likely to improve exergy efficiency, which therefore can be pushed up using green investment (Brockway et al., 2024; Semieniuk et al., 2021). One of the forces that reduces overall exergy efficiency is the increasing composition of low efficiency processes (particularly transport and heating/cooling), and a government that acted to reduce the need and increase the efficiency of these processes would likely be able to increase efficiency beyond current limits. We can therefore think of the limits to exergy efficiency as, to an extent, institutionally determined. A government that takes the green transition more seriously and acts to prevent efficiency dilution would be able to increase efficiency, but this does not eliminate the problem of declining

Figure 2.4: Final to useful exergy efficiency



Source: Author's calculation from data in (Marquetti et al., 2021; Marshall et al., 2024)
Notes: Aggregates include 101 countries selected according to data availability.Country classifications from the World Bank (2019). High income countries excluding the US and upper middle income countries excluding China

returns. The more efficient a process, the more difficult and expensive it is to achieve further efficiency gains, and therefore a declining rate of efficiency improvements is likely to assert itself in the long run.

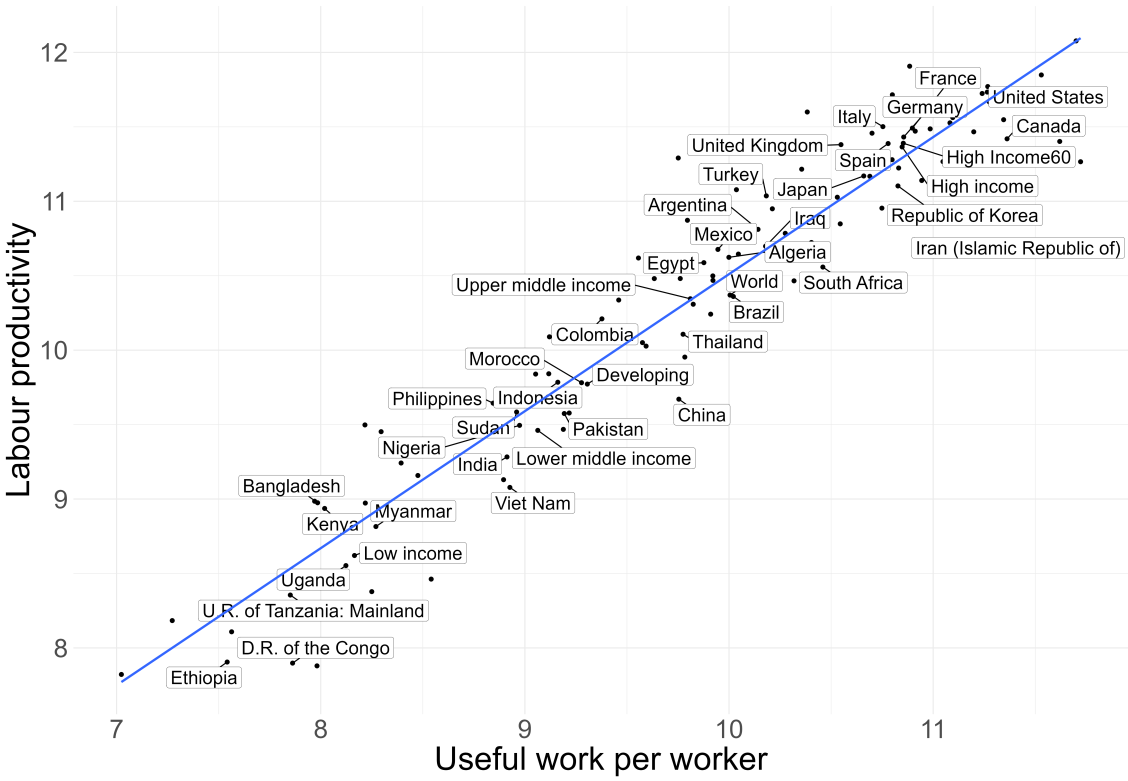
Exergy efficiency is also the result of opposing forces. Industrial processes tend to have higher exergy efficiency, while space heating and cooling and personal transport have low efficiencies (Sousa et al., 2017). In high income countries, higher process efficiency (the efficiency of particular processes) has been balanced by an increasing composition of these lower efficiency processes in the aggregate, known as efficiency dilution (Williams et al., 2008; Brockway et al., 2014). Figure 2.4 shows the development of exergy efficiency for each income category, the world, and for the US and China. The importance of composition for overall efficiency can be seen by the impressive efficiency gains of China, which has surpassed both the US and the high income level. This is not due to higher process efficiency, which remains lower in China, but to a lower proportion of low-efficiency processes (Brockway et al., 2015). This shows the potential for policies that would reduce efficiency dilution and improve overall efficiency, but this can only postpone and not remove the thermodynamic limits to exergy efficiency.

Decoupling from useful work

The final objection is to maintain that growth is, or can become, entirely decoupled from useful work. This has been central to the concept of sustainable development promoted by international institutions (World Bank, 2012; OECD, 2011; UN, 1987). If growth can take place, not through increased production, but through improvements to the utility of given production, then there is no constraint. Empirically, this would mean increasing growth while useful work or other measures of material impact remain flat or fall. However, this is a very poor description of the history of growth to this point. Many papers, using a variety of different measures of the materiality of the economy, have shown that while GDP has begun a relative decoupling from energy and materials, it is far from absolute decoupling (Hickel & Kallis, 2020; Haberl et al., 2020; Wiedenhofer et al., 2020; Wiedmann et al., 2015). SEA shows that a large proportion of measured decoupling from energy use is due to increased efficiency, but casts doubt on whether this reduces aggregate energy consumption due to rebound effects (Brockway et al., 2017, 2021) and argues that these efficiency gains are limited and subject to diminishing returns. Long-term sustainable decoupling from exergy input must mean a decoupling of growth from useful work, and previous studies have found little evidence of even relative decoupling of GDP from exergy at the useful stage (Haberl et al., 2020).

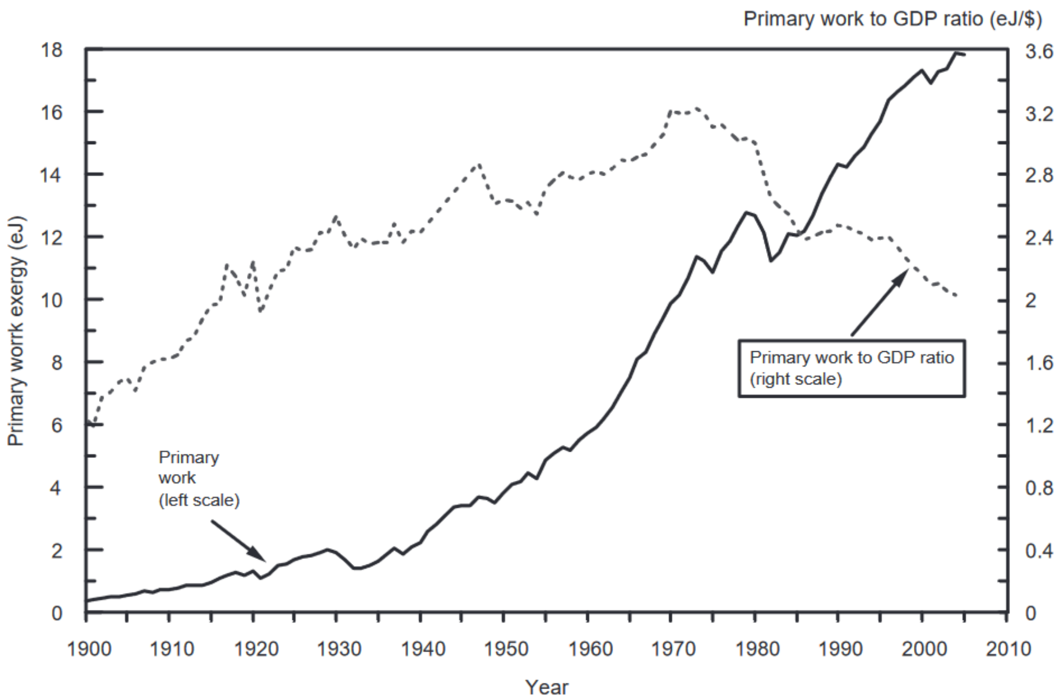
Figure 2.5 shows the tightness of the correlation between the logs of useful work and GDP per worker between countries (the R^2 is over 0.9). Inclusion of exergy at the useful stage improves the correlation versus final exergy (Figure A.1), which is generally done in energy economics(Aghdam et al., 2023). This does not say in which direction the correlation runs, but it does show that there is no example of low useful work-high productivity countries and suggests that increases in useful work are a necessary condition for productivity growth. Figure 2.6 shows the ratio of useful work (named primary work in the figure) to GDP for the US. This shows that useful work has been consistently increasing throughout the period and that the ratio of useful work to GDP changed little in the last 100 years. We can therefore see that historical growth and current differences in development between

Figure 2.5: Logs of labour productivity and useful work per worker



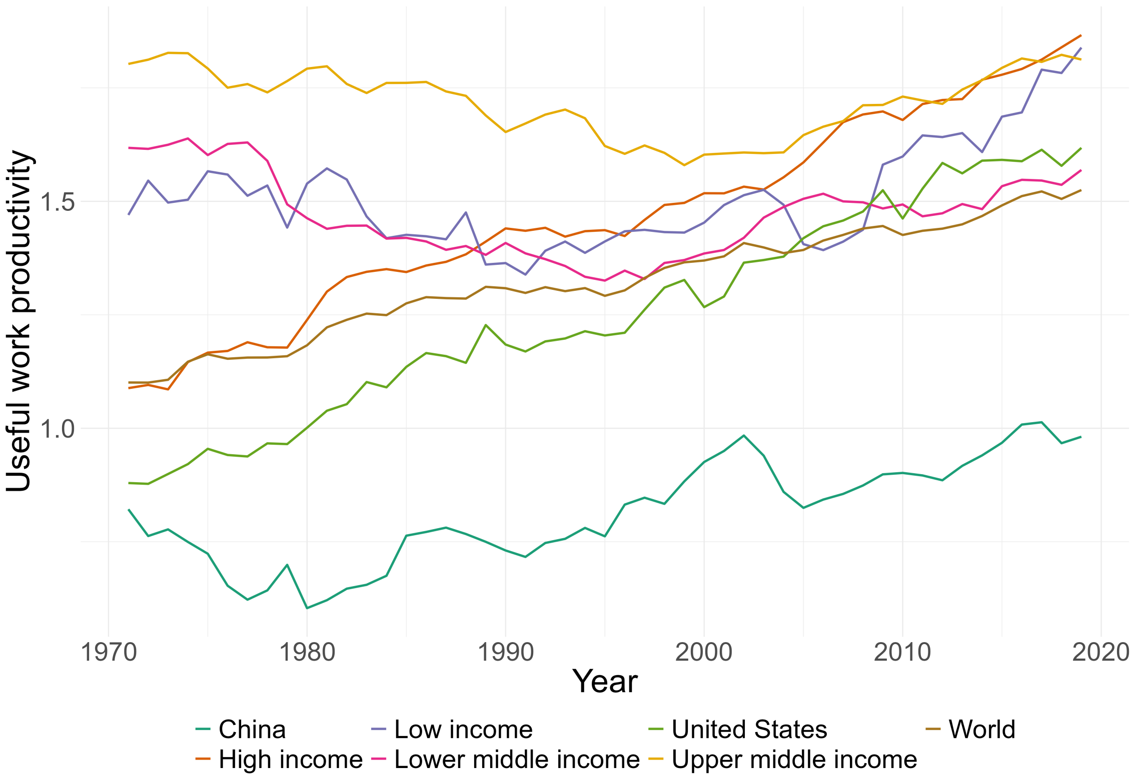
Source: Author's calculation from data in (Marquetti et al., 2021; Marshall et al., 2024)
Notes: Both variables in logs, selection of 101 countries selected according to data availability

Figure 2.6: Useful exergy and GDP



Source: (Ayres & Warr, 2009, p. 130)
Notes: Primary work refers to what we call useful work or useful exergy in this paper

Figure 2.7: Useful work productivity



Source: Author's calculation from data in (Marquetti et al., 2021; Marshall et al., 2024)
Notes: Aggregates include 101 countries selected according to data availability.Country classifications from the World Bank (2019). High income countries excluding the US and upper middle income countries excluding China. Useful work productivity in Joules per 2017 ppp$

countries depend on useful exergy. However, as can be seen from Figure 2.6, the ratio of useful work to GDP has begun to reduce since the 1970s. This suggests that some decoupling of GDP from useful work is possible, but unless the speed of this decoupling can increase enough to balance decreases in useful exergy, this entails productivity growth slower than that we have become used to in the past.

It is also perhaps questionable whether productivity growth driven by useful work productivity is comparable to that driven by useful work. Useful work productivity appears to be closely linked to financialisation. The six countries with the highest UWP in 2019 are all tax havens (Hong Kong, Ireland, Singapore, Panama, Mauritius, and Switzerland) and the highest for a large high-income country is the finance-dominated UK. Structural changes to the economy and revisions to GDP calculation methodology have led to a 'financialisation of GDP', where imputed or financialised components play an increasing role in growth (Assa, 2016; Basu & Foley, 2013). GDP redefinitions are significant and qualitatively shift calculations of the relationship between economic and environmental indicators (Semieniuk, 2024). The composite nature of GDP necessarily equates extremely disparate phenomena with varied economic and social effects. An increase in the efficiency of production of necessities and an increase in debt-servicing costs or imputed rental payments may have the same quantitative impact on productivity, but that does not mean they are the same. To the extent that UWP can drive productivity growth numerically, it is therefore unclear if it is comparable to useful-work driven productivity growth. Further research is required to determine the extent to which UWP growth depends on imputed and financialised components of GDP.

3 Energy, Exergy and the Neoclassical Production Function

To understand how exergy economics uses efficiency in its theory of growth, it is necessary to briefly outline the neoclassical theory they criticise, but also use as a basis. We then examine why Ayres and Warr persisted with a neoclassical approach despite their obvious misgivings.

3.1 Neoclassical theory of the environment

Since the work of Solow (1956, 1957) and Swan, (1956) neoclassical growth theory centred around the concept of an aggregate production function. Output (Y) is a function of factors of production, most commonly Capital (K), Labour (L) and Technical progress (A(t)). Each factor of production has diminishing marginal returns but can be substituted for the others to the point that with enough of factors B, C, etc., any level of production is reachable with infinitesimal amounts of factor A. For any given level of production, we can draw an isoquant through factor space that defines the ratios of factors that can produce a particular level of output. Firms are then able to select from an infinite set of 'blueprints' subject to the constraint of factor prices, which are ultimately determined by aggregate allocations. Technical change shifts the entire production surface, allowing all blueprints to be produced with fewer production factors.

Substitutability, together with standard neoclassical assumptions [5] means that the output elasticity of a production factor must equal its cost share. The most common mathematical form is the two factor (aggregate capital and labour) Cobb-Douglas, where the output

[5] Factors are paid their marginal products, firms are profit maximisers, and constant returns to scale

elasticities of the factors is constant and equal to their share in national output. Equation 7 shows a Cobb-Douglas production function, with α as the output elasticity of labour and $1-\alpha$ the output elasticity of capital [6].

$$Y = A(t)L^{\alpha}K^{1-\alpha} \tag{7}$$

As environmental critiques of the economy and economics became increasingly prominent in the 1970s, the aggregate production function and factor substitutability formed the key planks of the neoclassical counterargument. If natural resources are endlessly substitutable with man-made capital, then natural resources are no constraint and the optimal growth path is to exploit these resources now to build up stocks of man-made and human capital to maximise production in the future (Solow, 1974; Stiglitz, 1974; Hartwick, 1977; W. D. Nordhaus & Tobin, 1972). This led to the stark conclusions that 'sustained growth in per capita consumption (is) feasible', natural resources are currently consumed at approximately 'optimal rates' (Stiglitz, 1974, p. 136) or even that 'growth in output per capita will accelerate… even as stocks of natural resources decline' (W. D. Nordhaus & Tobin, 1972, p. 14).

The debates in the 1970s also led to neoclassical research into production functions that include energy and materials alongside capital and labour (KLEM) (Hudson & Jorgenson, 1974). However, the conclusion of many neoclassical economists was that since energy is a small part of overall cost, it cannot have a significant impact on growth. Denison (1979, p. 16), one of the pioneers of growth accounting, argued that: "If the elasticity of substitution is unity and the weight of energy is 5 percent, a 1-percent reduction in energy consumption with no change in labor and capital would reduce output by 0.05 percent and output per unit of input by the same percentage". The implication, spelled out by Denison, is therefore that a 50% reduction in energy consumption would only lower output by 2.5%, a reductio ad absurdum of the neoclassical approach.

Exergy economics is at heart a critique of this assumption that energy and materials play no essential role in the economic process. They critique economics for its failure to explain "physical production in physical terms" and aim to remedy this defect (Ayres &

[6] the two sum to 1 because of the constant returns to scale assumption

Warr, 2009, p. 16). Together with other forms of environmental economics and industrial ecology, they see the economy as nested within, and dependent upon, the biosphere as a source of resources and sink for wastes (Ayres & Ayres, 2002). Its most important distinguishing features are the use of exergy analysis, the construction of the exergy efficiency and useful work time series, and its use of these values in production functions.

3.2 Exergy and the production function

Ayres and Warr's work on exergy in production functions draws on the work of Kümmel, another physicist working on the importance of energy in production (Kümmel et al., 1985; Kümmel, 1989). Kümmel and co-authors adopt the neoclassical production function approach, but seek to explain, within the boundaries of this theory, how energy can have a far larger impact than its cost share. Their answer is to create a more general, LINEX, production function that incorporates the common neoclassical functions as special cases(Kümmel et al., 1985; Lindenberger & Kümmel, 2011). Their model accepts the neoclassical idea of substitution but uses time-varying elasticities of substitution and more constraints on factor allocations to create a more restricted allowable section of factor space. This allows factor elasticities to differ from cost shares, as the most cost-effective production methods may be restricted by technological constraints. Examples of these constraints include the energy capacity of machines and the preferences of consumers for goods that are labour-intensive (such as services). This restricts the substitution of cheap energy for expensive labour and provides justification for their argument that labour is overvalued and energy undervalued, relative to their technical rates of substitution.

Ayres and Warr (2005, 2009) use the LINEX function and the arguments of Kümmel around why elasticities can differ from cost shares, but use their estimated useful work time series in the production function instead of primary or final energy. They test both a LINEX function and a Cobb-Douglas (Equation 8) including useful work and with parameters freely estimated rather than constrained to factor shares. We will focus on the Cobb-Douglas function because it is more used in later literature and the arguments made also apply to the more general LINEX case.

$$
\begin{aligned}
&Y = L^{\alpha} K^{\beta} U^{\gamma} \\
&0 \leq \alpha \leq 1 \qquad 0 \leq \beta \leq 1 \\
&\gamma = 1 - \alpha - \beta
\end{aligned} \tag{8}
$$

Ayres and Warr argue that a useful work enhanced production function provides a very good fit to the past growth trajectories of a variety of different countries over long time periods (Ayres & Warr, 2009; Warr et al., 2010; Ayres & Warr, 2005). They acknowledge that a 'professional statistician', seeing the goodness of fit 'is likely to respond with some skepticism' to their results (Ayres & Warr, 2009, p. 213), but argue that the broad implications of the theory, that 'adding a unit of labour, by itself, produces almost no added value' (Ayres & Warr, 2009, p. 210), can be upheld. In the rest of this section, I argue that the scepticism of the professional statistician is justified and any attempt to empirically find marginal productivities of production factors on the basis of a neoclassical production function is inherently flawed.

3.3 The production function and its critics

Since first formulated by Cobb and Douglas in the 1920s and 30s, the aggregate production function was subjected to an intense criticism. This criticism reignited in the 1950s and 60s as Solow made the aggregate production function increasingly central to neoclassical economic theory and have continued till today (Felipe & McCombie, 2013). Ayres and Warr (2009, pp. 176-181) were aware of some problems with the neoclassical production function, but do not appear to fully grasp the implications. They mention aggregation problems, the Cambridge capital controversies, the difficulties of separating technical change from factor accumulation, and that empirical estimations of the production function can be fit to 'almost any set of collinear capital and labor time series'. From this, they conclude that: 'the case against using aggregate production functions of a very few variables seems overwhelming; certainly stronger than the case for using them' (Ayres & Warr, 2009, p. 181). They also mention the basic contradiction between their approach and the neoclassical production function. One of the central arguments made by Ayres and Warr, as well as Exergy economics more broadly is that exergy is an essential input that cannot be replaced by capital and labour, but 'an attribute common to all production function models is the built-in assumption of complete substitutability between all the factors' (Ayres & Warr, 2009, p. 177). In the end, however, despite these reservations they chose to use the production function as the basis for their further analysis, arguing: 'in the spirit of Milton Friedman (1953) that if an assumed relationship explains (that is, reproduces) the empirical observations, one need not worry too much about the realism of every one of the underlying assumptions' (Ayres & Warr, 2009, p. 183). The problems with the neo-classical production function have been exhaustively documented (Felipe & McCombie, 2013) and are cited by Ayres and Warr themselves. We will, therefore, only examine the reasons that they chose to persevere with the approach despite clear misgivings. There are three key arguments that they use in support of their use of the production function: aggregation of capital in terms of energy, that substitution is possible over longer timescales, and a minimisation of the national accounting identity problem. I focus on the work of Ayres and Warr because the approach is usually taken as established and the criticisms not discussed in later work (Voudouris et al., 2015; Santos et al., 2021, 2018).

Aggregation of capital by energy and information

Problems with the aggregation of capital and output are one of the best known critiques of the production function (Robinson, 1953; Fisher, 1969). Ayres and Warr (2009, p. 177) respond with a 'partial reconciliation of the physical interpretation of capital and the economic interpretation'. They cite Kümmel et al. (1985, p. 292), which argues that 'Capital K can be aggregated technologically in terms of the maximum amount of work and information which per unit time can be performed and processed by the machines of the system'[7]. This aggregation is possible in theory, but the data does not exist to run anything like this calculation in practice, and it is unclear why machines should be aggregated as the unweighted product of energy and information. Kümmel instead gives a theoretical justification based on the derivation of the mathematics underlying the production function on state functions in physics.

State functions require that outputs must depend 'only on the actual numerical values of

[7] Later, Kümmel (2011, pp. 252-260) defines this physical aggregation explicitly as an aggregation of the product of the energy use of a machine (in kilowatts) and the amount of information processed by the machine (kilobytes/second). The information processing of a machine is measured as 'the number of switching processes per unit time that pass along or shut down energy flows in the fully employed machines'

the inputs, and not on the path along which the system has arrived at these values'. 'There must exist an unequivocal cause-and-effect relation between value added Y and the production factors X' (Lindenberger & Kümmel, 2011, p. 6011). Kümmel concludes that only the 'laws of nature' can explain this correspondence and establish the 'causal relationship between outputs and inputs that is the necessary condition for macroeconomics production functions' (Kümmel, 2011, p. 254). The clear problem with this argument is that it assumes what it is trying to prove. Kümmel takes the existence of an aggregate production function as a given, when the question is if it exists at all.

The role of time in production functions

When justifying their use of the neoclassical production function, Ayres and Warr (2009) conflate an everyday meaning of substitution with its particular and stringent form in neoclassical theory. They state that 'there is really no possibility of substituting (production factors)… in the very short term' (p. 178), but in the long run 'substitution between factors does occur' (p. 182). That factor proportions change, and therefore in a certain sense capital and energy are 'substituted' for labour during economic development, is indisputable; the question is whether this is factor substitution or technical change and how these two can even be distinguished. The distinction in neoclassical theory, deriving from its basis in classical physics (subsection 3.4), relies on the idea that substitution is reversible and instantaneous, while technical change is a unidirectional function of time. Time, as Robinson (1971, p. 255) described it, 'is at right angles to the blackboard'. Irreversible substitution 'in the long run' (i.e. in historical time) is therefore not enough to justify the use of a neoclassical approach.

Minimisation of the national accounting identity critique

When pressed, neoclassicals admit that the aggregate production function cannot be justified theoretically and retreat to its supposed empirical strength (Solow, 1987). This is why the national accounting identity critique is perhaps the most fundamental. Starting with Phelps-Brown (1957) critics have shown that this supposed empirical strength of the neoclassical production function is due not to the laws of production but the 'laws of algebra' (Shaikh, 1974). Technical rates of substitution cannot be calculated (because there is no way to aggregate capital other than price), but simulations where the data is generated from a particular technical rate of substitution show that estimates of the production function give the income share rather than the technical rates of substitution. This is why a neoclassical production function can be fit to any data, even those where there is, by definition, no technical rates of substitution (Felipe & McCombie, 2013, Chapter 3).

The problem with the instrumental (Friedman) defence is that there are always many possible assumptions that can provide a fit to the data, and the model that provides the best fit to the data is not necessarily the best fit to the underlying mechanisms. A 'Friedman' model[8] can, at best, project historical trends, but it cannot truly understand the mechanisms behind these trends. This is a particular problem in light of the accounting identity critique. If, as Ayres and Warr acknowledge, the production function can be fit to almost any collinear data, then how can a good fit possibly tell us anything about the underlying mechanisms? If fit is no use, we must evaluate the production function on the basis of its assumptions and the problems with time, substitution, and aggregation outlined above cannot be ignored.

The empirical results of integrating exergy into a production function can be derived through a reflection on Equation 8 and the stylised facts. If we take the logarithm of (8), using a dot to denote the natural log, we get:

$$\dot{Y} = \alpha\dot{L} + \beta\dot{K} + \gamma\dot{U} \tag{9}$$

We can therefore make a good guess at the coefficients that will result from an empirical estimate of (9) from thinking about the covariances of Y with each of the factors of production. Going back to Kaldor's (1961) stylised facts, capital, and output tend to grow at the same rate, while output grows quicker than labour. The work of Ayres and Warr has shown that the ratio of useful work to output is also approximately constant in the long run. It is, therefore, expected that if we run the regression in (9) we will get an insignificant value for α and more significant values for β and γ. In our data for the world aggregate we get $\alpha = 0.073$, $\beta = 0.244$, and $\gamma = 0.683$ (Appendix B). The econometrics in the literature is undoubtably more complex, but this simple example is sufficient to show how

[8] i.e. one with accurate predictions but inaccurate assumptions

the basic results can be derived from the stylised facts. This also shows why the posited relationship begins to break down in Ayres and Warr's data after the 1970s, as the ratio of useful work to output, which had been rising prior to the 1970s, began to fall thereafter.

The empirical results from the exergy economics literature regarding the production function cannot therefore be taken as evidence for the theory. The results are consistent with the theory, but they are also consistent with any theory that can generate the above three stylised facts. To differentiate between the different theories, we cannot rely on Friedman's instrumentalism but must think about the plausibility of the assumptions. In other words, the severe conceptual problems and lack of realism of the neoclassical production function cannot be dismissed and undermine the entire approach.

3.4 Contradictions of SEA and neoclassical economics

What we are left with is an attempt to introduce exergy analysis into the neoclassical approach that is fraught with contradictions. Firstly, the most central point of the exergy economics approach is that energy is a vital input that cannot be replaced, but the central principle of the neoclassical production function is (almost) unlimited factor substitution. Secondly, exergy entails historical and irreversible time, but the neoclassical production function requires logical and reversible time. This difference has important ontological and epistemological implications. Neoclassical theory implies a changeless future, predictable from the present, but the essence of the entropy law is that all production produces fundamental and irreversible changes. Finally, Ayres and Warr and Kümmel centre production and the material basis of the economy, but the neoclassical approach centres exchange, with production merely an automatic and instantaneous result of position in factor space.

To try to overcome these contradictions, Ayres, Warr and Kümmel rely on some rather ad-hoc assumptions (restrictions on factor space, aggregation in terms of energy and information) that allow them to pick and choose the parts of neoclassical theory they want to maintain and those they wish to discard. The full implications of these assumptions for the neoclassical model are not developed to the level required. Ayres and Warr (2009, p. 211) argue at times with heterodox economics. For example, they state that the economy is 'far from equilibrium' and that firms are not profit maximisers, but there is little attempt to work out the contradictions between these points and their neoclassical models. In the next section, I argue that these contradictions are inevitable because the foundations of neoclassical economics in pre-second law physics cannot incorporate a theory based on this law.

Classical physics and neoclassical economics

Authors such as Georgescu-Roegen (1971) and Mirowski (1989) have shown that neoclassical economics drew its theories from 'the mathematical physics of 1850' (Wiener cf Mirowski, 1989, p. 357). Two bastions of neoclassical theory, consumer choice and the production function, are taken directly from this outdated physics. The isoquants, representing either indifference between commodities or production technology and substitution between factors, take the role of the potential energy field, while change of position, representing expenditure on commodities or production factors, represents kinetic energy. Although the early neoclassicals knew that they were borrowing from physics, this has been largely forgotten, and the striking implications of the field formalism have never been recognised (Mirowski, 1989, Chap. 5).

As noted by Mirowski, a vector field implies a conservation law; meaning a conservation of utility or technological potential and expenditure. There is no arrow of time, so the reverse transformation must always be possible There must also be a single unambiguous mapping from inputs to outputs, meaning, in the case of a neoclassical production function, that any two bundles of capital and labour with the same aggregate values (K, L) must produce the same output. Further, a neoclassical production function must be path independent, which means that any kind of frictional or dissipative force is impossible (Lindenberger & Kümmel, 2011) and factor substitution cannot be costly. Therefore, central aspects for any real theory of production, its duration, the irreversible use of inputs, its uncertainty, etc., are simply impossible within a neoclassical production function. Output can only be an automatic, instantaneous, and reversible characteristic of the technological potential field. [9]

Nineteenth century physics implies a certain epistemology and ontology, best articulated

[9] To see this point, consider an object in a gravitational or magnetic field. The force does not take time to apply and there is no uncertainty. The force is entirely described by position in the field.

by Laplace:

> "An intellect which at a given instant knew all the forces acting in nature, and the position of all things of which the world consists - supposing the said intellect were vast enough to subject these data to analysis — would embrace in the same formula the motions of the greatest bodies in the universe and those of the slightest atoms; nothing would be uncertain for it, and the future, like the past, would be present to its eyes" (Laplace cf Mirowski, 1989, p. 27)

Laplace's conception results from a theory of the world that can be fully described through the kinetic and potential energy of its particles. This dream is long dead in science but lives on in neoclassical economics, where a world described purely by analogues of potential (technology and utility) and kinetic energy (expenditure) is very much alive. The similarities can be seen through examining Lavoie's (2022, p. 12) five presuppositions of orthodox (neoclassical) economics (Table 3.1). The neoclassical optimism about rationality and perfect foresight posits each of us as Laplace's intellect, rationally plugging all available data into our correct models (Muth, 1961). Its insistence on atomicism mirrors Laplace's reductionism to particles and a single equation. Hein (2023, p. 11) writes that production is only an 'extension' of the neoclassical model, which focusses instead on exchange, but it is possible to go further. Neoclassical economics cannot focus on production because its framework makes real production impossible. Just as Laplace's world is described purely by potential and kinetic energy, the neoclassical world only has room for utility, technology, and expenditure. Given these stark deviations of the neoclassical assumptions from reality, the instrumentalism postulate is required as a rearguard defence to justify the lack of realism in their method.

Table 3.1: Presuppositions of the heterodox and orthodox research programmes

Presupposition	Heterodox schools	Orthodox schools
Epistemology/Ontology	Realism	Instrumentalism
Rationality	Environment-consistent rationality, satisficing agent	Hyper model-consistent rationality, optimizing agent
Method	Holism, organicism	Individualism, atomicism
Economic core	Production, growth, abundance	Exchange, allocation, scarcity
Political core	Regulated markets	Unfettered markets

Source: (Lavoie, 2022, p. 12)

Thus, neoclassicism's historical appropriation of physics is an important factor in its development and shapes its epistemic presuppositions. The attempt to introduce material production and the second law of thermodynamics into neoclassical economics is bound to produce contradictions because its ontology fundamentally excludes an entropy law. This is not just discardable simplifying assumptions. In the presence of an analogue of entropy (for example, any frictional force such as costly substitution between production factors) the neoclassical model collapses and a new model is required (Lindenberger & Kümmel, 2011; Mirowski, 1989).

4 Heterodox economics, Post-Keynesianism, and Biophysical limits

In this section, I firstly argue that heterodox theory can overcome the contradictions previously outlined. I then examine the strengths of a post-Keynsian model and what it can contribute to a theory that tackles the role of exergy in the economy. Finally, I examine a selection of ecological macroeconomic models, focusing on their assumptions on technical change and the role of energy. I argue that Exergy and post-Keynsian economics have much to gain from a theoretical dialogue.

4.1 Entropy and heterodox economics

Unlike neoclassicism, the ontology of heterodox economics is compatible with, and even requires, a world with an entropy law. Fundamental parts of the heterodox research programme cannot be conceptualised in the world of classical physics. This does not mean that heterodox economics has necessarily drawn its theories from thermodynamics, but that the ontology of heterodox economics presupposes an entropy law. For example, the movement from classical to statistical mechanics shifted the focus from the micro particles to the emergent properties at the macro level (Darrigol & Renn, 2013). It showed how systems that are extremely complex and chaotic at the micro level, can nevertheless have a statistical macro equilibrium that gives them stable properties. A world of complex systems that can generate emergent properties is necessary for the presupposition of holism/organicism. The theory of information has shown the connections between entropy and uncertainty, and that information is a part of the material world (Cottrell et al., 2009;

Shannon, 1948). This undermines the possibility of an optimising agent or Laplace's intellect, as information has an irreducible cost to acquire and store[10]. This ontological compatibility between the second law of thermodynamics and the heterodox research programme can also be shown practically with reference to the contradictions highlighted in subsection 3.4.

Historial and logical time

Perhaps the closest affinity between the philosophy of heterodox economics and thermodynamics, however, is in theories of time. In the world of classical physics there is no 'arrow' of time (Hrabovsky & Susskind, 2020). All processes are reversible, and therefore it makes no difference in which direction time runs. Economic's appropriation of this theory explains why economics uses what Robinson (1978, p. x) called logical time. If there is a perfect symmetry and reversibility between past and future, then you are free to move around on a timeless 'plane diagram' because the movement does not cause any true change (Georgescu-Roegen, 1971). It is the entropy law that first defines the arrow of time in physics, creating a fundamental asymmetry and irreversibility in time. This is a presupposition for a concept of time that views the present as 'an ever-moving break between the irrevocable past and the unknown future' (Robinson, 1978, p. x). Entropy breaks the symmetry and reversibility between past and future, and so introduces all kinds of complications that cannot be grasped in the neoclassical model (Robinson, 1978, Chapter 12). Robinson put historical time at the very centre of her understanding of the Keynesian revolution and her critique of the 'bastard Keynesians' (Robinson, 1978, 1981, 1962). Thus, while much heterodox economics has not addressed the issues of the entropy law and its implications for economics (Georgescu-Roegen, 1971; Fontana & Sawyer, 2013), the stress on historical time allows a place for these questions in a way that the neoclassical methodology cannot.

[10]A neoclassical reader may justifiably argue that there is a huge neoclassical literature on costs to acquire information (Grossman & Stiglitz, 1980, e.g.). However, this is an imperfection grafted onto the core neoclassical model that assumes perfect foresight and optimisation. Neoclassical methodology adds a few imperfections at a time, while leaving the main structure of the model unchanged. Zero costs of information acquisition are therefore the assumption in the overwhelming majority of models that do not focus on information.

Substitution and necessity

While neoclassical economics makes the distinction between timeless substitution and technical progress through time. Heterodox authors have consistently argued that this distinction is impossible to draw in practice (Kaldor, 1957). All movement from one technique to another entails effort, and there is no way to meaningfully distinguish the effort of substitution from the effort of technical change (Nelson & Winter, 1982; Rosenberg, 1982, 1976). This is why heterodox authors have generally assumed a Leontief production function, where a given technique requires inputs in fixed proportions (Blecker & Setterfield, 2019). This does not mean that the relative amounts of inputs are constant through time, as Ayres and Warr (2009, pp. 177-182) implicitly assume when rejecting a Leontief production function, but rather that changes in factor proportions are an inseparable and irreversible aspect (or bias) of the process of technical change (Foley et al., 2019, Chap. 8). In a neoclassical model, technical change is direction invariant. While real technical change has been primarily labour-saving and capital, energy, and materials using; there is nothing that prevents technical change from moving in any other direction in factor space. This is a source of neoclassical calmness in the face of climate change, as it is assumed that any scarcity will produce the required technical change, as long as price incentives can function correctly. For example, scarcity of energy will lead to a rise in prices and shift the direction of technical change from energy-using to energy-saving. By contrast, heterodox economics sees technical change as proceeding with particular biases through historical time (Foley et al., 2019). The idea of exergy as a central and necessary factor in technical change is therefore much more at home within this framework.

Role of production

Ayres and Warr's attempt to centre production in their analysis is at sharp odds with the model they take from neoclassical theory, which views output as an automatic outcome of factors and technology. Their theories dovetail much more closely with the ideas of classical political economy, which centred production and the limits to growth. Kümmel even uses explicitly Marxist terminology to describe his theory, talking about the 'physical basis' and the 'market superstructure' (Kümmel, 2011, p. 176; Lindenberger & Kümmel, 2011, p. 6011), but does not seem to grasp how incompatible this distinction is with the neoclassical approach he adopts. These two aspects: (1) the determinants of production as a physical process and (2) the determination of values or prices are linked, but they are not the same. [11]

Both neoclassical and exergy economics claim to be providing a theory of (1), but in fact mix concepts that properly apply only to (2). The physical production of goods is not done by labour or capital in general, but by particular machines and types of labour. When thinking about physical production, different kinds of machines and labour are simply too heterogeneous to be meaningfully aggregated. Kümmel tries to get round this with aggregation in physical terms, but this attempt is unconvincing (subsection 3.2). Aggregate labour and capital are concepts properly related, not to physical production but to the 'market superstructure'. They matter because workers are paid by the hour and capitalists estimate and calculate their rate of return on investment. Aggregate labour and capital are properly, therefore, not 'factors of production', but the two sources of income , and the basis for class distinctions, in a capitalist society. At this level of abstraction, energy or materials should not be included as an additional income source because, in its legal form, it is just another form of capital that provides income for a particular industry.

By contrast, physical production requires energy and materials (i.e. Exergy or low entropy Georgescu-Roegen, 1971). It therefore necessarily uses up energy and materials from, and emits wastes to, the biosphere. The production of useful exergy is central to production, and the price system ultimately rests on this physical basis. There is no reason to expect that the physical importance of energy in production should correspond to the value added of the energy sector, and so we do not need any special assumptions or market failures to explain it. Heterodox economics has primarily focused on determination of prices (2) rather than questions of physical production and its dependence on the biosphere (1), but it nevertheless provides a better basis for its examination. The field formalism of neoclassical economics disqualifies any conception of production (subsection 3.4), while the principle of realism in heterodox economics, means, at the least, that it is not philosophically closed to these questions.

[11] This distinction is similar to what Marx (2004, p. 132) called the dual character of the commodity, use-value (1) and exchange value (2).

4.2 Post-Keynesianism

The previous section has argued that heterodox theory can overcome the contradictions from introducing SEA into an incompatible neoclassical model. In this section, I argue the positive case that post-Keynesianism allows one to analyse aspects of growth that are vital and missed in the supply-side model of exergy economics (Ayres & Warr, 2009; Ayres et al., 2022; Serrenho et al., 2014; Santos et al., 2021, 2018). The discussion of the philosophical commonalities between post-Keynesian and ecological economics is long-standing and well established (Gowdy, 1991; Kronenberg, 2010; Fontana and Sawyer, 2013; Rezai et al., 2013; Hein, 2023, ch. 9) and so I will restrict myself to highlighting four contributions of post-Keynesian economics that are particularly relevant for our purposes.

Aggregate demand and the underutilisation of production factors

At the centre of post-Keynsian economics is the principle of effective demand. Neoclassical theory, and the exergy-economics models derived from it, assume Say's law. Namely, aggregate demand will quickly adjust to, and have no lasting effects on, supply. This means that the economy always converges towards a full utilisation of production factors, and demand is a purely short-term and ephemeral phenomenon that can be safely ignored in longer-term growth theory. This full-utilisation equilibrium requires perfect foresight, as production takes time and so decisions taken today need to exactly match future demand (Robinson, 1978, chap. 12). By contrast, post-Keynesians argue that demand and supply are only brought into equilibrium through changes in output, meaning that there are many supply-demand equilibriums, and it is the level of aggregate demand that determines the utilisation of production factors in the short and long-run (Hein, 2023, ch. 3). The future is fundamentally uncertain, meaning that there will be mismatches between expectations and reality, and firms will not aim for full capacity utilisation to insure against these deviations. In addition, post-Keynesians posit several channels through which demand affects supply variables. For example, if tight labour markets drive productivity or higher unemployment leads to increased economic inactivity, this introduces a path-dependency into the growth path (León-Ledesma & Thirlwall, 2002). This means that aggregate demand not only affects the degree of utilisation, but also shifts the full-utilisation growth path.

Distribution

Post-Keynesians (together with other heterodox schools) propose a different relationship between technology and distribution. For mainstream authors, distribution is endogenously determined by technology. Factors of production are paid their marginal contribution and, in the most commonly used Cobb-Douglas production function, factor shares are fixed. By contrast, heterodox authors view distribution as exogenously determined by a conflict between social classes (Dutt, 2018). This can be influenced by technology, but only as one among a host of other factors that change the balance of power in this conflict. Instead, the primary causality runs in the other direction, from distribution to output and productivity growth. Distribution has varied and opposing effects on output. On the one hand, a decrease in the profit share should increase consumption[12], but it may also decrease investment and net exports because of lower profits and competitiveness (Hein, 2014, ch. 6). The strength of these relative effects determines if growth is wage- or profit-led. There is a huge literature dedicated to examining this question empirically, which generally finds wage-led growth in most countries (Bhaduri & Marglin, 1990; Hartwig, 2014; Blecker, 2016; Hein & Vogel, 2008).

Post-Keynesian theory of technical change

Since Kaldor (1957, 1961, 1955), post-Keynesians have generally modelled productivity growth through a technical progress function (TPF). Solow (1987, p. 15) would likely argue that this is 'some sort of production function… (in) disguise', but there are important theoretical differences. The TPF makes no 'arbitrary' distinction between movement along and between production functions (Kaldor, 1957, p. 596). While a NPF gives the output resulting from every position in factor-time space, the TPF has the more limited aim of projecting the actual path in historical time. In a NPF, Technical change is unconnected with factor accumulation and substitution can proceed in any direction. While technical change has historically required increasing energy or 'natural capital', it will automatically move in another direction as soon as these become scarce (subsection 3.1). By contrast, Kaldor's work on TPFs always stressed that technical change is necessarily achieved through capital accumulation. This breaks the path-independency of the NPF,

[12]As the propensity to save out of wage income is likely to be lower than that out of profits

as decisions about investment now will affect the future trajectory of productivity growth (McCombie & Spreafico, 2016). The lack of a distinction between movement along and between production functions gives technical change a necessary direction that cannot freely shift due to scarcity. The introduction of the arguments of Ayres and Warr about the necessity of exergy for production and technical change therefore fit much more easily into a TPF, without the conceptual contradictions highlighted in subsection 3.3.

Kaldor shifted the content of his technical progress function over time, focusing first on the capital stock, then investment, before shifting to a more dynamic emphasis on cumulative causation and increasing returns to scale (McCombie & Spreafico, 2016; Kaldor, 1981). Modern post-Keynsian theory has developed two primary channels through which demand and distribution endogenously affect productivity growth. The first channel, the Kaldor-Verdoorn law, posits a causality from demand-driven output growth to technical change (Magacho & McCombie, 2017; McCombie et al., 2002). This channel has been widely researched and generally finds that a 1% increase in output growth causes a 0.5% increase in productivity growth. Secondly, post-Keynesians argue that higher real wages or wage shares drive productivity growth by increasing the incentive for capitalists to introduce labour-saving machinery (Marx, 2004; Hicks, 1963; Allen, 2015; Cassetti, 2003; Sylos-Labini, 1983). This is often known as the Marx-Hicks effect and there are many variations on how it is operationalised, including focusing on the wage rate or the wage share (Hein & Tarassow, 2010), or a focus on other aspects of labour market institutions (Kleinknecht, 2020; Vergeer & Kleinknecht, 2014) and papers will often use TPF that combine and estimate the strength of both of these channels (Hein & Tarassow, 2010; Storm & Naastepad, 2012). If there is an energy-driven slowdown in productivity growth, both of these channels are likely to further reduce productivity growth. Lower productivity growth leads to lower investment, and this reduces the Kaldor-Verdoorn effect, leading to a further growth reduction. Energy scarcity is likely to increase costs, which reduces the wage-share given a constant mark-up (Hein, 2024). This then leads to a further decline in productivity growth from the Marx-Hicks effect.

Consistent macroeconomic framework

The final advantage of post-Keynesianism for ecological theory is its use of a consistent macro perspective that respects accounting rules. Each agents' income is another's cost, and all financial assets are matched by liabilities. These linkages mean that decisions that are individually rational may have unintended consequences in the aggregate. This leads to a series of post-Keynsian macro paradoxes, where the macro-effect of economic decisions is the opposite of the micro-intent (Lavoie, 2022). This potential for paradoxical results is extremely important for addressing the ecological crisis, as attempts to reduce emissions or manage demand can have contradictory effects in the presence of biophysical limits. For example investments in green or energy saving technology may raise emissions because of the paradox of thrift and a macroeconomic rebound effect that cannot be coneptualised in a full employment model (Rezai et al., 2013). The stress placed on accounting consistency is most developed with stock-flow consistent (SFC) models, where stocks and flows are consistently linked. These advantages of the post-Keynsian macroeconomic analysis have led to post-Keynesian theory playing an increasingly central role in ecological macroeconomics (Hardt & O'Neill, 2017). Previous arguments about the lack of cross-fertilisation between ecological and macroeconomic thinking and models (Kronenberg, 2010; Rezai et al., 2013; Fontana & Sawyer, 2013) have led to a proliferation of models combining post-Keynsian and ecological theory, to which we now turn.

4.3 Biophysical limits in ecological macro models

Table 4.1 shows a selection of ecological macro models, all incorporating post-Keynesian assumptions, focusing on the incorporated biophysical limits and assumptions on technical change. Two ways of modelling biophysical limits stand out in the literature. The first method uses a damage function, which decreases output as a function of some environmental indicator (usually temperature). This comes from neoclassical environmental economics (W. D. Nordhaus, 1992; W. Nordhaus, 2008), but needs to be modified to fit within a demand-determined model. Approaches include damage effects on profits (Taylor et al., 2016; Bovari et al., 2018), debt (Bovari et al., 2018), the capital stock and labour productivity (Taylor et al., 2016; Dafermos et al., 2017), and the investment and savings functions (Dafermos et al., 2017). Secondly, several models incorporate biophysical limits by including declining resource quality or availability. Declining availability can be modelled using a renewable resource necessary for production (King, 2020), a detailed energy model and restrictions imposed by energy targets (Nieto et al., 2021), or stocks of materials and energy that reduce demand as they become depleted (Dafermos et al., 2017). Alternatively, papers focus on the declining quality, and therefore return, from energy resources (Jacques et al., 2023; A. Jackson & Jackson, 2021), or take the mitigation path as given and focus on economic effects such as the need for unproductive investment for climate mitigation (T. Jackson & Victor, 2019).

Table 4.1: Biophysical limits in ecological macro models

Paper	Biophysical Limits	Energy		Technical Change	
		Stage	Relationship[1]	Endogeneity	Path
(Taylor et al., 2016)	Damage function	P	Yes	Both	Mixed
(Dafermos et al., 2017)	Damage function, Resource availability, & Technical progress	P	No	Both	Declining[2]
(Bovari et al., 2018)	Damage function	-	-	Both	Exponential[3]
(Sakai et al., 2018)	None	P, F, U	Yes	Endogenous	Variable
(T. Jackson & Victor, 2019)	Unproductive investment	P	No	Endogenous	Exponential
(King, 2020)	Resource availability	-	No	-	Constant
(A. Jackson & Jackson, 2021)	Resource quality	EROI, F	No	Both	Exponential
(Nieto et al., 2021)	Resource availability	P, F	No	Exogenous	Exponential
(Jacques et al., 2023)	Resource availability/quality	EROI, F	No	Both	Exponential

Notes: P = Primary, F = Final, U = Useful, EROI = Energy Return on Investment
[1] Relationship between Energy and labour productivity in the model
[2] Includes four different kinds of technical progress (energy, materials, capital, and labour). Technical progress is declining for all factors other than labour which is mixed
[3] Technical progress is mostly exponential, but one specification models technical progress as a quadratic function of temperature, from (Burke et al., 2015).
Source: Author's Elaboration

Energy in Ecological Macro Models

Energy is at the very heart of the connections between the economy and the biosphere, so unsurprisingly occupies a central place in many of our sample papers. We focus on energy rather than exergy here, because exergy is only considered in Sakai et al. (2018). The techniques used to model energy and its connection to the economy are quite varied. Table 4.1 shows which stages of the energy conversion process (Figure 2.2) are included in the models. Energy Return on Investment (EROI) measures the energy required to produce energy and can be measured at either the primary stage, or combined with the primary to final efficiency to give final EROI (Brockway et al., 2019). The majority of the models in our sample do not explicitly model energy, or model it only at the primary stage. In economic models, the energy conversion process is often lumped into a primary energy productivity variable ($y_{Ep} = Y/E_P$) that mixes a physical and a value quantity, and model this variable as exponential. This misses important insights that can be gained from a deeper analysis of energy conversion stages. Using SEA, we can split energy productivity into primary to final efficiency ($\eta_{pf} = E/E_p$), final to useful efficiency ($\eta = U/E$), and useful work productivity ($y_U = Y/U$):

$$y_{Ep} = \eta_{pf} \cdot \eta \cdot y_U \tag{10}$$

This decomposition allows us to see the extent to which energy productivity is driven by efficiency changes, and to highlight the physical limits and drivers of these changes in efficiencies. Several of the models in the sample look more deeply at the energy conversion process, analysing the primary to final efficiencies in great detail (Nieto et al., 2021), or looking at the trajectories of EROI from both renewable and non-renewable sources (A. Jackson & Jackson, 2021; Jacques et al., 2023). The only model in our sample that looks at final to useful conversion efficiencies is Sakai et al. (2018).

Energy and technical change

Table 4.1 shows that even among ecological macroeconomic models, with a variety of assumptions and techniques, the assumption of exponential technical change is dominant. Most models assume exponential technical change and have no relationship between technical change and energy. This assumption cannot be sustained if, as argued in this paper, technical change is material and depends on useful exergy (Smil, 2018, 2005). As the production of energy has inherent limits (subsection 2.4), ecological macroeconomics needs to model declining returns to technical change, alongside resource constraints and damages, as a third form of biophysical limit. All three limits are modelled in Dafermos et al. (2017) who use four technical progress functions (energy, materials, labour, and capital). They use a sigmoid difference equation with a declining rate of growth, combined with Kaldor-Verdoorn and exogenous components for labour productivity, but used alone for the other three factors. The quantity of energy and materials, and the efficiency with which they are used, have no impact on the other productivities. The model therefore lacks a way to account for the role energy and materials play in driving productivity growth. Rezai et al. (2013)[13] makes the connection between energy usage and labour productivity, but the causality runs in the other direction, from (exponential) technical change to energy and emissions. However, two of the same authors later reverse the causality and include energy in a technical progress function alongside a positive effect from growth, and negative effects from employment and emissions (Taylor et al., 2016). The path of technical progress is therefore dependent on the exogenous variables and can, but does not necessarily, produce a declining technical progress function.

The same is true of Sakai et al. (2018) which models productivity indirectly. Output and the labour force are modelled separately, with exergy having a large impact on both values. It combines elements of post-Keynesian econometric models (such as Mercure et al., 2018) with elements from exergy economics. While some post-Keynesian assumptions are used, the aim and causality of the model is quite different to that generally found in post-Keynesian theory. The model is set up using econometric equations, with the exogenous variables being supplies of the production factors. The aim of the model is therefore closer to neoclassical theory, which centres factor scarcity, than post-Keynesianism, which sees factor supplies as endogenous[14]. Output is modelled as the sum of aggregate demand components, with energy playing a large role, while the labour force is calculated using a useful exergy-enhanced Cobb-Douglas production function. The model therefore contains a mix of post-Keynesian and neoclassical assumptions, without discussing the contradictions and providing little justification for particular functional forms. Wages are modelled as a function of profits, hourly wages, CPI, and quality adjusted labour hours; mixing variables from two methods of calculating wages through a national accounting identity: hourly wages multiplied by labour hours or as output minus profits. This opens up the possibility of a contradiction between wages calculated from each of these identities, and highlights the importance of a consistent accounting framework.

The foregoing discussion has highlighted two related gaps in the ecological macroeconomics literature. A lack of a connection between energy and productivity growth and the projection of indefinite exponential technical progress. If productivity growth has mate-

[13] Not reported in the table as it is not a full model

[14] Introducing scarce natural resources modifies this assumption but the exogenous and driving force in post-Keynesian models is still variables (such as the savings rate or the wage share) that influence aggregate demand. The inclusion of scarce labour and capital is only appropriate in the rare situation of full utilisation of production factors (Lavoie, 2022; Hein, 2023)

rial foundations it follows the laws of nature and we need to consider biophysical limits to technical change alongside damage functions and resource quality and availability in ecological macroeconomics. I have argued that SEA provides a framework that can be used to fill these gaps, but further research is required to integrate its insights into a macroeconomically consistant model that does not assume full utilisation of production factors and has a role for distribution and aggregate demand.

5 Conclusion

To conclude this paper, we return to the two primary aims set out in the introduction. SEA provides a powerful way to extend our understanding of the role of energy in the economic process that can be easily incorporated in parsimonious economic models. However, previous attempts to integrate SEA into economics have been undermined by a reliance on the neoclassical production function. Ayres and Warr were uncomfortable with their use of neoclassical theory and its contradictions with their approach, but chose to persevere. Their justifications for ignoring their misgivings are unconvincing, and result in several contradictions between different aspects of their theory. Fundamentally, these contradictions are inevitable because results of the second law of thermodynamics, central to SEA such as path-dependence and irreversibility, are incompatible with a neoclassical economics based on pre-second law classical physics. Using a heterodox approach allows you to overcome these contradictions, as the heterodox ontology has a central place for factors such as irreversibility and emergent properties.

However, using a heterodox basis forces you to abandon some aspects of the exergy economics research programme. Technical rates of substitution are incalculable, because they rely on non-necessity of inputs, unjustifiable aggregation of capital, and instantaneous and reversible substitution. The results from attempts to estimate them are pre-calculable from the accounting identity and the stylised facts, and so do not justify the interpretation they are given. Heterodox growth theory does not automatically answer counterfactual questions that lie far from the actuals. The effects, for example, of reducing primary energy by 20% are unknowable because this would disturb many features of an economy that must be abstracted away to produce models. We can speculate about these counterfactual questions, but the idea of a production surface that predicts the output resulting from every combination of inputs cannot be justified. I suspect that one of the reasons Ayres and Warr persevered with the neoclassical production function, was to try to have an impact on the much larger and more influential mainstream of economics. However, they perhaps underestimated the impermeability of mainstream economics to new ideas. SEA is likely to have a better hearing within heterodox economics, where pluralism and the dependence of economics on the biosphere are taken more seriously.

The models of exergy economics implicitly subscribe to Say's law (demand passively adjusts to supply) while much post-Keynsian economics uses what Blecker and Setterfield (2019, p. 38) call 'Say's law in reverse' (supply passively adjusts to demand). In the context of biophysical constraints, we need a theory that can bring together supply and demand factors and study their interactions. The emerging field of ecological macroeconomics has made great progress in this direction, but further research is required to identify the reciprocal effects and tendencies of the economy and the biosphere. This paper has identified a gap in the literature in connecting technical change to energy materials and the biosphere. SEA provides powerful tools to help us overcome this gap. It gives a deeper understanding of energy conversion and its historical connection to productivity growth, and highlights the limits imposed by the second law of thermodynamics. The growth rates of exergy and exergy efficiency have been declining for half a century in the high income countries, coinciding with the 'secular stagnation' of labour productivity. These tendencies may reverse for some time, but the inherent limits to both exergy production and efficiency mean that a declining growth rate will inevitably assert itself in the long run. The prospects for long-run productivity growth then depend on a new, as yet non-existent, absolute decoupling of productivity from useful work.

Appendices

A Data sources and methods

There are two primary sources for the data used in this paper. Estimates of exergy and exergy efficiency come from (Marshall et al., 2024). This construction of the database is described in (Heun et al., 2024; Brockway et al., 2024). The national accounts data on GDP, capital stock, etc. comes from the Extended Penn World Tables (Marquetti et al., 2021).

Countries were selected according to data availability, with any Country that did not have all key variables (Exergy at every stage, number of workers, capital stock, GDP) since at least 1971 excluded. The full list of included countries are: Albania, Algeria, Angola, Argentina, Australia, Austria, Bahrain, Bangladesh, Belgium, Bolivia (Plurinational State of), Botswana, Brazil, Bulgaria, Cameroon, Canada, Chile, China, China (Hong Kong SAR), Colombia, Congo, Costa Rica, Cyprus, Côte d'Ivoire, D.R. of the Congo, Denmark, Dominican Republic, Ecuador, Egypt, Ethiopia, Finland, France, Gabon, Germany, Ghana, Greece, Guatemala, Haiti, Honduras, Iceland, India, Indonesia, Iran (Islamic Republic of), Iraq, Ireland, Israel, Italy, Jamaica, Japan, Jordan, Kenya, Kuwait, Lebanon, Luxembourg, Madagascar, Malaysia, Malta, Mauritius, Mexico, Morocco, Mozambique, Myanmar, Netherlands, New Zealand, Niger, Nigeria, Norway, Oman, Pakistan, Panama, Paraguay, Peru, Philippines, Portugal, Qatar, Republic of Korea, Romania, Rwanda, Saudi Arabia, Senegal, Singapore, South Africa, Spain, Sri Lanka, Sudan, Sweden, Switzerland, Syrian Arab Republic, Taiwan, Thailand, Trinidad and Tobago, Tunisia, Turkey, U.R. of Tanzania (Mainland), Uganda, United Arab Emirates, United Kingdom, United States, Uruguay, Viet Nam, Zambia, Zimbabwe.

Some figures reference a group of high income countries with data going back to 1960. The countries included in this aggregation are: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom, United States

B Results of regression

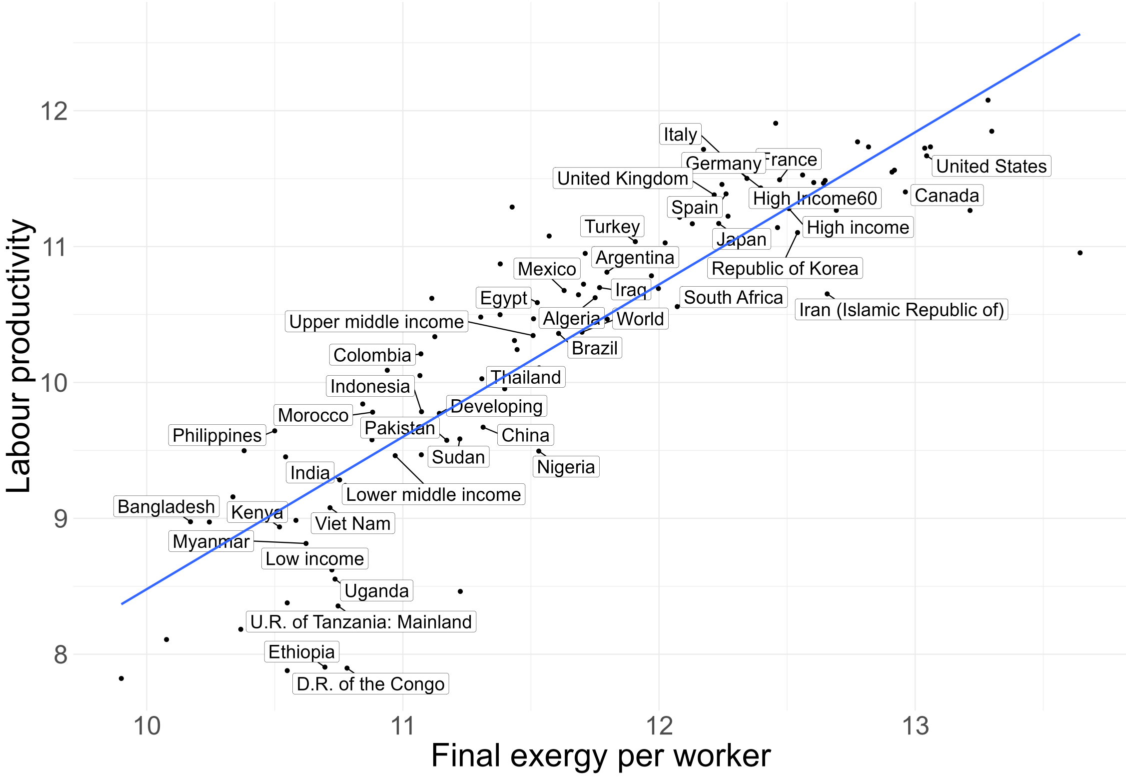
The following table shows the regression of world GDP against labour, capital, and useful exergy with the restriction that the coefficients must sum to 1. The coefficient for labour and useful exergy are given in the table, and for capital can be calculated as 1 - minus the sum of the other two coefficients. The remaining residual, called multifactor productivity in neoclassical theory, is 0.6%

Table A.1: Useful exergy enhanced Cobb-Douglas regression

	Dependent variable:
	Log GDP
Log labour - log capital	0.073
	(0.046)
Log useful exergy - log capital	0.683***
	(0.027)
Year	0.006***
	(0.001)
Constant	−10.501***
	(0.902)
Observations	49
R^2	0.936
Adjusted R^2	0.932
Residual Std. Error	0.009 (df = 45)
F Statistic	218.633*** (df = 3; 45)
Note:	*p<0.1; **p<0.05; ***p<0.01

C Additional figures

Figure A.1: Labour productivity and final exergy per worker



Source: Author's calculation from data in (Marquetti et al., 2021; Marshall et al., 2024)
Notes: Both variables in logs, selection of 101 countries selected according to data availability

References

Aghdam, R. F., Ahmad, N., Naveed, A., & Berenjforoush Azar, B. (2023). On the relationship between energy and development: A comprehensive note on causation and correlation. *Energy Strategy Reviews*, *46*, 101034. https://doi.org/10.1016/j.esr.2022.101034

Allen, R. C. (2015). The high wage economy and the industrial revolution: A restatement. *The Economic History Review*, *68*(1), 1–22. https://doi.org/10.1111/ehr.12079

APS. (2008). *Energy Future: Think Efficiency: How America Can Look Within to Achieve Energy Security and Reduce Global Warming*. American Physical Society.

Assa, J. (2016). *The Financialization of GDP*. Routledge. https://doi.org/10.4324/9781315658056

Ayres, R. U. (2016). *Energy, Complexity and Wealth Maximization*. Springer International Publishing. https://doi.org/10.1007/978-3-319-30545-5

Ayres, R. U., & Ayres, L. W. (2002). *A Handbook of Industrial Ecology*. Edward Elgar.

Ayres, R. U., Ayres, L. W., & Warr, B. (2003). Exergy, power and work in the US economy, 1900–1998. *Energy*, *28*(3), 219–273. Retrieved February 10, 2024, from https://www.sciencedirect.com/science/article/pii/S0360544202000890

Ayres, R. U., Savin, I., Bergh, J. V. D., & Hao, L. (2022). Exergy versus labour in aggregate production functions: Estimates for ten large economies. *International Journal of Exergy*, *38*(3), 320–332. https://doi.org/10.1504/IJEX.2022.124175

Ayres, R. U., & Warr, B. (2005). Accounting for growth: The role of physical work. *Structural Change and Economic Dynamics*, *16*(2), 181–209. https://doi.org/10.1016/j.strueco.2003.10.003

Ayres, R. U., & Warr, B. (2009). *The Economic Growth Engine: How Energy and Work Drive Material Prosperity*. Edward Elgar.

Basu, D., & Foley, D. K. (2013). Dynamics of output and employment in the US economy. *Cambridge Journal of Economics*, *37*(5), 1077–1106. Retrieved July 6, 2024, from https://www.jstor.org/stable/23601782

Berg, M., Hartley, B., & Richters, O. (2015). A stock-flow consistent input–output model with applications to energy price shocks, interest rates, and heat emissions. *New Journal of Physics*, *17*(1), 015011. https://doi.org/10.1088/1367-2630/17/1/015011

Berndt, E. R. (1990). Energy Use, Technical Progress and Productivity Growth: A Survey of Economic Issues. *Journal of Productivity Analysis*, *2*(1), 67–83. https://www.jstor.org/stable/41769828

Bhaduri, A., & Marglin, S. (1990). Unemployment and the real wage: The economic basis for contesting political ideologies. *Cambridge Journal of Economics*, *14*(4), 375–393. https://www.jstor.org/stable/23598376

Blecker, R. A. (2016). Wage-led versus profit-led demand regimes: The long and the short of it. *Review of Keynesian Economics*, *4*(4), 373–390. https://doi.org/10.4337/roke.2016.04.02

Blecker, R. A., & Setterfield, M. (2019). *Heterodox Macroeconomics: Models of Demand, Distribution and Growth*. Edward Elgar Publishing.

Bovari, E., Giraud, G., Mc Isaac, F., & Zatsepina, E. (2018). Coping With Collapse: A Stock-Flow Consistent Monetary Macrodynamics of Global Warming. *Ecological Economics*, *147*, 383–398. https://doi.org/10.1016/j.ecolecon.2018.01.034

Brockway, P. E., Barrett, J. R., Foxon, T. J., & Steinberger, J. K. (2014). Divergence of Trends in US and UK Aggregate Exergy Efficiencies 1960–2010. *Environmental Science & Technology*, *48*(16), 9874–9881. https://doi.org/10.1021/es501217t

Brockway, P. E., Heun, M. K., Marshall, Z., Aramendia, E., Steenwyk, P., Relph, T., Widjanarko, M., Kim, J., Sainju, A., & Irtube, J. (2024). A country-level primary-final-useful (CL-PFU) energy and exergy database: Overview of its construction and 1971–2020 world-level efficiency results. *Environmental Research: Energy*, *1*(2), 025005. https://doi.org/10.1088/2753-3751/ad4e39

Brockway, P. E., Kjelstrup, S., Dewulf, J., Siebentritt, S., Valero, A., & Whelan, c. (2016). *In a resource-constrained world: Think exergy not energy* (tech. rep. No. 13.324/5). Science Europe Cross-border Collaboration Working Group. https://doi.org/10.13140/RG.2.1.4507.0326

Brockway, P. E., Owen, A., Brand-Correa, L. I., & Hardt, L. (2019). Estimation of global final-stage energy-return-on-investment for fossil fuels with comparison to renewable energy sources. *Nature Energy*, *4*(7), 612–621. https://doi.org/10.1038/s41560-019-0425-z

Brockway, P. E., Saunders, H., Heun, M. K., Foxon, T. J., Steinberger, J. K., Barrett, J. R., & Sorrell, S. (2017). Energy Rebound as a Potential Threat to a Low-Carbon Future: Findings from a New Exergy-Based National-Level Rebound Approach. *Energies*, *10*(1), 51. https://doi.org/10.3390/en10010051

Brockway, P. E., Sorrell, S., Semieniuk, G., Heun, M. K., & Court, V. (2021). Energy efficiency and economy-wide rebound effects: A review of the evidence and its implications. *Renewable and Sustainable Energy Reviews*, *141*, 110781. https://doi.org/10.1016/j.rser.2021.110781

Brockway, P. E., Steinberger, J. K., Barrett, J. R., & Foxon, T. J. (2015). Understanding China's past and future energy demand: An exergy efficiency and decomposition analysis. *Applied Energy*, *155*, 892–903. https://doi.org/10.1016/j.apenergy.2015.05.082

Burke, M., Hsiang, S. M., & Miguel, E. (2015). Global non-linear effect of temperature on economic production. *Nature*, *527*(7577), 235–239. https://doi.org/10.1038/nature15725

Carnahan, W., Ford, K. W., Prosperetti, A., Rochlin, G. I., & Rosenfeld, A. H. (1975). Efficient use of energy: A physics perspective, a report of the Research Opportunities Group of a summer study held in Princeton, New Jersey in July 1974. https://www.osti.gov/biblio/7134080

Cassetti, M. (2003). Bargaining power, effective demand and technical progress: A Kaleckian model of growth. *Cambridge Journal of Economics*, *27*(3), 449–464. https://doi.org/10.1093/cje/27.3.449

Christophers, B. (2024). *The Price is Wrong: Why Capitalism Won't Save the Planet*. Verso Books.

Cottrell, A. F., Cockshott, P., Michaelson, G. J., Wright, I. P., & Yakovenko, V. (2009). *Classical Econophysics*. Routledge. https://doi.org/10.4324/9780203877548

Dafermos, Y., Nikolaidi, M., & Galanis, G. (2017). A stock-flow-fund ecological macroeconomic model. *Ecological Economics*, *131*, 191–207. https://doi.org/10.1016/j.ecolecon.2016.08.013

Darrigol, O., & Renn, J. (2013). The Emergence of Statistical Mechanics. In J. Z. Buchwald & R. Fox (Eds.), *The Oxford Handbook of the History of Physics* (pp. 765–788). Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199696253.013.26

Denison, E. F. (1979). Explanations of declining productivity growth. *Brookings Survey of Current Business*, *59*(8), 1–24.

Dewulf, J., Valero, A., Brockway, P. E., & Barrett, J. (2015). *A Common Scale for Our Common Future: Exergy, a Thermodynamic Metric for Energy* (tech. rep.). 10.5281/zenodo.7022853

Dincer, I. (2020). Entropy and Exergy. In *Thermodynamics: A Smart Approach* (pp. 169–232). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781119711117.ch4

Dutt, A. K. (2018). Heterodox Theories of Economic Growth and Income Distribution: A Partial Survey. In L. Zamparelli & R. Veneziani (Eds.), *Analytical Political Economy* (pp. 103–138). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781119483328.ch5

Felipe, J., & McCombie, J. S. L. (2013). *The Aggregate Production Function and the Measurement of Technical Change: 'Not Even Wrong'*. Edward Elgar. https://doi.org/10.4337/9781782549680

Fisher, F. M. (1969). The existence of aggregate production functions. *Econometrica: Journal of the Econometric Society*, 553–577.

Foley, D. K., Michl, T. R., & Tavani, D. (2019). *Growth and Distribution: Second Edition*. Harvard University Press.

Fontana, G., & Sawyer, M. (2013). Post-Keynesian and Kaleckian thoughts on ecological macroeconomics. *European Journal of Economics and Economic Policies*, *10*(2), 256–267. https://doi.org/10.4337/ejeep.2013.02.09

Georgescu-Roegen, N. (1971). *The Entropy Law and the Economic Process*. Harvard university press.

Goldin, I., Koutroumpis, P., Lafond, F., & Winkler, J. (2024). Why Is Productivity Slowing Down? *Journal of Economic Literature*, *62*(1), 196–268. https://doi.org/10.1257/jel.20221543

Gordon, R. J. (2016). Perspectives on *The Rise and Fall of American Growth*. *American Economic Review*, *106*(5), 72–76. https://doi.org/10.1257/aer.p20161126

Gowdy, J. M. (1991). Bioeconomics and post Keynesian economics: A search for common ground. *Ecological Economics*, *3*(1), 77–87. https://doi.org/10.1016/0921-8009(91)90049-K

Grossman, S. J., & Stiglitz, J. E. (1980). On the Impossibility of Informationally Efficient Markets. *The American Economic Review*, *70*(3), 393–408. Retrieved June 21, 2024, from https://www.jstor.org/stable/1805228

Haberl, H., Wiedenhofer, D., Virág, D., Kalt, G., Plank, B., Brockway, P. E., Fishman, T., Hausknost, D., Krausmann, F., Leon-Gruchalski, B., Mayer, A., Pichler, M., Schaffartzik, A., Sousa, T., Streeck, J., & Creutzig, F. (2020). A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part II: Synthesizing the insights. *Environmental Research Letters*, *15*(6), 065003. https://doi.org/10.1088/1748-9326/ab842a

Hardt, L., & O’Neill, D. W. (2017). Ecological Macroeconomic Models: Assessing Current Developments. *Ecological Economics*, *134*, 198–211. https://doi.org/10.1016/j.ecolecon.2016.12.027

Hartwick, J. M. (1977). Intergenerational Equity and the Investing of Rents from Exhaustible Resources. *The American Economic Review*, *67*(5), 972–974. https://www.jstor.org/stable/1828079

Hartwig, J. (2014). Testing the Bhaduri–Marglin model with OECD panel data. *International Review of Applied Economics*, *28*(4), 419–435. https://doi.org/10.1080/02692171.2014.896881

Hein, E., & Vogel, L. (2008). Distribution and growth reconsidered: Empirical results for six OECD countries. *Cambridge Journal of Economics*, *32*(3), 479–511. https://doi.org/10.1093/cje/bem047

Hein, E. (2014). *Distribution and Growth after Keynes: A Post-Keynesian Guide*. Edward Elgar.

Hein, E. (2023). *Macroeconomics after Kalecki and Keynes: Post-Keynesian Foundations*. Edward Elgar. https://doi.org/10.4337/9781803927282

Hein, E. (2024). Inflation is always and everywhere … a conflict phenomenon: Post-Keynesian inflation theory and energy price driven conflict inflation, distribution, demand and employment. *European Journal of Economics and Economic Policies*, *21*(2), 202–231. https://doi.org/10.4337/ejeep.2024.0135

Hein, E., & Tarassow, A. (2010). Distribution, aggregate demand and productivity growth: Theory and empirical results for six OECD countries based on a post-Kaleckian model. *Cambridge Journal of Economics*, *34*(4), 727–754. https://doi.org/10.1093/cje/bep066

Heun, M. K., Marshall, Z., & Aramendia, E. (2024). CLPFUDatabase: A suite of R packages for energy conversion chain analysis. *Journal of Open Source Software*, *9*(93), 6057. https://doi.org/10.21105/joss.06057

Hickel, J., & Kallis, G. (2020). Is Green Growth Possible? *New Political Economy*, *25*(4), 469–486. https://doi.org/10.1080/13563467.2019.1598964

Hicks, J. R. (1963). *The Theory of Wages*. Palgrave Macmillan UK. https://doi.org/10.1007/978-1-349-00189-7

Howitt, P. (2018). Endogenous growth theory. In *The New Palgrave dictionary of economics* (pp. 3632–3636). Springer.

Hrabovsky, G., & Susskind, L. (2020). *Classical mechanics: The theoretical minimum*. Penguin UK.

Hudson, E. A., & Jorgenson, D. W. (1974). U. S. Energy Policy and Economic Growth, 1975-2000. *The Bell Journal of Economics and Management Science*, *5*(2), 461–514. https://doi.org/10.2307/3003118

Jackson, A., & Jackson, T. (2021). Modelling energy transition risk: The impact of declining energy return on investment (EROI). *Ecological Economics*, *185*, 107023. https://doi.org/10.1016/j.ecolecon.2021.107023

Jackson, T., & Victor, P. (2019). LowGrow SFC: A stock-flow-consistent ecological macroeconomic model for Canada. *CUSP Working Paper*, (16), 71.

Jacques, P., Delannoy, L., Andrieu, B., Yilmaz, D., Jeanmart, H., & Godin, A. (2023). Assessing the economic consequences of an energy transition through a biophysical stock-flow consistent model. *Ecological Economics*, *209*, 107832. https://doi.org/10.1016/j.ecolecon.2023.107832

Kaldor, N. (1955). Alternative Theories of Distribution. *The Review of Economic Studies*, *23*(2), 83–100. https://doi.org/10.2307/2296292

Kaldor, N. (1957). A Model of Economic Growth. *The Economic Journal*, *67*(268), 591–624. https://doi.org/10.2307/2227704

Kaldor, N. (1961). Capital accumulation and economic growth. In F. Lutz & D. Hague (Eds.), *The Theory of Capital* (pp. 177–222). Macmillan.

Kaldor, N. (1981). The role of increasing returns, technical progress and cumulative causation in the theory of international trade and economic growth. *Économie appliquée*, *34*(4), 593–617. https://doi.org/10.3406/ecoap.1981.4324

Keen, S., Ayres, R. U., & Standish, R. (2019). A Note on the Role of Energy in Production. *Ecological Economics*, *157*, 40–46. https://doi.org/10.1016/j.ecolecon.2018.11.002

King, C. W. (2020). An integrated biophysical and economic modeling framework for long-term sustainability analysis: The HARMONEY model. *Ecological Economics*, *169*, 106464. https://doi.org/10.1016/j.ecolecon.2019.106464

Kleinknecht, A. (2020). The (negative) impact of supply-side labour market reforms on productivity: An overview of the evidence. *Cambridge Journal of Economics*, *44*(2), 445–464. https://doi.org/10.1093/cje/bez068

Kronenberg, T. (2010). Finding common ground between ecological economics and post-Keynesian economics. *Ecological Economics*, *69*(7), 1488–1494. https://doi.org/10.1016/j.ecolecon.2010.03.002

Kümmel, R. (1989). Energy as a factor of production and entropy as a pollution indicator in macroeconomic modelling. *Ecological Economics*, *1*(2), 161–180. https://doi.org/10.1016/0921-8009(89)90003-7

Kümmel, R. (2011). *The Second Law of Economics*. Springer New York. https://doi.org/10.1007/978-1-4419-9365-6

Kümmel, R., Strassl, W., Gossner, A., & Eichhorn, W. (1985). Technical Progress and Energy Dependent Production Functions. *Zeitschrift für Nationalökonomie / Journal of Economics*, *45*(3), 285–311. http://www.jstor.org/stable/41796330

Lavoie, M. (2022). *Post-Keynesian Economics: New Foundations*. Edward Elgar Publishing. https://doi.org/10.4337/9781839109621

León-Ledesma, M. A., & Thirlwall, A. P. (2002). The endogeneity of the natural rate of growth. *Cambridge journal of Economics*, *26*(4), 441–459.

Lindenberger, D., & Kümmel, R. (2011). Energy and the state of nations. *Energy*, *36*(10), 6010–6018. https://doi.org/10.1016/j.energy.2011.08.014

Magacho, G. R., & McCombie, J. S. L. (2017). Verdoorn's law and productivity dynamics: An empirical investigation into the demand and supply approaches. *Journal of Post Keynesian Economics*, *40*(4), 600–621. https://doi.org/10.1080/01603477.2017.1299580

Marquetti, A., Miebach, A., & Morrone, H. (2021). The Extended Penn World Tables 7.0. Retrieved March 4, 2024, from https://people.umass.edu/dbasu/Data/EPWT%207.0%20FV.xlsx

Marshall, Z., Brockway, P. E., Heun, M. K., Aramendia, E., Steenwyk, P., Relph, T., Widjanarko, M., Kim, J., Sainju, A., & Franzius, J. I. (2024). A country-level primary-final-useful (CL-PFU) energy and exergy database v1. 2, 1960-2020. Retrieved April 4, 2024, from https://archive.researchdata.leeds.ac.uk/1234/

Marx, K. (2004). *Capital: Volume I* (Vol. 1). Penguin UK.

McCombie, J. S. L., Pugno, M., & Soro, B. (Eds.). (2002). *Productivity Growth and Economic Performance: Essays on Verdoorn's Law*. Palgrave.

McCombie, J. S. L., & Spreafico, M. R. M. (2016). Kaldor's 'technical progress function' and Verdoorn's law revisited. *Cambridge Journal of Economics*, *40*(4), 1117–1136. https://doi.org/10.1093/cje/bev030

Mercure, J.-F., Pollitt, H., Edwards, N. R., Holden, P. B., Chewpreecha, U., Salas, P., Lam, A., Knobloch, F., & Vinuales, J. E. (2018). Environmental impact assessment for climate change policy with the simulation-based integrated assessment model E3ME-FTT-GENIE. *Energy strategy reviews*, *20*, 195–208.

Mirowski, P. (1988). Energy and Energetics in Economic Theory: A Review Essay. *Journal of Economic Issues*, *22*(3), 811–830. Retrieved February 26, 2024, from https://www.jstor.org/stable/4226039

Mirowski, P. (1989). *More Heat Than Light: Economics as Social Physics: Physics as Nature's Economics*. Cambridge University Press.

Murphy, T. W. (2021). *Energy and Human Ambitions on a Finite Planet*. https://doi.org/10.21221/S2978-0-578-86717-5

Muth, J. F. (1961). Rational Expectations and the Theory of Price Movements. *Econometrica*, *29*(3), 315. https://doi.org/10.2307/1909635

Nelson, R. R., & Winter, S. G. (1982). *An Evolutionary Theory of Economic Change*. The Belknap Press of Harvard Univ. Press.

Nieto, J., Pollitt, H., Brockway, P. E., Clements, L., Sakai, M., & Barrett, J. (2021). Socio-macroeconomic impacts of implementing different post-Brexit UK energy reduction targets to 2030. *Energy Policy*, *158*, 112556. https://doi.org/10.1016/j.enpol.2021.112556

Nordhaus, W. (2008). *A Question of Balance: Weighing the Options on Global Warming Policies*. Yale University Press. https://doi.org/10.2307/j.ctt1npzkh

Nordhaus, W. D. (1992). An Optimal Transition Path for Controlling Greenhouse Gases. *Science*, *258*(5086), 1315–1319. https://doi.org/10.1126/science.258.5086.1315

Nordhaus, W. D., & Tobin, J. (1972). Is growth obsolete? In *Economic research: Retrospect and prospect, volume 5, economic growth* (pp. 1–80). nber.

OECD. (2011). Towards Green Growth. *OECD Green Growth Studies*. Retrieved January 7, 2024, from https://doi.org/10.1787/9789264111318-en

Phelps-Brown, E. (1957). The meaning of the fitted Cobb-Douglas function. *The Quarterly Journal of Economics*, *71*(4), 546–560.

Rant, Z. (1956). Exergie, ein neues Wort für "technische Arbeitsfähigkeit". *Forsch Ingenieurweser*, *22*(1), 36–37.

Reistad, G. M. (1975). Available Energy Conversion and Utilization in the United States. *Journal of Engineering for Power*, *97*(3), 429–434. https://doi.org/10.1115/1.3446026

Rezai, A., Taylor, L., & Mechler, R. (2013). Ecological macroeconomics: An application to climate change. *Ecological Economics*, *85*, 69–76. https://doi.org/10.1016/j.ecolecon.2012.10.008

Robinson, J. (1953). The Production Function and the Theory of Capital. *The Review of Economic Studies*, *21*(2), 81. https://doi.org/10.2307/2296002

Robinson, J. (1962). Review of money, trade and economic growth by HG Johnson. *Economic Journal*, *72*(257), 690–92.

Robinson, J. (1971). Capital Theory up to Date: A Reply. *The Canadian Journal of Economics / Revue canadienne d'Economique*, *4*(2), 254–256. https://doi.org/10.2307/133531

Robinson, J. (1978). *Contributions to modern economics*. Academic Press.

Robinson, J. (1981). *What are the questions? : And other essays : Further contributions to modern economics*. Armonk, N.Y. : M. E. Sharpe. Retrieved June 10, 2024, from http://archive.org/details/whatarequestions0000robi

Rosen, M. A. (2015). Limits to Efficiency for Energy Utilization. *Handbook of Clean Energy Systems*, 1–13.

Rosenberg, N. (1976). *Perspectives on technology*. Cambridge University Press.

Rosenberg, N. (1982). *Inside the black box: Technology and economics*. Cambridge University Press.

Sakai, M., Brockway, P. E., Barrett, J., & Taylor, P. (2018). Thermodynamic Efficiency Gains and their Role as a Key 'Engine of Economic Growth'. *Energies*, *12*(1), 110. https://doi.org/10.3390/en12010110

Santos, J., Borges, A. S., & Domingos, T. (2021). Exploring the links between total factor productivity and energy efficiency: Portugal, 1960–2014. *Energy Economics*, *101*, 105407. https://doi.org/10.1016/j.eneco.2021.105407

Santos, J., Domingos, T., Sousa, T., & St. Aubyn, M. (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*, 103–120. https://doi.org/10.1016/j.ecolecon.2018.01.008

Semieniuk, G. (2024). Inconsistent definitions of GDP: Implications for estimates of decoupling. *Ecological Economics*, *215*, 108000. https://doi.org/10.1016/j.ecolecon.2023.108000

Semieniuk, G., Taylor, L., Rezai, A., & Foley, D. K. (2021). Plausible energy demand patterns in a growing global economy with climate policy. *Nature Climate Change*, *11*(4), 313–318. https://doi.org/10.1038/s41558-020-00975-7

Serrenho, A. C., Sousa, T., Warr, B., Ayres, R. U., & Domingos, T. (2014). Decomposition of useful work intensity: The EU (European Union)-15 countries from 1960 to 2009. *Energy*, *76*, 704–715. https://doi.org/10.1016/j.energy.2014.08.068

Shaikh, A. (1974). Laws of Production and Laws of Algebra: The Humbug Production Function. *The Review of Economics and Statistics*, *56*, 115–20. https://doi.org/10.2307/1927538

Shannon, C. E. (1948). A mathematical theory of communication. *The Bell System Technical Journal*, *27*(3), 379–423. https://doi.org/10.1002/j.1538-7305.1948.tb01338.x

Smil, V. (2005). *Energy at the Crossroads: Global Perspectives and Uncertainties*. MIT press.

Smil, V. (2018). *Energy and Civilization: A History*. MIT press.

Smil, V. (2022). *How the World Really Works: A Scientist's Guide to Our Past, Present and Future*. Penguin UK.

Solow, R. M. (1974). Intergenerational Equity and Exhaustible Resources. *The Review of Economic Studies*, *41*, 29–45. https://doi.org/10.2307/2296370

Solow, R. M. (1956). A Contribution to the Theory of Economic Growth. *The Quarterly Journal of Economics*, *70*(1), 65–94. https://doi.org/10.2307/1884513

Solow, R. M. (1957). Technical Change and the Aggregate Production Function. *The Review of Economics and Statistics*, *39*(3), 312. https://doi.org/10.2307/1926047

Solow, R. M. (1987). Second Thoughts on Growth Theory. In A. Steinherr & D. Weiserbs (Eds.), *Employment and Growth: Issues for the 1980s* (pp. 13–28). Springer Netherlands. https://doi.org/10.1007/978-94-009-3605-8_2

Sousa, T., Brockway, P. E., Cullen, J. M., Henriques, S. T., Miller, J., Serrenho, A. C., & Domingos, T. (2017). The Need for Robust, Consistent Methods in Societal Exergy Accounting. *Ecological Economics*, *141*, 11–21. https://doi.org/10.1016/j.ecolecon.2017.05.020

Stern, D. I. (2011). The role of energy in economic growth. *Annals of the New York Academy of Sciences*, *1219*(1), 26–51. https://doi.org/10.1111/j.1749-6632.2010.05921.x

Stiglitz, J. (1974). Growth with Exhaustible Natural Resources: Efficient and Optimal Growth Paths. *The Review of Economic Studies*, *41*, 123. https://doi.org/10.2307/2296377

Storm, S., & Naastepad, C. W. M. (2012). *Macroeconomics beyond the NAIRU*. Harvard University Press.

Swan, T. W. (1956). Economic growth and capital accumulation. *Economic record*, *32*(2), 334–361.

Sylos-Labini, P. (1983). Factors Affecting Changes in Productivity. *Journal of Post Keynesian Economics*, *6*(2), 161–179. https://doi.org/10.1080/01603477.1983.11489428

Tavani, D., & Zamparelli, L. (2018). Endogenous Technical Change in Alternative Theories of Growth and Distribution. In *Analytical Political Economy* (pp. 139–174). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781119483328.ch6

Taylor, L., Rezai, A., & Foley, D. K. (2016). An integrated approach to climate change, income distribution, employment, and economic growth. *Ecological Economics*, *121*, 196–205. https://doi.org/10.1016/j.ecolecon.2015.05.015

UN. (1987). Our Common Future. Report of the World Commission on Environment and Development. UN Document. Retrieved July 4, 2024, from https://digitallibrary.un.org/record/139811

Vergeer, R., & Kleinknecht, A. (2014). Do labour market reforms reduce labour productivity growth? A panel data analysis of 20 OECD countries (1960-2004). *International Labour Review*, *153*(3), 365–393. https://doi.org/10.1111/j.1564-913X.2014.00209.x

Voudouris, V., Ayres, R., Serrenho, A. C., & Kiose, D. (2015). The economic growth enigma revisited: The EU-15 since the 1970s. *Energy Policy*, *86*, 812–832. https://doi.org/10.1016/j.enpol.2015.04.027

Warr, B., Ayres, R., Eisenmenger, N., Krausmann, F., & Schandl, H. (2010). Energy use and economic development: A comparative analysis of useful work supply in Austria, Japan, the United Kingdom and the US during 100 years of economic growth.

Ecological Economics, *69*(10), 1904–1917. https://doi.org/10.1016/j.ecolecon.2010.03.021

Wettstein, H. E. (2023). Exergy, Anergy, and Sustainability. In G. Márquez, B. Lev, & F. Pedro (Eds.), *Sustainability: Cases and Studies in Using Operations Research and Management Science Methods* (pp. 393–426). Springer International Publishing. https://doi.org/10.1007/978-3-031-16620-4_18

Wiedenhofer, D., Virág, D., Kalt, G., Plank, B., Streeck, J., Pichler, M., Mayer, A., Krausmann, F., Brockway, P., Schaffartzik, A., Fishman, T., Hausknost, D., Leon-Gruchalski, B., Sousa, T., Creutzig, F., & Haberl, H. (2020). A systematic review of the evidence on decoupling of GDP, resource use and GHG emissions, part I: Bibliometric and conceptual mapping. *Environmental Research Letters*, *15*(6), 063002. https://doi.org/10.1088/1748-9326/ab8429

Wiedmann, T. O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., & Kanemoto, K. (2015). The material footprint of nations. *Proceedings of the National Academy of Sciences*, *112*(20), 6271–6276. https://doi.org/10.1073/pnas.1220362110

Williams, E., Warr, B., & Ayres, R. U. (2008). Efficiency Dilution: Long-Term Exergy Conversion Trends in Japan. *Environmental Science & Technology*, *42*(13), 4964–4970. https://doi.org/10.1021/es0716756

World Bank. (2012). Inclusive Green Growth: The Pathway to Sustainable Development. Retrieved April 20, 2024, from https://documents.worldbank.org/en/publication/documents-reports/documentdetail/368361468313515918/main-report

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