# To Infinity and Beyond! Anthropocentric Stories of Innovation and Growth

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## Abstract

This paper provides a non-technical and selective explanation of the theory of innovation and economic growth, in light of the 2025 Bank of Sweden Prize in Memory of Alfred Nobel, awarded to Joel Mokyr, Philippe Aghion, and Peter Howitt. Their body of scholarship is critically evaluated, and the useful, less useful, and most problematic aspects are highlighted. The verdict is that it is largely a collection of anthropocentric stories of innovation and growth. It avoids spelling out why sustained growth is desirable, it reduces innovation's ultimate goal to the pursuit of economic growth, it is based on a deep-seated notion of human exceptionalism, and it promotes directed technical change - based on the assumption that all resources are fungible and can be substituted - as a way to sustain economic growth without causing environmental destruction. Their analysis of growth is useful for highlighting the importance of scientific knowledge, for showing that creative destruction can be more destructive than creative, and that economic growth will only be sustained under very special conditions. However, the failure to satisfactorily address energy in innovation and growth remains a glaring gap in modern economic growth theory. For economics to become more useful, it would require becoming an Earth Systems Science based on biocentric holism.

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# 1    Introduction

*"To infinity and beyond"* - Buzz Lightyear, in Toy Story (Pixar/Disney)

The 2025 Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel was awarded to Joel Mokyr, Philippe Aghion and Peter Howitt. According to the press release of the Royal Swedish Academy of Sciences, this award was made to these scholars "for having explained innovation-driven economic growth, "for having identified the prerequisites for sustained growth through technological progress," and "for the theory of sustained growth through creative destruction" (RSAS, 2025).

This Riksbank Prize is thus a prize for scholarship about *innovation and economic growth.* Given its elevation of these topics, it provides the opportunity to critically assess this body of scholarship, noting what is useful, what is less useful, and what contains fairy-tale[1] or story-like elements.

The verdict is that the body of scholarship of Mokyr, Aghion and Howitt, and the broader neoclassical economics paradigm - the economics mainstream - which they represent, has been useful to identify and describe the relationship between scientific knowledge and the innovative commercialization thereof and how this enabled humans to transform the planet. The scholarship has been useful for describing the nature of innovation as "creative destruction" within the system of capitalism and for highlighting that not all innovations are welcome or desirable. It has also been useful to show that economic growth will only be sustained under very special conditions, given that both under- and over-investment in innovation is likely.

The verdict, however, is that there are also less useful and even outright story-like aspects to neoclassical economics' innovation-growth scholarship. One is that it tends to obscure or

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[1]See Greta Thunberg's speech at the United Nations Climate Action Summit on September 23, 2019, where she criticized the global economic growth obsession stating "all you can talk about is money and fairy tales of eternal economic growth" (NPR Staff, 2019)

avoid spelling out whether, and why, economic growth is desirable. If economic growth is to be sustained merely for the continuation of capital accumulation, and hence to sustain global capitalism, are the benefits of more growth outweighing the possible costs?

A second, less useful and related aspect is that the body of work for which these scholars have been awarded, reduces "innovation's ultimate goal as the endless pursuit of economic growth" (Robra et al., 2023, p.1). Humans have been remarkably innovative for a very long time before the economic growth take-off during the Industrial Revolution at the end of the 18th century. However, neoclassical economists tend to be dismissive of these innovation records, finding them somewhat lacking.

A third less useful aspect of modern innovation-and-growth theory and implicit in much of the work of Mokyr, Aghion and Howitt - and the rest of neoclassical economics- is its anthropocentric bias - its belief in human exceptionalism. Humans are, in this view, exceptional creatures, and the top innovators are exceptionally exceptional and to be venerated. In her work "*The Arrogant Ape*", primatologist Christine Webb writes " human exceptionalism - a.k.a. anthropocentrism or human supremacy - is at the root of the ecological crisis. This pervasive mindset gives humans a sense of dominion over Nature, set apart from being entitled to commodify the earth and other species for own our exclusive benefit" (Webb, 2025, p.3). Human exceptionalism is perhaps nowhere as evident as in the lack of concern in neoclassical economic growth theory about biodiversity and material environmental destruction, and its almost exclusive focus on decarbonisation.

Related to this mindset that humans are distinct from Nature and with dominion to exploit it to the full, is the most fairy-tale or story-like aspect of modern innovation and growth theory: the belief that sustained economic growth can be environmentally sustainable. This belief is supported by a magical trick: the trick known as *Directed Technical Change* - the steering of innovation in socially desirable directions. Applied to the environment, Aghion and co-authors have claimed that government policies such as carbon taxes, R&D subsidies

and regulations can mitigate climate change by effecting a transition away from fossil fuel burning (a major cause of global warming) towards renewable energies (Acemoglu et al., 2012, 2023). Part of why directed technological change is story-like is the assumption, deeply ingrained in neoclassical economics, of strong substitutability among inputs. In the case of fossil fuels and renewables, this assumption is retained due to the "energy blindness" of much of modern economic growth theory (Hagens, 2024).

The overall verdict in this paper is that the body of scholarship for which the Sveriges Riksbank has been awarded in 2025 is a collection of anthropocentric stories of innovation and growth. As a result, the current state of neoclassical economics is akin to a Pixar/Disney's Toy Story belief in the power of human exceptionalism through innovation to take the world to "infinity and beyond."

The rest of the paper motivates this verdict. It is structured as follows. Section two provides a non-technical narrative that critically outlines the key features of modern economic growth and innovation theory, as laid down by, among others, Mokyr, Aghion, and Howitt. Section three evaluates the belief that sustained growth can be environmentally sustainable by considering the assumption of resource substitutability. This section also considers the ecological costs of sustained growth. Section four discusses energy blindness and human exceptionalism as two reasons for neoclassical economics' fairy-tale assumptions of substitutability, infinite growth on a finite planet, and the need for sustained growth. Section five explores what the appropriate new directions for research in economic growth theory could be, given the conclusions that sustained economic growth may not be desirable after a certain point, that economic growth may be neither sustained nor sustainable, and that innovation may need to be decoupled from an instrument solely aimed at furthering economic growth and firm profits. Section six concludes.

# 2 Innovation and Growth: The Basic Story

*"Growth! Growth of gross domestic product! That is a goal on which the world's nations all agree. This imperative is taken for granted, and no further explanation is needed."* (Binswanger, 2013, p.1).

As this quote indicates, economic growth, as measured by changes over time in Gross Domestic Product (GDP), has become an imperative taken for granted. This section first answers the question, why is this the case? (see section 2.1). Given the 2025 Sveriges Riksbank Prize for the role of innovation in economic growth, the section critically answers the question: why is innovation seen as the driver of sustained economic growth? (see section 2.2). The answer is threefold: innovation was central in triggering the Industrial Revolution (section 2.2.1), innovation counters the Law of Diminishing Returns (section 2.2.2), and innovation results in "creative destruction" that renews the economy and hence sustains growth (section 2.2.3).

Having critically evaluated the relationship between innovation and growth in sections 2.2.1 to 2.2.3, the question is: why, despite the resources invested in innovation in advanced economies, has economic growth stagnated over the past 50 years? And how, if at all, can innovations in artificial intelligence (AI) counter this growth stagnation? (see section 2.3).

## 2.1 Why Economic Growth?

Awarding the Sveriges Riksbank Prize in Economic Sciences for scholarship on innovation and economic growth presupposes that economic growth is important. Indeed, as Robra et al. (2023, p.1) relates, the "endless pursuit of economic growth" has become a deeply entrenched economic and political goal in modern society. "No government will support an anti-growth agenda," the *London Consensus*, the view of a self-selected number of main-

stream neoclassical economists, recently declared (Burgess and Dobermann, 2025, p.476). Why is this the case? There are at least three related reasons.

First, growth may be "an omnipresent protean reality of our lives" (Smil, 2019, p.vii). Living as well as non-living dynamic systems are characterized by cycles of change, of which growth during a part of the cycle is a manifestation. Growth is in many ways "a sign of progress," as put by Smil (2019, p.ix). As such, economic growth in itself is not an aberration. A growing population will require a growing economy to provide a satisfactory quality of life for everyone.

The challenge is to sustain such growth over time, which may entail increasing risks or costs. These may eventually exceed the benefits. Many are arguing that the world is approaching, if it has not already reached, such a point where further economic growth will cause so much ecological damage that planetary boundaries will be breached, biodiversity stripped, tipping points set off, and catastrophic climate change occur that will threaten human existence (Bradshaw et al., 2021).

Second, looking back at deep history, it was only since the take-off of economic growth at the end of the 18th century that human prosperity has significantly improved. For most of modern humans' roughly 300,000 years on the planet, humans had lived in small hunter-gatherer bands or in agricultural communities where average incomes hovered just above subsistence levels. There was no sustained economic growth as such. Since the Industrial Revolution, roughly since 1750/1800, economic growth has taken off. Since then, average incomes per capita, first in the West where the Industrial Revolution started, and later in much of the rest of the world, averaged more than 2% per annum - exponential growth - as shown in Figure 1. This take-off since the Industrial Revolution has been called the most significant event in economic history (Bryan, 2025). The world had never experienced anything like it before.

Figure 1: The Great Take-Off in GDP and Sustained Economic Growth Since Around 1820
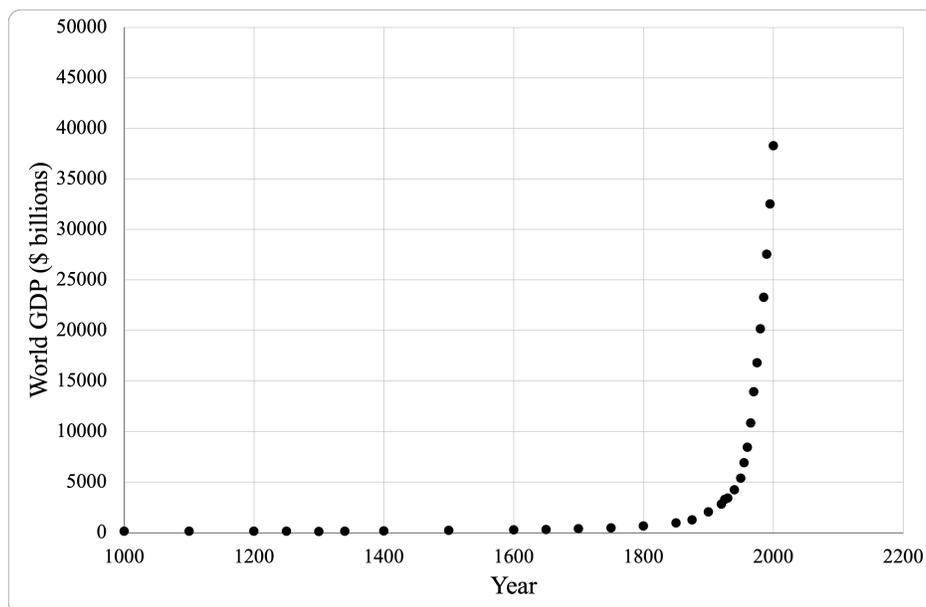
Since the 1950s, the rate of economic growth has accelerated, and the period since 1950 has been described as the "Great Acceleration" (Steffen et al., 2015). During this period, the size of the world economy, as well as related measures such as population and energy consumption, roughly doubled every 35 years. The scale of human activity is now impacting Earth systems so substantially that a new geologic epoch is said to have begun in the 1950s: the Anthropocene (Waters and Turner, 2022).

Since the growth Take-Off and the Great Acceleration are correlated with improvements in a large range of desired development outcomes, from better health, longer lives, to less violence (see e.g. Pinker (2018)), today, humans are frequently reminded that the current generation is living in the most affluent period in human history. The average income in the world today is around 5400% higher than it was at the dawn of human history (Syvitski et al., 2020). Modern economic growth is "entirely unlike anything that had come before" (Susskind, 2024, p.ix).

As such, it is no surprise that economic growth has come to be seen as the foundation of

human civilization and prosperity, and that hence, any body of scholarly work that can determine whether and how it can be sustained is worthy of praise. Hence, the selection for the 2025 Sveriges Riksbank Prize in Economic Sciences should come as no surprise either.

There is also a third reason why the endless pursuit of economic growth has become entrenched in modern society. As argued by Binswanger (2013), the capitalist system has a built-in growth imperative: it is either growing or shrinking, with no in-between; stagnation or zero-growth is impossible, or the system will collapse. In other words, as far as economic growth is concerned, the world faces a "doomed-if-we-do, doomed-if-we-don't situation" (Douthwaite, 1992, p.3).

In terms of Binswanger (2013)'s economic growth spiral, an innovative firm typically will need to borrow money to invest in new innovations and their roll out, and expect to make a profit in the future by selling to consumers, from which the interest or dividends on the borrowed money need to be paid. Economic growth is required to ensure there are enough consumers with disposable income to absorb the previous period's production. Because innovative firms will invest in labor-saving technology (capital accumulation) to raise their profits, labor income in total may decline, thereby reducing households' potential consumption (Jackson and Victor, 2015).

This context of a slowdown in consumption - and also saturation of consumption demand - explains the ubiquity and sophistication of modern marketing, and the deeply embedded idea in society that ever-increasing consumption is desirable. This is, as Boulding (1966, p.9) pointed out, a rather strange idea, because the less consumption we need to maintain a given state, the better off we are. "If we had clothes that did not wear out, houses that did not depreciate, and even if we could maintain our bodily condition without eating, we would clearly be much better off."

When local markets eventually become saturated, firms will turn to international expansion.

According to the Luxemburg thesis (Luxemburg, 1913), capitalist firms depend on perpetual growth, so that when they inevitably face domestic demand constraints, they will become imperialistic. This results in the rise of global corporate giants that prey on and subjugate non-capitalist entities, such as foreign governments and their peoples. The Luxemburg thesis implies that capitalism would collapse if this "rapacious" growth spiral were to be stopped (Monbiot and Hutchison, 2024, p.13). Hence, the need for continual capital accumulation and market expansion by capitalistic firms has entrenched economic growth as an imperative.

Before proceeding to discuss the role assigned to innovation in generating this required growth, it is necessary to state clearly that *infinite* economic growth is at odds with basic physical reality. Whenever there is mention of "sustained" growth it cannot mean growth that it indefinitely sustained. For instance, if the world GDP continues to expand at its current rate of around 2% per annum, it will double every 35 years in size. By 2037 the world GDP would be US$500 trillion after which it explodes to $30.7 quadrillion in 2046 and to $1.9 quintillion a year later (Roodman, 2020).

Even if growth is decoupled from material inputs and based on 100% renewables, it would still generate waste heat. If such 100% clean global energy use continues to grow at only 2,3% p.a., as it did over the past century, then in 400 years, so much energy would be used that the waste heat would be so hot as to boil the surface of the Earth (Murphy, 2022).

Infinite growth is a fairy tale.

## 2.2 Why Innovation?

Given that the "endless pursuit of economic growth" has become a deeply entrenched economic and political goal in modern society for the reasons explained in the previous section, the challenge that modern society faces is to understand why the economic growth take-off

- the Industrial Revolution - occurred, and how exponential growth can be sustained. The answer, for which Mokyr, Aghion and Howitt received the Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel, is simple: it is **innovation** that drives economic growth.

### 2.2.1 Innovation and the Industrial Revolution

The answer to the question of what caused the Industrial Revolution earned Joel Mokyr his part of the Prize. His key contributions are contained in Mokyr (2002), Mokyr (2012), Mokyr (2016), Mokyr (2018). See also Mokyr (2007) for a description of the essence of innovation: the "power of ideas."

According to Mokyr, what happened was an "Industrial Enlightenment" that heralded in a "Culture of Growth" that raised the supply of ideas. This industrial enlightenment was an outcome of the scientific enlightenment that originated in Europe in the 16th century. It was marked by a recognition that scientific knowledge enabled humans to make social progress and that the search for new scientific knowledge and the application of reason could yield world-improving technologies. According to Howes (2025):

> "Mokyr tirelessly argued that it was rooted in ideas, in the intellectual entrepreneurship of figures like Francis Bacon and Isaac Newton, and in the uniquely precocious accumulation in eighteenth-century Britain of useful, often mechanically actionable knowledge. Britain, he argued, through its scientific and literary societies, and its penchant for publications and sharing ideas, was the site of a world-changing Industrial Enlightenment – the place where progress was thought possible, and then became real."

In Mokyr's narrative, science improved technology, and better technology (like better micro-

9

scopes or measuring tools) improved science. At the same time, the cost of accessing useful knowledge plummeted due to technological advances (e.g., the printing press). This created a virtuous cycle of science and technology.

At the core, thus, Mokyr's explanation for how the world stumbled onto using ideas as the engine of sustained growth is that it developed a culture of growth, which, above all, generated useful ideas about ideas. Human ingenuity, reflected in human ideas, and in this case, ideas about ideas, is at the centre of the narrative.

Mokyr's insights are certainly very useful. It is part of a growing tradition in economic history which tends to support his central thesis about the importance of scientific knowledge as useful knowledge, and hence the importance of ideas about ideas, and not just for economic growth. A selection of relevant work in this vein includes Diamond (1997), Freeman (1994), Jones (1995), Landes (1999), Landes et al. (2010), Lewis (1954), Lucas (1978), Maddison (1982), Morris (2010), Olson (1982), Pomeranz (2021), Swann (2009) and Weitzman (1998).

Mokyr's insights are not just of academic interest: the world is in 2026 arguably experiencing the most significant rise of anti-science and anti-rationalism sentiment since the Industrial Revolution (Naudé, 2024). Historian Fernández-Armesto (2001, p. 451), for instance, already noted by 2001 that "By the end of the century, people no longer trusted science to save the world; on the contrary, the Frankenstein image of science took over." And more recently, Hotez (2020) has chronicled and warned against the rise of antiscience activism in the West. He defines antiscience as "the rejection of mainstream scientific views and methods or their replacement with unproven or deliberately misleading theories, often for nefarious and political gains. It targets prominent scientists and attempts to discredit them" (Hotez, 2021, p.1).

Antiscience is fueled by the spread of postmodernist notions of subjectivity and equal relevance of all forms of knowledge acquisition, as well as by profit and political motivations,

which often misuse and thrive on pseudoscience and scientific illiteracy. For example, some student movements have, under their influence, insisted that science is only one way of knowing, and that witchcraft is a legitimate alternative (Pluckrose, 2017). The epistemic relativism characterizing postmodernism "underlies the 'post-truth politics' that is endemic to contemporary populism", as Bonatti (2023, p.21) points out.

Making use of this rise in anti-science sentiment, the USA's Trump administration started what can be called a war on science, particularly climate science. Kozlov et al. (2026), in *Nature*, catalogs the administration's assault, noting that "more than 7,800 research grants terminated or frozen. Some 25,000 scientists and personnel gone from agencies that oversee research. Proposed budget cuts of 35% — amounting to US$32 billion. These are just a few of the ways in which Donald Trump has downsized and disrupted US science since returning to the White House last January."

While Mokyr has provided useful insights into the importance of science and knowledge for society broadly, and how these can contribute to a *Culture of Growth*, there are weaknesses in his explanation of the growth take-off. The first is that Mokyr under-emphasize the role of what has been called the *Great Expropriation* in catalyzing the Industrial Revolution, which started in the UK. As Foster (2022) put it, "The expropriation of the commons, its simplification, division, violent seizure, and transformation into private property constituted the fundamental precondition for the historical origin of industrial capitalism." What he means by this is that the expropriation of land and labor through commodification by the elite, first in England and Ireland and later through imperialism and colonialism - often by violent means described as "war capitalism" (Beckert, 2014) were important drivers of the Industrial Revolution.

A second weakness in Mokyr's story of the Industrial Revolution is that he underestimated the role of energy (Allen, 2009). The Industrial Revolution has been argued to have been primarily a (fossil fuel) energy revolution, rather than an innovation revolution. It was thus

no coincidence that the Industrial Revolution started in England, because the country was "the first country where coal had already become the dominant fuel by the middle of the 17th century" (Smil, 2019, p.377). The extensive use of coal in England provided energy to carry out work, freeing human labor for providing all the energy by working 14-hour days, and affording leisure time in which to pursue science and education and spreading knowledge. Fossil fuel energy provided the time for the Industrial Enlightenment to unfold.

Following the Industrial Revolution, global energy consumption increased ninefold between 1900 and 2000, with the bulk - 80% - being supplied by fossil fuels (Smil, 2019). Given the importance of energy in economic growth, Murphy et al. (2021, p.2) concludes that "future generations will label the past two centuries as the Fossil Fuel Age rather than the Industrial Revolution - emphasizing the critical importance of a now-depleted resource over a self-flattering celebration of human innovation."

### 2.2.2 Innovation and Diminishing Returns

In Figure 1, GDP is essentially flat-lined until around 1800. This era is known as the Malthusian Stagnation. This is after the Reverend Thomas Malthus, who, writing up his thesis in 1798 (Malthus, 1798), strengthened the suspicion of economics as the dismal science.

According to Malthus, if more people entered the economy, they would add to production and thus cause economic growth, which would in turn fuel further population growth. However, because each additional laborer's value added to GDP production - including the production of food - is subject to diminishing returns, eventually population growth will outstrip the availability of food, which will lead to a reduction in population and the size of the economy (Gross Domestic Product).

The critical element in this Malthusian view, which keeps the world economy in stagnation, is the diminishing returns to inputs into production, such as labor and capital. **Appendix**

**A** illustrates this diminishing returns using a standard Cobb-Douglas production function.

The challenge facing economists after Malthus was how to deal with the law of diminishing returns. The solution was that innovation (technology) can counteract the effects of diminishing returns. There are three ways in which to model such innovation. The first is, as in the work of Robert Solow, to treat innovation as exogenous - as manna from heaven. The second, as in the work of Paul Romer, is to treat innovation as endogenous to the economy, but arriving in the form of infinite "horizontal" varieties of products based on an infinite number of possible recipes or ideas. The third, as in the work of Aghion and Howitt, is to treat innovation as endogenous, but arriving through "creative destruction" in the form of "horizontal" quality improvements in products and technologies.

Consider first the approach of Robert Solow. According to Solow, aggregate economic output (GDP, denoted by $Y$) is a function of technology ($A$), capital ($K$) and labor ($L$):

$$Y_t = A_t K_t^\alpha L_t^{1-\alpha} \tag{1}$$

With $\alpha$ and $1 - \alpha$ denoting the shares of capital and labor in GDP respectively.

While Solow recognized that without technological innovation, the Law of Diminishing Returns would mean that economic growth cannot be sustained, he did not explain where technological innovation came from. It was assumed to be exogenous. That is, determined outside the economy. It rained like manna from the skies.

In a 1990 paper, economist Paul Romer explained how technological innovation arose from within the economy, endogenously (Romer, 1990). In his endogenous growth model, GDP (denoted $Y$) is the outcome of *horizontal* differentiation. The economy produces a final consumption good using labor and a set of intermediate goods. The production function typically takes what is known as a Dixit-Stiglitz (Dixit and Stiglitz, 1977) or Ethier (1982)

form:

$$Y = L^{1-\alpha} \left[ \int_0^A x(i)^\rho di \right]^{\frac{\alpha}{\rho}} \tag{2}$$

Where $x(i)$ denotes a variety of intermediate goods, with $A$ the technology frontier or total variety (ideas) in the economy. Note, and this is also necessary in what follows, that $\rho$ is the substitution parameter between the inputs, indicating how easily an input can be substituted for another. The substitution elasticity $\sigma$ is obtained as $\sigma = \frac{1}{1-\rho}$.

If $\rho < 1$ then it means $\sigma > 1$ which means there is easy substitution between different varieties if the price of one changes. From this flow the "love for variety" result of Romer: with $\sigma > 1$, the economy benefits from expanding variety. Adding a new type of input (increasing $A$) increases total output $Y$ more efficiently than simply adding more of the existing inputs. Whilst there are diminishing returns to individual varieties in intermediate inputs, and to labor, there is increasing returns to the range of inputs, because of the addition of new varieties. **Appendix B** illustrates these increasing returns mathematically, using the above production function.

The innovation in the model is in the varieties of $x(i)$ which are infinite in number. This is because $A$ denotes the total number of varieties (ideas) which is the outcome of an *Ideas Production Function* (IPF) which for present purposes, can be written as

$$A_t = \lambda s(P) A_{t-1}^\phi \tag{3}$$

Equation (3) states that new ideas on varieties in period $t$ (new tech) are the result of the share of the population that are searching for new ideas $s(P)$, times their research or innovation productivity ($\lambda$), times the stock of existing knowledge ($A_{t-1}$).

The assumption that Romer made is that (3) is a linear function, i.e. that the intertemporal spillover of knowledge parameter $\phi = 1$. This means that new ideas are just as easy as previous ideas to find, and that researchers or innovators are "standing on the shoulders" of previous generations' knowledge. In other words, innovation is cumulative. The invention of generation $t + 1$ relies on the existence of generation $t$. In technical terms, knowledge and ideas have intertemporal knowledge spillovers.

In Romer's model, a new idea results in a new variety of an input $x(i)$ into production. So, entrepreneurs will innovate by inventing a new variety of a product. Because this idea of a new variety can be copied costlessly and is non-rival in use - it overcomes the diminishing returns problem. Thus, constant economic growth can be sustained as long as there are a constant number of researchers $s(P)$ (thus no decline in population) with a constant research productivity $\lambda$.

Romer recognized that a challenge to the constant innovation effort lies in the non-rival nature of ideas: because there is a fixed cost involved in creating a new idea, but the cost of copying that idea is essentially zero (the new idea can spill over) the private entrepreneur may not be able to capture all the benefits of the new idea - the private benefits are smaller than the social benefits. Essentially, coming up with a new idea or piece of knowledge generates a positive externality. Also, because of intertemporal knowledge spillovers, the current innovator is not compensated by future generations for their innovation service, and thus does not internalize this benefit.

Because of these positive externalities to innovation, there would tend to be an under-investment in innovation in a laissez-faire economy. Romer was not the first economist to highlight the possibility that, because of its positive externalities, the market may, on its own, fail to supply sufficient innovation. In his paper "Economic Welfare and the Allocation of Resources for Invention," Arrow (1962) argued that without government intervention, even a perfectly competitive market would supply less innovation than what was "socially

desirable", in other words, the government must fund basic innovation because the private sector would not do enough of it (Arrow, 1962, p.619).

To remedy this less than socially desirable outcome, Romer recognized the importance of patent rights to protect intellectual property, to, in essence, give the inventor the sole right - a monopoly - to exploit the innovation.

Here, thus, economic growth is now driven by entrepreneurs coming up with new varieties of goods over which they hold a patent, and all new varieties, which are infinite in number, add value to GDP. It overcomes the problem of diminishing returns because, as soon as diminishing returns set in for one variety, a new variety is introduced, ensuring that, on an aggregate level, growth can be sustained through increasing returns to scale - see **Appendix B**.

Romer's model had at least two important implications for present purposes. One, there will be sustained growth. Growth is constant as long as there is effective patent protection and a constant number of constantly productive researchers. Two, all innovation is beneficial – the more innovation, the better. Everyone benefits from innovation.

There was, however, a possibly fatal shortcoming in Romer's model. Indeed, it turned out that Romer had omitted a crucial feature of the modern system of capitalism, namely "Creative Destruction," as elaborated in 1942 by economist Joseph Schumpeter (Schumpeter, 1942). With Creative Destruction, existing technology is rendered obsolete by the new technologies that entrepreneurs bring to market. Thus, not all technology remains valuable, as according to the Romer model: some becomes useless due to entrepreneurs' innovative activities.

Moreover, the threat that a new technology could render an incumbent enterprise's technology obsolete, along with the innovation costs that went into it, means that innovation now also has negative externalities (negative spillovers). This negative externality can exacer-

bate the underinvestment problem in innovation, as recognized by Romer, due to its positive externalities.

However, Creative Destruction also means that not only can there be under-investment in technology, but also over-investment - a wasting of resources, as firms scramble to achieve the "prize" of a new innovation. Think, for instance, of the exorbitant resources that a few competing firms are throwing at developing AI at present,[2] blowing up what many have described as an "AI bubble' (Floridi, 2024). Both cases - under-investment and over-investment in innovation could prevent sustained economic growth.

### 2.2.3 Innovation and Creative Destruction

Aghion and Howitt (1992) addressed these concerns by developing an endogenous economic growth model that formalizes Schumpeter's idea of Creative Destruction. Aghion et al. (2015, p.94) summarizes this Schumpeterian growth model as being *"based on three main ideas: (i) it is about growth generated by innovations; (ii) innovations result from entrepreneurial investments that are themselves motivated by the prospects of monopoly rents; and (iii) new innovations replace old technologies: in other words, growth involves creative destruction."*

Thus, just as in Romer's model, economic growth in Aghion and Howitt's model (the A-H model) is driven by innovation (ideas). But whereas Romer conceived of innovations leading to new varieties that all contribute to GDP - a horizontal expansion of complementary technologies and products - in the A-H model, innovations can also substitute for existing technology and make them obsolete.

As such, they conceived of the quality of any new technology as lying somewhere on a ladder, with each higher rung representing a better technology. Technologies higher on the

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[2]As reported by the Wall Street Journal, the top four tech firms in the USA planned, for 2026, to spend more on pushing AI than the USA spent on the moon landing, see `https://www.wsj.com/tech/ai/ai-spending-tech-companies-compared-02b90046?`

rung increase the productivity of all production factors, raising GDP. Old, less productive technologies are discarded. The firms that depend on these may go bankrupt and exit the market. This churn of firms is seen as a fundamental advantage of capitalism, continually driving the allocation of investment and production factors towards higher-productivity uses.

In the A-H model, economic growth is driven, just as in the Romer model, by a linear ideas production function, where the growth rate $g$ can be written for present purposes as the outcome of roughly the same determinants as in Romer's model:

$$g = \lambda z \times ln\gamma \qquad (4)$$

Where $\lambda$ is again the productivity of R&D; and $z = s(P)$ is the population devoted to research. The parameter $ln\gamma$ denotes the size of the quality jump in a technology made by the new innovation brought to market. This quality jump creates a new higher "rung" on the quality ladder of a good.

Important assumptions are that $\gamma > 1$, and that these arrive according to a Poisson process rate $\lambda z$, with $z$ the share of population working in the R&D sector (Aghion et al., 2015).

In their modelling of entrepreneurs' decision to invest in innovation, A-H drew on the work of economist Glenn Loury. Loury (1979) had formulated a Stochastic Patent Race model wherein he showed how market structure (the number of competitors) affects innovation. Loury demonstrated a counter-intuitive tension, namely that as more firms enter the race for a new innovation, where there is an upfront investment cost,[3] the incentive for any single firm to invest actually decreases. Why? This is because the more rivals a firm faces, the lower the probability that it may be the one to win the prize. He also showed that, even though each firm spends less, the total amount of R&D in the industry might be higher than

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[3]Lee and Wilde (1980) refined Loury's model to make R&D spending not an upfront cost, but a flow cost. This turns out to change the basic Loury result.

optimal, leading to excess capacity in R&D - too many firms wasting resources chasing the same prize (Loury, 1979).

With a Stochastic Patent Race (and over-investment possibility) incorporated, A-H thus presented an economic growth model wherein economic growth is sustainable on condition that as long as the size jump in innovation quality is positive, and the productivity of R&D, and the population devoted to innovation remain constant, the growth rate $g$ remains positive forever. Sustained growth is saved.

The crucial determinant here is that firms continue to climb up the quality ladder of technology over time ($\lambda > 1$). A-H's model implied however, that this may not necessarily be the case, and that it will, as in Loury (1979), depend on market structure - the extent of competition.

For instance, under creative destruction, new market entrants will face an incentive to innovate so as to "steal" the business of an incumbent. This "business stealing" motivation, however, will in turn incentivize the incumbent firm to try and erect moats around its technology, in other words, to try and keep any new entrants - potential competitors - out. Incumbent firms may spend billions on R&D not to create a better product, but to create "defensive" patents that block rivals (building moats). This is wasteful because the labor (scientists and engineers) is used to build legal walls rather than to create better technologies or products.

Firms may also engage in over-investment in R&D: when competition is very intense, firms will invest vast resources to displace or outpace rivals through only tiny improvements in quality, fearing that if they do not raise R&D, they will lose their market share. This may result in rapid capital obsolescence and wasteful resource allocation, with possibly very little gain in aggregate welfare.

The "Business Stealing" and "Building Moats" motives could both lead to sub-optimal

innovation and, hence, undermine sustained growth. The upshot is that sustained economic growth is no automatic outcome.

A-H and co-authors refined this implication to show how the extent of competition can affect innovation - see Aghion et al. (2005). They argue that there is a sweet spot for competition where innovation is optimal, because, based on empirical evidence, there is an inverted U-shaped relationship between the extent of competition in an industry and innovation. This inverted U-shape is shown in Figure 2. The implication is that if governments can turn the dial of competition just to the right level, sustained economic growth is possible.

Figure 2: An Inverted U-shape relation between Innovation and Competition
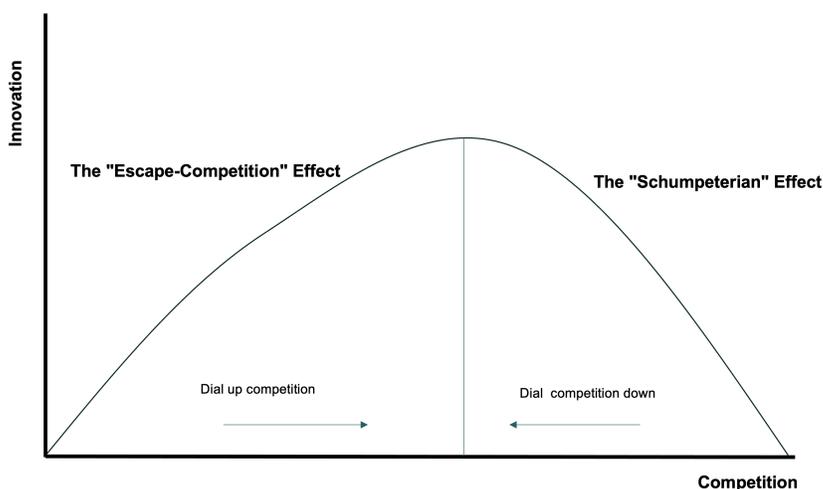


*Source*: Author's compilation, based on Aghion et al. (2005, p.706)

On the upward slope of the inverted U, for firms that are neck-and-neck (technologically similar to their rivals), competition is a powerful motivator. If they do not innovate, their competitors will steal their thin profit margins. This is labelled the "Escape-Competition" Effect. Past the peak of the inverted U, on the downward slope, competition is too intense, so the rewards for innovating disappear. If a firm invents something new but competitors can immediately copy it or price-cut so aggressively that the firm never recoups its R&D costs,

the firm will not bother innovating. This is labelled the "Schumpeterian" Effect (Aghion et al., 2015).

The policy implication for A-H is clear: if there is not enough competition, the government should dial up competition until firms have enough neck-and-neck competition; if the economy or industry is experiencing the *Schumpeterian Effect*, the government should dial down competition.

Despite saving sustained economic growth, albeit conditional on appropriate competition policy, which may be impossible to set in the real world, there is another problematic implication from Creative Destruction in the A-H model, and that is that, unlike in the Romer model, not all innovation may necessarily be socially desirable.

The *Dark Side* of innovation (see also Coad et al. (2021)) rears its head in the A-H model. This is because their model is built on the recognition that modern innovations are often close substitutes for what they replace. The higher rung on the quality ladder of technology most often represents only a marginal, incremental improvement over the technology on the previous rung, but destroys a technology with much sunk costs and possibly wide adoption.

For example, one may argue that the innovation of the internet provides channels for news that are only slightly faster than a traditional newspaper, but in offering this new channel, it destroys the entire revenue stream of the newspaper industry that funded sense-making, so that the net social welfare might actually decline in the long run.

In the A-H model, it is also possible for innovation to become regressive. For example, today, significant investment is made to promote innovation for surveillance, social control, military suppression, and even the financialization of the economy and the automation of jobs through AI. While this uses and extends the quality ladder for these high-tech tools, it diverts the smartest minds away from productive growth, potentially leading to a decline in living standards and jobs.

For A-H, the fact that Creative Destruction leads to innovation, creating winners and losers, with the losers' welfare losses potentially overshadowing the winners' gains, generates further policies for government intervention. For instance, Schumpeterian growth scholars, including Aghion, have expressed support[4] for Danish-style "Flexicurity" (generous unemployment benefits plus aggressive retraining), through which the government makes it socially acceptable for old firms to die (Kramarz, 2017).

## 2.3    Innovation, the Great Stagnation and AI

A-H had presented a model, outlined in the previous sub-section, in which economic growth can be sustained by innovation, helping the economy overcome diminishing returns from rival-in-use production factors. Their model is useful in that it makes clear that sustained growth is possible, but not inevitable. It is highly conditional on several factors; if these are not met, growth may not be sustained.

The Royal Swedish Academy of Sciences, in its motivation for awarding the 2025 Prize to Mokyr, Aghion, and Howitt, acknowledges the precariousness of economic growth. In their press release, they specifically raise the point that "economic growth cannot be taken for granted."

This indeed seems to be the case in advanced economies, where economic growth has been stagnating since the late 1970s. In more recent times, expectations have been raised that innovation in AI can counter this stagnation in growth. This sub-section explores these two themes as an application of the A-H insights on innovation and growth discussed in the previous section.

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[4]In an interview at : `https://tinyurl.com/48acpc6m`

### 2.3.1 The Great Stagnation

Given that much of the West has been in a "Great Stagnation" since the late 1970s, marked by declining economic growth (Cowen, 2010) and that advanced Western economies such as the USA have been experiencing "headwinds" against innovation (Gordon, 2012), it is again no surprise that scholarly work that can potentially address this stagnation would receive praise.

From the basic story of innovation and economic growth related in the previous sub-sections, the causes of economic stagnation and the failure of sustained growth must then be due to violations of the following *MAH conditions for sustained growth*:

- Patent rights and other property right protections (given the positive externalities of innovation)

- Finely-tuned competition policy and avoidance of policy capture by incumbent firms (to limit the negative externalities of innovation)

- Social policies to make the destruction of incumbent firms and their technology and jobs socially acceptable (A-H) (to limit political and public resistance against innovation-supportive policies)

- Constant research productivity (to maintain the stream of new innovations arriving)

- Constant population share engaged in R&D to search for new ideas (to maintain the stream of new innovations arriving, which depends on the number of people doing innovation)

- New ideas at least as easy to find as old ideas (to exploit inter-temporal spillovers of knowledge and prevent innovators from standing on each other's toes in the research process)

- Appropriate ideas about ideas: a culture of growth based on the belief that progress is possible -and desirable - through scientific knowledge which can generate new technologies, which can be applied to generate private profits, and in doing so benefit everyone.

A growing literature has reported apparent violations of these conditions in advanced economies. For instance, since the 1970s, population growth in advanced economies has slowed. Jones (2022a, p.9) has estimated that if global population growth turns negative, and declines by 1% p.a., then world GDP growth would drop to zero in "somewhere between 85 to 250 years."

Similarly, research productivity appears to have slowed. Klüppel and Knott (2023) report "substantial evidence that aggregate research productivity has declined", interpreting their results as due to imbalances between research versus development, with more and more research being done and outsourced to universities, resulting in "excess research" and also to a "deterioration" of R&D practices on the firm level.

Bloom et al. (2020) found that "ideas are getting harder to find" (Bloom et al., 2020). They conclude that "just to sustain constant growth in GDP per person, the U.S. must double the amount of research effort searching for new ideas every 18 years to offset the difficulty of finding new ideas" (Bloom et al., 2020, p.46).

Another violation is that industry concentration and monopoly power have increased, with incumbents abusing and misusing the patent system, and using political connections and lobbying to defend against new entrants, building "moats" to avoid being displaced. Evidence shows that in the USA, concentration levels have risen by around 90% in recent times and have been accompanied by firms raising mark-ups and restricting entry, even to the extent of creating so-called "kill zones" around their businesses (Covarrubias et al., 2019; Grullon et al., 2019; Gutiérrez and Philippon, 2019; Kamepalli et al., 2020). Aghion et al. (2023)

partly explains this by arguing that new digital technologies may have made it much cheaper for a few highly efficient firms to expand into multiple product lines and geographic markets simultaneously, thereby replacing less efficient local players. But once these "superstar" firms become dominant, they make it much harder for new, small innovators to enter the market.

### 2.3.2 Innovation and Artificial Intelligence

With many of the conditions for sustained growth in jeopardy, and especially in light of fears of the effects of a population decline on innovation (Jones, 2022a), scholars and policy makers have asked whether artificial intelligence (AI) cannot save sustained growth, by boosting innovation. Can AI end the Great Stagnation?

There have indeed been many claims that this will be the case; there are even some that have claimed that AI may lead to *explosive economic growth*, that is, growth in Gross World Production (GWP) of 30% per annum or more (Aghion et al., 2019; Erdil and Besiroglu, 2023; Davidson, 2021).

What is at play here is another substitution hope - the hope that AI can substitute for human labor - but also substitute for human innovation. These are then the two channels through which AI has been argued to generate sustained - and possibly even explosive - economic growth (Jones, 2022b).

Consider first the case of AI fully substituting for human labor. This would leave only capital as production factor. In this case, the basic production function that was specified in equation (1) above, would become simply $Y_t = A_t K_t$ with

$$\Delta A_t = (K_t)A_{t-1}^{\phi} \tag{5}$$

It is easy to see that as long as $A_t$ is unlimited, as Romer (1990) and others indeed argued it is, because new ideas can be formed simply by recombining existing ideas, and that new ideas are easy to find ($\phi = 1$), then there could be explosive growth -i.e. $Y_t$ goes to infinity in finite time.

Note that, apart from ignoring the biophysical dimensions of growth, such as energy needed to run the AI, that here no innovation is required - apart from the innovation of creating an Artificial General Intelligence (AGI) that can substitute for all human labor, and make labor, which is typically non-accumulable, accumulable like capital (Erdil and Besiroglu, 2023).

While there is an intense debate on whether or not an AGI is possible or eminent, most economists tend to be skeptical that it will be invented soon. For instance, according to Jones (2022b, p.147) the likelihood of an AGI is "quite far-fetched." Nordhaus (2021, p.300) ventures to state that an AGI is "not near" and hence, that there should not be any reasonable expectation of explosive growth through this channel soon.

And even if a AGI is invented that can fully substitute for labor, it has been argued that since AI agents, unlike human laborers, will not consume, and all the profits accumulate to the few (human) owners of the AI agents, that the economy would run into demand constraints due to the high income inequality - see e.g. Gries and Naudé (2020).

So until an AGI is invented, the sustaining and even acceleration of economic growth through AI fully substituting human labor can be discounted.

This leaves the second channel - that AI may substitute (or take over) human innovation or part of it. In this respect, AI will enter into the ideas production function, already specified in equation (3) above. Aghion et al. (2019) adjusts this ideas production function by splitting the ideas discovery process into various tasks ($X_{it}$), of which some may be substituted for by AI

$$\Delta A_t = A_t^{\phi} \left( \int_0^1 X_{it}^{\rho} di \right)^{\frac{1}{\rho}} \tag{6}$$

Here, they assume $\rho < 0$, which means, as was indicated in the case of equation (2) that the elasticity of substitution between inputs $\sigma > 1$, indicating easy substitution of AI and human inputs into the ideas production function. They then show that, importantly assuming a Constant Elasticity of Supply (CES) production function, that if $\phi < 1$, (i.e. ideas become harder to find) then AI substituting for human innovation leaves "the long-run growth rate of the economy unchanged" and if $\phi \geq 1$ such substitution will increase the rate of long-run growth (Aghion et al., 2019, p.251).

The upshot is that an acceleration of economic growth through AI substituting for humans in innovation is only possible in the Aghion et al. (2019) model if there is high intertemporal spillover effects of knowledge, i.e that new ideas are just as easy to find as in the past. Now, in the previous sub-section it has already been shown that empirical evidence has so far tended to reject this assumption - see for instance the findings of Bloom et al. (2020).

It can also be pointed out that whereas the ideas production function set out in equation (3) contains $\lambda$, the productivity of R&D - which also appears in Aghion and Howitt's creative destruction model - this parameter is omitted in equation (6). Implicitly, the assumption in (6) is that research productivity $\lambda$ remains constant. Now, in the previous section it has been pointed out that evidence is accumulating that this is not the case - see for instance the findings of Klüppel and Knott (2023).

It should be clear that if AI is to save sustained economic growth and reverse the Great Stagnation through re-invigorating innovation, then this is highly conditional: conditional on constant R&D productivity and on ideas not being "fished out." In both of these, while it is certainly possible that AI can complement human innovation efforts, and increase R&D

productivity[5] (see e.g. Bouschery et al. (2023); Haefner et al. (2021)) it is also possible that AI may introduce further "pathologies" into the research and development process, and thus slow down R&D productivity, rather that accelerate it (Almeida et al., 2024).

Another potentially adverse consequence of AI on innovation and economic growth is that AI-driven disinformation can manipulate public opinion and raise polarization on issues like climate change, making it even more difficult to implement innovation support policies (Vinuesa et al., 2020). For instance van der Ven et al. (2024) discusses how AI can be weaponized over social media by incumbent firms to stifle creative destruction that may threaten their business - the example is of the fossil fuel industry (see also section 3).

Finally, van der Ven et al. (2024) argues that a growing reliance on generative AI, particularly LLMs, may hinder the world's ability to develop innovative solutions to significant societal challenges, such as the climate crisis (see section 3.1 below). They argue that the danger lies in becoming overly dependent on AI for problem-solving, potentially atrophying the parts of the human brain crucial for creative and forward-thinking approaches.

Moreover, because LLMs are trained on historical data, they may bias their recommendations toward incremental solutions, which are ill-suited to the urgent need for transformative innovation.

And this does not even consider whether the high energy demands of AI development[6] may act as a further factor hindering the innovation and growth impact of AI.

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[5]For a broad review of the use of artificial intelligence in scientific discovery, see Wang et al. (2023).

[6]The International Energy Agency (IEA) predicts that the electricity consumption from datacentres (where AI systems are hosted) will double between 2022 and 2026, requiring as much energy as a country such as Japan (Dolby, 2023).

# 3    Innovation and Sustainable Growth

The question that arises is, if economic growth can indeed be sustained through innovation - into infinity and beyond - conditional on policy successfully fixing all the possible headwinds that innovation may face - should it be? Is infinite growth possible on a finite planet? What if sustained economic growth leads to environmental destruction? What if the world runs out of the fossil-fuel energy that helped trigger the Industrial Revolution?

This sub-section deals with these questions. In sub-section 3.1, the costs of economic growth in terms of its environmental impacts are summarized. Then, in subsection 3.2, the tech-optimism of Aghion and Howitt and of neoclassical economics is outlined with reference to the notion of Directed Technical Change. Sub-section 3.3 argues that such tech-optimism may be misplaced because it is based on a belief in the fungibility - the substitutability - of any natural resource.

## 3.1    The Costs of Economic Growth: Ecological Overshoot

The environmental costs of the economic growth experienced since the Industrial Revolution have been substantial. The world is now deemed to be in ecological overshoot (Rees, 2020), with several planetary boundaries - potential tipping points in the Earth System -already being breached(Richardson and et al, 2023). A finite planet cannot afford sustained economic growth of the kind that it has experienced over the past two hundred years or so.

It is appropriate at this point to list, without being exhaustive, the litany of environmental destruction that two centuries of exponential economic growth have caused.

One symptom of ecological overshoot is climate change[7] caused by greenhouse gas emissions

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[7]Climate change can pose an existential threat to humanity for several reasons, as outlined by Kemp et al. (2022).

from human activities - in particular those associated with the use of fossil fuels. It is estimated that humans have emitted around 2.5 trillion tons of $CO_2$ since the Industrial Revolution, of which around 1,770 billion tons were from burning fossil fuels and 750 billion tons from land use change (Hausfather, 2023). By 2024, more than 80% of the world's primary energy consumption came from fossil fuels. By 2022, this has already led to global warming of 0,8 degree Celsius above the 1961-1990 period. By 2023, it had increased to about 1,17 degrees Celsius, and possibly more likely 1,49 degrees Celsius (Jarvis and Forster, 2024).

To prevent catastrophic climate change, it has been recommended that global warming stabilize at no more than 1.7 degrees above pre-industrial levels, which in turn implies limiting atmospheric carbon to no more than **350** ppm (Hansen et al., 2008). At the time this paper was written, it was already  textbf 428 ppm.

Failure to limit global warming to 1,7 degrees Celsius above pre-industrial levels may result in what has been described as a "ghastly future" (Bradshaw et al., 2021). This is because 1,7 degrees may trigger tipping points. There are at least nine climate tipping points which if triggered may cause irreversible and catastrophic ecological collapse, such as the Arctic Sea-Ice, the Greenland Ice Sheet (GIS), the West Antarctic Ice Sheet (WAIS), the Atlantic Thermohaline Circulation (THC), the El Ninõ-Southern Oscillation (ENSO), the Indian Summer Monsoon (ISM), the Sahara/Sahel and West African Monsoon (WAM), the Amazon Rainforest and the Boreal Forest (Lenton et al., 2008, 2019). Six of the nine Planetary Boundaries have already been breached by 2023(Richardson and et al, 2023).

Another impact of expanding human population and economic activity is the acceleration of biodiversity loss. According to Bradshaw et al. (2021, p.3) "some 20% of all species are in danger of extinction over the next few decades [...] That we are already on the path of a sixth major extinction is now scientifically undeniable." Klebl et al. (2025) report that extinction rates are now around 1,000 times higher than natural rates. Dasgupta (2021, pp.1-4) notes that around 1,000 species are becoming extinct every year.

According to a 2026 report commissioned by the UK Government, the loss of biodiversity signals the collapse of ecosystems and is more than just an economic inconvenience, but rather a national security risk (HM Government, 2026). As the report describe the risk, (HM Government, 2026, p.6):

> "Nature is a foundation of national security. Biodiversity loss is putting at risk the ecosystem services on which human societies depend, including water, food, clean air and critical resources. The impacts will range from crop failures, intensified natural disasters and infectious disease outbreaks to conflict within and between states, political instability, and erosion of global economic prosperity. Increasingly scarce natural resources will become the focus of greater competition between state and non-state actors, exacerbating existing conflicts, starting new ones and threatening global security and prosperity."

It should be noted that, in contrast to the UK Government's assessment of biodiversity loss and ecosystem collapse as a national security risk, the World Bank, an institution designed to spread neoclassical economics and neoliberal tenets, have estimated that ecosystem collapse would reduce global GDP by a relatively small 2,3% annually by 2030 (see Johnson et al. (2021)).

Finally, sustained economic growth not only threatens catastrophic climate change, the breaching of Planetary Boundaries, and biodiversity loss and ecosystem collapse, it is also associated with the physical destruction of Earth Systems through the material demands of economic growth.

Aghion et al. (2025) argues that this physical destruction and huge material demands need not be a problem and that economic growth can continue, because suitably directed innovation will steer the economy to use "quality service" rather than "quantity" inputs. The assumption of course, is that the substitution between material and quality service inputs

in production has an elasticity of substitution larger than one, i.e. as per equations (2) and (6), that $\sigma > 1$. This substitution assumption then allows Aghion et al. (2025) to show that economic growth could continue without environmental damage by just substituting the material inputs with services - in other words, de-materializing economic growth.

Alas, there is little evidence of this substitution and de-materialization occurring, suggesting that the elasticity of substitution between quantity inputs and quality service inputs is not as high as Aghion et al. (2025) takes it to be. On a global level, the world economy is not being "de-materialized" by innovation-driven growth.

Figure 3 shows the close relationship between the world's material footprint and GDP.

Figure 3: Global Material Footprint (t) and GDP (constant 2015 US$)



*Source*: Author's compilation, based on data from the UN Global Material Flows Database

In fact, instead of de-materializing production through innovation, economic growth remains

a deeply material affair as Figure 3 suggests, with the weight of material goods manufactured by humans reaching 1.1 teratonnes by 2020, already "exceeding overall global biomass" (Elhacham et al., 2020).

The extent to which sustained economic growth causes ecological overshoot and material extraction can be measured by calculating the *Ecological Footprint* of the world economy. According to the Global Footprint Network,[8] "The Ecological Footprint is a metric of human demand on ecosystems, or more precisely on the planet's bio-capacity. It tracks how much mutually exclusive, biologically productive area is necessary to renew people's demand for nature's products and services." See also Borucke et al. (2013) and Wackernagel and Beyers (2019).

The world exceeded its bio-capacity already in the 1970s. According to the Global Footprint Network,[9] "Humanity demands goods and services from nature that require 20.8 billion global hectares to renew them, as of 2023. This is more than the 12.2 billion global hectares of biologically productive area (or bio-capacity) available on the planet. Excessive demand means that humanity now uses 1.7 times more than the biosphere can renew. Some describe this level of consumption as using 1.7 Earths."

This means that the world needs to consume fewer materials and free up bio-capacity. This challenge has also been framed as a need to decrease the Material Footprint (MF) of the world economy. The MF is defined as "the global allocation of used raw material extraction to the final demand of an economy" (Wiedmann et al., 2015). *Absolute Decoupling* occurs when the same or higher GDP can be produced with less MF, and *Relative Decoupling* occurs when the growth rate in GDP is higher than the growth rate in MF, where the latter remains positive, but declining growth (Ward et al., 2016).

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[8]See https://www.footprintnetwork.org/what-ecological-footprints-measure/
[9]See https://www.footprintnetwork.org/what-ecological-footprints-measure/

## 3.2 Directed Technical Change

While Mokyr, Aghion, and Howitt's analyses of the causes of the Industrial Revolution and the factors that can sustain economic growth have resulted in useful ideas on the roles of scientific knowledge, and on the need for a finely-balanced competition and incentive structure to avoid either over-or-under investment in innovation, there are aspects that are more contentious.

Fears that sustained economic growth would cause ecological destruction, including catastrophic climate change, as outlined in the previous sub-section, have been countered by economists such as Aghion and Howitt and others by invoking a magical trick of sorts, as will be explained in this sub-section. This is the trick known as *Directed Technical Change* - the steering of innovation in desirable directions (see chapter eight in Aghion (2009)). For instance, Acemoglu et al. (2023) declares that "*a redirection of technological change towards greener innovation can combat climate change without sacrificing long-term economic growth.*" And the self-stylized *London Consensus* recently declared similar faith in innovation to enable sustained growth, stating confidently that we "*know that there are promising innovations that can make sustainable growth a reality*" (Burgess and Dobermann, 2025, p.494).

The story of Directed Technical Change - see for instance Acemoglu et al. (2012) - permeates neoclassical economics. Acemoglu and Johnson (2023, chapt.11) even uses the case of directed technical change in the case of energy to argue that this is a prime example to follow to direct technical change in the field of Artificial Intelligence (AI). Never mind, as will be argued below, that it is not clear at all that directed technical change has reduced the dependence of economic growth on fossil fuel consumption, or led to absolute decoupling between economic growth and material use (see e.g. Figure 3 above).

Before directed technical change became the tool of choice against climate change in neo-

classical economics, there was another story that was popular, namely the story of the Environmental Kuznets Curve (EKC) - the belief that as countries start to grow from a state of poverty, their emissions would first increase, and then, after a certain level of prosperity, as measured by GDP per capita was reached, these emissions would decline - a trajectory that can be depicted by an inverse-U shaped graph. The reasons for the decline over time are that, as countries' GDP rises, they place greater value on the environment and can afford better technologies to protect nature. This EKC story has been labelled the "Achilles' Lance" myth, since it posits that economic growth would eventually, like the mythical lance of Achilles,"heal the wounds that it inflicts" (Barry, 2020, p.123).

Recent research, examining empirical evidence for 214 countries rejected a inverted U-shape between GDP per capita and carbon emissions, instead finding evidence for an N-shape relation which is "because the carbon emission trajectory may still be bent upward at a high level of economic development if the technological effects brought about by green innovation cannot keep up with the growing scale effects" (Wang et al., 2024, p.1). What they refer to here by growing scale effects is the rebound effect or "Jevons Paradox" - which refers to the phenomenon that *"in the long term, an increase in efficiency in resource use [due to technological innovation] will generate an increase in resource consumption rather than a decrease"* (Mario and Kozo, 2018, p.2).

Directed technical change is also subject to the Jevons Paradox. Carbon taxes, for instance incentivizes more efficient use of fossil fuel energy, which can increase the demand in aggregate for fossil fuels. Before discussing the limitations of directed technical change, it is useful to lay out its basic elements.

Directed Technical Change means that the government can, through policies, direct technological innovations away from damaging technologies - such as those that depend on fossil fuels - towards cleaner technologies that do not. Aghion and Howitt, and many mainstream economists, thus recognizes the reality of climate change, and that it is caused by the burning

of fossil fuels. In terms of their model, the global economy has climbed the technology ladder of fossil fuels for two hundred years or so, resulting in path dependency due to substantial sunk and fixed costs, efficient oil and gas networks, and powerful incumbents, who may not want change (Aghion et al., 2014, 2016).

Hence, for Aghion and Howitt (and most green growth supporters), the solution is not to climb ever higher on the fossil fuel technology ladder by developing new access to fossil fuels (such as fracking) but rather to break with the path-dependency of fossil fuels and "jump" to another technology ladder. For them, creative destruction is occurring on the wrong ladder (fossil fuels).

To enable the jumping from the fossil fuel technology ladder (the main culprit in climate change) to the green energy technology ladder requires a combination of economic carrots and sticks: sticks, such as high and consistent carbon taxes (including carbon tax border mechanisms) and regulations; and carrots, such as subsidies for renewable energies (Aghion et al., 2014). The mantra of green growth advocates, following from the A-H model's logic, is that economic growth can be decoupled from resource use, pollution, and $CO_2$ emissions through taxes and subsidies (Aghion et al., 2016).

The confidence that economists have in the success of altering the incentives for the use of fossil fuels and renewables is based on a fundamental belief of neoclassical economics: the substitutability and fungibility of resources. As soon as a resource becomes scarce and/or its price rises, an alternative will be found to replace it - so it is believed. For example, Nordhaus and Tobin (1974, p.522) sums up this position, stating "reproducible capital is a near-perfect substitute for land and other exhaustible resources." Thus, if economic growth demands material inputs that result in environmental destruction - such as the destruction of a forest - then the services provided by the forest can be taken over by some form of reproducible capital. Or if all copper, used in electric batteries, is fully extracted, its price will rise, stimulating innovation in alternatives.

There is therefore no reason to curtail growth or entertain notions of degrowth (see below), to save the planet. Philippe Aghion is very explicit about this, stating in an interview[10] that *"I'm not sure decline is the best way to take up the challenge of climate change. Innovation, on the contrary, makes it possible to invent ways to produce green energy and aim at a good quality of life for everyone."*

Oded Galor, a chief editor of the mainstream *Journal of Economic Growth*, provided a succinct summary of this mainstream economics belief in human exceptionalism and innovation to solve the climate crisis, writing (see Galor (2022, p.117)):

> "sustaining economic growth while mitigating further environmental degradation and reducing the likelihood of 'collapse' will rely on some of the same key factors that have brought us to our current predicament: technological innovation [...] the incredible power of human innovation that was so spectacularly unleashed during the age of progress [...] should permit the timely advancement of the revolutionary technologies that will be needed, turning this climate crisis into a fading memory in the centuries to come."

In short, the mainstream economic position is that economic growth can be sustained, in line with the central prescriptions noted, and it can be made green through innovation. Moreover, the (implicit) belief is that the carrots and sticks and regulations of directed technological change will be effective within the narrow time horizon - yes, time is of the essence - left for humanity to avoid that climate change triggers irreversible tipping points.

This is an incredibly heroic belief, which is based on a very tenuous assumption - that of substitutability, as has been seen above, that $\sigma > 1$. Jumping across ladders in terms of replacing fossil fuel energy requires substitutability between energy inputs to hold. Only if green energy can sufficiently replace fossil fuels is it possible to make the jump to a different

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[10]See: https://news.cnrs.fr/articles/innovation-is-what-will-get-us-out-of-this-crisis

quality ladder. Substitutability is, of course, the essential feature of Creative Destruction: new technologies substitute for the old, thereby making them obsolete. The next sub-section casts doubt on this central assumption.

## 3.3   The Fairy Tale of Substitution

> "*Resources are, to use a favorite word of economists, fungible in a certain sense. They can take the place of each other. That is extremely important because it suggests that we do not owe to the future any particular thing*" – Robert Solow, quoted in Foster (2022).

So, how realistic is this belief in substitutability and creative destruction to make growth sustainable? There is, increasingly, at least outside the mainstream of economics, the realisation that it is more complex than is assumed. Certainly, renewables need to displace fossil fuels completely, with the success of mitigating climate change depending on the phasing out of fossil fuels.

In terms of renewable energy substituting for fossil fuels, Jean-Baptiste Fressoz has presented a strong case that there is no energy transition (yet) but rather an energy addition (Fressoz, 2024). He calls the idea of creative destruction a "simplistic idea" that "was refuted even before Schumpeter formulated it." According to Fressoz (2024, p.16), "Not only is this idea generally false from the point of view of the history of technology - the new does not make the old disappear - but as far as climate change and the environment are concerned, it is entirely and totally refuted by the history of materials."

We see the failure of substitutability in energy most clearly in the evolution of the energy mix, depicted in Figure 4. The Figure in **Appendix C** depicts this slightly differently, showing the trend of increasing fossil fuel consumption as renewable energy consumption rises, giving effect to what has been called "eating two meals at once."

38

Figure 4: The Energy Mix: Global Primary Energy Consumption by Source
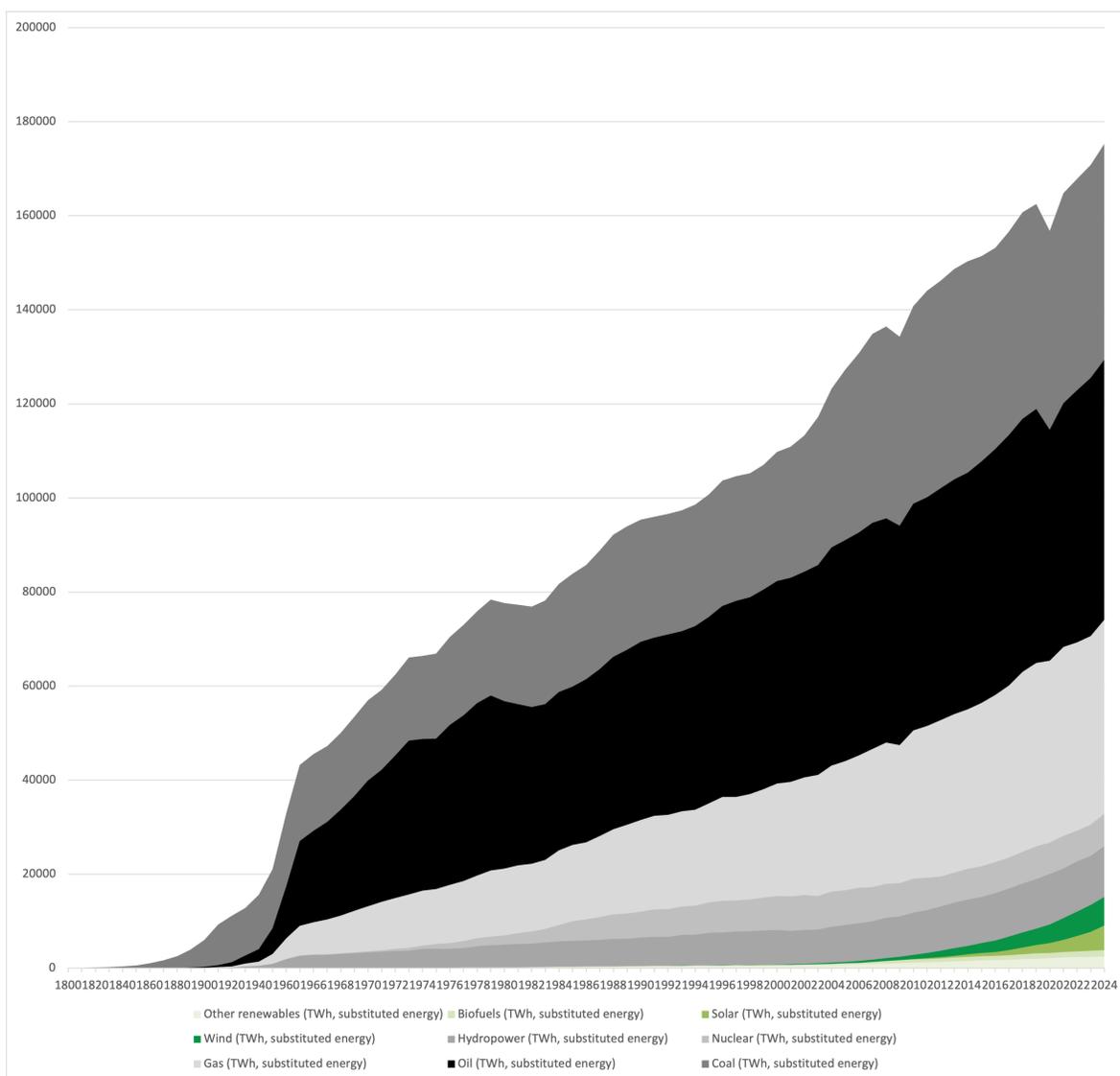
Figure 4 shows that, despite the rise in renewables (shown at the very bottom of the figure), the use of fossil fuels has also expanded. Renewables thus enter the energy mix not as perfect substitutes for fossil fuels. It is, as Tollefson (2018, p.422) concluded in *Nature*, that "*Renewable energy is indeed undergoing a revolution, as prices for things such as solar panels, wind turbines and lithium-ion batteries continue to plummet. And yet it is also true that the world remains dependent on fossil fuels — so much so that even small economic shifts can quickly overwhelm the gains made with clean energy.*"

There are several reasons why the belief in substitutability is difficult to hold in the case of energy, in particular for the belief that renewables can sufficiently substitute for fossil fuel energy - and important, substitute for fossil fuel energy in the very limited time[11] that is available to avoid ghastly climate change (Bradshaw et al., 2021). For comprehensive critiques see Seibert and Rees (2021), Michaux (2021), and Heinberg (2024).

According to these critiques, the lack of significant substitutability - and hence creative destruction - in the demand for energy is first, because the roll-out of renewable infrastructure currently requires fossil fuels for mining, manufacturing, transportation, and maintenance. Fressoz (2024, p.212) for instance reports that "35-40 per cent of the wind and solar capacity built recently in China has been bundled with coal power."

Second, substituting fossil fuels with renewables is triggering a re-materialization of the global economy, demanding massive quantities of critical minerals that involve complex supply chains, physical supply limitations, and also human rights abuses. Renewable energy systems require critical minerals such as cobalt, copper, graphite, iridium, lithium, manganese, nickel, platinum, and several rare-earth elements, such as neodymium and dysprosium (Luckeneder et al., 2021; Mervine et al., 2025).

Consider the use of copper, which is the physical backbone of all Information and Communication Technology (ICT). It has unique physical properties, including its low resistance (minimising energy loss), heat dissipation (generating less waste heat), and its ability to carry both data and power simultaneously. It is vital for smartphones, data centres, AI, microprocessors and broadband. Copper is, moreover, vital for renewable energy systems, which require[12] "between 6-12 times more per unit of power generated." It has been estimated that just to maintain an average 3% GDP growth rate per year over the next 18 years,

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[11]To achieve the Paris Agreement's goals, it has been estimated that 90% of energy consumption by 2050 should be met by renewables. This will require that the current renewables-based installed capacity increase 100-fold from 3300 gigawatts (GW) in 2022 to 33000 GW in 2050. And that 90% of vehicles be Electric Vehicles (EVs) by 2050. Time for substitution is limited.

[12]See: https://discoveryalert.com.au/copper-demand-clean-energy-2025/

around 700 million tons of copper need to be mined - the same amount as have been mined over the past 10,000 years (Editorial Team, 2026). Hence, it is clear why Malmaeus et al. (2025, p.1) warns that "basing a green transition on such a large overuse of critical metals is not sustainable."

Typically, though, neoclassical economics does not see these critical mineral requirements and their finite supplies as a stumbling block to generating sufficient renewable energy to completely substitute for fossil fuels. Again, the assumption is simply that if the price of these minerals rises, there will be incentives for further exploration and discovery, and for, yes, substitutes to be developed. As the quote from Solow above indicates, economists believe that resources are fungible. In effect, the belief in substitutability between resources is, in essence, a belief that there is no such thing as natural resources. As explicitly declared by Crawford (2022) "there's really no such thing as a natural resource. All resources are artificial. They are a product of technology" (Crawford, 2022).

Apart from the troublesome anthropocentric implications from the belief that there are no such things as natural resources (that all is created by human inventiveness!) and hence that limited minerals pose no obstacle to directed technical change, it is the case that the mining of these renewable energy metals is having a hugely negative environmental impact. One reason is that " the vast majority of metal and minerals mining takes place in species-rich biomes, or 20 km or less from protected territories, with around 90% of mining sites in areas with significant water scarcity (Luckeneder et al., 2021, p.12).

A warning has been sounded that mining for green minerals has an enormous spatial footprint not specifically factored into global biodiversity threat maps or conservation plans" (Sonter et al., 2020, p.2). But again, even the destruction of biodiversity is no issue for neoclassical economists living in the fairy tale land of no-such-thing-as-natural-resources and perfect substitutability through human ingenuity. In fact, economists, including Aghion and Howitt, have had remarkably little to say about biodiversity, and often when they do, their worldview

41

frames biodiversity as all other "resources" as substitutable - or even worse. Neoclassical economic modelling has, for instance, been used to conclude that under certain conditions, the "extermination of the entire population' of a species may be "the most attractive policy." (Clark, 1973, p.950).

Third, renewable energy sources face well-known problems, such as intermittency and unpredictability. This means that energy from renewable energy systems, such as solar PV panels and wind turbines, must be stored and distributed using battery technology. Without these, solar and wind systems need to be backstopped by fossil-fueled grids (or nuclear power) for grid stability. At COP29, the UN set the target[13] of achieving a battery storage capacity of 1,500 GW (1.5 TW) for the world by 2030, which would mean a six-fold increase over 2022 capacity. To achieve this, the IEA has estimated investment in batteries of US$ 800 billion by 2030,[14] an increase of around 400%. Given progress in battery technology, efforts to develop and commercialize Sodium-ion (Na-ion) and Iron-air batteries in case lithium and copper supplies are not available, and sharp declines in the cost of batteries, reaching this target may be technically possible. The reality, however, is that the binding obstacle may be logistical; for instance, it is estimated that around 25 million kilometers of grid need to be refurbished or added **by 2030** to accommodate these batteries on the grid. According to the IEA,[15] the practical difficulties of doing so are already causing "at least 3,000 GW of renewable power projects, of which 1,500 GW are in advanced stages, are waiting in grid connection queues."

Battery systems are rapidly evolving, but are still not a good substitute for petroleum, especially for supporting transportation at scale. Petroleum is very energy dense and safe to store in a tank onboard a vehicle - it provides around 45 MJkg energy. In comparison, a lithium battery on board an EV provides only 0,5 MJkg energy - petroleum is thus around

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[13]See: https://cop29.az/en/pages/cop29-global-energy-storage-and-grids-pledge

[14]See: https://www.iea.org/reports/batteries-and-secure-energy-transitions/outlook-for-battery-demand-and-supply

[15]See: https://ember-energy.org/latest-insights/the-clean-flexibility-cop/

100 times more powerful.[16] This, of course, is not to say that continued technological innovations in battery storage will not take place, and that as a result the intermittency and unpredictability problems of renewables will diminish. This will certainly be the case; the question is whether it will be achieved in time, at scale, and whether financial and logistical obstacles can be overcome.

Fourth, and ironically, creative destruction is itself retarding the green technology pivot - the jump from the fossil fuel ladder to the renewable energy ladder in terms of the Aghion-Howitt framework - by incumbent leaders in renewable technologies already acting to stifle competition and further entry into the market. This has been described as the "geoeconomic turn in decarbonisation" and "green mercantilism" (Meckling, 2024; Barbier, 2025). The former refers to the increasing use of so-called "green" industrial policies to foster local economic growth, "facilitating the rise of trade protectionism, creating international conflict, and reproducing economic divides" (Meckling, 2024, p.869).

Green mercantilism, relatedly, refers to the growing practice where countries "adopt protective strategies to enhance their competitive advantage in the global green market" (Barbier, 2025, p.307). The concern is that this will result in "walled markets that deter diffusion of green technologies across borders, making it harder for other economies to adopt innovations" and that this will ultimately result in failure to "decouple increased economic prosperity from environmental destruction" (Barbier, 2025, p.307).

A fifth reason why the belief in substitutability is difficult to maintain in the case of energy is that the use of energy is proportional to the size of the world economy, as shown in Figure 5 below. This means that creative destruction needs to occur over a much larger scale than in the case of the typical products and technologies that it is typically considered to disrupt or displace. As Sequeira et al. (2018, p.103) put it:

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[16]See: https://tinyurl.com/2snbsj9w

"The difficulty of introducing new products and replacing old ones is proportional to the market size [...] the larger the market size, the larger the costs necessary to discover, develop and market the associated technology, e.g. costs pertaining to the construction of prototypes and samples, new assembly lines and training of workers, and generic coordination, organizational, marketing and transportation costs."

Partly as a result of the rather imperfect substitutability in energy use, it is not yet the case that GDP growth has been decoupled - in an absolute sense - from the environment, although there is some evidence of relative decoupling[17] in various countries as a result of increased efficiency but also outsourcing of polluting industries to other countries (Haberl et al., 2020). Studies that have documented the absence of absolute decoupling on a global level includes Hannesson (2021); Jackson and Victor (2019); Ward et al. (2016) and Wiedmann et al. (2015).

Figure 5 depicts, for the world as a whole, total $CO_2$ emissions and World GDP over time. The strong positive correlation implies no absolute decoupling. It shows that $CO_2$ emissions from energy in 2024 reached a record level, and that, over time, there is a strong positive association between GDP and carbon emissions. The correlation coefficient over the series in Figure 5 is almost perfect: 0.97.

Jackson and Victor (2019) argues that even if absolute decoupling could be achieved under green growth policies, it would not be sufficient to prevent a climate breakdown because the extent of absolute decoupling that would be required to sufficiently reduce carbon emissions to limit global warming in line with the Paris Agreement would not be attainable. They calculate that this requires a decline in the carbon intensity of global GDP of 14% per year for at least three decades, which they conclude is too great a requirement (Jackson and

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[17]Relative decoupling may however have little aggregate advantages in terms of reducing resource use due to the Jevons paradox - the rebound effect, as already discussed.

Figure 5: No Evidence of Absolute Decoupling
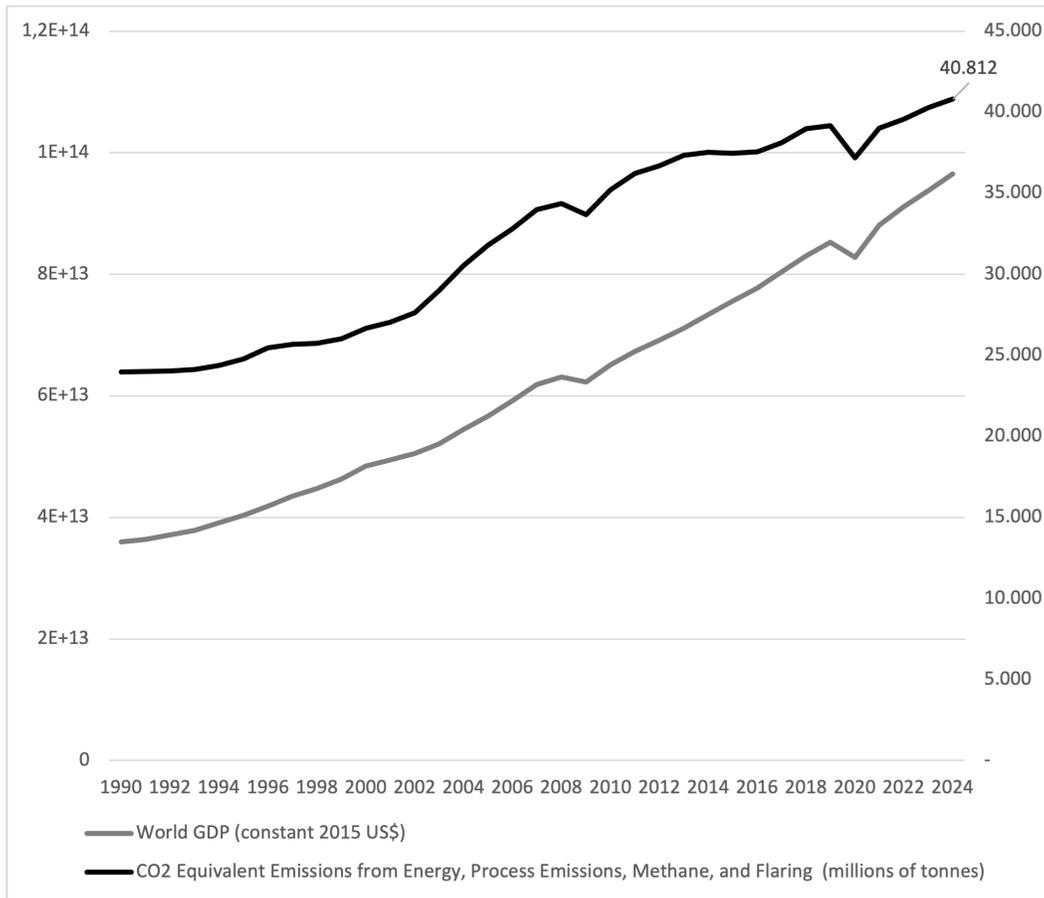


*Source*: Author's Compilation based on data from Our World in Data

Victor, 2019).

Similarly, Colcombet (2026) report that "To keep global warming below 1.5 degrees Celsius by 2100, the use of fossil fuels must fall by 5–8% each year — a pace that is too fast for low-carbon energy to keep up with." Even if these technologies can be developed to do this, the problem remains, as pointed out by the Limits to Growth Report back in the 1970s, namely that "while technology can change rapidly, political and social institutions generally change very slowly" (Meadows et al., 1972, p.148).

It is not just that renewable technologies need to be improved and rolled out in a technical sense that is a challenge; perhaps even more of a challenge is changing the political

and social institutions that underpin dependence on fossil fuels. These institutions determine, for instance, how creative destruction proceeds within the renewable energy sector, and how renewable energy markets are structured and regulated. In this regard, Burgess and Dobermann (2025, p. 481) recognizes that "*Reforming energy markets and introducing more wholesale competition is a complex institutional endeavor that takes years or decades of planning.*"

The inability of renewables to fully and in time substitute for fossil fuels is likely why climate activist and author Bill McKibbin, a strong support of renewables, nevertheless have concluded[18] that "renewable energy represents the first real tool that might ... not stop global warming, but shave tenths of a degree off how hot the planet will get."

With *timely* substitutability (creative destruction) not holding for energy, the conclusion is that economic growth is not environmentally sustainable, outside the Aghion-Howitt fairy tale.

# 4    Energy Blindness and Human Exceptionalism

"*It seems likely that future generations will label the past two centuries as the Fossil Fuel Age rather than the Industrial Revolution - emphasizing the critical importance of a now-depleted resource over a self-flattering celebration of human innovation*" (Murphy et al., 2021, p.2).

Sustained economic growth causes great ecological damage, as the previous section outlined. This is recognized by neoclassical economists such as Aghion and Howitt, who nevertheless insist that the solution is not to stop or reduce economic growth, but to continue "green" economic growth, that is, economic growth that is decoupled from emissions and material

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[18]See: https://www.nybooks.com/articles/2026/02/26/is-it-easy-being-green/

demands.

Such economic growth can be established, they argue, through directed technical change - a suite of economic policies to incentivize substituting renewables for fossil fuels. That human ingenuity would rise to the occasion and deliver the resulting green technologies and products is never doubted. That substitutability could be a problem is assumed away by regarding, as the previous section discussed, natural resources as non-existent, with human innovation perfectly able to find substitutes for any scarce or polluting resource.

As such, the quote at the top of this paragraph is aptly referring to the key problem - neoclassical economists' energy blindness and the *"self-flattering celebration of human innovation"* - which stems from the deep-rooted belief in human exceptionalism.

This section explores how energy blindness (section 4.1) and human exceptionalism (section 4.2) have combined to create a divorce between economic theory and the biophysical reality of the world, and with this, a complacency as to the risks facing human civilization from an economic system where the "endless pursuit of economic growth" has become a deeply entrenched economic and political goal.

## 4.1   The Detritovores

*"Humans have become detritovores, organisms that live off the dead remains of other organisms"* (Cobb, 2015).

Why do neoclassical economists hold on to the assumption of substitutability between resources, which, as the previous section has argued, is not reflected in the case of energy? One reason is that it is an ideological bias deeply baked into the fabric of neoclassical economics, which many economists are perhaps not even aware of. It is because, inherently, neoclassical economics is concerned with the *exchange* of goods rather than their production (Cleveland

47

and et al, 1984).

A second reason is the belief in human exceptionalism, the belief that human innovation will find substitutes for any resource that becomes scarce. Brown et al. (2011, p.24) discusses how "mainstream economists historically have dismissed warnings that resource shortages might permanently limit economic growth" and that this is due to the belief that "the capacity for technological innovation to meet the demand for resources is as much a law of human nature." They take issue with this belief, however, stating that "*there is no scientific support for this proposition; it is either an article of faith or based on statistically flawed extrapolations of historical trends.*"

A third reason is that neoclassical economics has neglected nature and natural resources, and as a result, does not properly understand and appreciate the distinctive role of energy. For economists such as Aghion and Howitt, energy appears to be just another input into production, like any other. As a result of this energy blindness, not only do economists assume substitutability, but they also tend to take it for granted that innovation causes economic growth, rather than the other way around. What if there is a third factor, as is often the case when two variables are correlated?

To illustrate the distinctiveness of energy, and of fossil fuel energy in particular as a difficult-to-substitute resource, as well as the role of energy in facilitating innovation and driving growth, it is useful to begin by returning to Figure 1. When considering the timing of the Great Take-Off in Figure 1, it is clear that the Industrial Revolution took off in the early 19th century. Why then?

Whilst Joel Mokyr has made valuable contributions in outlining the importance of scientific discovery in the setting of this revolution, it is also the case that the Industrial Revolution could not have taken off without the massive use of coal. Fossil fuel energy powered the industrial revolution, which started in the UK, and which propelled the UK into the world's

first "industrial superpower." Between 1300 and 1750, between 30% and 50% of England's GDP was devoted to energy, which, after the introduction of fossil fuels, dropped to around 5% (Hall, 2017).

Fix (2020) describes how the fossil fuel boom helped to propel the UK into a global empire, relating that "*Britain plundered the resources of the world at the same time that it plundered the coal reserves under its belly. The results were spectacular. From an unremarkable nation in 1600, Britain accumulated so much power that by the late 1800s, it was effectively the world's administrator. This rise is written in the language of energy. At the empire's peak, the typical Brit consumed about 7 times more energy than the world average.* "

The rise of the UK was followed in the 19th century by the rise of the US, again as in the UK, propelled by fossil fuels - this time not coal, but oil. The world's first commercial oil well was drilled in 1861 in the USA by the Seneca Oil Company (Naudé, 2023). After this, the global economy grew rapidly at exponential growth rates as depicted in Figure 1.

What is unprecedented in human history over the past two hundred or so years is not just the rapid increase in per capita GDP (and population), but the massive use of fossil fuels. As Rees (2020, p.4) points out, "for 99.9% of human history our species functioned within thermodynamically 'healthy' limits." The discovery and use of fossil fuels as a source of energy changed all of this. As described by Kasting (2010, p.567-569)

> "Starting about 150 years ago, we discovered the great energy potential locked
> in fossil fuels. Access to external energy augments our average power by twenty
> to a hundred times compared to animal metabolism [...] This energy gives us the
> capabilities of superheroes. We can fly higher and faster than a bird, easily access
> building rooftops, punch through walls, excavate mountains, stop speeding bul-
> lets, send fire and destruction long distances, and communicate instantaneously
> with others all over the world [..] [fossil fuels] has permitted a ferocious growth

in population, particularly since the dawn of the industrial age, when our energy use so greatly expanded. Extinction of 97% of human beings living on Earth today would reduce us only to the number of people on Earth at the dawn of the scientific revolution, some 500 years ago."

Between 1800 and 2019, human energy consumption increased 28-fold (Re, 2022). Between 1850 and 2000, fossil-fuel use increased more than 150 times (Brown et al., 2011). Never before in history have humans had access to and used so much energy. As recognized by Hagens (2018) *"the constant growth we've experienced was correlated with human inventions and economic theories, but the cause was finding a bolus of fossil sunlight. We behave like squirrels living in a forest where a truck full of hazelnuts crashed, living off the freight and thinking it will last forever."*

Of course, such an energy boon - finding the "bolus of fossil sunlight" would have a significant impact on GDP. Is it any coincidence that after these energy sources were accessed, GDP growth accelerated so much? Fossil fuel energy has endowed humans with "superpowers" (Jancovici and Blain, 2024). These superpowers include boosting population growth (through synthetic fertilizers), adding billions of "virtual" laborers to the world economy, and supercharging innovation, including fuelling the machines that the modern economy depends on to excavate, transport, transform, and distribute the goods consumed every day. Thus, by boosting population, virtual labor, and innovation, fossil fuels can be seen as an important driver of the economic growth the world has experienced.

Consider first how fossil fuels have boosted population, a key variable in all of the endogenous growth models discussed in Section 2. Fossil fuels are essential for producing synthetic fertilizers used in food production. "Almost half the world's population would not be alive today" without synthetic nitrogen (Harford, 2017). Erisman et al. (2008) estimated that "by 2000, nitrogen fertilizers were responsible for feeding 44% of the world's population." And,

as equations (2) and (4) indicate, population is a key determinant in the ideas production function. So, no surprise that energy use, GDP per capita and population in the world all follow the same hockey stick graph since the 1800s.

Consider, secondly, the amount of virtual labor that fossil fuel energy provides. As Smil (2017) put it, "An average inhabitant of the Earth nowadays has at their disposal nearly 700 times more useful energy than their ancestors had at the beginning of the 19th century [...] it is as if 60 adults would be working non-stop, day and night, for each average person."

Nate Hagens[19] has similarly described our exceptional position in terms of energy by pointing out that "The global human economy uses the equivalent of $\approx$100 billion barrels of oil (in the form of coal, oil, and natural gas) every year. That's the equivalent of $\approx$ 400 billion human workers, whose labor is added to the five billion actual human workers on Earth." See also Hagens (2020) for a discussion of the vital importance of energy for economic growth.

Consider next how fossil fuels have propelled innovation, not only through increasing the world's population but by facilitating innovation in products that can use and embed energy. Technological innovations and the products and services based on them, that many take for granted today, such as the internal combustion engine, electrical batteries, computers, medicines, clothing, and much more, *embeds* energy. Without the availability of cheap fossil fuels, no one would have innovated the internal combustion engine. No one would have thought of introducing extensive railway systems and ever-better locomotives. Without rocket fuel, there would have been no Moonshot in the 1960s, and hence no technological innovations associated with it. It is also particularly important for the production of petrochemicals, which has resulted in the innovation of thousands of products - from clothing to pharmaceuticals, which have become ubiquitous in the modern economy. And, as was also mentioned in section 2.1, even the scientific discoveries that triggered the Industrial Revolution, according to Mokyr, would not have occurred if people did not have time to pursue

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[19]See: https://www.natehagens.com/economics

learning, research, and discovery, time made available by the time-saving energy from coal.

Figure 6 shows the close relationship between global GDP per capita and energy supply from 1990 to 2024.

Figure 6: Global GDP per capita and Global Energy Use, 1990-2024
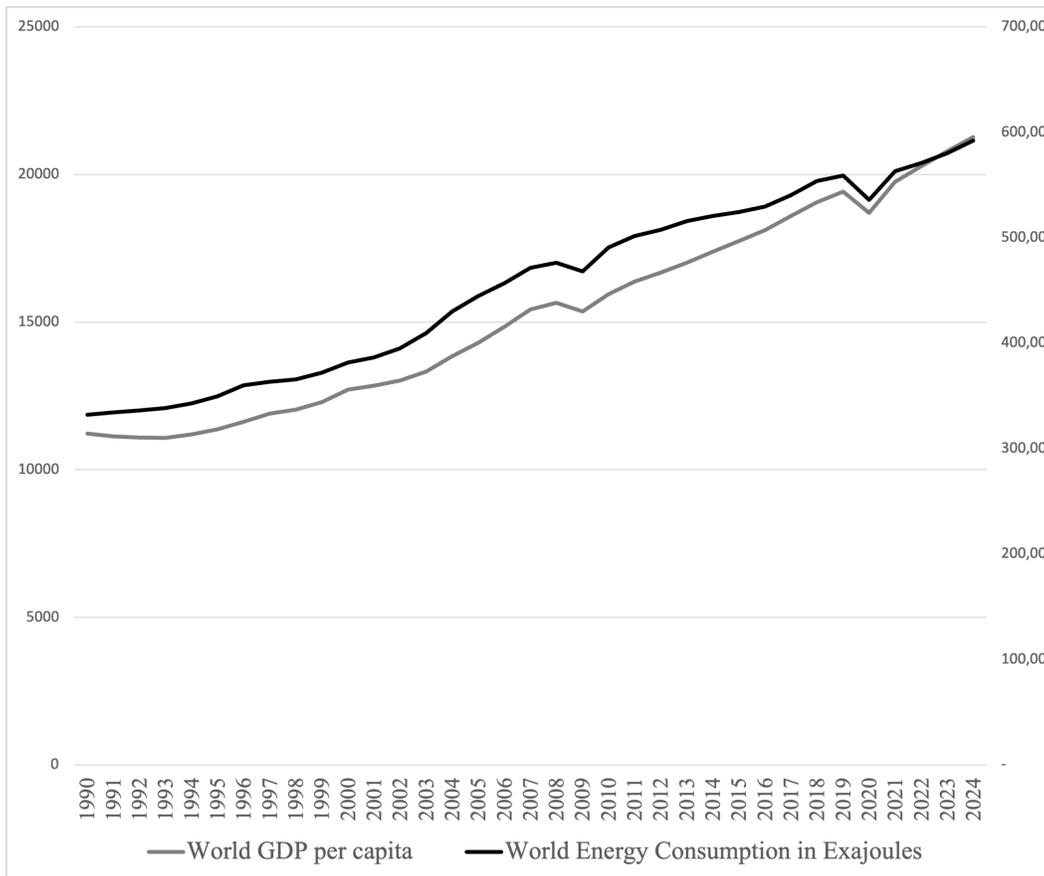
The correlation between global GDP per capita and global energy use in Figure 6 is 0.99. This is much higher than the 0.74 which Brown et al. (2011) found in the case of the USA. To investigate the relationship between energy and GDp per capita on the macro-level further, Brown et al. (2011) ran a regression of the form $E = \alpha \times GDP^{\beta}$ of energy use on GDP per capita in the USA, finding that $\beta = 0.76$. They comment on this finding remarking that "*the exponent for the scaling of energy use as a function of GDP, 0.76, is reminiscent of*

*the three-quarter-power scaling[20] of metabolic rate with body mass in animals [...] This may not be coincidental. In a very real sense both animals and economies have 'metabolisms.' Both consume, transform, and allocate energy to maintain complex adaptive systems far from thermodynamic equilibrium."*

In the case of the whole world as in Figure 6, a similar regression finds for the period 1990-2024 that $\beta = 0.89$. Because $\beta < 1$ this indicates sub-linear scaling, meaning that a 10% increase in average world GDP per capita will require a 9% increase in energy use. It reflects economies of scale and efficiency on a per capita level. However, at 0.9 it is close to linear scale, as as such reflects much less efficiency and scale economies than is found in biology - i.e. animal bodies are more energy efficient that the global economy.

The difference between $\beta$ on country level (i.e. the USA) and global level indicates the individual countries can reduce the energy inefficiencies in GDP growth, but that this does not seem to scale to global level. It is consistent with findings elsewhere which finds relative decoupling between energy and emissions in some countries, but no absolute decoupling globally.

The almost linear scaling between GDP and energy use may also reflect the energy wastefulness inherent in creative destruction - the mechanism that drives GDP scaling in the growth models of Aghion and Howitt and Romer. The very idea of creative destruction - the new displacing the old - would cease without plenty of energy. The simple reason is that fixing and maintaining an existing old product requires less energy than making a new product. As Dessler (2025) explains,

> "Making a new product always consumes far more energy than repairing one that
> already exists. Your toaster might embody 100 MJ of energy from producing
> metal parts, wiring, and heating elements. Repairing a broken lever or replacing

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[20]This scaling law that they refer to is Kleiber's Law.

a heating coil might require only a few MJ of new materials and manufacturing effort. Throwing out the broken toaster and buying a new one wastes nearly all of the energy already invested in the original product and leaves behind mountains of waste."

Schumpeterian creative destruction, therefore, is energy-intensive and wasteful. This is even the case when such creative destruction is being incentivized to "destruct" the fossil fuel industry through directed technical change. For instance, incumbent fossil fuel companies, expecting that they will be made obsolete if creative destruction is successful, may, as Sinn (2012) has argued, preempt this by accelerating the production of fossil fuels, which will then lead to an acceleration of climate change.

Finally, it goes without saying that fossil fuels are non-renewable and hence will not last forever. Rystad Energy[21] reports that total recoverable oil resources are estimated at around 1,500 billion barrels. They point out that if oil demand stays constant, then this means that "total oil production would peak around 2035 at 120 million barrels per day (bpd), then decline steeply to 85 million bpd in 2050." And ExxonMobil, in its 2024 Global Outlook[22] reported that with no new investment in oil exploration, by 2030 "oil supplies would fall from 100 million barrels per day to less than 30 million." The Report also warn that a permanent loss of 15% of oil supply per year could raise oil prices by more than 400%.

The situation is likely to be much worse because energy is needed to extract fossil fuels, and this requirement is rising. Thus, with oil supplies declining, and the energy needed to extract the remaining supplies rising, even less energy will be left for human use. According to Delannoy et al. (2021, p.1), currently 15.5% of the gross energy from oil is needed to extract and produce that oil, and that this cost is "growing at an exponential rate: by 2050, a proportion equivalent to half of the gross energy output will be engulfed in its own

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[21]At: https://tinyurl.com/4bwe5v3w
[22]See https://tinyurl.com/3rmwdy5v

production."

Making up for a loss of anywhere between 15 million and 70 million barrels of oil per day by 2050 through renewables is highly unlikely, given the lack of significant substitution within such a short time frame, as discussed in the previous sub-section. Humans will have to learn to get by on much less energy in the near future, which also implies, in the light of the discussion in this section, having to learn to get by with less, or no economic growth.

## 4.2   The Arrogant Ape

In his popular novel of environmental awakening, "Ishmael", Daniel Quinn's leading character learns that there is a basic creation myth that most human societies today share - that humans are special and separate from the rest of nature (Quinn, 1992). As he describes this,

> "*Man's destiny was to conquer and rule the world, and this is what he has done - almost. He hasn't quite made it, and it looks as though this may be his undoing. The problem is that man's conquest of the world has itself devastated the world [...] We've poured our poisons into the world as though it were a bottomless pit [...] we've gobbled up irreplaceable resources as though they could never run out*" (Quinn, 1992, p.84).

As Quinn concludes, the anthropocentric view of the Earth has become counterproductive, given that humanity is, against its own self-interest, destroying the ecosystems on which it depends: ecosystems that took billions of years to form, yet are valued at next to nothing (Murphy et al., 2021).

In her book "The Arrogant Ape," primatologist Christine Webb writes "human exceptionalism - a.k.a. anthropocentrism or human supremacy - is at the root of the ecological crisis.

This pervasive mindset gives humans a sense of dominion over Nature, set apart from an entitled to commodify the earth and other species for own our exclusive benefit" (Webb, 2025, p.3).

The Arrogant Ape is predisposed to feel separate from the rest of nature, and entitled to "dominion" over it - to use the Earth and its resources as it sees fit. Risks of ecological overshoot and the destruction of biodiversity and ecosystems do not enter into much of mainstream economic theory. Recall Solow's words, quoted at the top of sub-section 3.3, that "we do not owe to the future any particular thing", or the recommendation of Clark (1973, p.950) that there may be instances where the "extermination of the entire population' of a species may be "the most attractive policy."

This anthropocentric view underpins much of modern mainstream economics, which has relegated the rest of the planet to the category of resources to be used by humans to maximize their utility, and which are believed to be essentially infinite and perfectly substitutable.

Rees (2023, p.19) takes issue with this view of human exceptionalism, arguing that rather than being brilliantly equipped to tackle the ecological crisis, a result of the way in which evolution has shaped human cognition is that "*contemporary humans tend to respond to problems in relatively simplistic, reductionist, mechanical ways. People don't generally think in terms of discontinuous behaviour – lags, thresholds (tipping points), and other non-linearities; we don't 'get' complexity. [...] Is it any surprise that ordinary people today still seek explanations for unusual phenomena in terms of simple cause-effect relationships, that we deny uncomfortable truths, that we discount the future, and that many of our contemporaries are still given to mystical thinking?*"

Based on human exceptionalism and the belief that there are no natural resources as such, neoclassical economists such as Aghion and Howitt discuss direct technical change only aimed at climate change, the negative externality caused by too much carbon emissions. Spratt and

Dunlop (2021, p.4) are therefore correct in lamenting that mainstream economics has given up "on protecting major Earth systems and ecologies" by striving only for decarbonisation.

While this shortsightedness is a problem given the over-exploitation of natural resources and the crossing of planetary boundaries, when it is acknowledged in neoclassical economics, it is acknowledged as a *bona fide* problem of negative externalities from well-intentioned efforts. All that then needs to be done is to internalize the external costs of economic growth through "simple cause-effect" policies such as carbon pricing. This is the core position of the recent neoclassical economists' *London Consensus*, which advocates for the continued striving for sustained economic growth, so long as there is a proper accounting "for the damaging effects of environmental externalities" (Burgess and Dobermann, 2025, p.476).

The London Consensus identifies public and political opposition to carbon taxes as a possible obstacle, but one that can be overcome by, yes indeed, innovation. According to (Burgess and Dobermann, 2025, p.478) "innovation can ease the trade-offs that make political action on the environment so difficult." Here, innovation - so-called "green innovation" makes its appearance as a tool to help internalize the costs of economic growth. Directed technical change and its goal of green economic growth are instances of reform environmentalism, which considers innovation sufficient to avoid ecological overshoot and mitigate climate change without abandoning economic growth.

While the professed importance of innovation to substitute for fossil fuel dependency and to reduce political and public obstacles to policies from directed technological change seems, on the face of it, harmless, if indeed perhaps unattainable, given the limitations on substitutability and energy blindness, there is a deeper and more disturbing dimension. It is here where mere mystical thinking is superseded by greed.

This disturbing dimension is that green innovation and directed technical change are being repurposed not so much as tools or approaches to make economic growth environmentally

sustainable, but rather to ensure that growth can be sustained. In other words, faced with the Great Stagnation, advanced economies have turned to "green growth" to sustain economic growth. What then often appears as noble attempts to save the planet masks attempts towards complete exploitation and commodification of all the Earth's resources, mostly for the profits of a powerful elite.

It has become a mantra that socially and environmentally responsible firms will grow faster, not that they will sacrifice growth for the sake of protecting the environment. Sustainable economic growth has been repackaged as a significant business opportunity (Anand et al., 2021). Directed technical change, based on the theory of endogenous growth, is the instrument to seize this opportunity.

Moreover, directed technical change has come to be associated not only with "Green mercantilism" (as discussed in sub-section 3.1), but also with a green growth industry that is furthering capitalism's expansion imperative (see sub-section 2.1) by aiming to monetize, financialize and commodify nature as far as possible - doing so by harnessing human innovativeness. Green growth initiatives now include schemes to "make biodiversity conservation profitable and scalable" (Michaelides, 2024). These include "innovative" schemes such as "biodiversity banking, offsetting, green/blue bonds, species credits, extinction futures markets, and climate catastrophe bonds" (Spash, 2022). It also includes "tokenizing the planet to save it," which is the latest innovative green growth and business profit enabler (Koetsier, 2021).

As argued in Naudé (2025) with reference to Klebl et al. (2025, pp.2-3), it would be necessary for economic growth theory to go beyond its anthropocentrism towards biocentric holism. A position of biocentric holism would mean that "the entities deserving of moral concern are not just individual species or cultural elements but the 'wholes' – that is, ecosystems or cultural landscapes." This recognizes a moral value in biodiversity itself and is consistent with emerging Earth Systems Science (ESS), which is "grounded in a new scientific understanding

of life and planets as a complex whole - a system of systems" (Frank, 2024).

Any future economics that is not integrated into Earth Systems Science and based on bio-centric holism would be a fairy-tale economics.

# 5  Not Your Father's Innovation and Growth

*"So I can twist my head into thinking of quality of life development in an otherwise steady-state as being a form of indefinite growth. But it's not your father's growth. It's not growing GDP, growing energy use, interest on bank accounts, loans, fractional reserve money, investment. It's a whole different ballgame, folks"* (Murphy, 2012).

In contrast to the tech-optimism of Aghion and Howitt, and of neoclassical economics in general, the verdict of this paper may seem more pessimistic. It would seem that economic growth can neither be sustained, nor is it sustainable. Moreover, the costs of economic growth now appear to be such that massive ecological damage is being caused, threatening mass extinction.

Nevertheless, mainstream neoclassical economics remains wedded to its simplistic prescriptions for sustainable growth, based on beliefs in the importance and need for economic growth, in innovation as merely a tool to drive economic growth, and in the infallibility of human innovativeness to always come up with substitutions for natural resources (the reality of which is denied).

In addition to the human exceptionalism ingrained in neoclassical economics, the problem also stems from neoclassical economics's energy blindness. Creative Destruction is the wrong paradigm for steering an energy transition. A better understanding and appreciation of energy shows that it is not merely a resource like any other to be easily substituted for, and

moreover that it plays a much more important role as a determinant of both innovation and economic growth. Without energy, neither the capital stock nor labor, would exist in its quantities and varieties.

With the lack of substitution possibilities for fossil fuels, at least in time to avert catastrophic climate change, and the importance of fossil fuel energy at present (delivering 80% of primary energy supplies) for innovation and economic growth, the conclusion is that the inevitable depletion of fossil fuels in the foreseeable future would require the world to get by with less energy, and with less economic growth.

The depletion of fossil fuels will, however, come too late to halt climate change, implying that over the next century or so, humanity will not only have to face declines in energy availability, economic growth, and innovation, but also adapt to a warmer climate. On top of this, the total world population, a driver of innovation in all growth models, would also start to decline.

The implications of energy and GDP growth collapse are not novel. Back in 1972, the Club of Rome's Limits to Growth (LtG) study already concluded that "If the present growth trends in world population, industrialization, pollution, food production, and resource depletion continue unchanged, the limits to growth on this planet will be reached sometime within the next one hundred years" (Meadows et al., 1972, p.23). Its standard-run scenario, under business-as-usual conditions, predicted the limits to be reached and the collapse of global society around the middle of the 21st century (Turner, 2008). Updates of the LtG study by Turner (2014) and Herrington (2021) indicated that the global economy was tracking the standard-run scenario.

Indeed, as a result of the recognized (mostly outside of neoclassical economics) failures of directed technical change, there has been a growing scholarship that has started to ask why the world is still so obsessed with economic growth, how it can *degrow* the global economy

60

so as to alleviate the material footprint of humanity, and how to prepare for an imminent post-growth economy (Hickel et al., 2022; Jackson, 2016; Kallis et al., 2012; Kallis and et al, 2025).

Calls for degrowth and post-growth, however, are rejected by neoclassical economists, including Aghion, Howitt, and Mokyr. This is another error in economic growth scholarship, to add to its various erroneous beliefs already identified and discussed in this paper.

In a recent paper Gries and Naudé (2025) calls for a closer consideration of degrowth and post-growth within traditional economic growth models, proposing a degrowth-green growth model that abandons the Aghion and Howitt assumption of high substitutability ($\sigma > 1$) and of infinite resources, and which incorporates finite resources and planetary boundaries. They conclude from their model simulations that "a full transition to renewable energy and materials will be needed to sustain consumption levels in a post-growth economy" [p.1]. Thus, only under the rather fairy tale assumption of full substitutability of resources, upon which this paper has cast doubt, can a stationary, post-growth economy exist within planetary boundaries, without a decline in consumption. **Appendix D** describes the essence of such a sustainable economy, as described by Gries and Naudé (2025).

A post-growth economy, with an inevitable decline in global consumption, need not be seen as a pessimistic outcome (Naudé, 2023). It can still be an economy featuring progress, with growth being defined differently[23] than GDP growth, or the infinite pursuit of growing consumption.

It can moreover be an economy where innovation ceases to be merely an instrument for pursuing material GDP growth, corporate dominance, and profits, but rather becomes a tool for ensuring and promoting flourishing Earth Systems - and planetary habitability (Naudé,

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[23]There is a growing literature that deals with the need to move away from GDP as the central measure of economic and societal success - see e.g. the discussions in Costanza et al. (2014), Masood (2022) and Stiglitz et al. (2009).

2025).

Perhaps the transition to such a post-growth, post-fossil fuel economy will require more innovation than ever, in particular social, political and organizational innovations that will bring about substantive changes to the nature and functioning of the economy, for one, liberating it from its growth addiction and avoiding a zero-sum game dystopian *Mad Max* scenario as energy and growth run out. As Murphy puts it in the quote at the top of this section, an economy successfully liberated from its growth addiction, and compatible with planetary boundaries, will not be "your father's" economy. It will also not be characterized by "your father's" innovation and growth. It will not be an anthropocentric story of innovation and growth. It will be a whole different ballgame. It is, alas, not a ballgame that most corporate innovation labs, university departments, or business schools, are fit for yet.

# 6    Concluding Remarks

The 2025 awarding of the Sveriges Riksbank Prize in Economic Sciences to Joel Mokyr, Philippe Aghion, and Peter Howitt marks the apotheosis of a seductive worldview: the belief that human ingenuity can drive economic growth to infinity and beyond. These scholars have mapped how scientific knowledge and "creative destruction" propel economic growth - the engine of capitalism - constructing a theoretical edifice on human ingenuity and innovation that counters the law of diminishing returns. However, the mathematical elegance of their growth models obscures a detachment from biophysical reality. The modern neoclassical paradigm offers not a scientific roadmap for the future, but a collection of anthropocentric fairy tales that jeopardize planetary habitability.

The central dogma of this economic creed is the "endless pursuit of economic growth." Neo-classical economics acknowledges the environmental damage caused by this pursuit - from

climate change to the breaching of planetary boundaries- but offers a magical trick: Directed Technical Change. The argument is comforting: through carbon taxes and subsidies, governments can steer innovation toward green technologies, decoupling GDP from environmental destruction. Moreover, this argument is also attractive, as it suggests massive opportunities for profit. This optimism rests on the precarious assumption of substitutability - the belief that all resources are fungible – and the belief that human innovation can always find a replacement for any scarce natural capital.

Evidence, however, suggests these beliefs are delusions. The lack of timely substitutability of renewables for fossil fuels is reflected in an energy addition, not an energy transition, where green energy simply piles on top of expanding fossil fuel consumption. The creative destruction championed by Aghion and Howitt is itself energy-intensive and wasteful, rendering the old obsolete and generating much waste in that recycling cannot match. Furthermore, the so-called dematerialization of the economy is a myth; the global material footprint tracks almost perfectly with GDP, confirming that absolute decoupling is not occurring. The transition to renewables, far from being weightless, requires a massive re-materialization of the economy, driving mining into vulnerable ecosystems, and failing to significantly reduce the threat to biodiversity.

Why do neoclassical economists cling to these mistaken beliefs? The answer lies in two profound blind spots: energy blindness and human exceptionalism.

Neoclassical theory suffers from severe "energy blindness," treating energy as just another input in a production function, to be substituted at ease. This view ignores historical reality: the Industrial Revolution was not merely an explosion of "ideas about ideas," as Mokyr suggests, but a fossil fuel revolution. It was the access to a "bolus of fossil sunlight" that endowed humanity with the "superpowers" to reshape the planet, expanding populations and economies exponentially. By attributing this growth solely to human innovation rather than to the exploitation of dense, non-renewable energy, economists fail to see that sustained

growth may be physically impossible as fossil fuels run out.

Compounding this error is a deep-seated human exceptionalism - the arrogant conviction that humans are separate from and superior to Nature. This "Arrogant Ape" mindset leads economists to declare that "there is really no such thing as a natural resource," implying that everything is a product of human technology and therefore infinite. This anthropocentrism reduces the natural world to a mere storehouse of commodities, blinding policymakers to the intrinsic value of biodiversity and the risk of ecological collapse. It fosters the dangerous illusion that the current generation does not owe future generations any specific ecological state because it can simply innovate its way out of extinction and collapse.

If humanity is to navigate the adjustment towards an inevitable post-growth future, it must discard the *Toy Story* economics that promises infinite expansion on a finite planet. This needs to include a fundamental repurposing of innovation, away from being merely a tool for sustaining capitalism and capital accumulation. The transition to a post-growth, post-fossil fuel economy will require more innovation than ever, in particular social, political, and organizational innovations that will bring about substantive changes to the nature and functioning of the economy: liberating it from its growth addiction, and avoiding a zero-sum game dystopian Mad Max scenario as energy and growth dwindles.

Ultimately, economics must evolve into an Earth Systems Science based on biocentric holism. Innovation must no longer be an instrument solely for firm profits and GDP growth; it must be redirected toward servicing Earth Systems and maintaining planetary habitability. This requires a post-growth economy that accepts biophysical limits and recognizes that the endless pursuit of economic growth is an outdated relic of the fossil-fuel era.

The defining challenge of the next twenty-five years is not for humanity to innovate its way to infinity, but to innovate the social, economic and political institutions necessary to flourish within the boundaries of the only home it has, the only inhabited planet in the universe that

it is aware of.

# Appendix A: Diminishing Returns

In economic growth models before Romer and Aghion-Howitt, such as those of Solow (1956), the problem of Diminishing Returns arise. This can be shown mathematically as follows.

Let the Cobb-Douglas production function be written as $y = k^\alpha$, where $y$ is output per laborer ($\frac{Y}{L}$), $k$ is capital per laborer ($\frac{K}{L}$) and $0 < \alpha < 1$, the share of capital in output.

Because $0 < \alpha < 1$ the first derivative, which is the marginal product of capital, is positive. The second derivative is however, $f''(k) < 0$. That it is negative, means that as more capital is used, return to capital will diminish.

# Appendix B: Increasing Returns

In contrast to diminishing returns in the Solow model, it can easily be illustrated mathematically that increasing returns holds in the Romer model with non-rival ideas.

The production function is now written to reflect that the economy's total capital stock $(K)$ is divided into a great number of varieties of intermediate goods, $x_i$. Final output is producing using total labor $(L)$ and all $(A)$ the varieties of these intermediate goods: $Y = L^{1-\alpha} \int_0^A x(i)^\alpha di$.

With the simplifying assumption that all capital equipment is produced in the average quantity $\bar{x}$, then it follow total capital in the economy is $K = A \times \bar{x}$.

Substituting $\bar{x} = \frac{K}{A}$ into the production function gives:

$$Y = L^{1-\alpha} \times A \times (\tfrac{K}{A})^\alpha = L^{1-\alpha} K^\alpha A^{1-\alpha}$$

To see that increasing returns indeed arises in this model, all the inputs - capital, labor and varieties (ideas) - in this production function are doubled.

Thus, $Y_{new} = (2L)^{1-\alpha} \times (2K)^\alpha \times (2A)^{1-\alpha}$

Factoring out the 2's and combining the powers of 2 in the above leads to:

$Y_{new} = 2^{(1-\alpha)+\alpha+(1-\alpha)} Y$

Simplifying:

$$Y_{new} = 2^{2-\alpha}Y$$

Since $\alpha < 1$ it means $2^{2-\alpha} > 2$. In other words, doubling all the inputs lead to a more the doubling of output. Returns are increasing.

# Appendix C: Eating Two Meals At Once - The Energy Addition

While there has been remarkable progress in the supply and consumption of renewable energy sources, what is important to mitigate climate change is a absolute reduction in fossil fuel consumption, responsible for $CO_2$ emissions. Due to various reasons discussed in section 3.3, because renewable energy is not substituting for fossil fuels well, it may be more accurate to refer to an energy addition rather an energy transition occurring.

Figure 7: Eating Two Meals at Once: Fossil Fuel and Renewable Energy Use
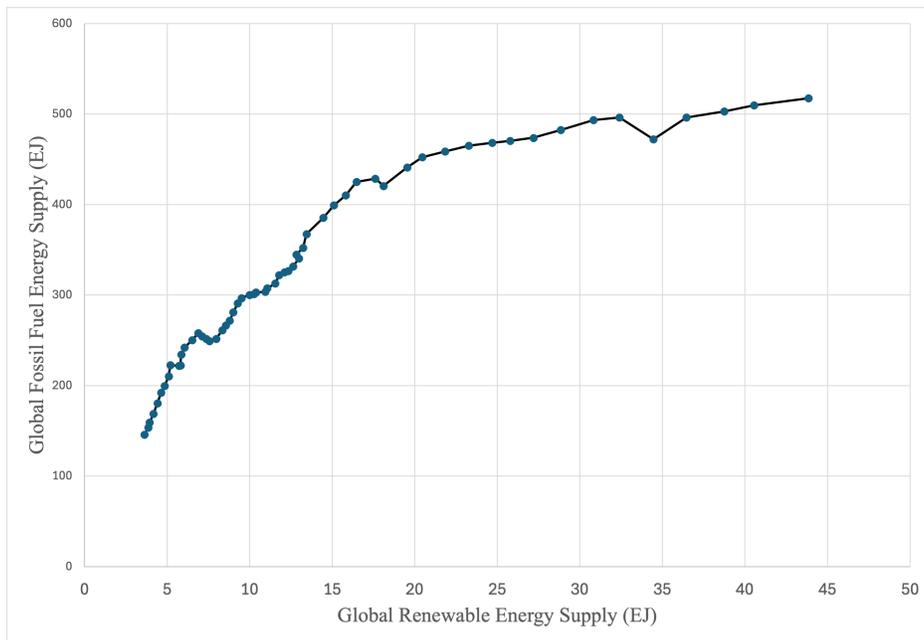


*Source*: Author's Compilation based on data from 2025 Energy Institute Statistical Review of World Energy

# Appendix D: Economic Growth Theory with Planetary Boundaries

According to Gries and Naudé (2025) a *sustainable economy* is defined by three elements.

The first element is that for an infinite time horizon the economy must not fall below a comfortable minimum level of physical consumption, i.e.:

$$c(t) = \frac{C(t)}{L(t)} \geqq c_{\min}, \quad \text{for } t = 0, .., \infty \tag{7}$$

The second condition is that a *sustainable growth path* of an economy must be non-negative, i.e.:

$$g_c(t) = \frac{\dot{c}(t)}{c(t)} \geqq 0, \quad \text{as systematic trend} \tag{8}$$

Equations (7) and (8) define the term sustainable economy and sustainable growth path with respect to the outcome for humans.

The third condition is the *Resource Conservation* condition which relates to the state of a planetary resource, including biodiversity. It also include resource stocks such as oil reserves or critical materials such as copper or lithium, or the ecosystem basis of a regeneration process for a renewable resource. Even more generally, it can also be a global or local ecological system - a planetary boundary - that needs to be maintained at a particular state or range. This state is defined as the permanently maintained state $S^{boundary}$.

It is not necessarily the initial state or natural state $S^{natural}$, but rather the state that must be maintained at a minimum to prevent triggering ecological tipping points. Therefore, all states between the natural state and the state that must be maintained are fundamentally feasible. E.g. for a natural stock of a finite material resource $S^{natural}$ this means that the available stock for human uses $\bar{S}$ is

$$\bar{S} = S^{natural} - S^{boundary},$$

and all extraction from now until infinity must not exceed this stock

$$\bar{S} = \int_{t=0}^{t=\infty} R_t^{ex} dt, \tag{9}$$

with $R_t^{ex}$ denoting the extracted material resource flow in period $t$.

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