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ABSTRACT

Melancholy Hues: The Futility of Green Growth and Degrowth, and the Inevitability of Societal Collapse

The economic expansion witnessed in the last 0,08% of modern human history is an anomalous event. It has been compared to a "rocket ship that took off five seconds ago, and nobody knows where it's going." This paper explores the destiny of this rocket ship. It shows that economic growth cannot continue indefinitely and critically reviews Green Growth and Degrowth as responses to planetary overshoot. It concludes that neither Green Growth nor Degrowth will stop overshoot. Moreover, Degrowth may worsen the environment, is a costly method to reduce carbon emissions, is a form of austerity for the working class, is redundant, and is politically infeasible. Finally, a third approach beyond Green Growth and Degrowth is outlined: acceptance of an inevitable societal collapse (as a feature, and not a bug, of complexity) and managing such a collapse to minimise harm, and to get rid of obsolete structures. This may lay the foundation for rebound growth, and a transition to a new kind of economy, which could be as qualitatively different from the current global economy as the industrial world differed from the hunter-gatherer world.

JEL Classification: O40, O33, D01, D64

Keywords: Green Growth, Degrowth, energy, ecology, development, collapse

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1 Introduction

> "Estimates put all biomass at about 2 trillion tons (including water content), and if that were spread uniformly across the Earth's surface it would stack to a height of 4 mm; a delicate gossamer film across planet Earth. Life on this planet is indeed thin and precious" (Murphy et al., 2021, p.3).

Astronomer Carl Sagan described the Earth as a "pale blue dot" reminding us that "on it everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives [...]- on a mote of dust suspended in a sunbeam" (Sagan, 1994). So far, we have found no evidence of live anywhere else in the universe. Life is "indeed thin and precious."

The presence of human civilization on this pale blue dot has been of almost negligibly small duration in the context of the age of the cosmos. The universe and planet Earth are estimated to be around 13,7 and 4,5 billion years old, respectively (Lehto et al., 2013). Compared to this immense time span, modern human ancestors only separated from so-called archaic human groups between 1 million and 300,000 years ago (Bergström et al., 2021). The expansion of humans across the globe started around 60,000 years ago (Bergström et al., 2021), and recorded history began even more recently - around 5,000 years ago (Lehto et al., 2013).

The economy that sustained human populations over the past 300,000 years were marked by different economic growth modes, in other words, different ways in which society was organized and technology[1] used to ensure survival, fitness and reproduction of the species. Economist and economic historians have identified three such economic growth modes: humans were first foragers, then became farmers and then industrialists. This corresponds to the hunter-gatherer, agricultural and industrial eras (Hanson, 2018, 2020).

[1] "Technology is the sum total of instrumentally useful culturally-transmissible information" (Bostrom, 2009, p.42).

Each successive era was marked by faster economic growth: whereas economies remained stationary during the hunter-gathered period, growth picked up during the agricultural era as food production and urbanization accelerated, from roughly 11,000 years ago. Then, during the industrial era, starting around 250 years ago, exponential and super-exponential economic growth rates were achieved - accompanied by similar growth in energy use and population (Johansen and Sornette, 2001). Over the past century, the size of the economy, 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).

Seen against the span of 300,000 years, the economic expansion witnessed in the last 0,08% of modern human history is clearly an anomalous event. It is an "unusual" time period (MacAskill, 2022). It has challenged religious scholars, philosophers, historians and others to ask what the future holds for humanity (Bostrom, 2009). Less prosaically, it has been exclaimed that humans "live on this rocket ship that took off five seconds ago, and nobody knows where it's going" (Wiblin and Harris, 2021).

One possibility is that humanity may continue its technologically-driven growth trajectory and expand into the galaxy, resulting in a long future wherein trillions of potential future human beings could live and lead meaningful lives. This implies that any reduction in the speed of technological advancement carries an "astronomical cost" : As calculated by Bostrom (2003, p.308) "the potential for approximately 10^{38} human lives is lost every century that colonization of our local supercluster is delayed."

Another possibility is that humanity may go extinct, or face a catastrophic disaster of such magnitude that the potential of humanity is permanently truncated (Bostrom, 2009; Ord, 2020). One risk is that human economic activity would overshoot planetary biophysical boundaries - and hence that an anthropomorphic environmental disaster will make Earth uninhabitable - or create conditions too hostile for civilization to continue as is. Some warn that this will cause a civilization collapse, akin to the collapse of Easter Island's society (Diamond, 2005; Kemp et al., 2022; Steel et al., 2022). Others see it causing severe curtailment of civilization that will not cause human extinction, but rather result in a *Great Simplification* - an involuntary and unplanned reduction in the "the size, complexity, and (literal) 'burn rate' of our civilization" (Hagens, 2020, p.14). Yet others, fearing a collapse, extinction or great simplification, want to pre-empt this by purposefully and in a managed and controlled fashion, reduce the scale of human economic activity - they want to *degrow* the world economy to avoid disaster or involuntary truncation of civilization (Kallis, 2011, 2021). All of these possibilities will mean that trillions of humans who could have lived, would never do so.

As such, much is at stake, and the current generation of humans may live in the most consequential era, the most important century (Karnofsky, 2021a; MacAskill, 2022). Whether humans can continue, or even accelerate, economic growth without triggering an environmental collapse until such time as it can expand into the galaxy, or whether humans will impose its own, political limits on growth, will determine where the "rocket ship" that is modern civilization, will be headed. Barring some exogenous extinction event such as a large meteor impact, of course.

This paper explores the destiny of this rocket ship that is modern civilization from the point of view of economic growth. In section 2 is it explained that the destiny of human civilization has been a topic of intense debate at least since the end of the 18th century. This debate has been characterised on the one hand by Malthusians, who take the position that economic growth is limited and that if it overshoots planetary boundaries, this may pose an existential risk, and on the other hand Cornucopians, who trust that technological innovation and human ingenuity will be able to overcome any planetary - physical - limits to economic growth.

Section 3 and sections 4.1 delves deeper into the Cornucopian position given the fact that human society has become detritovores, being greatly depended on fossil fuel energy. The use of its fossil fuel bonanza (a"carbon pulse"), and the economic growth it has enabled, is starting to overshoot planetary boundaries (section 3). The Cornucopian response is embodied in the approach of Green Growth (section 4.1), which is the mainstream global approach to enable continued economic growth without causing an overshoot and in particular to mitigate climate change. Section 4.1 critically analyzes Green Growth, and concludes that it may not be able to result in complete dematerialization and absolute decoupling. It may therefore not be able to stop an ecological overshoot and the risks that this will pose to human civilization.

Section 4.2 dissects the Malthusian response to green growth - the Degrowth Agenda. Degrowthers reject green growth, arguing that the only way to avoid resource depletion and an existential climate crisis is to make a concerted effort to scale down GDP - to "degrow" the economy. It was argued that Degrowth will also not be likely to stop an ecological overshoot. It would likely worsen the environmental predicament, and on top of this it is a costly method to reduce carbon emissions and may biol down in its implementation to a form of austerity for the working class. For these reasons, amongst others, degrowth as policy agenda is politically infeasible.

Finally, section 4.3 outlines a third approach beyond Green Growth and Degrowth: acceptance of an inevitable societal collapse (as a feature, and not a bug, of complexity) and managing such a collapse to minimise harm and get rid of obsolete structures. This may lay the foundation for *rebound growth*, and a transition to a new mode of "growth": which could be as qualitatively different from the current global economy as the industrial world was different from the world of the hunter-gatherer economy.

Section 5 concludes with a summary and some cautionary remarks.

2 The Malthusians and the Cornucopians

> "In the decades-old tensions involving environmental science, population, resource dynamics, and ecology, it's the Malthusians and the Cornucopians" (Gleick, 2020).

Whether human civilization will endure has been a topic of intense debate, at least since 1798, when the Reverend Thomas Malthus published his *Essay on the Principle of Population* warning that progress is inherently limited. Two-hundred and twenty years later, Harvard psychologist Steven Pinker published *Enlightenment Now: The Case for Reason, Science, Humanism, and Progress*, arguing that progress is not inherently limited, and documenting how reason, science and humanism trumped Malthus's pessimism (Pinker, 2018). He also argued that although progress is not inherently limited, it is not automatic, or guaranteed[2]: "if we apply knowledge to increase human flourishing, then progress may happen. (If we don't, it won't.)."

In the following sub-sections the decades old tension between these positions in the intervening two-hundred and twenty years between Thomas Malthus and Steven Pinker, the two-hundred and twenty years that also saw the most substantial progress in human population and human wealth ever, are discussed. It includes the rise of neo-Malthusianism in the mid-20th century, and the response of Ester Boserup, Julian Simon and other "cornucopians" as they have been labelled, who assume the position that "people are resource creators, not resource destroyers" (Aligica, 2009, p.73). Implications for the future of economic growth and technological development are elaborated.

[2] Pinker, as quoted in an interview with Cook (2018).

2.1 The (Neo) Malthusians

In *Essay on the Principle of Population*, Malthus argued that civilisation's progress is limited by fixed natural resources, such as land. Because "the power of population is so superior to the power of the earth to produce subsistence for man," it is inevitable, he argued, "that premature death must in some shape or other visit the human race" (Malthus, 1798, p.44) In the preface to his essay, he acknowledged his deep pessimism, and referring to himself in the third person declared

> "The view which he has given of human life has a melancholy hue, but he feels conscious that he has drawn these dark tints from a conviction that they are really in the picture, and not from a jaundiced eye or an inherent spleen of disposition" (Malthus, 1798, p.vii)

It is no coincidence that Malthus' essay was published in 1798: it was a time of strong reaction against the rationalism and secularism of the European Enlightenment. Only a few decades earlier the Enlightenment had inspired the idea that human progress is possible - as against the age-old notion to leave human fate in the hands of Providence.[3] By 1798 Enlightenment ideas had led to the 1st Industrial Revolution through a spate of institutional and technological innovations, including the steam engine (Mokyr, 2016). Progress did not come equally to all, however, and threatened vested interests. The French Revolution, which started out with high Enlightenment ideals, turned out horribly.

In 1811 the "Luddites," fearing mass job losses, turned in anger on technologies such as threshing machines and power looms, destroying many of these in public protests (Naudé and Nagler, 2015). Half a century before Karl Marx's reacted in his Communist Manifesto

[3] An important contribution to the idea of progress was made by A.R.J Turgot, the French economist who was the "founder of classical economics" (Brewer, 1987). According to Nisbet (1975, p.215) "What Turgot had to say about the advancement of human society, from its most primitive state through the long vistas of evolutionary time to the contemporary world, falls among the most impressive intellectual contributions of the whole eighteenth century."

against the impacts of the Industrial Revolution, the Romantic Poets were amongst the first critics of capitalism (Löwy, 1987). Romantic poet John Keats lamented that scientists were "unweaving the rainbow" (Dawkins, 1998). Malthus's melancholy hued view of human life was thus born at the dawn of Romanticism, with its scepticism of science and longing for a pre-industrial age.

In the 1960s and 1970s, following two World Wars, the Great Depression, a Cold War, and the proliferation of nuclear arms, Malthus' melancholy hue would seep back into economics and the public consciousness. Neo-Malthusianism was born. In 1960, Von Foerster et al. (1960) in a paper in *Science*, predicted that Doomsday would occur on Friday 13th November 2026, because given up until then super-exponential growth rates in population, extrapolation indicated that global population would approach infinity by 2026. And in 1968 Ehrlich (1968, p.11) predicted that, as a result of population growth, "In the 1970s hundreds of millions of people will starve to death [...] At this late date nothing can prevent a substantial increase in the world death rate."

Fortunately, Malthus, Von Foerster and Ehrlich underestimated the power of ideas - of innovation in technology and in governance institutions. Premature death did not visit the human race. Consider for instance that while in the 1960s, around 50 people per 100,000 died per decade due to famine: by the 2010s it was down to 0,5. The key technological innovations that have driven food production include innovations in fertilizer production and use, and innovations that allowed international trade to expand.

Before the 20th century, agricultural production was limited by the availability of manure - virtually the only fertilizer available. In the 19th century, guano from Peru became such a vital source of fertilizer for the USA and Europe, that various "guano wars" were fought in Latin America (Brazeau, 2018). With the invention and commercialization of synthetic nitrogen between 1908-1913 by Fritz Haber and Carl Bosch, by a process that converts nitrogen in the air into ammonia, the world obtained access to a plentiful source of fertilizer

(Smil, 2004). It has been claimed that without the Haber-Bosch process that "almost half the world's population would not be alive today" (Harford, 2017). Erisman et al. (2008, p.636) estimated[4] "by 2000, nitrogen fertilizers were responsible for feeding 44% of the world's population. Our updated estimate for 2008 is 48% - so the lives of around half of humanity are made possible by Haber-Bosch nitrogen."

As mentioned there was a second, complementary innovation that has magnified the impact of synthetic fertilizers. This is the modern globalised economy which is the result of process and business model innovations in the rules, institutions and conventions underpinning trade. International trade, as Ridley (2020) described it, allows all countries and regions of the world to "specialise in production and diversify consumption." Coupled with transport innovations such as cold storage, the shipping container, modern ICT driven logistics and port handling systems, food can move from the farm in one country to the fork in another rapidly - in a matter of hours in some cases. International trade allows countries to consume more food than their ecological systems can produce (Kissinger and Rees, 2009).

In sum, technological innovations in fertilizers and international trade have brought abundant and cheap food to households across the world, fuelling economic development and population growth. This in turn generates further innovation and economic growth. In the 1960s, while Paul Ehrlich was predicting an overpopulated planet about to starve to death, Cornucupians such as Ester Boserup and Julian Simon argued that population pressure drives innovation (Boserup, 1965, 1981; Simon, 1982, 1996). It is now accepted, also in the light of Paul Romer's elaboration of the mechanisms of growth, that population is indeed a driver of innovation (Romer, 1990). This is because innovation depends on ideas, and the more people there are, the more researchers and tinkerers there are, and the better and faster they get transmitted (Mokyr, 2007).

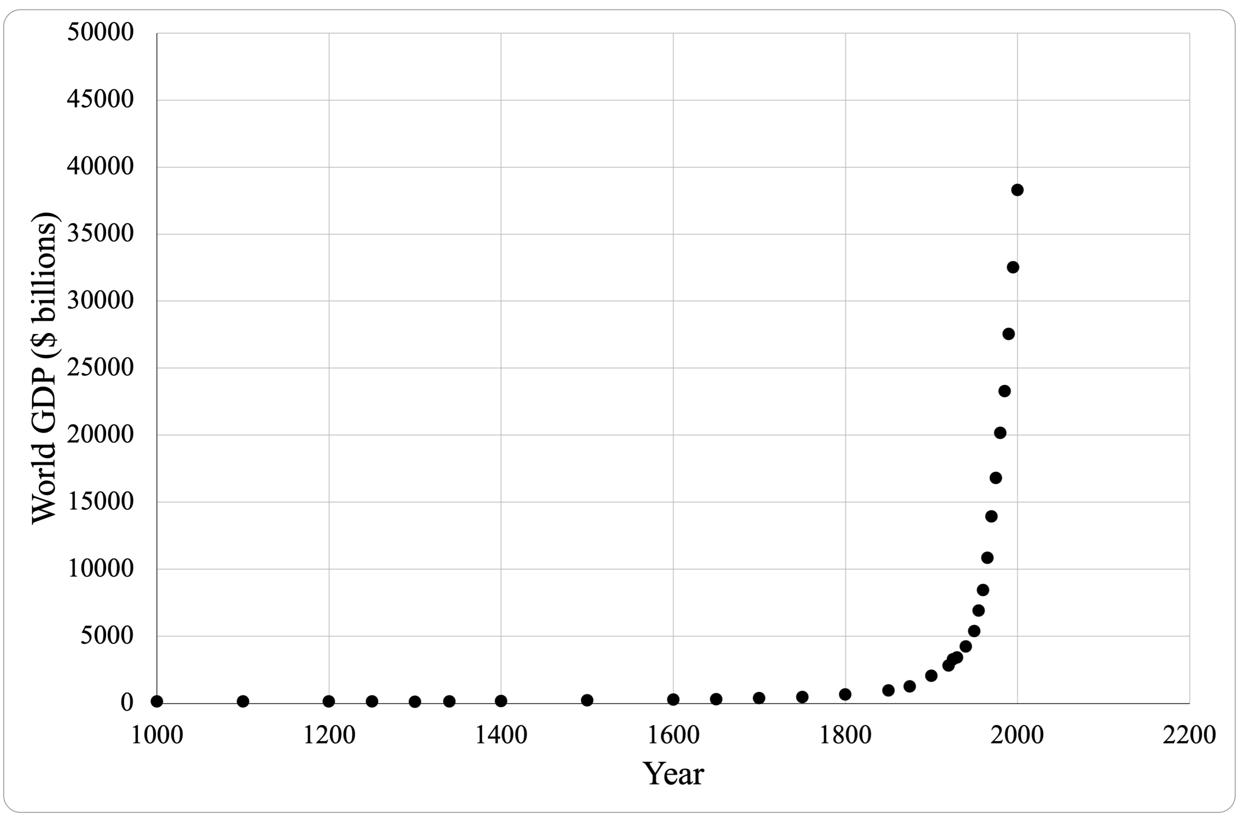
[4]These estimates and conclusions have not gone unchallenged - see e.g. And Benanav (2020) has pointed out that millions of farm workers' jobs were made redundant, and urbanisation fostered, as a result of synthetic nitrogen which made farming more productive.

2.2 The Cornucopians

The consequence of escaping the Malthusian population trap, and positive feedback effects between population growth, new ideas (which lead to new technologies), and the spread of ideas through international trade resulted in historically unprecedented economic growth over the past two centuries.

Figure 1 depicts world GDP over the past millennium. It can be seen that GDP growth has been exponential and accelerating over the past three centuries. The average annual world GDP growth rate over the past century alone was around 2%. At such a rate, the world economy doubles in size every 35 years. A graph of GDP per capita would look similar.

Figure 1: World GDP, 1000 - 2000



Source: Author's compilation based on data from DeLong (1998, pp.7-8).

As a result of this economic transformation, human life never had it materially so good as the current generation has it (Pinker, 2018; Ridley, 2011). Barack Obama made the point that "if you had to choose any time in the course of human history to be alive, you'd choose this one" (Obama, 2016).

By 2020, world GDP per capita was, at an estimated US$5400, around 5600% higher than what it were around 10,000 years before, during the Greenlandian Age, (Syvitski et al., 2020). Population and energy consumption growth closely tracked this growth in GDP: for instance population growth accelerated from an average 0,01% per annum during the Greenlandian Age to 1,6% per year over the past 70 years, and per capita energy consumption from 6,2 GJ/y to 61 GJ/y between the same periods (Syvitski et al., 2020). Humans are healthier, wealthier and safer than ever before, on virtually all human development indicators (Landes, 1999; Mokyr, 2016; Pinker, 2018; Ridley, 2011).

According to economic growth theory - endogenous and semi-endogenous growth - the fundamental driver of economic growth is ***ideas*** (Romer, 1986, 1987, 1990). Ideas (or knowledge) are generated by people (R&D workers) and commercialized by entrepreneurs bringing new technologies to the economy - if they have the incentive to benefit from such commercialization (Jones, 1995). Because ideas are non-rival in use, entrepreneurs would only face an incentive to exploit new ideas if these could also be made excludable[5] - and there is a sufficient population to provide a large enough market (Romer, 1990).

The more people there are, the more ideas are generated, and the faster economic growth from the technologies based on these new ideas (Davidson, 2021). Latter can sustain a larger population, creating a population-ideas feedback loop, which explains the simultaneous exponential growth in GDP and population over the past 1000 years (Lee, 1988; Kremer, 1993; Davidson, 2021) New ideas, moreover, emerge from existing ideas: a new idea can be the combination of two older ideas. This process is known as combinatorial innovation (Weitzman, 1998; Koppl et al., 2019). It is almost limitless - the world will never run out of

[5] This justifies the use of legal instruments such as intellectual property (IP) rights and patents (to trade these IP rights).

ideas. As Romer (2019) explains

> "The periodic table contains about a hundred different types of atoms. If a recipe is simply an indication of whether an element is included or not, there will be 100 x 99 recipes like the one for bronze or steel that involve only two elements. For recipes that can have four elements, there are 100 x 99 x 98 x 97 recipes, which is more 94 million. With up to 5 elements, more than 9 billion. [...]. Once you get to 10 elements, there are more recipes than seconds since the big bang created the universe."

Growth via ideas can follow the pattern as depicted in Figure 2: a long period of slow growth, followed by a sharp, hockey-stick like upturn, into accelerating (super-) exponential growth (Jones, 2001; Clancy, 2021) and mathematically if not physically, potential hyperbolic growth (Aleksander, 2019; Sandberg, 2013). What is at play here is a positive feedback loop between ideas - technology - population - ideas.

This accelerating exponential economic growth from new ideas cannot, however, be sustained and will not reach infinity, because either population growth will slow down - a demographic transition (Aleksander, 2019), and/or R&D funding will not keep up investing in commercializing each and every new idea (Weitzman, 1998), and/or research teams run our of cognitive resources (Agrawal et al., 2018). The consequence is that growth would settle into constant exponential growth, as has been the case for much of the past century (Weitzman, 1998; Clancy, 2021).

As long as total population remains constant, however, the economy can continue growing at a constant rate, albeit slower than before, as the stock of new ideas generated by that population grows at constant exponential rate (Kremer, 1993; Jones, 2022). Moreover, arguments that the world will run out of natural resources and thus limit growth have been dismissed by some, based on the argument that because ideas (technology) transforms all resources, "there's really no such thing as a natural resource. All resources are artificial. They are a product of technology" (Crawford, 2022). See also Pooley and Tupy (2018).

The conclusions that the economy can continue to grow indefinitely at a constant rate and that there are no such things as natural resources have, however, been questioned: it implies an explosion in the *size* of the economy after some time and, even if growth is decoupled from most material inputs, it would still generate waste-heat. In section 3 below this limit to growth is discuss in greater detail.

For the moment however, if population growth turns *negative*, total population will decline, the flow of new ideas will stagnate, and economic growth will eventually collapse. In recent decades, with populations in more and more countries in decline (in most advanced economies, fertility rates dropped to below replacement level in the 1970s and 1980s) the prospects of a real population decline, and an eventual "Empty Planet" has arisen (Bricker and Ibbitson, 2020; Jones, 2022).

Furthermore, research productivity and innovation in advanced western economies have also been declining - ideas have been "getting harder to find" (Bloom et al., 2020; Jones, 2009). New ideas, as measured by patents and scientific papers have also become less disruptive over time (Park et al., 2023). Huebner (2005) finds that the global rate of innovation peaked in 1873.

As a result of declining population growth rates and declining research productivity and innovation in an increasing number of countries, economic growth in these countries has been slowing down. It has been described as the Great Stagnation (Cowen, 2010) and Ossified Economy (Naudé, 2022a). Jones (2022, p.3), using models with both exogenous and endogenous population growth illustrates that "*when population growth is negative, both endogenous and semi-endogenous growth models produce what we call the Empty Planet result: knowledge and living standards stagnate for a population that gradually vanishes.*" He calculates that with a 1% annual decline in population, that world GDP growth would drop to zero somewhere between 85 to 250 years (Jones, 2022, p.9).

The "Cornucopian" position to the seemingly inevitable decline in economic growth due to a decline in population growth is that technology may make up for the decline in human population. Specifically, Artificial Intelligence (AI). Since around 2011/2012 AI systems based on Deep Learning (DL) has made rapid progress, to the extent that a growing number of scientists expect that the development of an Artificial General Intelligence (AGI), which would be an intelligence on par with or exceeding human intelligence, is imminent (Bostrom, 2014; Naudé, 2021). Auch an AGI may avert an economic growth collapse and herald in a new "mode" of economic growth, making super-exponential economic growth possible, according to some (Hanson, 2001). This is because an AGI may substitute for humans - thus lack of population ceases to be a constraint - and AGI may improve R&D productivity dramatically, by being an innovation in the manner of innovation. Thus, by overcoming population constraints, the burden of knowledge and the challenge of finding new ideas, AGI will unblock an ideas-lock on economic growth, causing economic growth rates to explode: these would be annual growth in Global World Production (GWP) of 30% - at this rate, the size of the world economy would double every two years, as opposed to the current doubling every 35 years (Davidson, 2021).

At the core of the expectation that an AGI will unleash a flood of growth-enhancing new ideas is the belief that AGI is not just a tool for making existing business models more efficient and competitive, but an innovation in the method of innovation (IMI) (Agrawal et al., 2019). It will be a General Purpose Technology (GPT) that will alter the "playbook" of innovation (Cockburn et al., 2019).

What if Deep Learning does not scale up to an AGI? A modern day Cornucopian may point out that an AGI is not necessary to accelerate economic growth - other digital technologies may also bring this about. One such technology will be the creation of digital people, or

Ems, who could possible be the result of whole brain emulations. Hanson (2018, p.7) define a whole brain emulation (em) as resulting "from taking a particular human brain, scanning it to record its particular cell features and connections, and then building a computer model that processes signals according to those same features and connections." Once "*Ems*" - digital people - are possible, they will quickly dominate the economy. They can be (almost costlessly) copied and they are much faster than humans. According to Karnofsky (2021b) Ems could generate "unprecedented (in history or in sci-fi movies) levels of economic growth and productivity."

The digital people - "*Ems*" - will "largely work and play in virtually reality" at subsistence levels in a hyper-fast economy to produce the computer hardware and the supporting infrastructure for the virtual reality. Economic growth is so fast - because of all the billions and billions cheap digital people and the combinations of new ideas that can generated very rapidly - that the world economy could double every month (as against the current 35 years it takes to double.[6]As described by Hanson (2018, pp.13,438)

> "The em world is richer, faster-growing, and it is more specialized, adaptive, urban, populous and fertile. It has weaker gender differences in personality and roles, and larger more coherent plans and designs [...] To most ems, it seems good to be an em [...] if the life of an em counts even a small fraction as much as does a typical life today, then the fact that there are so many ems could make for a big increase in total happiness and meaning relative to our world today."

In a sense, Hanson (2018) provides the ultimate description of human society and economy in a future "Metaverse."[7]

[6]According to Hanson (2000, p.18) one may think that such growth rates where the economy doubles every month - or even every two weeks are "too fantastic to consider, were it not for the fact that similar predictions before previous transitions would have seemed similarly fantastic."

[7]The label "Metaverse" comes from Neal Stephenson's 1992 science fiction novel Snow Crash and has come to refer to virtual and augmented realities enabled through the internet and as found for example in multiplayer online games (Knox, 2022).

In this Em-Metaverse humans end up as a dying-out minority "mostly enjoying a comfortable retirement on their em-economy investment" (Hanson, 2018, p.9). According to Alexander (2016) the retired humans will "*become rarer, less relevant, but fantastically rich - a sort of doddering Neanderthal aristocracy spending sums on a cheeseburger that could support thousands of ems in luxury for entire lifetimes.*"

In conclusion, Cornucopians are tech-optimists. They see economic growth as the beneficial outcome of growth in new ideas (technologies). Because these ideas (technologies) are unlimited, economic growth is essentially unlimited. Even if populations decline and human research and science stagnate, these could be overcome by establishing new modes of growth, just as in the past agriculture introduced a new mode of growth for foragers, and just as the industrial revolution introduced a new growth mode for farmers. Eventually in these new modes of future growth, humanity's descendants will be radically different from humans alive today - we may be transcended by digital, AI-merged sentient beings, whose eventual future population will vastly outnumber all humans that have ever lived.

3 What to Do About the Detritovores?

> "[...] humans have become detritovores, organisms that live off the dead remains of other organisms" (Cobb, 2015).

There are two fundamental problems with the tech-optimists' hope in never-ending economic growth and eventual transhuman future described in the previous section. The first is that while ideas of an AGI and digital people (Ems) are not violating laws of physics, they still are to be found only in the realms of science fiction. Current human civilization lacks the knowledge and the economics to realise these. The second is the assumption that there are no natural resources (or materials) scarcity, given the overriding importance of ideas (technology).

The first problem - how far humanity is from being able to develop an AGI or Ems, or whether it is at all possible given humans' intellectual and material resources, is a topic that falls outside the scope of the present paper.

The second problem returns the attention to the material resources needed to sustain economic growth. In this section, two main aspects or themes in the debate between the neo-Malthusians and the Cornucopians will be discussed. The first is the idea that human civilization is through continued economic growth overshooting planetary boundaries, and that this poses an existential threat - threatening civilization collapse (section 3.1). The second is the idea of a carbon pulse as being the main mechanism that has been driving exponential economic growth (as shown in Figure 1) over the past two hundred years, and what this implies for the continuation of growth (section 3.2).

3.1 Overshooting Planetary Boundaries and Societal Collapse

In section 2.1 it was discussed how Malthus, and later neo-Malthusians, argued that land, and hence food production, was fixed and would in the face of population growth eventually result in famine. In such a Malthusian world, economic growth is limited by resources - land and food - and other material inputs. Malthus and the neo-Malthusians, we now now, underestimated the role of technology and population growth (as was discussed in section 2.2) and consequently made many wrong predictions of food and other resources running out[8]. The most famous of these were by the biologist Paul Ehrlich who made a bet with economist Julian Simon in 1980 that five key mineral resources - chromium, copper, nickel, tin, and tungsten - would run out, and as as they do, their prices would increase. Ten years later, the prices of all five resources has fallen, and Ehrlich had lost his bet (Sabin, 2013).

As a result, and still believing that material resources are ultimately finite, much of the

[8] See for instance Perry (2016).

concern of latter-day neo-Malthusians have been on systemic scarcity - rather than scarcity of specific resources. They often refer to the finite nature of an Earth System[9] that create conditions or carrying capacities - and boundaries - within which the world economy must function.

While technological solutions may alleviate individual resource scarcities, and moreover improve the efficiency of resource use, the overall impact on the planet's ecosystem will inevitably increase with economic growth, to the point where continued growth would *overshoot* the capacity of the planetary ecosystem.[10] The term overshoot can be defined as "the tendency of the system to generate flows larger than the carrying capacity", where carrying capacity is "the maximum flow of energy that the system can maintain for a long time " (Bardi, 2020, p.34).

Catton (1982) was one of the first to stress the problem of *overshoot*. In an imaginary interview with the Reverend Thomas Malthus, he has Malthus describe how overshoot comes from overuse by humans of the environment's supply sources, activity spaces and disposal sites:

> "Malthus: I would point out that all creatures have to use their environment in three ways - as a supply source (S), as activity space (A), and as a disposal site (D). Use the acronym, SAD, to focus on a sad fact — people depend far more than most of them realize on other (living and nonliving) components of an ecosystem, not only to supply their subsistence requirements but also to absorb and recycle everything human living gives off. Overuse of a country or a world by humans inevitably begins breaking down the system, ultimately hurting its

[9] "The Earth System is defined as the integrated biophysical and socioeconomic processes and interactions (cycles) among the atmosphere, hydrosphere, cryosphere, biosphere, geosphere, and anthroposphere (human enterprise) in both spatial — from local to global—and temporal scales, which determine the environmental state of the planet within its current position in the universe. Thus, humans and their activities are fully part of the Earth System, interacting with other components" (Rockström et al., 2009, p.24).

[10] The term "ecosystem" was coined by Tansley (1935).

human users" (Catton, 1998, p.436).

Overshooting the Earth System thus means that the supply sources, activity spaces and disposal sites are overused (Catton, 1982, 1998). According to Rees (2021) overshoot is "a meta-problem, the cause of most so-called 'environmental problems' including climate change [...]. Climate change is therefore only a symptom of overshoot, implying that only reducing carbon emissions, the cause of anthropogenic global warming, will not solve all environmental problems."

The neo-Malthusian problem has become one, not of scarcity of some particular resource, food, or of too much carbon emissions, but of the entire human "*ecological footprint*" which is too large, and causes an overshoot. The term ecological footprint was introduced by Wackernagel and Rees (1996). Hoekstra and Wiedmann (2014, p.1114) describe an ecological footprint as an indicator "of human pressure on the environment and form the basis for understanding environmental changes that result from this pressure (such as land-use changes, land degradation, reduced river flows, water pollution, climate change) and resultant impacts (such as biodiversity loss or effects on human health or economy)." They distinguish seven types of ecological or environmental footprints: land, energy, water, materials, carbon, nitrogen, and biodiversity footprints - and state that the carrying capacity of the Earth system in terms of carbon, energy, land, material, and water has been exceeded (Hoekstra and Wiedmann, 2014).

Measuring the carrying capacity of Earth systems and determining whether a particular environmental footprint is exceeding this, which would signal overshoot, has resulted in the development of the concept of "*planetary boundaries*" (Rockström et al., 2009). Nine planetary boundaries have been identified. These are climate change, ocean acidification, ozone depletion, nitrogen and phosphorus cycles, global freshwater use, land systems change, rate of biodiversity loss, atmospheric aerosol loading and chemical pollution (Rockström et al., 2009; Steffen et al., 2015).

Rockström et al. (2009) estimated that at least three of the planetary boundaries have been exceeded: "for climate change, rate of biodiversity loss, and changes to the global nitrogen cycle" (Rockström et al., 2009, p.1). While in itself problematic, the bigger danger is that the breach of only a few planetary boundaries can potentially lead to the entire Earth system tipping, resulting in "abrupt global environmental change." This is due to the interdependence between the various planetary boundaries and non-linear feedback effects between them, which implies that there could be potential *climate tipping points*,[11] or thresholds, which if exceeded, may cause the tipping of the Earth system into a state which would be detrimental to civilization and life (Rockström et al., 2009; Lenton et al., 2019; Ritchie et al., 2021). It threatens societal collapse, and even poses an existential risk (Richards et al., 2021). "The prospect of civilization collapse has now entered the mainstream of scientific and popular discourse" (Gowdy, 2020, p.2).

Climate change, which through a cascade of breached tipping points could cause a mega-hothouse, is considered an existential threat for several reasons (Kemp et al., 2022). One is that global warming directly threatens agriculture and food supply. According to Gowdy (2020, p.2) "Climate models indicate that the Earth could warm by 3°C-4 °C by the year 2100 and eventually by as much as 8 °C or more. This would return the planet to the unstable climate conditions of the Pleistocene when agriculture was impossible." He refers here to the fact that climates have been comparatively stable over the past 12,000 years (the

[11] A tipping point is "a critical threshold at which a tiny perturbation can qualitatively alter the state or development of a system" (Lenton et al., 2008, p.1). Earth systems wherein tipping points could occur to trigger abrupt climate change include the Arctic Sea-Ice, the Greenland Ice Sheet (GIS), the West Antarctic Ice Sheet (WAIS), the Atlantic Thermohaline Circulation (THC), the El Niño–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). See also Lenton et al. (2019). Even if the world manages to keep global warming in the range of 1,5 degrees to 2 degrees as per the Paris Agreement of 2015, six climate tipping points may still be triggered, such as the collapse of the Greenland and West Antarctic ice sheets, the die-off of coral reefs, and the melting of permafrost (Armstrong McKay et al., 2022). There is, to be noted, much uncertainty about tipping points, given the complexity of modelling non-linear interdependencies in a complex system (Wunderling et al., 2020).

Holocene) which allowed human societies to switch from hunting and gathering to large scale farming.

A second reason why breaching planetary boundaries could pose an existential threat is that environmental change is implicated in all past mass extinction events (Kemp et al., 2022). Song et al. (2021, p.1) points out that mass species extinction[12] in the past have been associated with tipping points in climate change of >5.2 degrees Celsius magnitudes. Bradshaw et al. (2021) and Dirzo et al. (2022) consider the current rate of biodiversity loss to be so significant that it signifies that humans have triggered the planet's sixth mass extinction. A growing number of authors and scientists indeed warn that a sixth mass extinction may be beginning or imminent - e.g. Barnosky et al. (2011), Cowie et al. (2022), Kaiho (2022), Kolbert (2014) and McCallum (2015).

Other reasons that have been cited for the breaching of planetary boundaries as existential threat, is that environmental collapse, say due to climate change, or water scarcity, or biodiversity loss, could cause global conflict, could increase vulnerability to other shocks, cause systemic crises, and reduce humanity's ability to recover from other catastrophes (Kemp et al., 2022).

Thus, economic growth has lead humanity to overshoot the capacity of the Earth system, and this poses an existential risk. This is why Rees (2021) has described overshoot as "ultimately a fatal condition."The existential risk is increasing given that the extent of overshooting is increasing[13] and shows no sign of diminishing, as measured for instance by the Material Footprint (MF) / Raw Material Consumption (RMC) indicator (Fanning et al., 2022; Giljum et al., 2015; Wiedmann et al., 2015).

[12] A mass extinction is defined as when "the Earth loses more than three-quarters of its species in a geologically short interval"(Barnosky et al., 2011, p.51). There have been five mass extinctions in the past - respectively 444, 372, 252, 201, and 66 million years ago (Cowie et al., 2022; Kaiho, 2022).

[13] In 2022, *Earth Overshoot Day*, "when humanity has used all the biological resources that the Earth regenerates during the entire year" fell on 28th July. In 1971 it fell on 25th December.

Despite these existential dangers “existential risk is not a narrative or term that has been widely adopted or further developed by the climate change research community. Neither the concept of existential risks nor theterm ‘existential’ was used in the IPCC 5th Assessment Report (AR5), nor in the IPCC Special Reports of the 6th Assessment Cycle” (Huggel et al., 2022, p.4). And climate catastrophe remains “relatively under-studied and poorly understood” (Kemp et al., 2022, p.1).

Bradshaw et al. (2021, p.1) concludes therefore perhaps not unsurprisingly that “future environmental conditions will be far more dangerous than currently believed. The scale of the threats to the biosphere and all its lifeforms — including humanity — is in fact so great that it is difficult to grasp for even well-informed experts.” They envisage a “ghastly” future for humanity.

Others have also concluded that the collapse of global society is inevitable but that humanity should “embrace it” and not resist it (which will just make the final collapse worse) and prepare for a post-growth, simplified future (Bardi, 2017; Brozović, 2023; Hagens, 2020; Odum and Odum, 2001). For Gowdy (2020, p.8) the other side of collapse may be something to look forward to, since “we became human as hunters and gatherers and we can regain our humanity when we return to that way of life.”

> The gap between the Cornucopians and the Malthusians has never been as wide: between the one group envisioning digital future humans colonizing the galaxy and enjoying super-exponential growth, and the other envisioning collapse and a return to a foraging existence.

3.2 The Carbon Pulse

In section 2.2 of this paper the Cornucopian (tech-optimists) hope in never-ending economic growth and eventual transhuman future was described. One problem with this hope is that it is based on the assumptions that there are fundamentally no natural resources (or materials) scarcity, given the overriding importance of ideas (technology), which would dematerialize production and consumption, and find appropriate substitutes when materials become scarce.

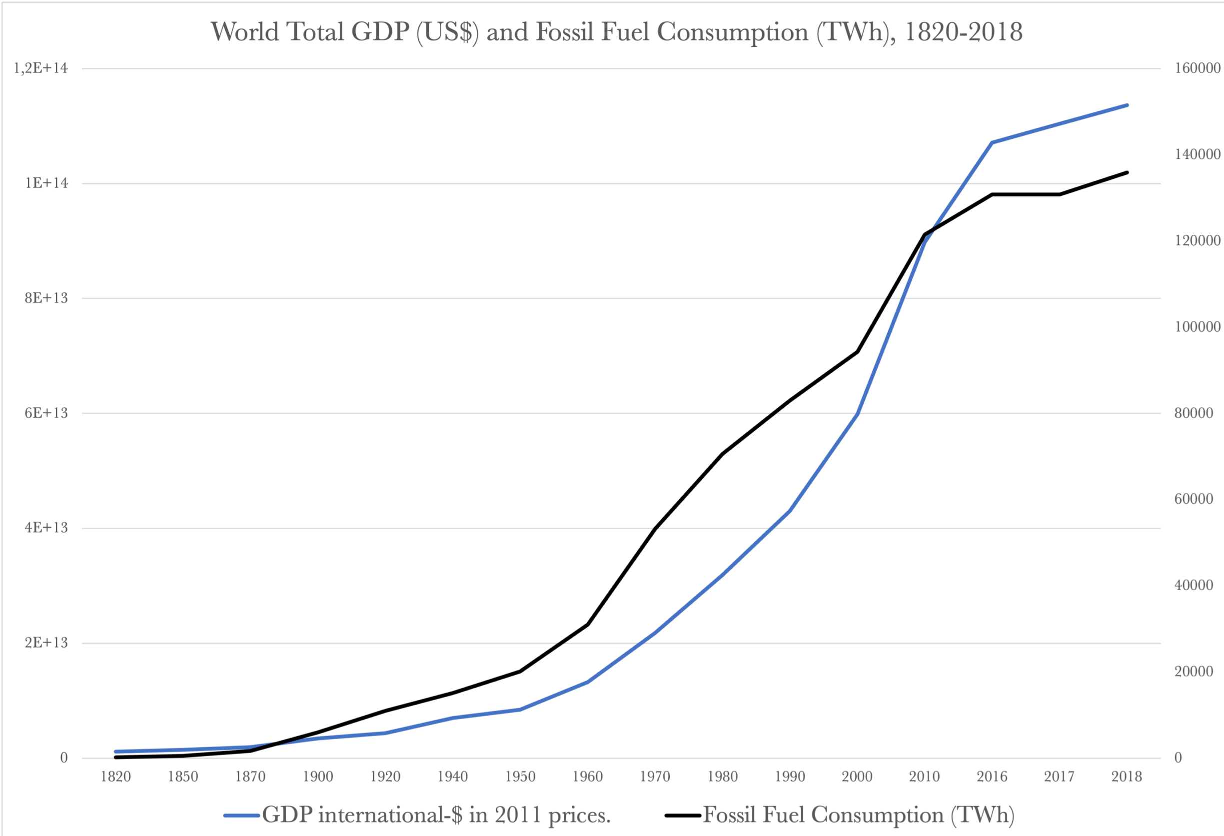
The blind-spot in the case for unlimited growth as set out in section 2.2 is that it ignores or trivializes the role of energy - in particular of fossil fuel energy. The Industrial Revolution which started in the late 18th century in the UK was driven by technological and institutional innovations, including greater trade, but also by cheap, and easily accessible coal[14] which powered the "dark satanic mills" of industry as poet William Blake described it (Clark and Jacks, 2007; Pomeranz, 2000; Wrigley, 2010). The industrial revolution was an energy revolution (Wrigley, 2011).

From 1861, when the first commercial oil-well was drilled in the USA, crude oil was added to the fossil fuel bonanza that would facilitate exponential rates of global economic growth. Figure 2 shows the close relationship (the correlation is 0,97) between world GDP and fossil fuel consumption since 1820.

By around 2021/2022, 82% and 62% respectively of total primary energy and electricity consumption in the world were supplied by fossil fuels. This is responsible for around 87% of all global greenhouse gas emissions worldwide - which drives global warming. Thus economic growth, which requires energy as input, and which also results in goods and services that stimulates further demand for energy is very closely associated with the exponential growth in GDP depicted in Figures 1 and 2.

[14]By 2015, more than 200 years after the start of the industrial revolution, coal was still providing 20% of energy used in the UK (Curtis, 2015).

Figure 2: World GDP and Fossil Fuel Consumption, 1820-2018

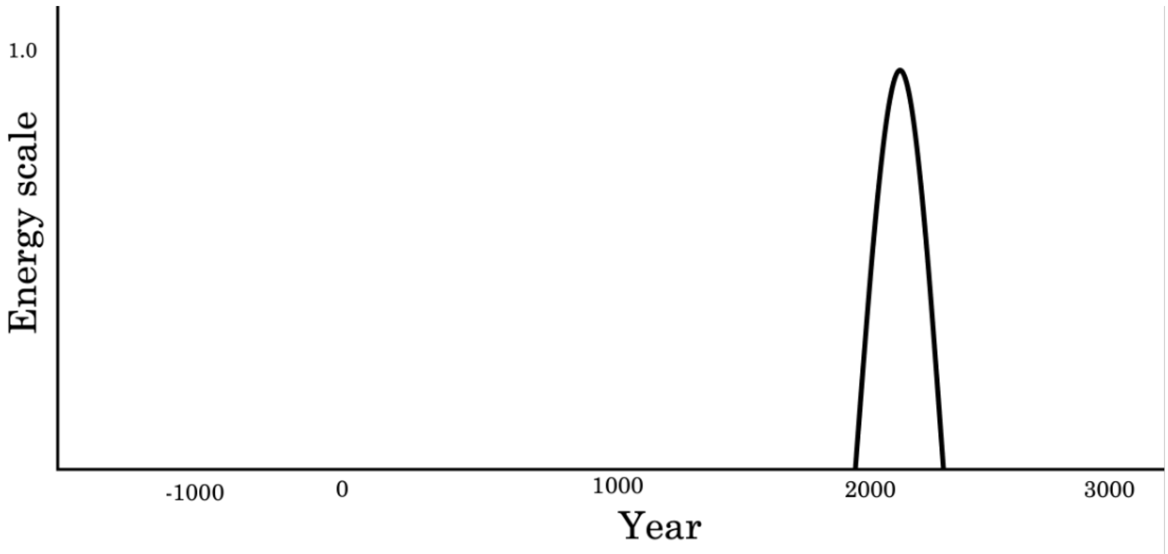


Source: Author's compilation based Our World in Data and the bp Statistical Review of World Energy.

The problem is twofold. One is the unintended consequences that the greenhouse gas emissions from using fossil fuels contributed to global warming. The potential consequences were discussed in section 3.1. A second is that fossil fuels are finite resources. As put 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." Because of the "addiction" of humanity to this bolus of fossil sunlight, Catton (1982) called humans *detritovores* : "organisms that live off the dead remains of other organisms" (Cobb, 2015).

Over the very long-run, the discovery of this "bolus of fossil sunlight" can be seen as a "carbon pulse", described by Hagens (2018) as "a one time bolus of fossil productivity injected into the human ecosystem" and whose singular, once-off appearance over time can be depicted as in Figure 3.

Figure 3: The Carbon Pulse: A Bolus of Fossil Sunlight in Long-Term Perspective



Source: Author's compilation based on Murphy et al. (2021, p.2), Hagens (2018) and Hagens and White (2021, p.260).

The bolus of fossil sunlight has provided the average inhabitant of the Earth "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" (Smil, 2022, p.19). Murphy et al. (2021, p.2) observes that "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."

To provide a perspective on the magnitude of the contribution of fossil fuel energy to GDP, Hagens (2020) compares its ability to do work with human labor. He calculates that the 110 billion barrels of oil that were needed in 2018 to power the world economy is equivalent to more than 500 billion human workers toiling day and night.

The problem is, oil and coal are finite stocks that took hundreds of millions of years to form, which are since the industrial revolution being drawn down in a comparatively brief period of time (Hagens and White, 2021). It implies two important questions: how long will the fossil fuel bonanza last? and what will happen if the world runs out of fossil fuels?

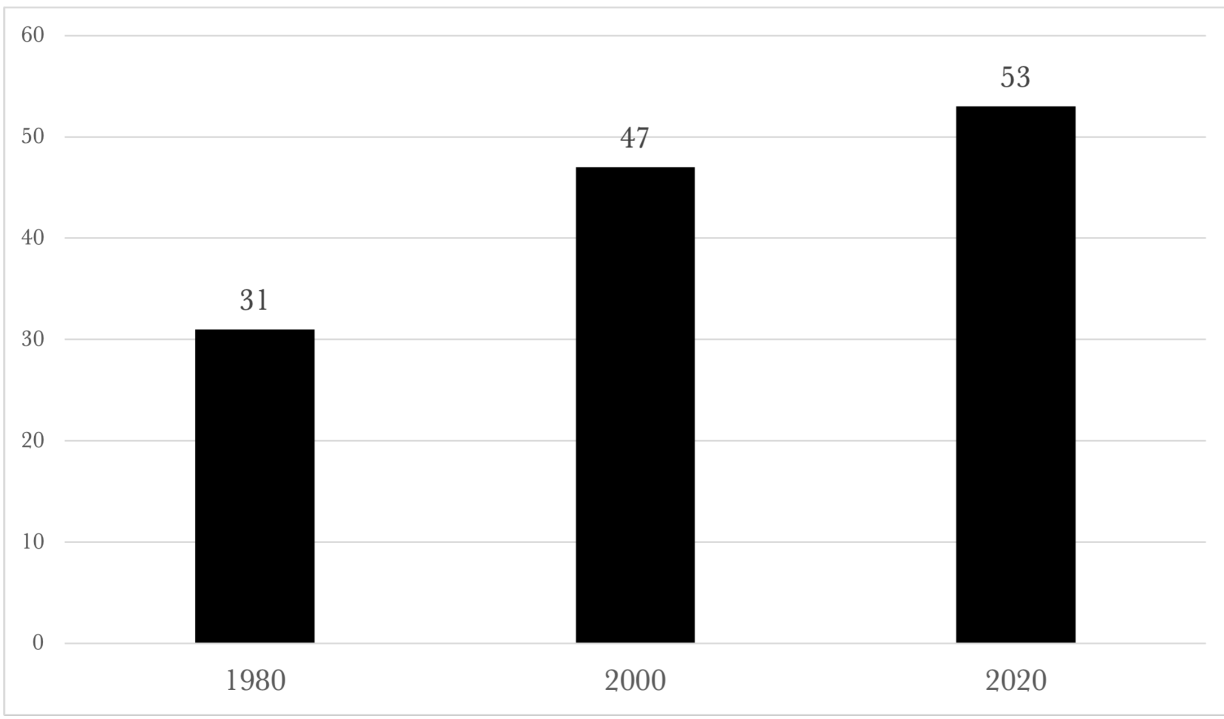
The first question is often discussed with reference to the concept of Peak Oil - the rate of maximum production of oil after which production would decline (Campbell and Laherrere, 1998). Hubbert (1956) proposed that the rate of oil production would follow a bell-shaped curve (according to a semi-logistical curved model). Based on information at the time he estimated that for 48 US States Peak Oil production would be reached in 1970. More recent estimates suggests world peak oil production will be reached in the mid-2020s - if it has in fact not yet been reached (Turner, 2014). Murray and King (2012) found that there has been a "step change" in the economics of oil around 2005, after which the production of oil has become much less price elastic, with the consequence that oil prices have become much more sensitive to changes in demand. This, and the decline in oil production from existing oil field of between 5% to 6% per year (Murray and King, 2012) together suggests that oil production may peak in the first half of the 21st century - see also Hall (2017) and Mohr et al. (2015).

Cornucopians would argue that this is all too pessimistic, and that technological advances would keep increasing oil reserves, citing amongst other the example of non-conventional oils such as from Canada's tar sands or the USA's fracking industry. For instance, Epstein (2022, p.54-55) states that as far as "proven reserves" of oil are concerned, "the more we consume, the more reserves increase [...] humanity keeps getting better at using fossil fuels to power the machines that enable us to transform more of the world's massive stockpile of raw fossil fuels into usable fossil fuel reserves."

There are two problems, however, with this optimism. One is the belief that "the more we consume, the more reserves increase." The second is the belief that the efficiency of extraction - transforming "raw fossil fuels into usable fossil fuel reserves" is increasing. Both statements from Epstein (2022) can be critiqued.

The belief that the more oil we consume, the more will reserves increase, is commonly based on the estimates of "proven reserves" of oil, typically published in the bp Statistical Review of World Energy. Indeed, according to the data, "proven" reserves of oil against production, expressed in the Oil Reserves to Production Ratio (R/P)[15] has been increasing over time - as Figure 4 show.

Figure 4: "Proven Oil Reserves": Oil Reserves to Production Ratio (R/P), 1980 - 2020



Source: Author's compilation based on data from the bp Statistical Review of World Energy.

Figure 4 suggests that, based on estimates of "proven" oil reserves, by 1980 there were 31 years of existing estimated oil stocks left[16]. By 2020 this had risen to 53 years! Thus indeed it seems, as Epstein (2022) claims, the more the world consumes oil, the more reserves increase. How very extraordinary this is has been criticised by Bardi (2020, p.126) who compared the world's use of oil like eating a cake and "as long as you have some cake left, there is nothing

[15]The Reserves to Production ratio (R/P) is the ratio of total estimated oil reserves to the annual production (extraction) of usable fuel. It indicates how many years of oil supply is left.

[16]This does not include the possibility that in future new reserves will be discovered. Most of this will have to come from opening up new oil fields and exploiting non-conventional oil. Estimates of the extent of such possible future oil discoveries are however contentious and subject to much uncertainty (McGlade, 2012; Murray and King, 2012).

to be worried about. Actually, the peculiar cake that is crude oil has the characteristic that it becomes bigger as you eat it."

Naturally, this cake that gets bigger as you eat it, has lead several scientists and journalists to attempt to scrutinise how estimates of "proven" reserves are obtained. Just how "proven" are these (politically welcome) estimates? Estimates of oil reserves cannot be done directly and rely on many assumptions on technology, economics and geology; moreover how these assumptions are combined with other information is not transparent as "probably half to three-quarters of the world's oil is in countries where the oil sector is a state monopoly and whose governments do not feel the need to explain the basis of their reserves estimates (Mitchell, 2004, p.1). As a result, and because they face economic incentives to do so (it influences their share prices), oil companies tend to significantly overstate[17] their reserves (Jefferson, 2016). In the case of non-conventional oil from fracking, Olson et al. (2019) reported on several methods that oil companies use to inflate their reserves and expected output, including cherry picking data and understating depreciation expenses.

The second response of Cornucopians to the question of how long the oil bonanza will last, is the belief that the efficiency of extraction - transforming "raw fossil fuels into usable fossil fuel reserves" is increasing, as Epstein (2022) claims. Such greater efficiency would lengthen the curation of the bonanza. It seems however, contrary to Epstein (2022)'s claim, that it is getting more and more difficult and expensive to extract and use oil - usable oil, a flow, is more and more costly to obtain. Even if one would assume that provable oil reserves are not overstated, a higher cost of extraction would in effect deflate the value of the available stocks. As put by (Murray and King, 2012, p.434) "we are not running out of oil, but we are running out of oil that can be produced easily and cheaply.

It takes energy to extract and make oil usable. Taking the cost and energy of extracting raw

[17] For example, in 2004 Shell admitted to overstating its reserves by 4,47 billion barrels, see `https://www.sec.gov/news/press/2004-116.htm`.

oil to use-able oil therefore raises the importance of making a distinction between energy and *net* energy. This is the energy available for use "after the energy costs of getting and concentrating that energy are subtracted" (Odum, 1973, p.220). The ratio between the energy and costs in producing net energy (usable oil) is known as the Energy Return to Energy Invested (EROI) ratio.[18] In the case of resource depletion the EROI would be declining (Bardi and Lavacchi, 2009). This is indeed what has been happening in recent years (Brockway et al., 2019; Court and Fizaine, 2017; Jackson, 2021).

Thus, the problem as formulated above remains: oil and coal are finite stocks that took hundreds of millions of years to form, which are since the industrial revolution being drawn down in a comparatively brief period of time, with the fossil fuel bonanza likely drawing to a close in the first half of the 21st century. The next big question then is, as raised above, is what will happen if the world runs out of fossil fuels?

For present purposes the conclusion is that it will spell the end of economic growth. As already pointed out in 1973 by Odum (1973, p.225) "During periods when expansion of energy sources is not possible, then the many high density and growth promoting policies and structures become an energy liability because their high energy cost is no longer accelerating energy yields." As the world will not run out of fossil fuels suddenly, but would rather follow the more gradual decline along the contours of a semi-logistical curve, as fossil fuels become scarcer and the only the most difficult reserves remains to be extracted, with the EROI continuing to decline, the impact will be "an increase in energy prices, the general rate of price inflation, and the unemployment rate, and negatively impacts the functional income distribution. Combined, these effects cause a recession followed by a period of below trend output growth" (Jackson, 2021). It has been argued that the secular decline in economic and economic growth experienced in the West since the 1970s already partly reflect the growing

[18] For fossil fuels at the primary energy stage, this is typically more than 25:1 (it peaked in the 1930s-1940s at 50:1); however after turning this into end-stage energy for example petrol or electricity, the EROI drops to around 6:1 - and this has been declining in recent years (Brockway et al., 2019; Court and Fizaine, 2017).

cost of energy (as reflected in EROI declines) (Naudé, 2022a; Heinberg, 2011).

This section will conclude by sharing the likely consequences of the decline in oil as aptly described by (Bardi, 2020, p.122):

> "Without liquid fuels, everything would stop in the world [....] No fuels, no trucks, no food, no civilization. Could it really happen? It could. Something similar already happened with the great "oil crisis" of the 1970s that for a period seemed to destroy the very foundations of the Western civilization. If you experienced that crisis, you cannot forget what happened: gas prices suddenly skyrocketing, long lines at the gas stations, governments enacting all sorts of measures: lower speed limits on highways, "odd-even rationing" schemes, support to the production of small cars, and more. The shock on the financial system was even worse: recession and two-digit inflation. It was a disaster for a world that had experienced, up to then, more than 2 decades of uninterrupted economic growth."

4 Green Growth, Degrowth, or Rebound?

In this paper so far, the question of whether the exponential economic growth that had brought humanity unprecedented incomes, wealth and consumption in the comparatively short time-span of a few centuries can be sustained indefinitely, was discussed from the perspectives of the (neo)-Malthusians and Cornucopians - two opposite positions. It was explained that the Cornucopians are tech-optimists who reject the Malthusian belief in limits to growth. The conclusion was drawn, however, that if the Cornucopians are to present a convincing narrative in favor of unlimited economic growth, they need to be able to provide a case that technological innovations will be able to mitigate climate change and steer around possible existential threats from ecological overshoot, and moreover in doing so, they would need to argue a convincing case that technological innovation can make up for the energy loss implied by the end of the carbon pulse (cheap and abundant fossil fuels).

Cornucopians have made their case largely through advocating for the notion of Green Growth. Through Green Growth the trust is that economic growth can be decoupled from the environment - that is to say that economic growth can continue without exhausting resources or contributing to global warming, and that alternative, renewable and non-carbon energy sources can be found to substitute for the phasing our of fossil fuels.

Neo-Malthusians (of sort) have responded by rejecting green growth, arguing that the only way to avoid resource depletion and an existential climate crisis is to make a concerted effort to scale down GDP - to degrow the economy. The Degrowth agenda is thus Malthusian in stating limits to economic activity. It attempts to provide an agenda for enabling this and to provide for high levels of human welfare within planetary boundaries.

A third group of thinkers, not necessarily aligned, have been suggesting a third alternative response to the end of the carbon pulse: an acceptance of societal collapse and a preparation for the eventual rebound that they believe will take place. In their view societal collapse is "not a bug, but a feature" of complexity in the universe, and unduly resisting it may only make matters worse (Bardi, 2017).

In the remainder of this section, these three responses will be critically discussed.

4.1 Green Growth

To prevent a "ghastly future" from existentially risky climate change and the running out of the oil bonanza, the mainstream or central approach adopted across international organizations and in many countries is that of Green Growth (D'Alessandro et al., 2020). The green growth approach underpins amongst others the 2015 Paris Climate Agreement to reduce carbon emissions by 2050 to keep global warming to less than 1,5 degrees above pre-industrial levels, the European Green Deal of 2020 to achieve net-zero emissions of greenhouse gases by 2050, and the 2022 UN Biodiversity Conference to at least 30% of terrestrial, inland water and marine areas by 2030.

The OECD (2011, p.9) defines green growth as "fostering economic growth and development while ensuring that natural assets continue to provide the resources and environmental services on which our well-being relies." It sees this as a subset of the older concept of sustainable development. The World Bank defines green growth as "growth that is efficient in its use of natural resources, clean in that it minimizes pollution and environmental impacts, and resilient in that it accounts for natural hazards and the role of environmental management and natural capital in preventing physical disasters" (World Bank, 2012, p.2).

In practice policies to promote green growth results in attempts to decarbonize the global economy, transition economic growth into growth that will be decoupled from resource use and carbon emissions, promote as much as possible circularity in production and consumption, regulate the protection of biodiversity and other natural assets, and ban pollution. The steering of technological innovation - and stimulation of eco-innovation - together with "getting the prices rights", e.g. carbon taxes are crucial aspects of the approach (Capasso et al., 2019).

There is however also a political dimension to green growth. In essence, green growth is an attempt to overcome the collective action problem of addressing climate change by framing it in a positive light: countries can have their cake and eat it, i.e. grow and reduce their environmental footprints. Moreover, pursuing green growth is often painted as offering many opportunities to enhance growth[19] and job creation - and moreover to have "the shift to a low-emissions economy pay for itself" (Zysman and Huberty, 2012, p.140). The European

[19]Green growth as catalyst of economic growth is described as "strong" green growth to contrast it with green growth which may entail short term costs, but deliver longer-term benefits (Jakob and Edenhofer, 2014).

Commission (EC, 2011, p.8) moreover noted that many believe that "environmental technology/resource efficiency [is] one of the drivers of profound global structural change that will bring in the next long-term period of growth." Based on these views of green growth as paying for itself and offering many new opportunities for a new period of long-term growth, there has been a proliferation in recent years of green finance and green industrialization plans.

At the core of green growth is the Cornucopian assumption that the right kind of technological innovation and correctly pricing externalities, so as to change behaviour, will allow for a decoupling between economic growth and material inputs and between economic growth and its ecological impacts (such as carbon emissions). Technological innovations, for example in the form of digitalization has been touted as causing the dematerialization of the economy. McAfee (2019), a proponent of dematerialization, argues that "we invented the computer, the network, and a host of other digital tools that let us swap atoms for bits [think, for example, of how many different devices and media have vanished into the smartphone]. Quite literally, these inventions have changed the world."

One way in which decoupling is concretely envisaged is through an energy transition: the phasing out fossil fuel energy and replace these with renewable and low-carbon emitting sources of energy, such as nuclear power. There are two types of decoupling: *relative decoupling*, when growth in material inputs or carbon emissions grows slower than GDP, and *absolute decoupling*, when material inputs and carbon emissions decline when GDP grow (Ward et al., 2016; Jackson and Victor, 2019).

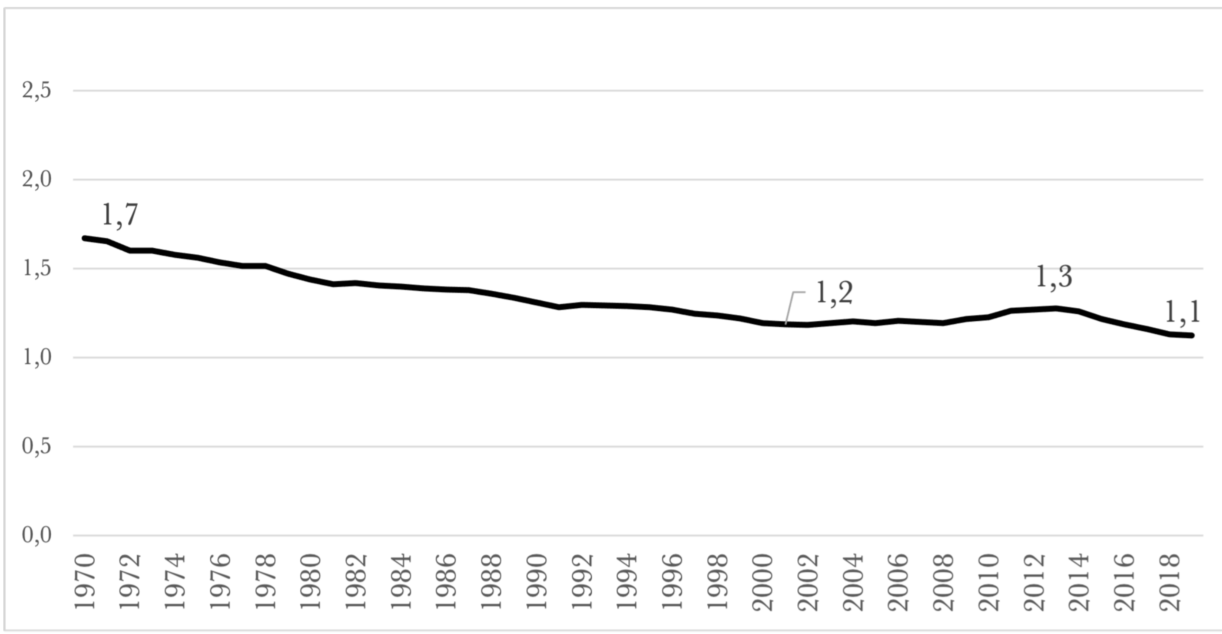
One measure used by the European Commission, OECD, UNEP and other global organizations to measure decoupling between GDP growth and material through-put, is Domestic Material Consumption (DMC) (OECD, 2014). According to Eurostat,[20]the DMC "measures

[20]See https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Domestic_material_consumption_(DMC)

the total amount of materials directly used by an economy and is defined as the annual quantity of raw materials extracted from the domestic territory, plus all physical imports minus all physical exports." The ratio between DMC and GDP expresses DMC as the kilograms of materials used to produce a unit value of inflation-adjusted GDP. It is a resource efficiency measure: if it declines it would indicate more efficient resource use[21] which would be consistent with green growth.

Figure 5 shows the DMC to GDP ratio for the world economy between 1970 and 2019.

Figure 5: Green Growth? Domestic Material Consumption to produce a unit of constant (2015) GDP - per kg



Source: Author's compilation based on data from the UNEP IRP Global Material Flows Database.

Figure 5 shows that resource efficiency in the world economy did improve between 1970 and 2019 - from around 1,7 kg per unit of GDP value produced in 1970 to around 1,1 kg per unit of GDP by 2019. Moreover, most of the resource efficiency gains seems to have been achieved before 2000, since when DMC has remained around the 1,1 kg level for the world as

[21]The limitations of the DMC-GDP ratio, such as that it measures resources by weight while impacts of resource use may not always depend on weight, and that if used on a country level it ignored consumption impacts taking place outside of that country's borders, is recognized by the European Commission which advocates also using additional measures of environmental impact (EC, 2011).

a whole (and even increased between 2001 and 2013). It is not consistent with global green growth - at least not in the last two decades.

As opposed to the global lack of green growth, several mainly high-income western countries, have been able to achieve more significant resource efficiency as measured by the DMC:GDP ratio. For example in the Netherlands, the DMC to produce a unit of constant GDP fell from 0,7 kg in 1970 to 0,3 kg in 2019, which is indicative of green growth. However, a shortcoming of the DMC on a country level is that, as Eurostat points[22] out, "does not include upstream 'hidden' flows related to imports and exports of raw materials and products."

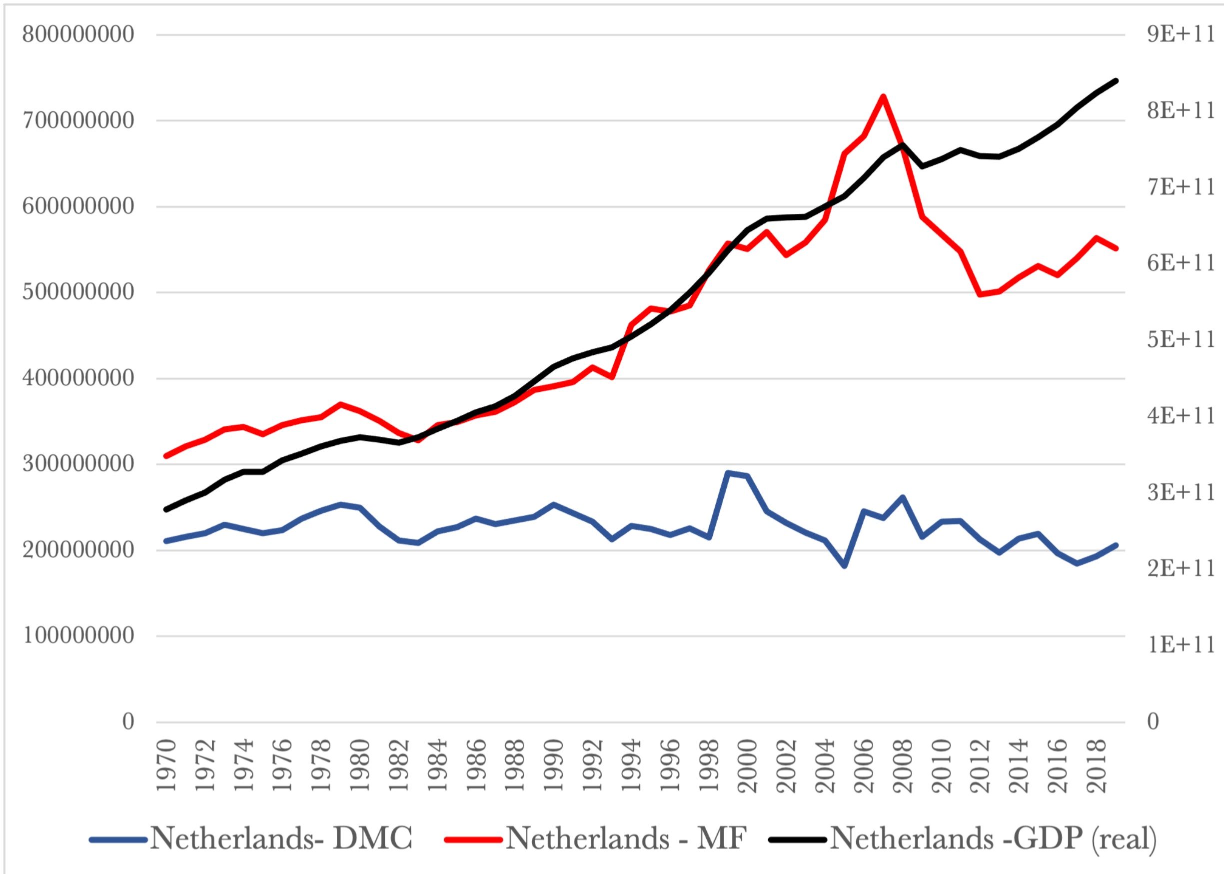
A measure that does include these upstream flow effects, is the Material Footprint (MF) measure, proposed by Wiedmann et al. (2015) who define it as "the global allocation of used raw material extraction to the final demand of an economy" (Wiedmann et al., 2015). If for example the MF for the Netherlands is calculated, it shows a MF to GDP ratio in 2019 much higher than the DMC:GDP ratio, namely 0,7 - thus twice as high as the DMC:GDP measure. This indicates that the global resource use impact of the Netherlands is much larger than its domestic resource impact - its demand for resources raised resource us in other countries. Moreover, over time the MF:GDP ratio in the Netherlands have not declined much and has at least until 2008 tended to follow GDP closely.

Figure 6 depicts DMC, MF and GDP (in constant prices) in the Netherlands between 1970 and 2019 to illustrate this point. It shows that while DMC in absolute use (in tons) have remained fairly constant over the period, the MF has increased in absolute values quite significantly between 1970 and 2008. It briefly declined during the global financial crisis and its immediate aftermath (2008-2012) but thereafter, in line with GDP growth, continued its upward trajectory.

In sum, what Figure 6 indicates is that in a country such as the Netherlands, while there has

[22] See https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Domestic_material_consumption_(DMC)

Figure 6: The Netherlands: DMC and MT (per ton) and GDP in constant 2015 US$, 1970-2019

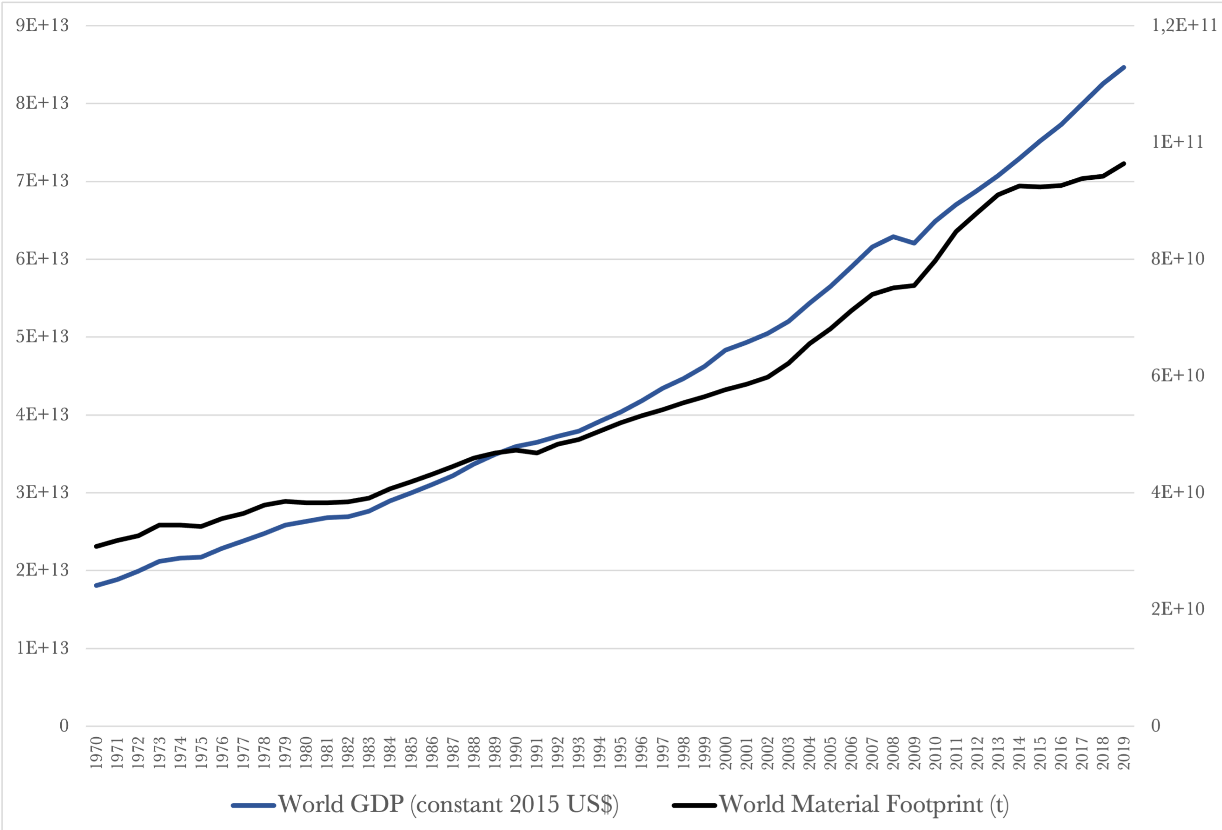


Source: Author's compilation based on data from the UNEP IRP Global Material Flows Database.

been evidence of relative decoupling at best, there is little evidence of absolute decoupling. Neither DMC nor MF are declining in absolute terms over time. And, as Figure 5 has shown, on a global level there is little evidence of absolute decoupling as GDP and DMC seems to have a relatively stable 1:1 relationship.

Figure 7 plots global GDP in comparison to global MF of all countries: it shows no indication of absolute decoupling: GDP growth implies more resource use. The relationship between GDP and the MF is similar to the relationship between GDP and fossil fuel use (see Figure 2). The apparent decline in the slopes of fossil fuel use and MF suggests some degree of relative decoupling.

Figure 7: World Material Footprint and GDP in constant 2015 US$, 1970-2019

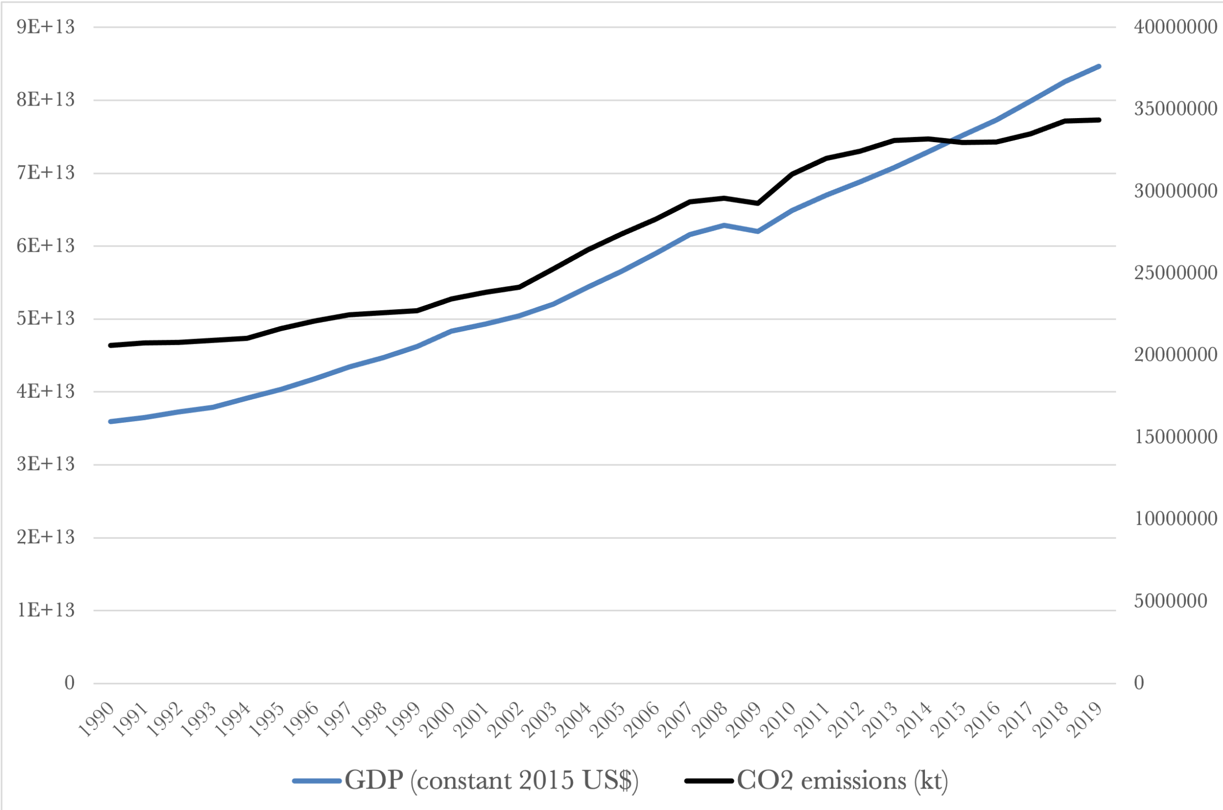


Source: Author's compilation based on data from the UNEP IRP Global Material Flows Database.

The conclusion that can be made on the basis of Figures 2, 5, 6, and 7 is that there is no absolute decoupling between fossil fuel use and the material footprint (MF) on the one hand, and global GDP growth. Similarly, whereas many countries have been decoupling GDP growth in relative terms from CO_2 emissions (amongst others, but not exclusively, by shifting some production overseas), in absolute terms, CO_2 emissions have not declined.

This conclusion of no absolute decoupling and possible relative decoupling is made by several more rigorous studies. For example (Wiedmann et al., 2015) finds that there has been improvements in resource us in the EU-27, the OECD, the United States, Japan, and the United Kingdom - consistent with relative decoupling - but no absolute decoupling. Ward et al. (2016) concludes that "while relative decoupling has been observed in multiple countries, absolute decoupling remains elusive [...] no country has achieved absolute decoupling

Figure 8: Carbon Emissions (tons) and World GDP in constant 2015 US$, 1990-2019



Source: Author's compilation based on data from World Bank's World Development Indicators Online.

during the past 50 years". Haberl et al. (2020), surveying the empirical literature on decoupling concludes that there is evidence of relative decoupling between GDP growth and carbon emissions, but not for decoupling between GDP growth and energy use. They conclude that "large rapid absolute reductions of resource use and GHG emissions cannot be achieved through observed decoupling rates" (Haberl et al., 2020). Jackson and Victor (2019) similarly cite examples of relative decoupling, but conclude that there is no evidence for absolute decoupling on the global level. Moreover, 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 this as to require 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 Victor, 2019).

Not only is there little evidence of absolute decoupling, the magnitude required seems to be impossible to achieve given what is required to limit global warming. Furthermore, even relative decoupling may have little aggregate advantages in terms of reducing resource use due to the Jevons paradox,[23] also described as a rebound effect. Increased resource efficiency, resulting in productivity gains and price declines, will result in higher aggregate demand, which in turn stimulates further absolute resource use (Bardi, 2020; Bowen and Hepburn, 2014; Magee and Devezas, 2017).

The fundamental criticism against green growth that emerges from the preceding discussion is that green growth has not yet, and also does not seem able in future to achieve absolute decoupling between GDP growth and material inputs (resource uses) and carbon emissions (growth impacts). It will therefore not able to prevent, or roll back, the overshooting of planetary systems. Relative decoupling is possible, can extend the availability of resources, and reduce the impact of emissions by a small magnitude, but even these efficiency gains may end up increase total energy use due to rebound (Jevons Paradox) effects.

In addition to this devastating criticism, there are also other criticisms of green growth. These will be briefly introduced.

One further criticism is that green growth is economically costly, and may make poverty reduction more difficult (Resnick et al., 2012; Dercon, 2014). This has raised the issue of climate justice as a ancillary to global green growth initiatives, reflecting concerns that developing countries who may suffer the worse impacts of climate change, have contributed the least to the current stocks of human emitted $CO2$ in the atmosphere. In exchange for subscribing to green growth, developing countries are therefore demanding substantial

[23] Jevons (1866) noted that technological progress in the efficiency of coal-driven locomotives lead not to the decline in the demand for coal, but in an increase, due to productivity and cost effects.

financial[24] and know-how transfers from advanced economies - who have pledged US$ 100 billion in financial resources for developing countries to fight climate change, but has failed to live up to this commitment (Diffenbaugh and Burke, 2019; Ehresman and Okereke, 2015; Robinson and Shine, 2018; Timperley, 2021).

Another criticism of green growth is that green growth places undue hope in the energy transition, i.e. the phasing out of fossil fuels, and replacing these with renewable energy sources. The first problem is that replacing fossil fuels with renewable energy is not feasible: all renewable energy technologies need fossil fuel energy to be manufactured and renewable energy systems need back-up from fossil fuel or nuclear energy (Hagens, 2020; Rees, 2021). And second problem is that promotion of renewable energy will stimulate the re-materialization of world production - due to the need for various mineral resources as inputs for renewable energy systems. Bleischwitz (2010) and Zeihan (2022) lists some of the critical mineral resources needed for renewable energies, which include copper, lithium, gallium, aluminium, tantalum, nickel, cobalt, silicon, chromium, graphite, zinc, manganese, molybdenum, gold, silver and platinum. In addition to the re-materialization of the world economy that this would stimulate, many of these minerals are found in countries with poor institutional development, meaning that the exploitation of these resources could lead to significant human rights abuses.[25] Kara (2023) documents such human rights abuses, which he calls a human rights and environmental catastrophe, in cobalt[26] mines in the Democratic Republic of Congo.

A final and also devastating criticism of the hope that green economic growth is possible, and could moreover be sustained indefinitely, is provided by the laws of physics. This suggest

[24] According to the IPCC between $1.6 and $3.8 trillion is required annually to achieve climate targets in line with keeping global warming below 1,5 degrees celsius (Timperley, 2021).

[25] Zeihan (2022) considers the complications surrounding integrating the mineral extraction and supply chains for green technologies to be significantly more daunting than that faced in the oil industry: "In 'moving on from oil' we would be walking away from a complex and often-violent and always critical supply and transport system, only to replace it with at least ten more."

[26] Cobalt is an essential requirement in rechargeable lithium-ion batteries that are found in every smartphone, electric vehicle and laptop.

that even if in a science fiction world full absolute decoupling from physical inputs could be obtained, then there would still be the waste heat, an outcome of the 2nd Law of Thermodynamics, that will eventually stop growth. 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). In just over 8,000 years it would be 3×10^{70} its current size, which would be a physical impossibility(Karnofsky, 2021c).

Even if growth slowed and the world economy doubled in size only every 100 years, then after a million years (a very brief period on cosmic timescale) the economy would be 10^{3010} times larger, which implies that if there are around 10^{80} atoms in the galaxy[27], that "each atom would have to support an average of around 10^{2950} people" (Hanson, 2009).

One particular constraint which would limit growth long before these time scales is that even if the global economy would be able to increase energy efficiency and be able to decouple much growth from physical resources, it would still need significant amounts of energy to run its soft-and-hardware. The share of the economy that can be non-physical (and that can thus be de-materialized) is ultimately bounded. The economic growth implied in Figure 1 has been due to an annual average growth in energy consumption of around 2,3% per annum (Murphy, 2022b). If one assumes that a Cornucopian economy would eventually be able to generate economic growth which doubles the world economy every month as discussed in the section 2.2 (see also Hanson (2018)) but with such energy efficiency that energy use continues to grow at only 2,3% then energy use on the planet will grow from its current (2019) level of 18 Terawatt (TW) to 100 TW in 2100 and 1,000 TW in 2200. Murphy (2022b) calculates that at such a rate the economy would use up all the solar power that reaches the earth in 400 years and in 1700 years all of the energy of the sun. The use of so much energy would generate tremendous waste heat independent of any future smart green-energy technology.

[27]It is estimated that there are between 10^{78} and 10^{82} atoms in the observable universe, see https://www.universetoday.com/36302/atoms-in-the-universe/

It would be so hot as to boil the surface of the Earth in about 400 years (Murphy, 2022b).

The upshot is that even if the optimistic Cornucopian green economy scenarios could be realised, any acceleration in economic growth will ultimately be a transient event - if it ever happens. As Murphy (2022b, p.847) has warned, "we would be wise to plan for a post-growth world."

4.2 Degrowth

The previous sub-section described the mainstream approach known as green growth, and noted that although it will contribute to resource efficiency, this is insufficient to keep economic growth from overshooting planetary boundaries. There is a 1:1 relationship between GDP and material inputs. Even if GDP could be completely and absolutely dematerialized and decoupled from material inputs, it will still need energy and the waste heat that even a relatively modest 2% growth in energy demand would entail would imply an end to economic growth within a few centuries.

As a consequence of the ultimate futility of green growth, the have been arguments for deliberate and planned "degrowth" - in other words, economic downsizing. Pro-actively downsizing the economy is considered the only way to avoid a catastrophic environmental overshoot. As put by Murphy et al. (2021, p.4) "It is time [to] admit that growth is not only temporary, but ultimately may constitute an existential threat to human wellbeing." And to achieve climate justice, the proposal is for advanced economies to downsize while allowing developing countries to reach a better level of per capita income. More formally, Hickel (2021, p.1105) defines degrowth as "a planned reduction of energy and resource use designed to bring the economy back into balance with the living world in a way that reduces inequality and improves human well-being."

The idea of degrowth agenda is related to concepts of post-growth (e.g. Jackson (2009), steady-state economics (e.g. Daly (1992), and "Doughnut" economics (e.g. Raworth (2017)) which also considers GDP growth unsustainable, and moreover not meaningful after a certain level of income has been attained.[28]

Degrowth is Malthusian in that it recognises clear limits to growth (planetary boundaries) and it rejects the tech-optimism of Cornucopians. It does not offer a coherent theory of sustainable economic growth; rather, it is a better described as a movement or agenda, with its roots in the 1970s views of Marxist philosopher André Gorz and economist Nicolas Georgescu-Roegen (Georgescu-Roegen, 1971, 1975). As described by Kallis and March (2015, p.360) "Degrowth is an advanced reincarnation of the radical environmentalism of the 1970s and speaks to pertinent debates within geography [...] degrowth is on purpose subversive [...] it embraces conflict as its constitutive element." In a similar vein it has been hailed as "a powerful oppositional Marxist[29] ecology that represents a path to a truly sustainable Earth" (Boettcher, 2021, p.vi).

The degrowth movement's agenda is thus a radical one (Kallis, 2011). Its deep-seated belief is that GDP growth, green growth and the sustainable development goals (SDGs) are futile because these approaches are rooted in democratic capitalism, the ultimate problem. Therefore, "radical political project" is advocated (Kallis, 2011, p.873) that would displace capitalism and in that way force a reduction of over-consumption of consumer goods, and material inputs into production, and of fossil fuels.

Ultimately, the proposal for degrowth as proposed by the Degrowth movement turns out,

[28] Degrowth, post-growth and doughnut economics share the view, based on the Easterlin Paradox (see Easterlin et al. (2010)) that after a certain level of income, more money does not buy happiness. This view has been criticised, amongst others on the grounds that the Easterlin Paradox refers to changes in income and changes in happiness, not levels (Easterlin and O'Connor, 2020); and that Easterlin's orginal research was subject to measurement errors, which if corrected, shows "no evidence of a saturation point" for happiness (Stevenson and Wolfers, 2013).

[29] According to Harvard psychologist Steven Pinker, proponents of degrowth have an "obvious" agenda: "it's humiliating to their world view that the data show massive improvements due to markets and globalization rather than an overthrow of capitalism and global redistribution" - as quoted in Coyne (2019).

much like that of green growth, not to be a solution. Most importantly, degrowth has been criticised that its proposal to reduce the GDP of advanced economies will have no significant impact on reducing the world's Material Footprint (MF), or carbon emissions, significantly enough to avoid an ecological overshoot. This is because most (63%) of current carbon emissions come from developing countries - where it will only continue to increase in the foreseeable future. The 2022 Emissions Gap Report notes UNEP (2022, p. 67) that "virtually the entire future increase in global primary energy demand is expected to occur in these [developing] economies."

And after the GDP of rich economies are downsized - say by a significant 40%, there would still remain a footprint of 60% and 60% of their economies to de-carbonise (Hickel and Hallegatte, 2022). van den Bergh (2011, p.885) concluded that "Even if we would manage to 'scale the economy down' to 50% [....] we still only would have reduced the size of the environmental problems by half. But this is by far insufficient for most environmental problems." It is clearly insufficient to halt the growth in material footprints and carbon emissions and not reduce these "tout court." Phillips (2019) uses the example of the successful reduction in the hole in the ozone layer to illustrate the shortcoming of the Degrowth proposal, explaining that:

> " we embraced degrowth with respect to ozone depletion by attempting to arrest growth in, say, the number of fridges in the world—or even reduce the total number—instead of regulation to enforce technology-switching, disaster would have befallen us. Saying "this many fridges and no more" would only have arrested the growth in emissions, not emissions tout court" (Phillips, 2019).

Moreover, even if the GDP growth of all countries, not only that of the developed countries, could be curtailed, it may still not be effective to reduce carbon emissions and MF sufficiently to achieve climate goals. This can easily be seen using the so-called IPAT identity, used to gauge the drivers of the environmental impact of the economy (Bretschger, 2021; Stijn, 2021). The IPAT identity decomposes the environmental impact (I) of an economy into the consequences of population (P), affluence (A) and technology (T) (Holdren, 1993). It can be written as follows (where a 'hat' over a variable indicates a rate of change):

$$I = \hat{P} + \frac{\hat{A}}{P} + \frac{\hat{T}}{A} \tag{1}$$

If affluence (A) - say measured in GDP - is reduced as per degrowthers' proposal, it will lead to a reduction in impact (I). This is the basis of degrowth. However, if $\hat{P}$ continues to grow, and if technological innovation ($\hat{T}$) declines or remain slow, then the reduction in impact caused by GDP degrowth would be offset. The important point to note is that both of these offset mechanism are more likely to apply at lower levels of GDP. Furthermore, if reduced GDP lead to a reduction in technological innovation in the richer countries, the environmental impact may be even worse. Holdren (1993, p.5) shows in this regard that "a change for the worse in the technology of production is more serious environmentally if it occurs in a populous, affluent society than if it occurs in a small, poor one" - which are the type of the societies that the Degrowth movement want to downsize.

Worse even, not only is downsizing the economies of rich countries not likely to be effective, but it may worsen ecological overshoot in several ways. "degrowth might turn out to be dirty" (van den Bergh, 2011, p.882). One is that countries will have less resources to invest in climate change mitigation and adaptation technologies, and hence they will be more vulnerable to the impacts of ecological deterioration (Phillips, 2019). A second is that firms may substitute more expensive cleaner production techniques for cheaper, but more polluting, technologies. Third, government revenues will drop - an inevitable consequence of economic shrinkage. Governments would not be able to borrow further to spend on social and basic needs or environmental protection. They would need to repay their existing debt - in the

EU, the rule that government debt cannot exceed 60% of GDP implies that, if GDP declined, debt would also need to fall (Stijn, 2021). Fourth, poorer households in (degrowthed) rich countries are likely to revert to deforestation[30] and environmental destruction - as they did during the 2021/2022 winters in Europe when faced with rising energy prices following the Ukraine war (Moloney, 2022; Rankin, 2021; Kauppi et al., 2006).

A further shortcoming of degrowth is that if one considers degrowth as a method to decreasing carbon emissions, it is a much more expensive method than any currently comparable technological investments as green growth is pushing for. According to calculations by Jakob and Edenhofer (2014) if the world shrinks GDP per capita by 10% (around US$7,000 billion), it will reduce carbon emissions by about 3.3 gigatons, meaning a cost of US$ 2,100 per ton of emissions. In comparison, the social cost of carbon dioxide (SC-CO2) has been estimated at US$ 185 per ton of emissions (Rennert et al., 2022).

In addition to being likely ineffective, to worsen the environmental challenge, and a very expensive way to reduce carbon emissions, degrowth may disproportionately hurt the poorest of the poor - and make global inequality worse. One mechanism through which this could occur is that degrowth in the Global North will severely curtail development in the Global South because of the intertwined nature of the global economy (and there is no time for the Global South to successfully "decouple" if at all that is possible). The COVID-19 crisis emphasized this inter-dependency - poverty rose more sharply in the Global South than the Global North - and indicated how difficult it would be for the Global South to decouple from the Global North. Hence it may be indeed the case that, "the degrowth people are living a fantasy where they assume that if you bake a smaller cake, then for some reason, the poorest will get a bigger share of it [. . . .] that has never happened in history" (Horowitz, 2022).

[30]Downsizing the economies of developed countries in the global north should not be assumed to lead to less environmental destruction. Pre-industrial societies, which were less numerous and wealthy than modern society, were quite capable of significant ecological impact. For example, it has been estimated that "roughly three quarters of deforestation in temperate forests occurred before the industrial revolution" (Nordhaus, 2020). In contrast, Europe's forests have increased by a third between 1900 and 2010 (Fuchs et al., 2013). Higher GDP is associated with reforestation across the world, not deforestation (Kauppi et al., 2006).

Ultimately, degrowth will make global inequality worse because it will be the poor will pay the price, and not the rich, who has the means and connections to find shelter[31] - and who has arguably the most wasteful consumption. Hence, "Degrowth is, in essence, a form of ecological austerity for working-class people" (Chambers, 2021).

Finally, in the words of Stijn (2021) degrowth is not only ineffective, likely to worsen the environment, very expensive and a form of austerity for the working class, but redundant:

> "Economic degrowth is not necessary, because it targets the wrong enemy. GDP is not the enemy; environmental impact is the enemy. Environmental scientists are able to determine upper bounds on environmental impacts such as pollution. For example, climatologists have determined the carbon budget: how much greenhouse gases can still be emitted that keep the atmospheric temperature increase below 1,5°C. But GDP is measured in dollars, a totally different quantity than kg CO2. Hence, none of the economic degrowthers are able to say what is the upper bound or true limit on affluence. There are no scientific studies that estimate the maximum level of GDP that is still permissible."

The conclusion from drawing out the shortcomings of degrowth as a response to the overshoot crisis, is that as an policy agenda, is it politically infeasible[32] (Piper, 2021). Because of the endowment (loss aversion) effect, people attach high value to their current levels of GDP per capita where ever they live. They would be unlikely to vote for politicians who propose lowering their levels of GDP per capita. And politicians, being generally subject to a status quo bias, would be reluctant to propose such a radical policy. As degrowth proponents themselves acknowledge "political parties that have put forward degrowth ideas

[31] Remember, the empirical evidence is unanimous that environmental change has had and will likely have a much greater negative economic impact on developing countries than on advanced economies - see for instance Dell et al. (2012), Diffenbaugh and Burke (2019), Raddatz (2009) and Noy (2009).

[32] van der Leeuw (2020, p.440) argues that because degrowth is not politically and otherwise feasible or attainable in the short-or-medium term, green growth may be a way of eventually getting there over a longer time period.

have received limited support in elections" (Hickel et al., 2022, p.402). In 2023 in the Netherlands, the political party (BBB) who strongly opposed government policies to degrow the agricultural sector, so as to reduce nitrogen and other emissions, scored a massive election victory. Indeed, democracy and degrowth are inherently uncomfortable bedfellows. The only example in history of a sustainable and thriving stationary (non-growing) society was Japan during the Edo (Tokugawa) period (1603-1868). It was, however, a "a brutal dictatorship" (Bardi, 2020, p.221).

Given that a democracy is unlikely to choose degrowth voluntarily, the Degrowth Movement may set the world on the dangerous path towards rejecting democracy, and reverting to an authoritarian collective, to enforce its agenda. After all, so their proponents may argue, given that their lofty goal is to save the entire planet from destruction, no price - including sacrificing democracy and liberty - may be too high a price to pay...

4.3 Collapse - and Rebound?

> "What looks like a disaster may be nothing but a passage to a new condition which may be better than the old one" - Udo Bardi

A short recapitulation is needed. This section of the paper (section 4) addressed the question which emerged from section 3, namely what to do about the *Detritovores*, which is what human society has become, being greatly depended on fossil fuel energy. The use of its fossil fuel bonanza, and the economic growth it has enabled, is starting to overshoot planetary boundaries. In section 4.1 the Cornucopian response - *Green Growth* - was critically presented. It was argued that although green growth can result in many beneficial outcomes on the environment, through for example enabling greater resource efficiency and allowing for decoupling between economic growth and some environmental outcomes - all of this potentially good barring unintended consequences such as re-materialization and human rights abuses - it may not be able to result in complete dematerialization and absolute decoupling. It may therefore not be able to stop an ecological overshoot and the risks that this will pose to human civilization.

In section 4.2 the Malthusian response to green growth - the *Degrowth Agenda* - was critically laid out. Degrowthers reject green growth, arguing that the only way to avoid resource depletion and an existential climate crisis is to make a concerted effort to scale down GDP - to degrow the economy. It was argued that Degrowth will also not be likely to stop an ecological overshoot. Particularly, it was argued that degrowth would not only be ineffective, but it would be likely to worsen the environment; that it is a very expensive method to reduce carbon emissions; that it can be seen as a form of austerity for the working class; and that it is redundant. For these reasons, amongst others, degrowth as policy agenda is politically infeasible. In contrast, the appeal of green growth has been that it is more politically appealing, by presenting a narrative (even if not accurate) that pursuit of green growth is an opportunity for enhanced economic growth, job creation and poverty alleviation.

The question that remain is, what to do about the detritovores, if (exponential) growth, green growth and degrowth are not effective solutions? Perhaps the answer lies in a third way: acceptance of a coming societal collapse, and preparation for a possible rebound that could take place. A growing number of scholars have been engaging in this line of thinking, and some view societal collapse as "not a bug, but a feature" of complexity in the universe, arguing that unduly resisting it may only make matters worse (Bardi, 2017).

This section briefly, but critically, sets out the broad case for this view, noting at the outset that the scholarly and policy work on societal collapse is less established and less aligned than that of green growth and degrowth. It is an emerging and diverse field that also touches on complex ethical issues - as amongst others the "Longtermism" movement has controversially raised (see e.g. MacAskill (2022) and Torres (2021))- of which a full analysis falls outside the scope of the present paper.

4.3.1 Collapse as the End of the World?

Easter Island (Rapa Nui), a remote Polynesian island in the southeastern Pacific, is one of the most studied historical cases of societal collapse following an ecological crisis. Between roughly 1200 AD and 1600 AD it had a complex, developing society, numbering around 15,000 by 1600. It then dramatically collapsed, to around 2,000 inhabitants by 1700. Diamond (2005), not uncontroversially[33] ascribed this to the overshoot of the ecological system of the island. Decker and Reuveny (2005) asked "Could Simon and Boserup Have Saved Easter Island?" with reference to the view of Cornucopians like Julian Simon and Ester Boserup (see section 2.2) that technological innovation (driven by population pressure) can prevent a civilization falling into a Malthusian trap as happened on Easter Island. To try and answer this question, they construct a mathematical model to simulate a closed-system economy such as remote Easter Island, wherein technological innovation is endogenously determined by amongst others population growth and ecological pressures. From their model simulations they conclude that "endogenous innovation in the spirit of Simon and Boserup would not have saved Easter Island [...] It is questionable whether endogenous technological progress alone could save contemporary societies from a similar fate" (Decker and Reuveny, 2005, pp.137,138).

More than 40 years before Decker and Reuveny (2005) simulated the collapse of Easter Island, the first mathematical, computer-based simulation model to study potential societal collapse was the *World3* model used to generate the predictions for the 1972 Club of Rome's Limits to Growth (LtG) study (Meadows et al., 1972). This study 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-

[33] An alternative to Diamond (2005)'s theory of ecocide has been suggested by DiNapoli et al. (2020) who suggests that it was contact with Europeans, from the 1720s onwards, that lead to the collapse of Rapa Nui's civilization.

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) confirmed that the global economy was continuing to track the standard-run scenario well, implying that an Easter-Island like fate may await global society in the near future.

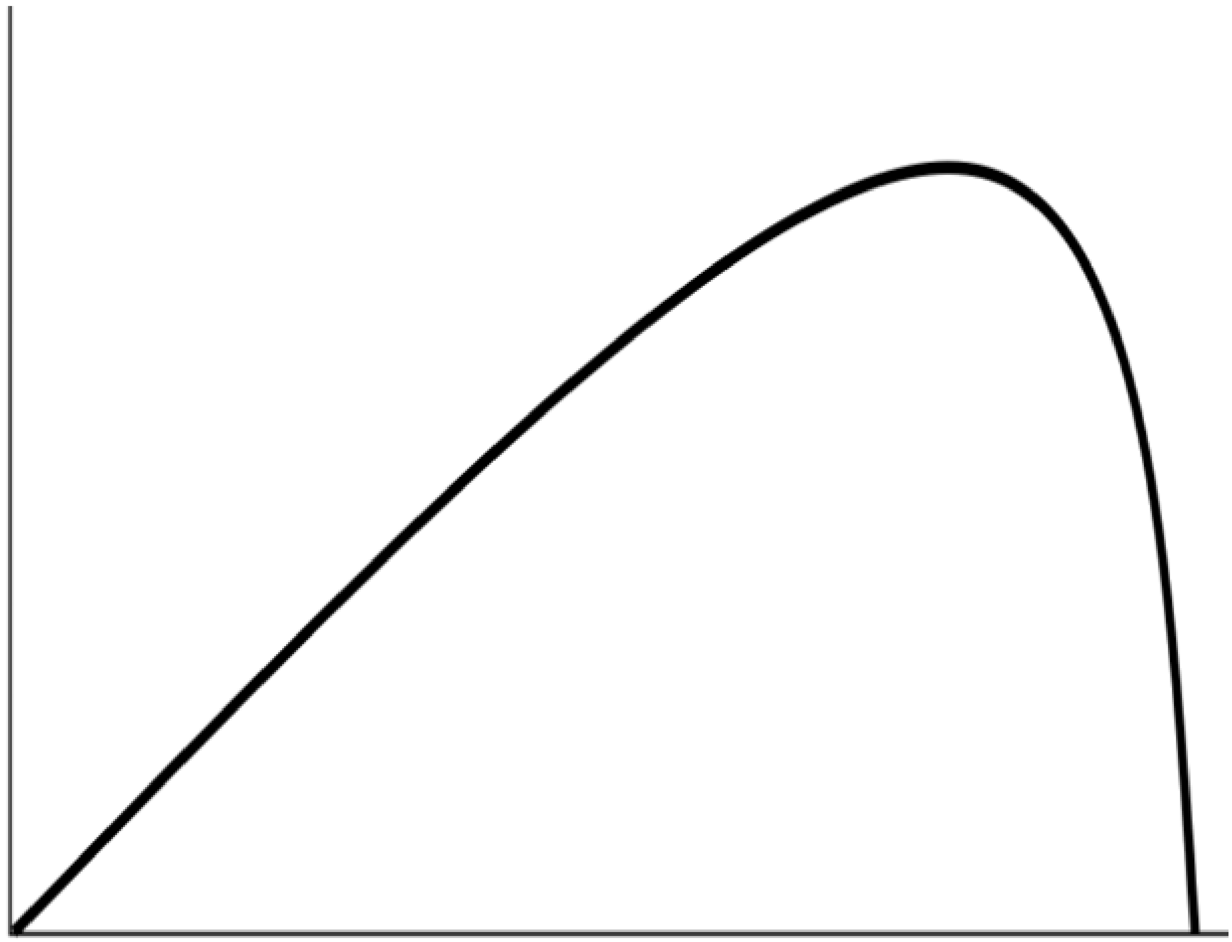
The LtG study stimulated much scholarly work on environmental limits and their role in potential societal collapse. Seminal contributions include Tainter (1988), Odum and Odum (2001), Weiss and Bradley (2001), Diamond (2005), Bardi (2020) and Kemp et al. (2022). Tainter (1988, p.4) defined societal collapse as having occured when a society "displays a rapid, significant loss of an established level of sociopolitical complexity."

Brozović (2023) surveys the literature on societal collapse brought about by an ecological overshoot.[34] He finds that amongst those who consider global societal collapse as inevitable there is a tension between those who think that collapse will be irreversible, and bring about an dystopian future, and those who hope that it is but a painful, but necessary step, to an Utopian future.

Those who associate societal collapse with a dystopian future (i.e. as the end of the world) expect, in line with the LtG study's predictions, collapse to occur fairly rapidly and to be irreversible. The trajectory of human civilization (and of GDP, given the focus in this paper on GDP growth) will in this pessimistic view follow a Seneca curve, named after the Stoic philosopher Lucius Seneca who emphasized that "increases are of sluggish growth, but the way to ruin is rapid" (Bardi, 2020, p.68). The predictions of the LtG study follows this trajectory - hence Turner (2014), in a update and review of the LtG study, concludes that "*it would appear that the global economy and population is on the cusp of collapse.*"

[34] It is related to the more recent literature that deals with the potential existential risks that humanity faces - a literature that largely dates back to 2002 to Bostrom (2002) who coined the term "existential risk."

Figure 9: The Seneca Curve: The Way to Ruin is Rapid



Source: Author's compilation based on Bardi (2020).

4.3.2 Collapse as the Beginning of a New World?

Others are, however, less pessimistic about the idea of societal collapse. The idea that societal collapse should be acknowledged and even welcomed as the beginning of a new world, rather than the end of the world, has found expression in the work of amongst others Bardi (2020), Odum and Odum (2001) and Scranton (2015). Relatedly, Vollrath (2019) has argued that the stagnation in economic growth that has already set in in many economies, and which are expected to deepen as one would expect as the fossil fuel bonanza runs out, and these societies age, should be seen as a "sign of success."

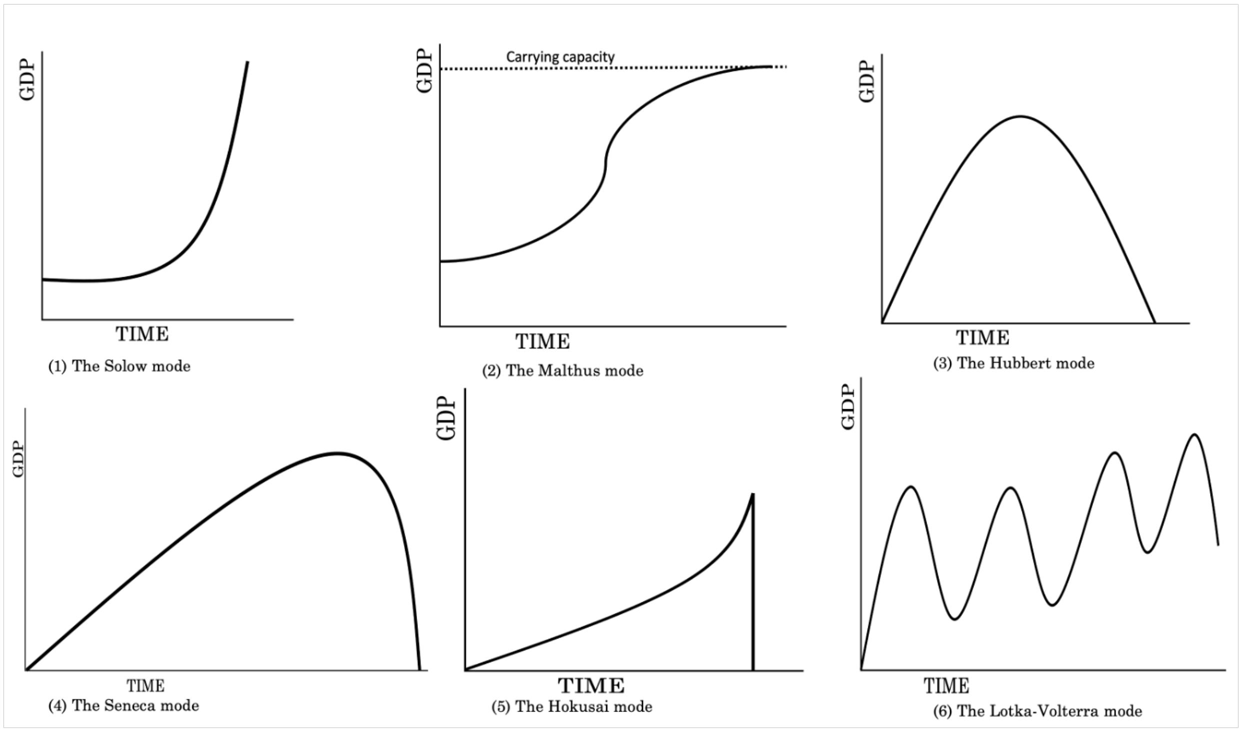
Bardi (2020, p.4), like Tainter (1988), defines societal collapse with reference to complexity, stating that collapse is “a phase transition that leads to a state of reduced complexity, typically being rapid and abrupt.” He argues (p.53) that there can be six growth modes in principle characterising the evolution of complex systems such as the economy. These are (i) the *Solow mode* where, as many Cornucopians believe, the economy can continue to grow exponentially indefinitely; (ii) the *Malthus mode* where the economy grows until a certain size and then stop growing; (iii) the *Hubbert mode* where the economy grows to a certain size and then gradually decline following an inverted bell-shape trajectory; (iv) the *Seneca mode* as discussed in the previous sub-section where the economy grows gradually over a long period and then after suddenly collapses; (v) the *Hokusai mode* where the economy suddenly collapses as result of an external existential impact, for instance cause by a meteorite or catastrophic pandemic; and (vi) the *Seneca Rebound mode* (also described as the Lotka-Volterra mode) where the economy collapses but recovers and restarts growth following a series of cycles.

These potential six growth models of complex systems are depicted in Figure 10.

In terms of these modes, proponents of exponential and of Green Growth, implicitly if not explicitly at least, are under the illusion that the global economy is a complex system in the Solow Mode. The Degrowth Movement seems implictly to labor under the illusion that the global economy follows either a Seneca or Hubbert mode, or even that abrupt climate change could imply a Hokusai mode. They want to avoid this by a deliberate invoking of the Hubbert mode, but forcing GDP (the complexity of the system) down to a level commensurate with the Malthus mode.

Put in this way, the difference between Green Growth and Degrowth is a difference between assumptions - or illusions - on the kind of growth mode that best characterises the complex global economic system. Putting it this way also shows that there is another growth mode that neither Green Growth, nor Degrowth, has considered: that the global economic system is

Figure 10: Six Growth Modes of Complex Systems



Source: Author's compilation based on Bardi (2020).

following a Lotka-Volterra (Seneca Rebound) mode. One reason why perhaps neither Green Growth nor Degrowth consider this, is that analysing such an economic system requires much deeper understanding of complexity and how complex systems' evolutionary paths are shaped. Bardi (2020, p.181) quotes Meadows, one of the authors of the LtG study, as admitting that "The Limits of Growth cannot mimic the emergence of the industrial revolution from the agrarian age. Nor, admits Meadows, can it take the world from the industrial revolution to whatever follows next beyond that."

If indeed the global economic system would over time follow an oscillating pattern described by the Seneca Rebound mode, then societal collapse could be seen "not a bug, but a feature" of complexity in the universe (Bardi, 2017). Hagens (2020) seems to see collapse, if not as a feature, as inevitable, and, in line with Tainter (1988)'s view that collapse is a result of societies becoming too bureaucratic and inflexible as a result of trying to assert control over its growing complexity, recommends[35] that the world prepare for a post-collapse, or "Great Simplification," inter alia by putting in place advance policies[36] which - are "solutions that the political and economic world are not yet ready to implement but will be critically important to plan for." Such a Great Simplification with advance policies is consistent with Bardi (2020, p.ix-xx)'s view that if collapse is not to be avoided, one should try to soften the blow (i.e. advance policies), but moreover that collapse - and a subsequent Great Stagnation - would offer the opportunity to "get rid of obsolete structures." This could lay the foundation for rebound growth and a transition to a new kind of economy - a kind of economy that we cannot now envisage, and which could be as qualitatively different from the current global economy as the industrial world was different from the world of the hunter-gatherer economy.

From a physics point, this is not ruled out. Physicists indeed consider rising and then falling complexity as a fundamental feature of the universe, given the Second Law of Thermodynamics which states that the entropy in a closed system (which the universe is) will always increase. Rising complexity can be seen as how the Universe accelerates from high order (low entropy) that marked the beginning of the universe (as a singularity before the Big Bang) to disorder (high entropy) that will mark the end of the universe. Aaronson et al. (2014, p.1)[37] explains that "our universe lacked complex structures at the Big Bang and will also lack them after black holes evaporate and particles are dispersed."

Olson (2015, p.1) points out that in the universe, "the appearance of aggressively expanding advanced life is geometrically similar to the process of nucleation and bubble growth in a first-order cosmological phase transition" and provides a model that describes how an intelligent complex civilization could arise and expand (i.e. increase its complexity and

[35]See for instance the Great Simplification Podcast at `https://www.thegreatsimplification.com/`.

[36]For the case for advance policy, See `https://vimeo.com/520475641`. An example of an advance policy that has been proposed is to put systems in place to "untax" human labor and tax non-renewable inputs at source.

[37]They use the example of milk being poured into a cup of black coffee: at first the black coffee has low complexity and high entropy. Once the milk is poured and its molecules interact with the coffee, it creates highly complex patterns, until the milk is fully dissipated and the coffee assumes an equal brown colour - a state of low complexity and higher entropy (Aaronson et al., 2014).

material footprint over time). Over time, such civilizations arise throughout the universe (not only on planet Earth) and utilization such amounts of energy that this and the resultant radiation eventually changes the very physical structure of the universe. This has been taken to imply that "we have completely misjudged the significance of life to the universe. Intelligent life may be the universe's large-scale, general-purpose tool for seeking out and minimizing deeply hidden reserves of free energy" (Fullarton, 2016). In other words, much as human have been doing with the energy bolus. In Olson (2015)'s model, while the universe is a closed system, the Earth and other planets are not - the Earth will continue to receive energy from its sun for another roughly 5 billion years.

The Second Law of Thermodynamics and its implications for whether economic growth could resemble a Seneca Rebound mode, therefore raises the question: is the Earth really, for all intents and purposes, an open system, or is it a closed system?

The Earth is not a closed system because it is clearly, in a thermodynamic sense, out of equilibrium - and this makes the planet habitable (Kleidon, 2012). Boulding (1966), in making the argument that the planet is a "Spaceship Earth," acknowledged that this is because the Earth is an open system with respect to energy from the sun, but stressed that it is a closed system with respect to materials. The belief in a Solow Mode of growth rests on assuming that humans can obtain more material-use efficiency, e.g through recycling, and continued value added growth through recombination of ideas and materials, and that the energy that will be needed to enable this recycling and recombinatory growth can be obtained from more efficiently harnessing renewable energy from the sun.[38] After all, "our total energy use is approximately 17 TW, which is roughly 10,000 times less than the power of the radiant solar energy arriving at the upper atmosphere " (Buchanan, 2017, p.106).

[38]Kardashev (1964) proposed that civilizations can be classified in terms of their technological ability to utilize energy. The Earth is a Type I civilization. A Type II civilization would utilize all the energy from its sun, e.g. through construction of a Dyson sphere; and a Type III civilization would utilise all the energy from all the stars in its galaxy.

Given the timescales that better harnessing the power of radiant solar energy would require against the timescales of peak oil, it seems unlikely that the global economy would follow a Solow mode of growth. Some collapse may be inevitable. Whether this will eventually rebound, perhaps characterised by qualitatively different growth as discussed, thus depend on whether humans can manage the transition from being Detritovores and manage the innovation to generate the technology to harness sufficient energy.[39] If so, and these may be big ifs[40], a Seneca Rebound may be the relevant growth mode, and humanity will be able to continue to fulfill its speculative destiny as the universe's tool to seek out and minimize "deeply hidden reserves of free energy."

5 Concluding Remarks

> "Never rid anyone of an illusion unless you can replace it in his mind with another illusion" — Nassim Nicholas Taleb

Against the span of 300,000 years that modern humans have been around, economic growth achieved in the last 0,08% of its history is an anomalous event. It has been compared to living on "this rocket ship that took off five seconds ago, and nobody knows where it's going" (Wiblin and Harris, 2021). This paper tried to provide some answers, from the perspective of economic growth, to the question where this "rocket ship" that is modern civilization, is headed.

In **section 2** it was pointed out that this question has been a topic of intense debate, at

[39]Not all scientists are convinced that seeking to harness renewable solar energy in this way would be appropriate. Murphy (2022a) is concerned that "if every jackass on the planet has access to cheap and abundant energy, what do you think they'll do with it? Will they use it to restore ecosystems, or hack more of it down for their own short-term gain?"

[40]There is at present no evidence of a Type II civilization anywhere in the universe. In the context of the Fermi Paradox this has been taken to possibly suggest that there is a "Great Filter" that prevents the rise and/or survival of technologically advanced civilizations (Hanson, 1998). Growth and subsequent collapse may be follow a Seneca Mode, after all. The search for extraterrestrial intelligence (SETI) has therefore great value in potentially resolving uncertainty about the possibility of a Seneca Rebound.

least since 1798, when the Reverend Thomas Malthus published *Essay on the Principle of Population*, warning that progress is inherently limited by natural resources. Subsequently, other "Malthusians" and "neo-Malthusians" similarly stressed the limits to growth; however, the failure of their predictions that food and other resources will run out and that over-population will lead to famine, gave fuel to the "Cornucopians." They trust that technological innovation will continue to turn scarcity into abundance, and that economic growth can be continued indefinitely.

In **section 3** it was argued that the Cornucopian belief in continued growth is based on assumption of no fundamental material resource scarcity, but that this belief is difficult to convincingly substantiate. Two problems were discussed in this regard: the first, was the growing evidence that economic growth is overshooting planetary boundaries, and that this poses an existential threat - threatening civilization collapse. The second was the idea of a carbon pulse as being the main mechanism that has been driving exponential economic growth - a stock of resources that has been largely ignored, or assumed away, by Cornucopians. Section 3 concluded that if the Cornucopians are to convincingly argue for unlimited economic growth, they need to be able to provide a case that technological innovations will be able to (i) mitigate climate change, (ii) steer around possible existential threats from ecological overshoot, and (iii) make up for the energy loss implied by the end of the carbon pulse (cheap and abundant fossil fuels).

In **section 4** the Cornucopians' response to these challenges was set out - which can broadly be described as a response that is built around the promotion of what can be labelled "Green Growth." Through Green Growth the hope is that economic growth can be decoupled from the environment - that is to say that economic growth can continue without exhausting resources or contributing to global warming, and that alternative, renewable and non-carbon energy sources can be found to substitute for the phasing our of fossil fuels. Green Growth is today the mainstream paradigm towards economic growth.

It was argued that although green growth can result in many beneficial outcomes on the environment, through for example enabling greater resource efficiency and allowing for decoupling between economic growth and some environmental outcomes - all of this potentially good barring unintended consequences such as re-materialization and human rights abuses - it may not be able to result in complete dematerialization and absolute decoupling. Green Growth may therefore not be able to stop an ecological overshoot and the risks that this will pose to human civilization.

Neo-Malthusians have in turn reacted to Green Growth by rejecting it - arguing that the only way to avoid resource depletion and an existential climate crisis is to make a concerted effort to scale down GDP - to "Degrow" the economy. The Degrowth Agenda is Malthusian in stating limits to economic activity. It attempts to provide an agenda - with a basis in Marxism - for enabling this and to provide for high levels of human welfare within planetary boundaries. It was argued that Degrowth will also not be likely to stop an ecological overshoot. Particularly, it was argued that degrowth would not only be ineffective, but it would be likely to worsen the environment; that it is a very expensive method to reduce carbon emissions; that it can be seen as a form of austerity for the working class; and that it is redundant. For these reasons, amongst others, degrowth as policy agenda is politically infeasible. The only example of a country where something similar to degrowth was ever maintained, was in 17th and 18th century Japan in the Edo period, but under a brutal dictatorship.

The question that remain is, what to do about the detritovores, if (exponential) growth, green growth and degrowth are not effective solutions?

In section 4.2 it was speculated that perhaps the answer lies in a third way: acceptance of a coming societal collapse, and preparation for a possible rebound that could take place. A growing number of scholars have been engaging in this line of thinking, and some view societal collapse as "not a bug, but a feature" of complexity in the universe. Such societal collapse could turn out to the irreversible - a veritable "end of the world." However, it may also be the case that a societal collapse could be followed by a rebound. In this view, a societal collapse could be an opportunity to get rid of obsolete structures, laying the foundation for rebound growth and a transition to a new kind of economy - a kind of economy that we cannot now envisage, and which could be as qualitatively different from the current global economy as the industrial world was different from the world of the hunter-gatherer economy.

Perhaps this possibility, like infinite Solow-type growth, Green Growth and Degrowth, may turn out to be an illusion. In the meantime, the slowing down of economic growth - the great stagnation - poses particular challenges for the world to make the transition away from fossil fuels and prepare to soften the collapse. First, it leaves the world much more exposed and vulnerable to shocks, including existential risks (Aschenbrenner, 2020; Bostrom, 2003). Two, it will make the adjustment to a zero-carbon emitting economy more costly (Lomborg, 2020). Three, it would raise the risk of conflict by turning the economy into a zero-sum game (Alexander, 2022; Naudé, 2022a). While growth, driven by new ideas and energy, contains its own risks, and perhaps it is the case that "the risks of stasis are far more troubling. Getting off the roller coaster mid-ride is not an option" (Mokyr, 2014). Whether on a rocket ship or a roller coaster, human civilization would need to learn how to become a better driver.

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