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ABSTRACT

Climate Technology Entrepreneurship: A Primer

This paper provides a primer on climate technology entrepreneurship, recognizing its limitations and potential adverse consequences. Climate technology entrepreneurship is needed to contribute to mitigation of and adaptation to climate change, and to help decouple economic growth from resource use. This paper identifies and describes three climate technology gaps: (i) an energy climate tech gap, an (ii) overshoot climate tech gap; and (iii) a resilience climate tech gap. The paper furthermore argues that policies for supporting climate technology entrepreneurship, including entrepreneurial ecosystems and mission-oriented approaches, have significant shortcomings. Furthermore, the paper concludes that Artificial Intelligence (AI) is unlikely to make a difference to the world's climate change predicament. Hence, climate technology entrepreneurship is no panacea for climate change and ecological overshoot caused by human activity. On its own it will not save the world.

JEL Classification: L26, Q54, O31, L53
Keywords: climate technology, entrepreneurship, climate change, sustainable development

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1 Introduction

The Paris Agreement of December 2015 committed[1] signatories to take action to try and limit "global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius" and to increase the "ability to adapt to the adverse impacts of climate change"(UN, 2015, p.3).

This is a hard challenge. To achieve this by 2100, with a 50 percent probability, the International Energy Agency (IEA) determined that concentrations of CO_2 should be stabilized at 450 ppm (parts per million) by 2030 (IEA, 2008). By 16 March 2025 there were already approximately 427.68 ppm CO_2 in the atmosphere.[2] Some scientists doubt that the Paris Agreement's target will be reached, and expect that the world will warm up by 2,5 degrees Celsius by 2100 (Tollefson, 2023).

Despite the world being off-target, *climate technology entrepreneurship* is widely expected to contribute to, if not exactly to achieve the target, to help the world come closer to it, and if all else fails, to facilitate adaptation to climate crises, at the least[3]. It is the edifice on which the notion of "green growth" is built, and underpins the "Green Deals" in the EU and pre-Trump 2.0 USA. It may also be useful to enable adaptation to global warming in the Global South, where vulnerability to environmental disruption is higher than in the Global North (Diffenbaugh and Burke, 2019).

The expectations of climate technology entrepreneurship is an instance of what Fressoz (2024, p.180) calls "playing the technology card" in the fight against climate change. Not everyone is convinced that climate technology entrepreneurship will save the world. The Degrowth movement warns that not only is it possible that the technology will not progress fast enough to decouple economic growth from the environment, but that it also require huge amounts of resources to create those technologies (Hickel, 2019). An important case against relying too much on climate technology entrepreneurship is that of the *Jevons Paradox*[4] which is that

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[1] This commitment to limit climate change is further elaborated in the UN's Sustainable Development Goals (SDGs), specifically SDG number 13, to "combat climate change and its impacts."

[2] See: `https://www.co2.earth/daily-co2`

[3] More cynical readers will remark that climate technology entrepreneurship is all about exploiting opportunities for profits due to climate change and that it has little concern for whether or not climate change is mitigated - see also Naudé (2024c) or Buller (2022). This may indeed be so; however this paper will depart from the assumption that promotion of climate technology entrepreneurship is a legitimate part of climate action.

[4] Jevons (1865) in his book "The Coal Question," argued that the technological innovations which improved the efficiency of steam engines in his day, would not result in a decrease in coal consumption in the

"in the long term, an increase in efficiency in resource use [due to technological innovation] will generate an increase in resource consumption rather than a decrease" (Mario and Kozo, 2018, p.2).

This paper provides a realistic primer on climate technology entrepreneurship, recognizing the limitations, and even unintended adverse consequences, of such entrepreneurship. It implies that climate technology entrepreneurship is no panacea for climate change and ecological overshoot caused by human activity. In short, climate technology entrepreneurship on its own will not save the world. As argued by Berners-Lee (2025) the belief that technology will save the world is "the new face of climate denial" (Jones, 2025). It needs at least to be supported by changes in "social" technologies, such as behavioral changes and changes in the underlying organization, norms and goals of society, including acceptance of the science (Berners-Lee, 2025). Naudé (2024c) calls on entrepreneurs and entrepreneurship scholars to let go of their obsession with firm growth and economic growth.

The paper is organized as follows. Section 2 motivates the need for climate technologies. Section 3 describes the challenge that this poses for entrepreneurs, outlining three climate technology gaps - which may be insurmountable. Section 4 examines the main policy approaches used to promote climate technology entrepreneurship, stressing their limitations. Section 5 asks whether AI could help climate technology entrepreneurs to bridge the gaps identified, concluding that this is unlikely given the nature and limitations of AI. Section 6 concludes.

2 The Need for Climate Technologies

Climate technology entrepreneurship can be defined as actions taken by entrepreneurs to develop, adopt, and adapt climate technologies through new ventures or new products and services within existing firms. Climate technology refers to any equipment, technique, practical knowledge or skill to reduce greenhouse gas emissions, adapt to climate change, reduce (or decouple) the ecological footprint of economic activity and extend clean energy to eradicate energy poverty (UNFCCC, 2018). Entrepreneurship, for purposes of this paper is defined, following Gries and Naudé (2011) as "the resource, process and state of being through and in which individuals utilize positive opportunities in the market by creating and growing new business firms."

UK, but rather would lead to an actual increase.

Climate technology entrepreneurs face a Herculean, if not impossible task. This section describes this task, which is defined by the need for climate technologies. The need is for climate technologies to (i) mitigate climate change through reductions in greenhouse gas (GHG) emissions; (ii) help societies adapt to the impacts of climate change and ecological overshoot; and (iii) decouple resource and material use, including fossil fuels, from economic growth. Climate technology entrepreneurs may not be able to meet all of these needs, with its best contribution perhaps being to assist in adaptation.

2.1 Mitigate Climate Change

Around two-hundred and fifty million years ago, the Siberian Traps, a vast network of volcanoes that covered a significant portion of modern-day Siberia, erupted. It released enormous amounts of greenhouse gases into the atmosphere, leading to acid raid, ocean de-oxygenation and the most severe global warming in the past 500 million years (Naudé, 2025a). When the dust settled, 90% of all species on Earth had gone extinct (Han et al., 2025). Now known as the Permian-Triassic Mass Extinction, it was the most severe of the five mass extinctions that has threatened life on the planet (Sun et al., 2024).

Today, human economic activity is re-enacting the Siberian Traps, causing billions of tons of greenhouse gases (GHGs) to be released into the atmosphere, causing global warming and a cascade of environmental consequences, including loss of biodiversity and threatening a sixth mass extinction(Dirzo et al., 2022; Cowie et al., 2022; Ehrlich et al., 2024). Biodiversity loss[5] has been warned to be "the greatest crisis humanity is facing," with "hundreds of species and myriad populations are being driven to extinction every year [...] Earth's richest biota ever is already well into a sixth mass extinction episode" (Ceballos et al., 2017).

Figure 1 plots the amount of CO_2 emissions in millions of tons since 1850 (approximately around the start of the Industrial Revolution) as well as the global average temperature anomaly relative to the 1961-1990 period. It clear shows the strong positive relationship between CO_2 emissions and global warming.

Figure 1 also shows that by 2022, the anomaly, or global warming, was 0,8 degree Celsius above the 1961-1990 period. By 2023, it had increased to about 1,17 degrees Celsius[6], and

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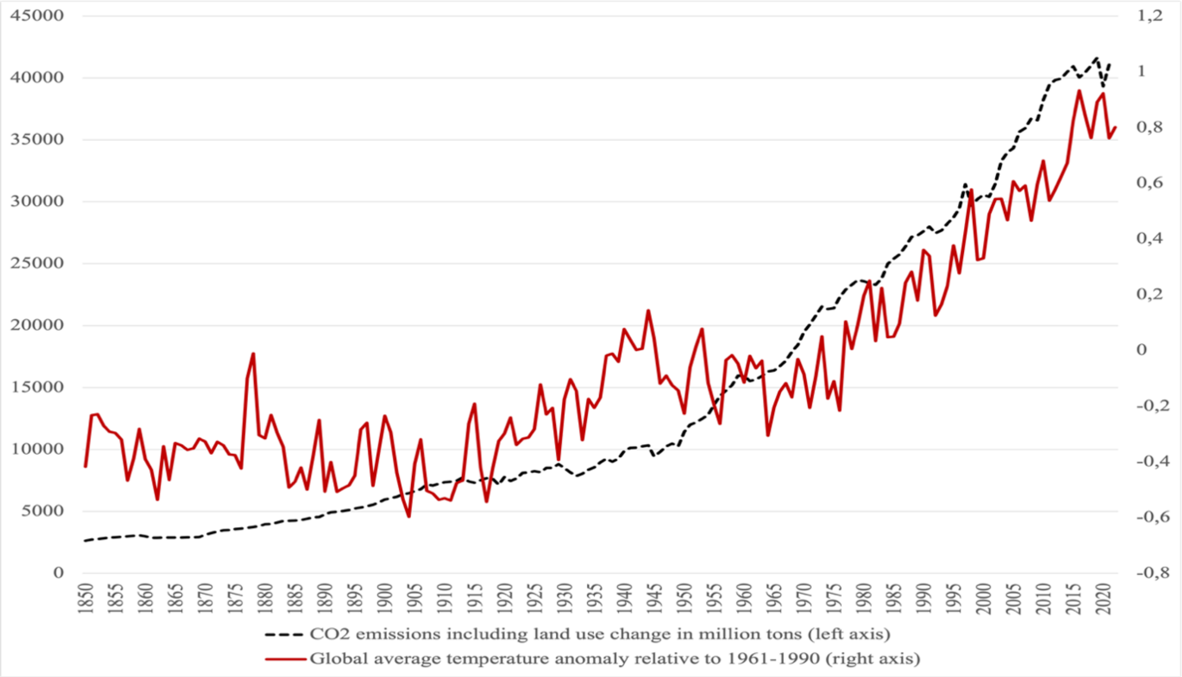
[5] Biodiversity loss is however, not a concern that is fully grasped in the field entrepreneurship, business and management. Giglio et al. (2023) points out that biodiversity risk is even by economists' standards and approaches, poorly priced.

[6] See NASA: `https://climate.nasa.gov/vital-signs/global-temperature/`

Figure 1: Carbon Emissions and Global Warming, 1850-2022



Source: Author's compilation based on data from Our World in Data : https://github.com/owid/co2-data

possibly more likely 1,49 degrees Celsius (Jarvis and Forster, 2024). This is of concern, as the Paris Agreement of 2015, adopted by 196 parties to the UN's COP21, set as target to limit global warming to to "well below 2, preferably to 1.5 degrees Celsius" compared to pre-industrial levels.

The amount by which carbon emissions have to decline to make achievement of this climate change target achievable implies that the world has a very limited carbon budget left, where the notion of a carbon budget refers to the amount of carbon dioxide (CO_2) that can be emitted into the atmosphere while still keeping global warming below 2 degrees Celsius. In per capita terms, to stabilize carbon in the atmosphere at a concentration of 450 parts per million (ppm) by 2050 to achieve this Paris Agreement goal, each person on Earth can only emit 2.5 tons of CO_2 equivalent (Matsuno et al., 2012). By 2021 already this was around 4.8 tons of CO_2 equivalent.

The Global North, consisting of historically industrialized nations, is responsible for the majority of historical carbon emissions. They have benefited from centuries of industrialization and economic growth fueled by fossil fuels. Countries in the Global South, which were often colonized and exploited during the Industrial Revolution, and who are still caught in an unequal global system where there resources are in net being appropriated by the Global North (see Hickel et al. (2022)) are have contributed less to historical emissions. However, their emissions have been increasing in recent decades as they industrialize and develop. While the Global South has contributed less historically, their emissions are rising as they strive for economic development.

Because developing countries have been responsible for only a relatively moderate share of the current stock of CO_2 in the atmosphere, *climate justice* implies that the carbon budget for developing countries are larger than for advanced economies. The challenge lies in balancing their development needs with climate mitigation efforts. This will require significant financial and technological support from developed nations- including finance for funding climate technology start-ups in developing countries, and technology transfer.

Failure to limit global warming to 2 degrees Celsius above pre-industrial levels may result in what has been described as a "ghastly future" (Bradshaw et al., 2021). This is because 2 degrees may represent a *tipping point*. In so-called *climate damage models* used by economists to estimate the monetary damage of climate change, these increase exponentially beyond 2 degrees Celsius rise in global warming - see for instance Dietz and Stern (2014), Nordhaus (2013) and Weitzman (2011).

Economic models far underestimate the economic damages from climate change for various reasons (see e.g. Buller (2022), Asefi-Najafabady et al. (2021), Keen (2020), Stern et al. (2022)) but especially due to cascading and non-linear feedback effects that are likely once Planetary Boundaries (PB) are breached (Naudé, 2024a). Once these are breached, there are at least nine *climate tipping points* which may trigger irreversible and catastrophic ecological collapse, such as the Arctic Sea-Ice, the Greenland Ice Sheet (GIS), the West Antarctic Ice Sheet (WAIS), the Atlantic Thermohaline Circulation (THC), the El Ninõ -Southern Oscillation (ENSO), the Indian Summer Monsoon (ISM), the Sahara/Sahel and West African Monsoon (WAM), the Amazon Rainforest and the Boreal Forest (Lenton et al., 2008, 2019). Six of the nine Planetary Boundaries have already been breached (Richardson and et al, 2023). See also the discussion in Naudé (2024a) on the implications for societal collapse.

Some scientists doubt that the Paris Agreement's target can still be reached, expecting that the world will face a 2,5 degrees Celsius warming by 2100 (Tollefson, 2023). Snyder (2016, p.226) claims that "stabilization at today's greenhouse gas levels may already commit Earth to an eventual total warming of 5 degrees Celsius."

2.2 Adaptation

Reducing carbon emissions to avoid an increase in global temperatures is therefore paramount, as the Paris Agreements and SDGs indicate - although given the extent of the predicament described in the previous sub-section one may be pessimistic about the prospects that entrepreneurs will be able to prevent a "ghastly" climate future. However, the mitigation of climate change is not the only climate challenge. There is also the challenge of adaptation to climate change.

The extent of global warming that has already occurred, as outlined, has already placed significant pressure on ecosystems and economies. Adaptation to the effects of climate change is therefore imperative. This adaptation challenge is worse in the Global South, as the evidence suggests that it already is and will in future be relatively worse off under global warming (Diffenbaugh and Burke, 2019). As Diffenbaugh and Burke (2019, p.9808) conclude "For most poor countries there is $>$ 90% likelihood that per capita GDP is lower today than if global warming had not occurred. Thus, our results show that, in addition to not sharing equally in the direct benefits of fossil fuel use, many poor countries have been significantly harmed by the warming arising from wealthy countries' energy consumption."

Given that the Global South faces a more substantial adaptation challenge than the Global North, does not mean however, that the Global South can or should go it alone as far as climate technology entrepreneurship is concerned. On the contrary, climate technology entrepreneurs in the Global South will benefit from international cooperation. In this it is useful to be aware of the differences in the needs and approaches of the Global South and Global North in the fight against climate change. The point is that the Global South and Global North have distinct needs when it comes to climate technology.

The Global South is particularly vulnerable to the impacts of climate change due to a variety of factors, including poverty, weak infrastructure, and reliance on climate-sensitive sectors like agriculture. Climate technologies can help overcome these, to an extent. Hence, the key impacts of climate change on the Global South, and examples of climate technologies that are relevant, are summarized in Table 1.

For the Global South, the key dimensions of climate technologies are that it should 1) have an adaption focus, 2) be affordable and accessible, 3) be able to generate technology transfer and capacity building and 4) balance development and climate action. In the Global North, the key dimensions of climate technologies are its 1) mitigation focus 2) innovation and

Table 1: Climate Changes Impacts on the Global South and Technology Solutions

Impact	**Consequence**	**Tech Solution**
Extreme Weather Events	Loss of life, property damage, and displacement of populations	Early warning systems, disaster risk reduction measures, climate-resilient infrastructure, and sustainable urban planning
Agricultural Disruptions	Changes in rainfall, temperature extremes, and increased pests and diseases that reduce crop yields and livestock	Climate-smart agriculture, drought-resistant crop varieties, efficient irrigation systems, and sustainable farming practices
Water Stress	Reduced water availability for agriculture and human health	Water conservation technologies, rainwater harvesting, efficient irrigation systems, and wastewater treatment
Sea-Level Rise and Coastal Erosion	Displaced coastal communities and damaged infrastructure	Seawalls and mangrove restoration; sustainable coastal zone management
Health Risks	Heat stress, waterborne diseases, and vector-borne diseases	Public health infrastructure, early warning systems for disease outbreaks, and climate-resilient health systems

Source: Author

research drive, 3) concern with scaling up and deployment and 4) provision of finance and investment.

While this broad distinction between the climate technology needs of the Global South and the Global North is useful, it is not watertight. For entrepreneurs in the Global South, the need to mitigate climate change do create opportunities - for instance conditions for the generation of solar energy and green hydrogen are often better in the Global South than in advanced economies, and much of the critical minerals that are needed for EVs are located in the Global South. However, the existence of these opportunities in the Global South are likely to be also another cause for conflict with and exploitation by the Global North - see e.g. Tricontinental (2024).

2.3 Avoiding Ecological Overshoot

In addition to climate change mitigation and adaptation, the third dimension of the climate challenge is to address the broader, or meta-problem, of *Ecological Overshoot* caused by human economic activity. Ecological Overshoot (EO) is “when the consumption of bio-resources and the production of wastes exceed the regenerative and assimilative capacities respectively, of supportive ecosystems” (Rees, 2022, p.2262). Climate change should be seen as one symptom or consequence of ecological overshoot. Ecological overshoot threatens the habitability of the planet - its growing extent implies that the global economy is not, at present, sustainable.

The extent to which human economic activity causes EO can be measured by calculating the *Ecological Footprint* of the world economy (and for countries). Figure 2 shows the world’s Ecological Footprint compared to available bio-capacity, measured in global hectares (gha), between 1961 and 2022. According to the Global Footprint Network,[7] “The Ecological Footprint is a metric of human demand on ecosystems, or more precisely on the planet’s bio-capacity. It tracks how much mutually exclusive, biologically productive area is necessary to renew people’s demand for nature’s products and services.” See also Borucke et al. (2013) and Wackernagel and Beyers (2019).

Figure 2 shows that the world has exceeded its bio-capacity already in the 1970s. According to the Global Footprint Network,[8] “Humanity demands goods and services from nature that require 20.8 billion global hectares to renew them, as of 2023. This is more than the 12.2 billion global hectares of biologically productive area (or bio-capacity) available on the planet. Excessive demand means that humanity, by now, uses 1.7 times more than the amount the biosphere currently renews. Some describe this level of consumption as using 1.7 Earths.”

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

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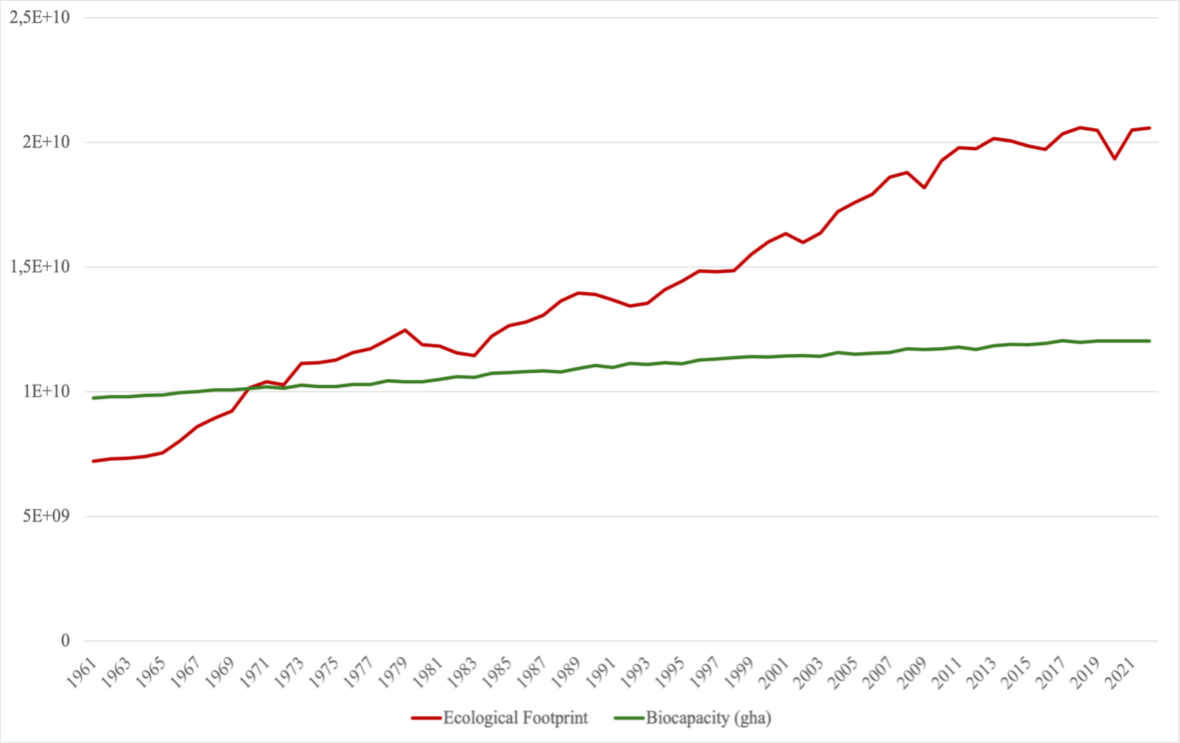
[7] See `https://www.footprintnetwork.org/what-ecological-footprints-measure/`

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

Figure 2: World Ecological Footprint vs Bio-capacity (in gha), 1961-2022

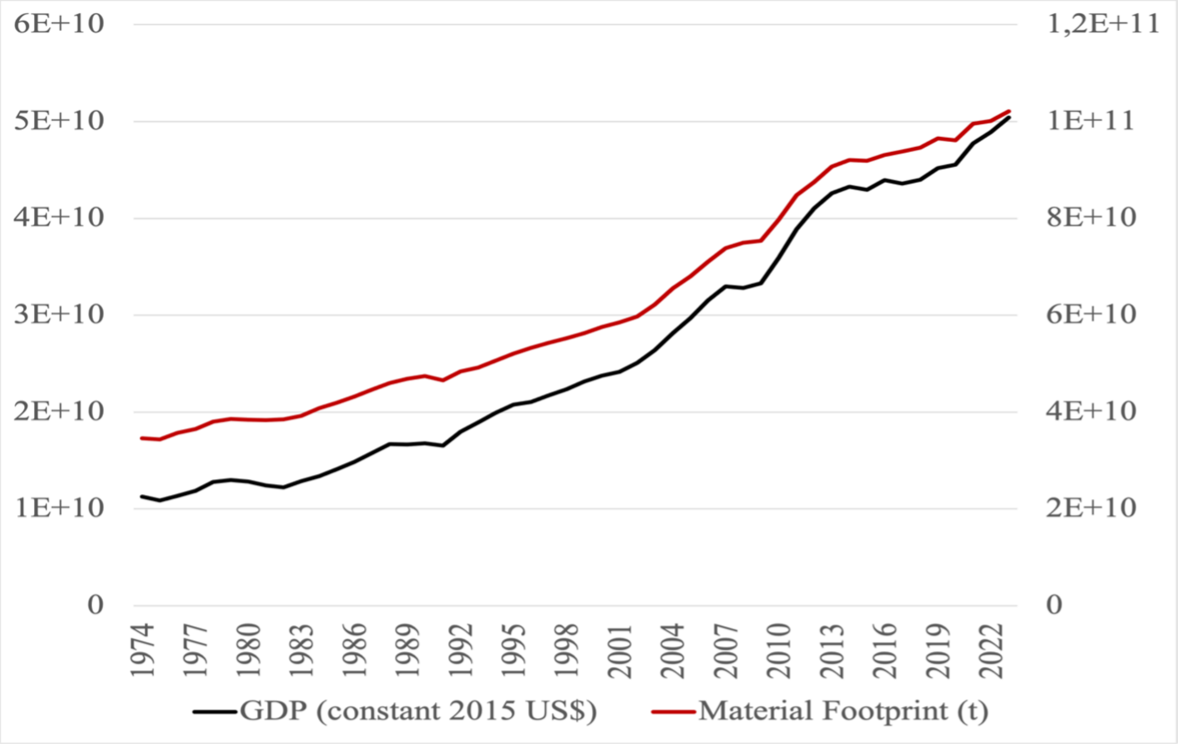


Source: Author's compilation based on data from the Global Footprint Network: https://data.footprintnetwork.org/)

Figure 3 shows the relationship between world GDP and the world's MF. It can be seen that there is a high correlation and that there is no evidence of absolute or relative decoupling on the global level. There is some evidence though of relative decoupling on the country level between GDP and growth in carbon emissions and pollution, for instance. However, globally, there is no decoupling, implying that further global economic growth will come at the price of further ecological overshoot. Haberl et al. (2020), surveying the empirical literature on decoupling finds that there is in many countries a relative decoupling between GDP growth and carbon emissions, but however, 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).

Figure 4 shows the relationships between GDP growth and fossil fuel use, confirming the conclusion of Haberl et al. (2020) that there is no decoupling between GDP growth and fossil fuel use. Fossil fuel use is the largest single contributor to GHG emissions.

Figure 3: World GDP and World Material Footprint (MF), 1974-2023



Source: Author's compilation based on data from UNEP's Global Material Flows Database and the World Bank Development Indicators Online

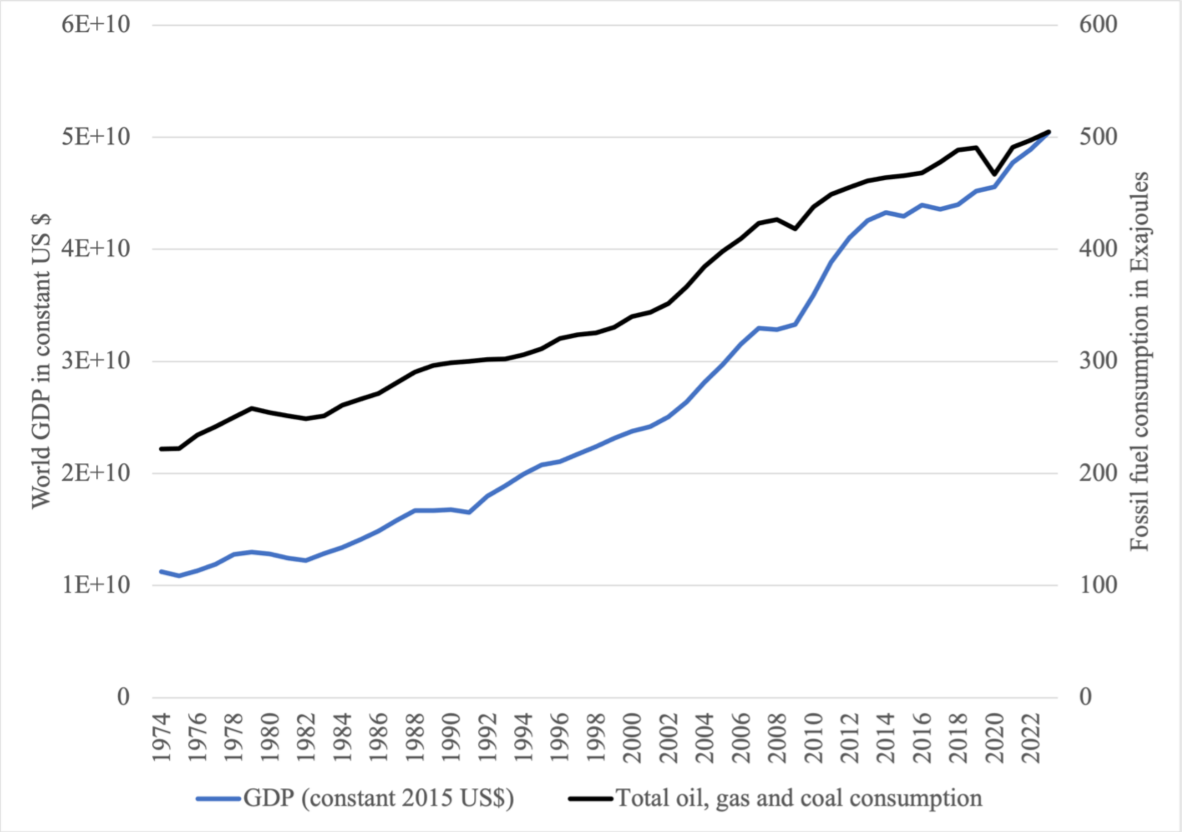
3 The Challenge: Climate Technology Gaps

In the previous section the need for climate technologies was discussed, namely to promote mitigation to climate change, to facilitate adaptation to climate change and to enable decoupling between the economy and the material world.

When generating and diffusion technologies to address these three needs, climate technology entrepreneurs need to simultaneously ensure that there technologies will be consistent with three bottom-line requirements: first, to facilitate the energy transition; two, to improve societal resilience; and three to eradicate energy poverty.

These three bottom-line requirements stem from the following. The Industrial Revolution and subsequent growth take-off that the world experienced since the early 18th century was not only the result of technological innovations, but also the result of the extensive use of fossil fuel energy: first coal, which kicked off the UK's industrialization, and then from around 1850 the use of oil and gas, which were critical for the subsequent development of the modern global economy.

Figure 4: Fossil Fuel Consumption and World GDP



Source: Author's compilation based on data from BP Statistical Review of World Energy and the World Bank Development Indicators Online

The downsides to fossil fuels as the engine of technological innovation and growth are twofold: one, fossil fuels is the source of the bulk of global GHG emissions and the provider of the energy for material resource extraction and use, which drives climate change and ecological overshoot; and two, fossil fuels are finite in supply, and moreover becoming more and more expensive to extract, meaning that more and more energy is needed to extract remaining supplies of fossil fuel energy - net energy is thus decreasing (Brockway et al., 2019; Court and Fizaine, 2017).

Hence, the meta-challenge is simple but stark: humanity must phase out consumption of fossil fuel energy and find alternative energy sources to prevent global economic collapse, strengthen the resilience of communities to climate change and its consequences, *and* address the need of communities who are in energy poverty.

The combination of needs and bottom-line requirements posed by Ecological Overshoot can be presented as a Challenge Matrix, as in Table 2.

Table 2: Climate Technology Challenge Matrix

	Facilitate Energy transition	**Improve Societal Resilience**	**Eradicate Energy Poverty**
Promote Mitigation	Phase out fossil fuel use; Increase share of renewable energy	Regenerate nature; Expand access to renewable energy; Efficiency gains in supply chains	Expand access to renewable energy
Facilitate Adaptation	Expand access to renewable energy; Improve efficiencies in resource use	Regenerate nature; Expand access to renewable energy; Improve governance	Improve efficiencies in resource use; Reduce energy consumption
Enable Decoupling	Improve efficiencies in resource use; Substitute material inputs	Improve efficiencies in resource use; Substitute material inputs	Reduce energy intensity; Improve governance

Source: Author

Table 2 indicates that technologies for enhancing and promoting mitigation of and adaptation to climate change and that enables decoupling, will also need to be able to simultaneously promote (and be consistent with) an energy transition, improvements in social resilience, and eradicate of energy poverty. This will require not only development and demonstration of new climate technologies, but also its dissemination and adoption - technology transfer.

For instance, solar panel-based technologies which will facilitate the energy transition out of fossil fuels, will help mitigate climate change; however, for it also to improve societal resilience and eradicate energy poverty, it will also have to be able to be accessible and adopted by households. An example of such a technology is green hydrogen (GH). This requires renewable energy sources, such as sun or wind power to help split water into hydrogen and oxygen, and then to store the hydrogen as an energy carrier. This can be used by the transportation and mining industries to reduce their GHG emissions. However, before this can be scaled up, there would need to be additional green technologies developed such as GH storage and distribution facilities, public transport using GH, GH powered cars and motorcycles, and moreover climate technologies that improves the safety of storing and using hydrogen in and around residential areas. These technologies may not yet exist or be ready to be rolled out. It means that there are areas where climate technology gaps exist.

For present purposes there are three climate technology gaps:

- The *energy climate tech gap* : the technological innovations and diffusion needed to make the energy transition.

- The *overshoot climate tech gap*: the technological innovations and diffusion needed to reduce ecological overshoot and decouple growth from harmful emissions and material (over) use.
- The *resilience climate tech gap*: the technological innovations and diffusion needed to enable countries to adapt to climate change and its consequences.

These climate technology gaps will be elaborated in the following sub-sections. It will be clear from the discussion that the extent of these gaps is such that it is doubtful that climate technology entrepreneurship will be able to fill all of these. Most success may perhaps be expected with respect to the resilience climate technology gap.

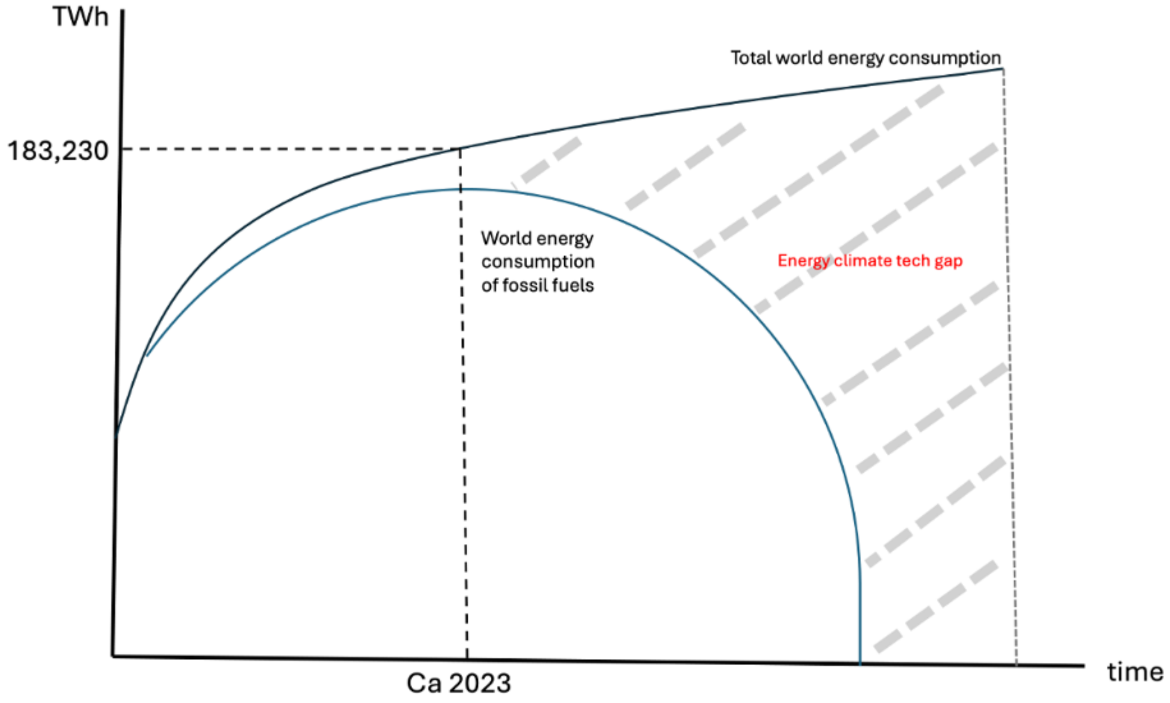
3.1 The Energy Climate Tech Gap

The energy climate tech gap arises because the extent to which an energy transition need to be made out of fossil fuels towards renewables, would require the development and dissemination of technologies that do not yet exist or exist only in embryonic form. In other words, without climate technologies that allows for an energy transition to be made, it would not be successful.

Figure 5 provides a diagrammatic depiction of the energy climate tech gap as a gap in terms of the TWh or energy consumption required to maintain current levels of economic activities and moreover meet the currently unmet needs of people in energy poverty. The energy climate tech gap shows a significant amount of renewable energy that would need to be supplied to prevent civilization from collapsing - this is the shaded area in the right part of the diagram.

Figure 5 shows that by 2023 the world was consuming around 183,230 TWh of energy per annum. Given the extent of energy poverty in the world, this would likely need to expand in future. However, as of 2023 the vast bulk of energy consumption globally was met from fossil fuels - oil, gas and coal - providing in total 140,231 TWh (77% of the total). However, as per the International Energy Agency (IEA) estimates, conventional oil peaked in 2008, and despite the shale and tar oil (non-conventional oil) contributions, total energy supply from oil and gas is set to gradually decline - not just because of declining stocks, but also because it becomes more expensive to extract and because countries are deliberating shifting our of

Figure 5: The Energy Climate Tech Gap



Source: Author

fossil fuels in order to meet their climate change commitments. The decline in fossil fuel energy consumption need to be made up from renewable and green sources (such as nuclear) to prevent the global economy from collapsing (Hagens, 2020; Naudé, 2024a).

The challenge is to produce sufficient and appropriate renewable energy to close this gap - meaning energy that provides in energy security and energy efficiency. Energy security refers to the uninterrupted availability of energy sources at an affordable price. Energy efficiency refers to using less energy to achieve the same level of service or output. It involves reducing energy consumption without compromising comfort, productivity, or quality of life. Examples of current technologies to improve energy security and energy efficiency include batteries and other storage technologies that can help balance supply and demand, ensuring a reliable energy supply, and building automation systems that can control lighting, heating, and cooling systems to reduce energy waste.

The key features or pathway for the energy transition, as most countries in the world and the global development community, including the UN system currently envisages it, is summarized by Michaux (2021, p.ii):

> “ICE vehicles are to be phased out and substituted with Electric Vehicles (EV) and Hydrogen Fuel cell powered (H2-Cell) vehicles. EV’s are to be powered with lithium io batteries. Coal-and-gas-fired electrical power generation is to be phased out and substituted with by solar photovoltaic, wind turbine, hydroelectric, nuclear, geothermal or biowaste energy power stations.”

According to IRENA,[9] what is needed to achieve the Paris Agreement’s goals, is that 90% of energy consumption by 2050 should be met by renewables. This will require that current renewables-based installed capacity increase 100-fold from 3300 gigawatts (GW) in 2022 to 33000 GW in 2050. It will also require that 90% of vehicles be Electrical Vehicles (EVs) by 2050.

Current renewable energy technologies, energy efficiency technologies, and green energy technologies such as nuclear, faces formidable challenges in making such an energy transition possible. The remainder of this subsection will discuss some of these challenges, drawing on (Gross, 2020), Michaux (2021), Heinberg (2024) and IRENA’s “Geopolitics of the Energy Transition” Report.

A first challenge is that renewable energy requires as inputs critical minerals such cobalt, copper, graphite, iridium, lithium, manganese, nickel, platinum, and several rare earth elements, such as neodymium and dysprosium. For example, as the Ellen MacArthur Foundation[10] describes,

> “Take a 500 megawatt offshore wind farm like the forthcoming Sydkustens Vind development in the Baltic Sea, which will be capable of powering around 250,000 Swedish homes. A development of this size currently requires around 4,400 tonnes of copper. Given that in 2050 it is estimated that installed wind power capacity will be 6 million megawatts, if half of this comes from offshore farms an estimated 27 million tonnes of copper will be needed to build the necessary infrastructure.”

This need raises various potential problems, such as physical limitations in available supply of minerals, supply bottleneck risks and value chain disruptions, delays due to the long time it may take to bring mining projects to production, price volatility due to supply-demand imbalances, and geopolitical risks, including new resource wars.

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[9] See: `https://tinyurl.com/yhzf35ym`

[10] See: `https://www.ellenmacarthurfoundation.org/we-need-to-talk-about-renewables/part-1`

The entrepreneurial opportunities that these challenges creates are for disruptive technological innovations to provide substitutes for these minerals, to lessen dependence on rare minerals, to shorten supply chains, and to improve the efficiency of the use of these minerals in renewable energy technologies. In this latter regard, the role of the minerals in current climate technologies are useful to highlight. Table 3 describes the connection.

Table 3: Critical Minerals in Renewable Energy Climate Technologies

Critical Mineral	**Main Role**	**Other Roles**
Cobalt	EV Batteries	Battery Storage; Bioenergy; Electrolysers
Copper	Electricity grid; EV Batteries; Solar PV	Battery Storage; Bioenergy; CSP; Electrolysers; Geothermal; Hydro
Dysprosium	EV Motors; Wind	
Graphite	EV Batteries	Battery Storage
Iridium	PEM Electrolyzers	
Lithium	EV Batteries	Battery Storage
Manganese	EV Batteries	Battery Storage; CSP; Electrolysers; Geothermal; Hydro; Wind
Neodymium	EV Motors; Wind	
Nickel	Electrolysers; EV Batteries	Battery Storage; Bioenergy; CSP; Geothermal; Hydro; Solar PV
Platinum	PEM Electrolyzers	

Source: Adapted from IRENA (2023, p.32).

A second challenge is that renewable energies still require fossil fuels to be produced and distributed. Expanding mining operations, manufacturing renewable energy infrastructure, and developing adequate storage solutions all require substantial energy and resources. Fressoz (2024, p.212) for instance reports that “35-40 per cent of the wind and solar capacity built recently in China has been bundled with coal power.” This is to overcome the intermittency problem of wind and solar and to recover the high costs of connecting renewable energies to the grid.

More generally, the initial construction of solar panels and wind turbines requires fossil fuel-powered machinery and energy-intensive materials like steel and concrete. Bio-fuels’ production can involve fossil fuel-powered machinery and fertilizers, the latter particularly dependent still on fossil fuels. Large-scale hydropower dams require significant building materials and construction, currently not possible without fossil fuel-powered equipment.

Transporting solar panels and wind turbines materials and components to manufacturing facilities and installation sites consumes fossil fuel energy. Moreover, solar panels and wind farms do not last forever: they require constant maintenance, and at some stage, estimated at around 25 - 30 years, solar panels and wind turbines would need to be replaced, again necessitating the use of fossil fuels (Heinberg, 2024).

It is unclear if society can dedicate the required energy and resources to this transition while maintaining existing energy consumption levels (Heinberg, 2024).

The entrepreneurial opportunities that these challenges create are for new climate technologies that reduces the energy intensity for manufacturing solar PV and wind turbines, including in terms of process and material inputs; that reduces the need for transportation and that may use clean transport energy sources, such as those from green hydrogen (GH). A further entrepreneurial opportunity is the invention and roll-out of solar and wind energy infrastructure with longer lifetimes.

A third challenge of transitioning to renewable energy is that it has negative environmental side-effects. These include adverse land use, noise, pollution and waste, and potentially adverse health impacts (Bosnjakovíć et al., 2023; Hamed and Alshare, 2022; Tsoutsos et al., 2005; Neff, 1981). Solar and wind farms can also threaten biodiversity (OECD, 2024).

It is particularly the mining for renewable energy critical minerals that has attracted much concern for its negative impacts on biodiversity. The OECD (2024, p.67) for instance warns that “Habitat loss and degradation are among the main direct impacts of mining.” They provide examples of this negative impact, such as the case of Brazil where “mining has destroyed exceptionally diverse plant communities” and to the Indonesia, where the “Grasberg copper and gold mine, which neighbors Lorentz National Park, a World Heritage Site, has been associated with pollution of rivers and lakes in the area due to riverine tailing disposal” (OECD, 2024, pp.67-68).

The entrepreneurial opportunities that these challenges create are for new climate technologies, including innovative business models that can mitigate these side-effects. For example, agrivoltaic technologies and sustainable business models based on these may facilitate the combination of solar panels with agriculture or livestock grazing (Asa’a et al., 2024); designing cost-effective and efficient floating solar farms may help minimize land use impacts; and inventing ever more efficient transmission and distribution networks that will minimize need for extensive and invasive infrastructure will reduce the negative environmental effects of these renewables.

Fourth, in addition to be low density and diffuse sources of energy that are relatively expensive to harvest, renewables are intermittent and unpredictable sources of energy. This means that energy harnessed from solar PV panels and wind turbines require battery technology to be stored and distributed. Moreover, renewable energy is and not yet efficient for supporting transportation at scale. EV engines are four times as efficient as oil based engines, however, it is much easier and cheaper to carry the fuel that is needed for the vehicle around than in the case of an ICE using oil, than on an EV (Jancovici and Blain, 2024). For instance, a liter of petroleum is very energy dense and safe to store in a tank onboard a vehicle - it provides around 45 MJkg energy. In comparison, a lithium battery on board an EV provides only 0,5 MJkg energy - petroleum is thus around 100 times more powerful.[11]

The entrepreneurial opportunities that these challenges create are for new climate technologies are to develop better battery technologies, and moreover to enable green hydrogen[12] (GH) to be used more cost effectively and safely as a means of energy for vehicles, including shipping liners, buses and aircraft. Hydrogen is the highest energy density fuel, providing around 142 MJkg energy. Climate technology entrepreneurs are needed to improve technologies that will bring down the costs of hydrogen fuel cell electric vehicles (FCEVs). This will require innovations along the entire supply chain of GH: from the development of cheaper and more effective electrolyzers - that can be mass produced - to the installation of GH refuelling stations and storage facilities, to the development of larger, affordable and safe fuel tanks on board vehicles (GH is highly flammable) (Islam et al., 2024; Soleimani et al., 2024).

In conclusion it should be clear that the challenges facing climate tech entrepreneurship in closing the energy climate tech is formidable, if not insurmountable.

3.2 The Overshoot Climate Tech Gap

The *overshoot climate tech gap* refers to the lack of sufficient the technological innovations and their diffusion to reduce Ecological Overshoot (EO), and decouple growth from harmful emissions and material (over-) use. Figure 3 has shown the relationship over time between GDP and the world's Material Footprint (MF). This showed that there is no absolute decoupling between GDP and the world's MF: economic growth will always require the physical

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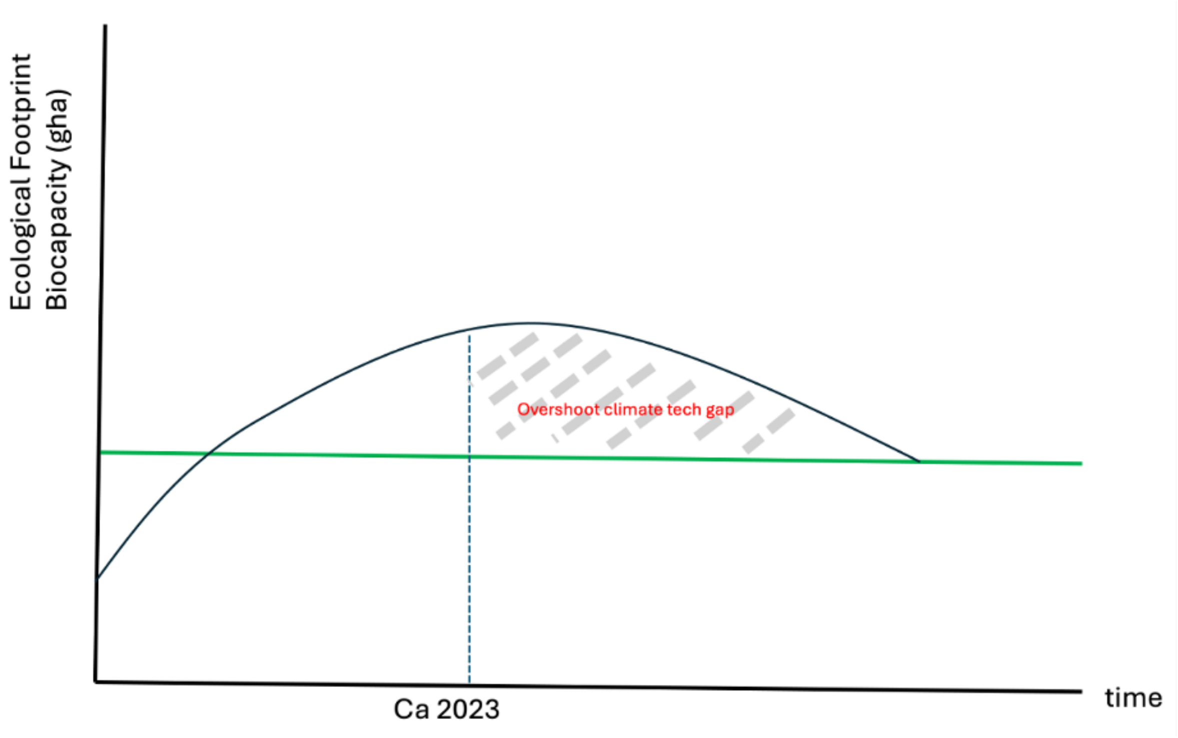
[11] See: `https://tinyurl.com/2snbsj9w`

[12] Green hydrogen results from water electrolysis that split water into oxygen and hydrogen using energy from renewable resources, such as solar or wind (Thomas, 2024). Hydrogen that is obtain from other energy sources, such as coal or gas are referred to as brown or grey hydrogen.

use of resources. As Figure 2 showed this inevitably leads to EO, where the bio-capacity - the bio-physical limits of the planet - is exceeded.

Figure 6 provides a diagrammatical depiction of the overshoot climate tech gap.

Figure 6: The Overshoot Climate Tech Gap



Source: Author

Figure 6 shows that ca 2023, the world was deep in Ecological Overshoot. The Global Footprint Network has calculated that by 2023, the global economy was using the bio-capacity of 1,7 planets. In other words, the planet is suffering an *ecological deficit*. The role of appropriate climate technologies is to help eradicate this ecological deficit, and the extent to which technologies current fail to do so, and in fact are contributing in many cases to worsen this ecological deficit, defines what is labeled here the overshoot climate tech gap.

According to the *Global Footprint Network*, the ecological footprint is the result of resource consumption due to food (land is needed to grow crops and raise livestock), fiber (land is needed to produce cotton, wool, and other fibers), timber (forest are required for timber production), sinks (land needed to absorb carbon dioxide emissions from burning fossil fuels) and the impact of built-up land (land is needed for infrastructure like cities and roads). Against this, bio-capacity is calculated, in geographically comparable global hectares (gha) by calculating the biological productivity of various ecosystems, including forests, grasslands, cropland, and fisheries.

Therefore, climate technologies appropriate to the overshoot climate tech gap are technologies that will enable the same or more resource consumption using less land, and that will improve the productivity of natural ecosystems. Appropriate technologies are technologies that decouple economic growth from material use - in other words, it enables economic growth to continue without increasing the economy's Ecological Footprint and resulting in Ecological Overshoot. There are two notions of decoupling, absolute decoupling and relative decoupling. Relative decoupling occurs when the rate of resource use or environmental impact grows slower than the rate of economic growth. Absolute Decoupling is the ideal scenario where resource use or environmental impact decreases while the economy continues to grow. This would mean a complete break between economic growth and resource consumption.

The key climate technologies to facilitate absolute and relative decoupling include many climate technologies already discussed, such as renewable energy technologies, energy efficiency technologies and green transportation technologies. These can be applied in key carbon-intensive sectors, such as agriculture - examples includes precision agriculture, vertical farming and hydroponics and aeroponics.[13]

There is also hope that circular economy technologies (which include technologies that enable recycling and waste reduction and extend the product life-cycle) and digitalization can partly dematerialize production and decouple economic growth from the material base. The challenge here is, as was noted in the introduction, the Jevons Paradox, which means that efficiency gains enabled by these technologies will lead to increased, not decreased total consumption. Indeed, it was already mentioned that empirical evidence has so far rejected that absolute decoupling is taking place (see Haberl et al. (2020)).

With little prospect of technologies that increase efficiency of resource use achieve the decarbonisation targets that the world needs to meet, the focus is increasingly shifting to Carbon Capture, Utilization, and Storage (CCUS) Technologies. These are known as negative emission technologies and include tools that directly remove carbon dioxide from the atmosphere (Direct Air Capture - DAC), that utilizes captured carbon dioxide to produce fuels, chemicals, or building materials and that stores captured carbon dioxide underground to prevent its release into the atmosphere (Kazlou et al., 2024).

According to the third part of the Sixth Assessment Report of the IPCC, CCUS technologies

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[13] See: `https://www.wur.nl/en/research-results/dossiers/file/vertical-farming.htm`

have a vital contribution to make to reduce emissions from sectors like industry and power generation that are difficult to decarbonize completely (IPCC, 2022). As described by the International Energy Agency[14] (IEA), “CCUS is an enabler of least-cost low-carbon hydrogen production, which can support the decarbonisation of other parts of the energy system, such as industry, trucks and ships.”

The amount of carbon that needs to be removed varies across different scenarios, but it is generally substantial. For instance, in scenarios aiming to limit warming to 1.5°C, several hundred gigatons of CO_2 will need to be captured and stored over the century. The IPCC (2022) points out that “without CCUS, the world’s fleet of coal and gas plants would need to retire 23 and 17 years early, respectively, to keep emissions low enough to restrict global warming to between 1.5 and 2°C” - see also IEF (2022).

The IEA[15] notes that despite there currently being “over 700 projects in various stages of development across the CCUS value chain” there is still a technology gap since “even at such level, CCUS deployment would remain well below what is required in the Net Zero Scenario.” At the end of 2024 there was only around 45 commercial capture facilities in operation in the world, removing an estimated paltry 50 Mt CO_2 annually.

3.3 The Resilience Climate Tech Gap

The third climate technology gap is the resilience climate tech gap. This refers to the technological innovations and diffusion that are needed to enable countries to adapt to climate change and its consequences. As was mentioned, the Global South tend to be much more vulnerable, and less resilient, to the impacts of climate change and Ecological Overshoot. This is partly due to lack of sufficient energy - hence eradicating energy poverty is a central plank in reducing the resilience climate tech gap. This gap can be further explained with the diagram in Figure 7.

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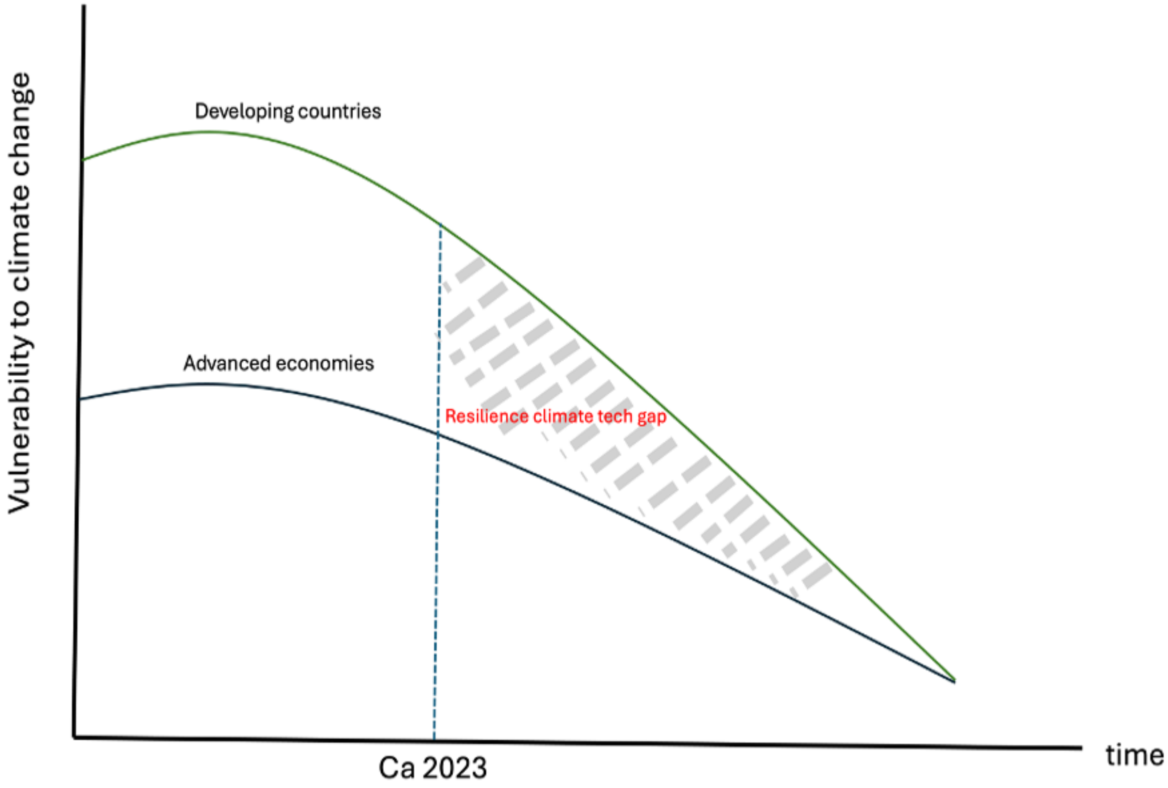
[14] See: `https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage`

[15] See: `https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage`

Figure 7: The Resilience Climate Tech Gap



Source: Author

Figure 7 shows that the resilience climate tech gap exists due to the fact that the Global South remains more exposed to climate change than the advanced economies of the Global North. There is a need for appropriate climate technologies to help the Global South to close this gap, including technologies that address energy poverty.

Figure 8 shows the gap in vulnerability to climate change between the Global South and Global North, as measured by the *GDL Vulnerability Index*.[16]

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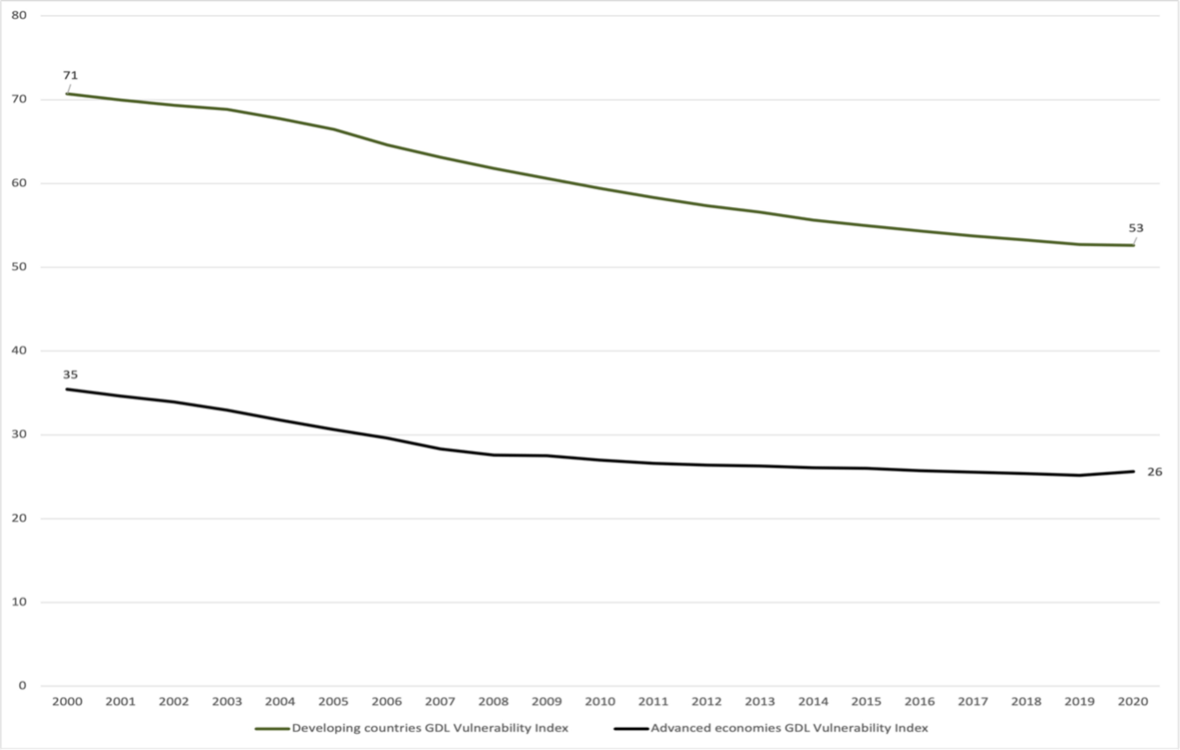
[16] See: `https://globaldatalab.org/gvi/`

Figure 8: Vulnerability to Climate Change: The Global South vs the Global North, 2002-2020



Source: Author, based on data from Global Data Lab at `https://globaldatalab.org/gvi/`

As shown in Figure 8 vulnerability to climate change has declined gradually over time. This is due to inter alia increases in GDP per capita which reflects technological progress, improved access and quality of human capital (education), increases access to and use of energy (particularly as electricity), and greater trade openness and mobility.

The need for further technological innovation - to deliver appropriate climate tech for adaptation to climate change (and hence to reduce vulnerability to climate change) is emphasized in the IPCC's 2017 Shared Socioeconomic Pathways (SSPs). The SSPs are scenarios from using Integrated Assessment Models (IAMs)[17] that outline potential future developments in human society, including population growth, economic development, technological advancements, and social changes.[18] They served as inputs to the IPCC's sixth assessment report and serve to focus attention on the future, including the future of required climate technologies. The five SSPs are (see also Riahi and et al (2017)):

- SSP1 - Sustainability: This pathway envisions a world focused on sustainability, with

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[17] The SSPs was generated using six different integrated assessment models (IAMs) - Vuuren et al. (2021).

[18] See: `https://tinyurl.com/ybvx6pee`

rapid technological development and global cooperation to achieve social and environmental goals.

- SSP2 - Middle of the Road: This pathway represents a continuation of current trends, with moderate economic growth, gradual technological advancements, and uneven progress in addressing social and environmental challenges.
- SSP3 - Regional Rivalry: This pathway depicts a fragmented world with regional conflicts, limited cooperation, and a focus on national interests. Economic growth is slower, and environmental concerns are often neglected.
- SSP4 - Inequality: This pathway highlights increasing inequality, both within and between countries. Economic growth is concentrated among the wealthy, while the poor face limited access to resources and opportunities.
- SSP5 - Fossil-Fuel Development: This pathway emphasizes fossil fuel-intensive development, with rapid economic growth and a focus on energy-intensive industries. Environmental concerns are prioritized less than economic development.

The best pathway for closing the vulnerability to climate change gap depicted in Figure 8 above, is the SSP1 scenario. Scenario SSP1 is also best for mitigation of climate change. The worst scenario for adaptation to climate change and for developing countries would be SSP4. SSP5 would be the worst scenario for mitigation of climate change.

SSP1 is however, the scenario in which the most strong assumptions are made as for climate technological progress. This scenario, as well as the targets set by the international community for decarbonisation, assumes rapid technological progress in several key climate technologies. It assumes vibrant and successful climate technology entrepreneurship. The key assumptions being made about climate technology progress are discussed in the following sub-sections - these can be seen as the challenges facing climate technology entrepreneurs, and which implies that much remains to be done.

3.3.1 Energy Efficiency

It is widely assumed that sufficient progress will be made to generate and diffuse affordable energy efficient technologies, such as energy-efficient appliances, smart grids that optimizes energy distribution and consumption, and with technologies that improve building energy efficiency such as insulation, ventilation, and lighting (e.g. LED) technologies; and also new technologies to reduce energy consumption in manufacturing / industrial processes. These can include technologies such as smart thermostats that automatically adjust temperature settings to optimize energy use; building automation systems that control lightning, heating and cooling and energy efficient motors.

It is also widely assumed that "inefficient, traditional bio-fuel use" will be phased out (Vuuren et al., 2021). Improving energy efficiency has been argued to be as important for achieving the climate goals as the shift to renewable energies. Shah (2024) reports that if appropriate energy efficiency technologies are implemented in sectors such as industrial manufacturing, transport and the built environment by 2030, that energy intensity in the global economy could decline by 30% and that around US $2 trillion could be saved on energy costs annually.

3.3.2 Renewable Energy

SSP1 assumes a fast growth of renewable energy use. It is assumed that renewable energy costs will decline even faster than in recent times and that technologies will be developed that will help renewables to be more easily absorbed into electricity grids (Vuuren et al., 2021). According IRENA 90 percent of the world's electricity can and should come from renewable energy by 2050.[19] By 2023 this was 30%, with most electricity still being generated using coal and gas - see Figure 9. Furthermore, around $4.5 trillion annual investment is needed to in renewable energy until 2030 to achieve net-zero emissions by 2050.[20]

This presents a significant entrepreneurial opportunity, particularly in regions such as Africa, where currently around 70% of energy consumption comes from renewable energies, but where the per capita energy consumption is significantly lower than in other regions. For instance, by 2023 the average per capita primary energy consumption in Africa was 14,3 Gigajoule per capita, compared to 230 Gigajoule per capita in North America, 115,2 in Europe and 142,9 in the Middle East (source: *2024 Energy Institute Statistical Review of World Energy*). If it is assumed that the per capita GJ primary energy consumption in Africa will equal that of Europe by 2050, and that all of the additional energy will be coming from renewable energy, the implication is that by 2050 a total of 288 billion GJ of energy need to be produced in Africa from renewables, up from the current 20 billion.[21]

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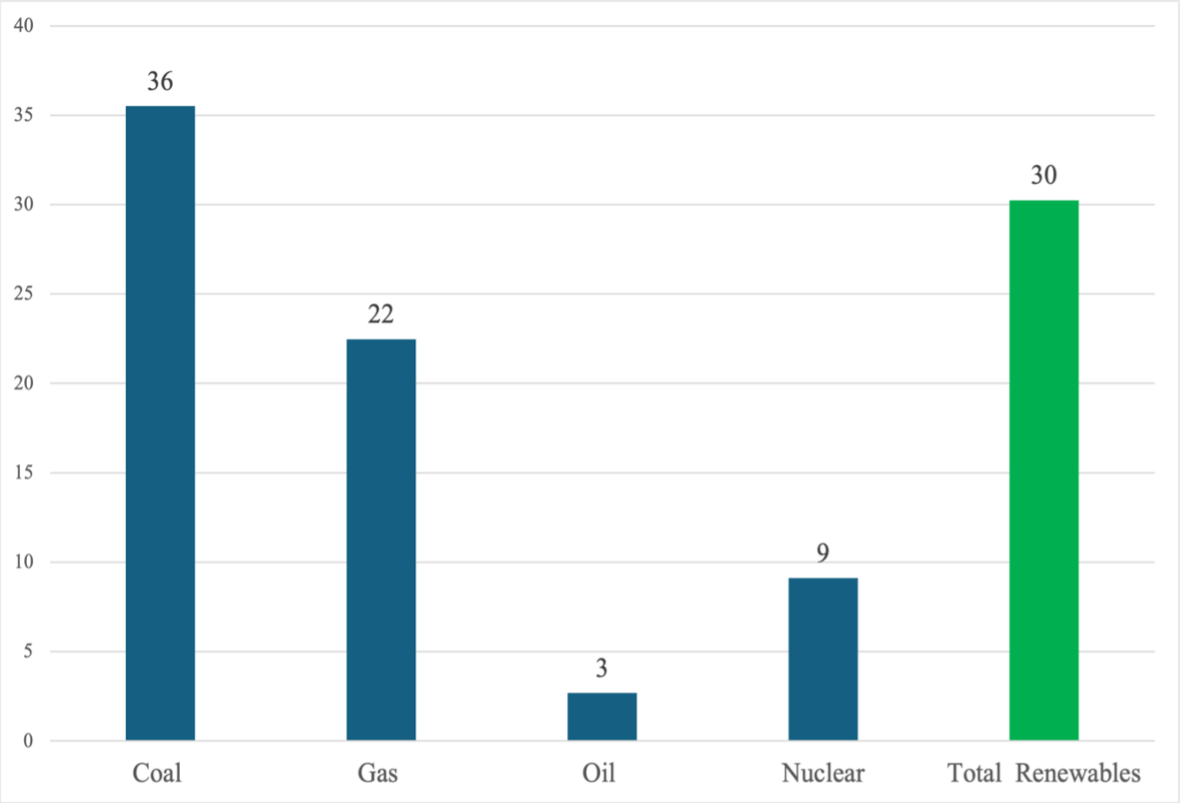
[19] See: `https://www.un.org/en/climatechange/raising-ambition/renewable-energy`

[20] See: `https://www.un.org/en/climatechange/raising-ambition/renewable-energy`

[21] This assumes, based on UN forecasts, that Africa's population increases from its current 1,4 billion to 2,5 billion by 2050. See: `https://www.imf.org/en/Publications/fandd/issues/2023/09/`

Figure 9: Share of Electricity by Source, World (%), 2023



Source: Author, based on data from Our World in Data, https://ourworldindata.org/electricity-mix

3.3.3 Carbon Capture, Utilization, and Storage (CCUS) Technologies

In climate scenarios it is assumed that mature CCUS technologies will be developed for capturing and storage of more than 90% of carbon dioxide emissions from energy plants and industries.

According to Kazlou et al. (2024, pp.1047-1049) if one assumes a doubling of CCUS plans by 2025 and that all of these would be successful, it would lead to the amount of carbon removed to be around 400 $GtCO_2$ by 2070 and 1,100 $GtCO_2$ by 2100. They note that this is less that the amount assumed in most of the IPCC's mitigation pathways, which "envision up to 700 $GtCO_2$ captured and stored by 2070 and 1,400 $GtCO_2$ by 2100."

`PT-african-century`

3.3.4 Bio-energy with Carbon Capture and Storage Technologies (BECCS)

These are what is known as carbon dioxide removal (CDR) technologies. BECCS is a process that combines bio-energy production with carbon capture and storage technology to remove CO_2 from the atmosphere. Note that CCUS and CDR tech both aim to reduce carbon dioxide, but does so using different mechanisms. CDR removes CO_2 from the atmosphere (Direct Air Capture - DAC), while CCUS captures CO_2 from point sources.

Other relevant CRD technologies include afforestation and reforestation. According to the International Energy Agency (IEA), BECCS will need to remove 250 million tonnes of carbon dioxide annually by 2030. This is a significantly more than the current level of just 1 million tonnes per year. Overall CDR need to remove 10 billion tonnes of CO_2 from the atmosphere by 2050 in order to stabilize climate change.

3.3.5 Climate Smart Agriculture

Although the SSPs do make explicit assumptions about progress in sustainable (or climate smart) agriculture, it is implicitly assumed that business models in agriculture would support both climate change adaptation as well as mitigation.

The implicit assumption in this is that food production will keep up with population growth and demand growth, but with less carbon and nitrogen emissions and less adverse land use. This will require a fine balancing act between technologies that enable adaptation, such as drought-resistant crops, precision, reduced water usage, and technologies that improve crop yields and expand value added (which causes higher demand for materials and transport and raises the ecological footprint of agriculture.

3.3.6 Climate-Resilient Infrastructure

It is assumed in the SSPs that significant investment takes place in climate-resilient infrastructure. This is “infrastructure that is planned, designed, built and operated with changing climate impacts in mind” (Cho, 2024). It includes coastal protection infrastructure and systems such as seawalls , natural barriers and early warning systems.

The OECD (2018) note that energy, transport, building and water infrastructure contribute more than 60% of global GHG emissions, and that infrastructure investment of up to “US$

6.9 trillion a year is required up to 2030 to meet climate and development objectives" (OECD, 2018, p.15).

3.3.7 Electric Vehicles

SSP scenario's recognize that, in order to reduce GHG emissions from transportation significantly, that the fleet of vehicles on the world's roads should be as far as possible be electrical - the assumption is that almost all new vehicle sales should be electric by the mid-2030s. In the Netherlands, the government has adopted a target of 100% of all new vehicle sales by 2030 to be electrical (Paradies et al., 2023).

The International Energy Agency (IEA) reports that, according to announced government targets and pledges at COP, the global EV fleet should be around 250 million in 2030 with total EV sales reaching 45 million. This would be an estimated 35% of all vehicle sales.[22]. The IEA also estimates that due to the growing sales of EV by 2030, the world would need 6 million barrels of oil a day less by 2030.[23] Of course, as per the Jevons Paradox, these barrels of oil will not remain in the Earth, but will be used elsewhere.

The challenge for climate technology entrepreneurship are to design, produce, finance and make affordable EVs, in particular in difficult to decarbonise sectors such as freight transportation. It would require much complementary climate technology, such as recharging stations, more efficient batteries.

According to Paradies et al. (2023) the Netherlands will not achieve its target of 100% of sales of new vehicles to be all EVs, and that the share will be most likely between 26% and 40%.

3.3.8 Climate Finance

The climate technological advancements that are needed to realize the assumptions that are made for reaching the world's climate goals, should be coupled with strong global cooperation particularly to ensure adequate finance for the investment in research, development and demonstration (RD&D) that this will required.

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[22] See: `https://tinyurl.com/nm9w357w`

[23] See: `https://www.iea.org/energy-system/transport/electric-vehicles`

According to Dunbar et al. (2024, p.1) there has been an significant "increase in climate technology investments, witnessing 210 % growth between 2020 and 2021, constituting approximately $87.5 billion. " But significantly more is needed, especially if climate technological entrepreneurship in the Global South is to receive adequate support. In 2009 a target of US $100 billion in climate finance for the Global South was agreed on. As this was not met, during the 2015 Paris COP, the New Collective Quantified Goal (NCQG) on climate finance was adopted, with the aim to determine the climate finance needs of the Global South, and to set a new goal.[24]

According to the the United Nations Global Policy Model, the Global South would need US$1.1 trillion in climate finance from 2025, and US$1.8 trillion from 2030 annually. At the 2024 COP 29 in Azerbaijan, the issue of climate finance and the necessary flows to the Global South were central. According to the agreement reached at this conference, the amount of climate finance allocated to the Global South have been raised from the 2009 goal of US$ 100 billion annually, to US $ 300 billion annual by 2035, and eventually to US$ 1,3 trillion per annum by 2035.[25] It is clearly still falling short of total needs. The world also needs better climate finance technologies.

In addition to the challenge to get more climate technologies developed and rolled out in the Global South, it also raises the question of what types of finance are most appropriate for supporting climate technology entrepreneurship? What other supporting conditions can be created by governments, given that climate technologies are susceptible to market failures? In the next section, the most appropriate entrepreneurial ecosystem for climate technology entrepreneurship are discussed.

4 Policies for Climate Technology Entrepreneurship

The need for climate technologies to be provided by entrepreneurs is urgent, as section 2 argued. Section 3 however showed that the challenge facing climate technology entrepreneurs may be insurmountable.

This section shares concerns that government policies and support are also inadequate to provide sufficient support to climate tech entrepreneurs in tackling the challenges.

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[24] See: `https://tinyurl.com/ycypwrr6`

[25] See: `https://tinyurl.com/8maamut4`

Given the widely recognized determinants of entrepreneurship (see e.g. Naudé (2008), Table 4 below summarizes key concerns whether support for entrepreneurship will be adequate for climate technology entrepreneurship, in light of the challenges notes.

Table 4: Determinants of Entrepreneurship and Concerns for Policy Support

Determinant	**Policy Implication**	**Concern**
Entrepreneurial ability	Support high-ability entrepreneurship; Improve entrepreneurial ability	The pipeline of high-ability entrepreneurs for climate tech entrepreneurship is short, also due to more lucrative alternative wage opportunities for high ability individuals.
Returns to Entrepreneurship	Support a vibrant, competitive economy with plenty of opportunities;Promote a culture that values ethical entrepreneurship; Strengthen institutions, including property rights and reduce market failures	Requires specific technical knowledge on climate science and engineering. These skills are lacking.The opportunities for climate tech entrepreneurs need to be scoped, highlighted and disseminated.The promotion of a culture that appreciated climate entrepreneurship as relevant and urgent is needed. The returns to climate change entrepreneurship includes much positive externalities which cannot be internalized by the entrepreneur. This act as disincentive by reducing the gains from such entrepreneurship.
Obstacles to entrepreneurship	Reduce barriers to entry; Address credit market imperfections	Climate technologies often have implications for the environment and related aspects such as health, both areas that are increasingly regulated by governments. While these regulations are well meant, they complicate the entry of entrepreneurship into these sectors. The lack of climate finance, in particular patient venture capital to support the medium to longer term gestation and development times of climate tech is a critical shortcoming.

Source: Author

Table 4 notes the key determinants of entrepreneurship, lists the typical policies that are most often recommended, and provide critical comments on the challenge facing the support of climate technology entrepreneurs.

The table implies that the critical challenges for enabling more climate technology entrepreneur to enter the market are to i) build climate-specific skills - the better entrepreneurs can understand the nature of the climate change challenge, and the better their engineering and technical skills, the more they will be able to identify appropriate technological solutions for problems , indeed "innovative new technology ventures will require entrepreneurs who are skilled at collaborating effectively with scientists and engineers as well as with financial managers and venture capitalists"(Barr et al., 2009, p.370); ii) provide subsidies for climate entrepreneurship to address the market failure given the positive externalities that climate tech entrepreneurs generate - for instance through subsidizing training, education, start-up costs and by helping to regulate an adequate price for carbon; and iii) alleviate shortcomings in venture capital (VC) by underwriting and providing finance for climate technology innovations that requires longer time periods to bring to market.

These policy challenges implies that successful climate tech entrepreneurship requires a comprehensive, multi-pronged approach and hands-on from government. The three challenges are intertwined - talent, finance and market failures require a comprehensive and coordinated policy approach - also internationally coordinated - and not a piecemeal approach.

Moreover, a fourth policy challenge is not only to enable more climate tech entrepreneurial start-ups, but also to help more and more climate technology start-ups become scale-ups, and also for more existing firms - stand-ups - not only to survive, but to adopt climate technologies and adapt to climate change. Thus, the climate technology entrepreneurship challenge is a comprehensive challenge - one that is arguably not met in practice.

In practice two approaches (not mutually exclusive) are used to support climate tech entrepreneurship. The one, which is a bottoms-up approach, is to strengthen the entrepreneurial ecosystem (EES). Here focusing on embedding climate technology requirements from start-ups to stand-ups to scale-ups are required. A second approach is a top-down approach, the mission (or moonshot) approach to innovation. This approach, associated with the work of Mazzucato (2018), considers climate change a global grand challenge, and hence requires an approach where government leads the process to develop and deploy new climate technologies. Neither of these approaches are however, entirely adequate for climate technology entrepreneurship, given the challenges outlined in section 2.

4.1 Shortcomings of Entrepreneurial Ecosystems

Entrepreneurial ecosystems (EES) are "sets of actors, institutions, social networks, and cultural values that produce and sustain entrepreneurial activity" (Roundy et al., 2018, p.1).

According to Leendertse et al. (2022, p.1) "An entrepreneurial ecosystem comprises a set of interdependent actors and factors that are governed in such a way that they enable productive entrepreneurship within a particular territory." They describe at least ten elements that define or make up an EES, namely "formal institutions, the entrepreneurship culture, networks, physical infrastructure (transport), finance, leadership, talent, new knowledge product, demand and intermediate services."

Policymakers spend much time and money improving these framework conditions to improve the nature and impact of entrepreneurship in their countries (Naudé, 2025b). Mostly it is in the pursuit of economic growth, via the instrumental goal of promoting high-growth firms (Naudé, 2024c). As such, the pursuit of high-growth entrepreneurship through EES has a net negative impact on Ecological Overshoot and the climate crisis.

There is of course, the notion of sustainable entrepreneurship, which is basically a belief that entrepreneurs can continue to pursue high firm growth without causing damage to the environment. It is behind the myth of green growth. In other words, sustainable entrepreneurship is an idea to not to save the planet by curbing economic growth, but to save economic growth by turning the green economy into a new business opportunity. More efficient resource use, reductions in emissions and waste, and establishing a more circular economy are all promoted as opportunities for continued growth. Under sustainable entrepreneurship, the world is now seeing the large-scale monetization, financialization, and commodification of nature (Naudé, 2025b).

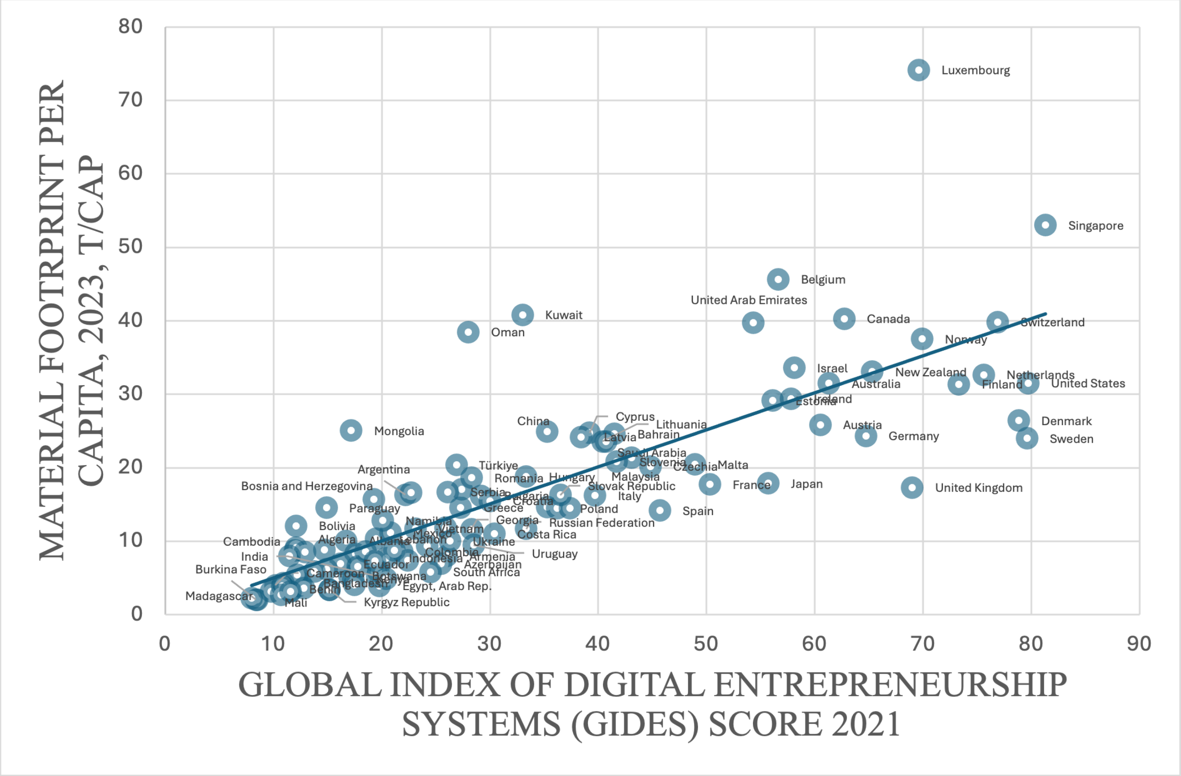
Promoters of the sustainable entrepreneurship ecosystems hope digital technologies will dematerialize production and consumption and that green climate tech entrepreneurs will catalyze the energy transition, bringing sufficient affordable renewable energy to all. In this mistaken view, entrepreneurship is the climate crisis's solution, not the cause (Naudé, 2025b).

This view is indeed mistaken - and dangerous for the planet. The following brief arguments will suffice for present purposes - for a deeper arguments, see e.g. Naudé (2024a,c).

First, taking the Global Index of Digital Entrepreneurship Systems (GIDES), which measures how much a country's entrepreneurship systems encourage mainly digital forms of entrepreneurship (they report it for 112 countries) (see Autio et al. (2021)). In that case, the entrepreneurship systems that are advocated by the authors, and followed by policymakers, are closely associated with environmental degradation. Countries scoring higher on the GIDES are worse off in terms of their negative impact on ecology and the environment.

Consider Figure 10. Using the GIDES Index, countries with a higher score have a higher Material Footprint per capita, using data from the Global Material Flows Database.[26] This confirms that stimulating entrepreneurship will not decouple the economy -even the “dematerialised’ digital economy - from the environment.

Figure 10: Countries that score higher in terms of their entrepreneurial ecosystems have a higher material footprint



Source: Author, based on data from GIDES Index and Global Material Flows Database

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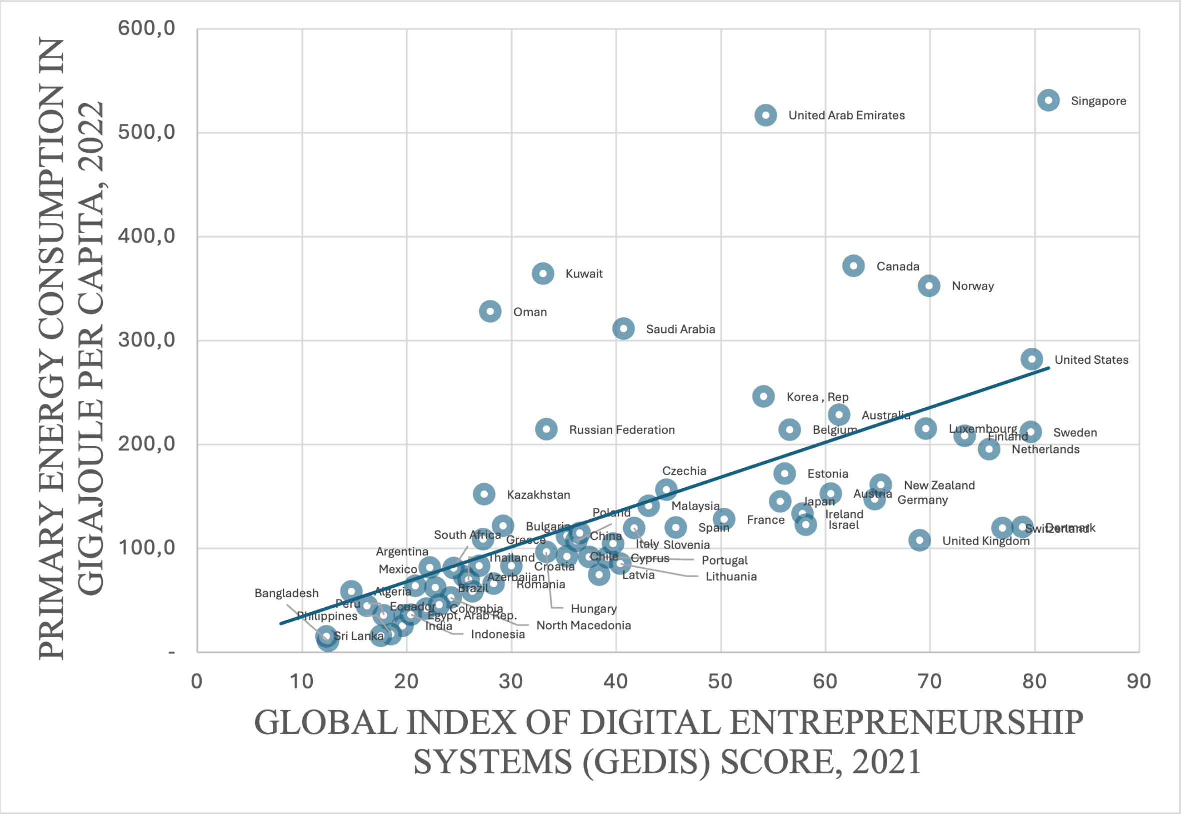
[26] See: `https://www.resourcepanel.org/global-material-flows-database`.

Next, consider Figure 11. It plots 122 countries' GIDES score against their primary energy consumption per capita. Clearly, there is a positive association: countries that score higher on the GIDES Index use far more energy, one of the major culprits contributing to climate change. The world obtains more than 80% of its primary energy consumption from fossil fuels, and this share has barely changed over half a century. The expansion of renewable energy has just been added to the world's fossil fuel use, and the use of fossil fuels reached record levels in 2024 (Plumer, 2024). This alone implies that the world is not exactly overwhelmed by hordes of sustainable entrepreneurs or genuinely sustainable entrepreneurial ecosystems.

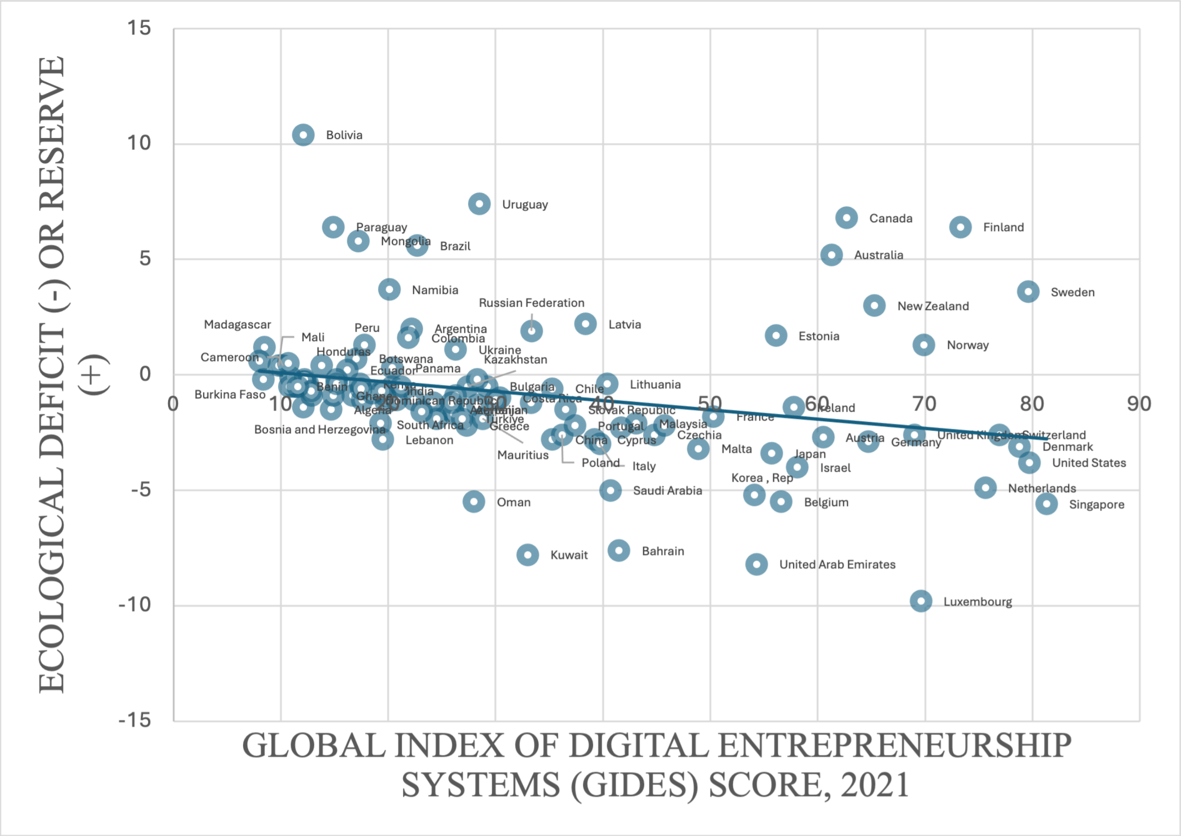
Figure 11: Countries that score higher in terms of entrepreneurial ecosystems have higher primary energy consumption



Source: Author, based on data from GIDES Index and Global Material Flows Database

Third, consider Figure 12. It shows that the ecological overshoot in countries with higher GEDIS Index scores is worse. Ecological overshoot is measured here using the Global Footprint Network's measures of the bio-capacity of a country and its ecological footprint, measured in global hectares (gha). An ecological deficit indicates that a country's ecological footprint exceeds its bio-capacity. According[27] to the Global Footprint Network "To live within the means of our planet's resources, the world's Ecological Footprint would have to equal the available bio-capacity per person on our planet, which is currently 1.6 global hectares."

Figure 12: Countries that score higher in terms of entrepreneurial ecosystems have higher ecological deficits



Source: Author, based on data from GIDES Index and Global Material Flows Database

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[27] See : `https://data.footprintnetwork.org`

The negative relation indicates that countries with more entrepreneurship suffer from a larger ecological deficit. For instance, the USA, with a GIDES score of 79, hence one of the world's most lauded (digital) entrepreneurial systems (which many countries foolishly wish to emulate), has an ecological deficit of -3,8 global hectares per person. What this means is that if every. country measures similarly in terms of their entrepreneurial system as the USA, we would need around three planets.

Thus, promoting entrepreneurial ecosystems - even so-called digital entrepreneurial ecosystems that are supposed to be decoupled, is not guaranteed to achieve sustainable outcomes - rather the opposite. That digital entrepreneurs can foster a decoupled, dematerialized, knowledge-driven economy where only ideas can drive economic growth is a fantasy. This is also evident from the fact that the digital economy emits more carbon than the world's entire fleet of trucks, with emissions coming from manufacturing screens, antennas, cables, and satellites, mining at least 44 minerals, and still being dependent on coal-fired electricity (Jancovici and Blain, 2024).

A reason for highlighting the relationship between entrepreneurial ecosystems and the material footprint, energy use and ecological overshoot of countries here is to stress that those promoting sustainable entrepreneurship ecosystems tend to focus only on climate change and carbon emissions. This is a shortcoming in the current economics, business, entrepreneurship and management literatures. It it a shortcoming because the entire Earth System is under pressure from the increasing scale of human activity and that this causes ecological overshoot - of which climate change is but one symptom. The climate is one of several planetary boundaries. Unfortunately, the concept of planetary boundaries is largely absent from most entrepreneurship research and policy making, and where it is given some attention, it is, typically for a growth-obsessed field, presented as an opportunity for competitiveness and growth - and not as a warning that a post-growth oriented entrepreneurship is sorely needed.

In addition to the inconsistency between EES in terms of their focus on growth and their association with adverse environmental outcomes, the start-up ecosystem provided by EES tend to be poorly organized from a climate technology entrepreneurship perspective. In this respect, the reader is referred to the discussion on incubators and start-up accelerators in the context of climate technology entrepreneurship by UNFCCC (2018). Although a 2018 report, much of the conclusions remain valid. UNFCCC (2018) noted that the number of climate technology incubators and accelerators remains limited. Of the estimated 7,000 incubators and 300 accelerators globally by 2018, only a small fraction focuses on climate technology, with even fewer located in the Global South. The UNFCCC (2018) further noted the key challenges that hinder climate tech incubator and accelerator success, including:

- Limited access to finance: Climate technology entrepreneurs generally face a chronic shortage of funding, especially in the Global South. Investors are often hesitant due to the long development timelines, high capital intensity, inherent risks associated with technology development, the youthfulness of entrepreneurs, and uncertainty surrounding climate policies.
- Unsuitable incubation models: The current accelerator model, generally a short three- to six-month burst of entrepreneurial support with the aim of achieving venture capital at the end, might not lend itself to climate technology development. Most existing incubators and accelerators are not financially self-sufficient, relying heavily on government support or international sponsorship. This dependence can make them vulnerable to political shifts and limit their long-term sustainability.
- Lack of local manufacturing and weak global value chain integration: This is especially a shortcoming in the Global South. This complicates entrepreneurial efforts at scaling up, which is crucial for success of climate technologies. The headwinds to globalization and global uncertainty about trade and investment openness due to supply-chain shocks, re-shoring and near-shoring, and trade and technology "wars," are at the time of writing further entrenching these obstacles.

4.2 Shortcomings of Mission-Oriented Policy for Climate Technology

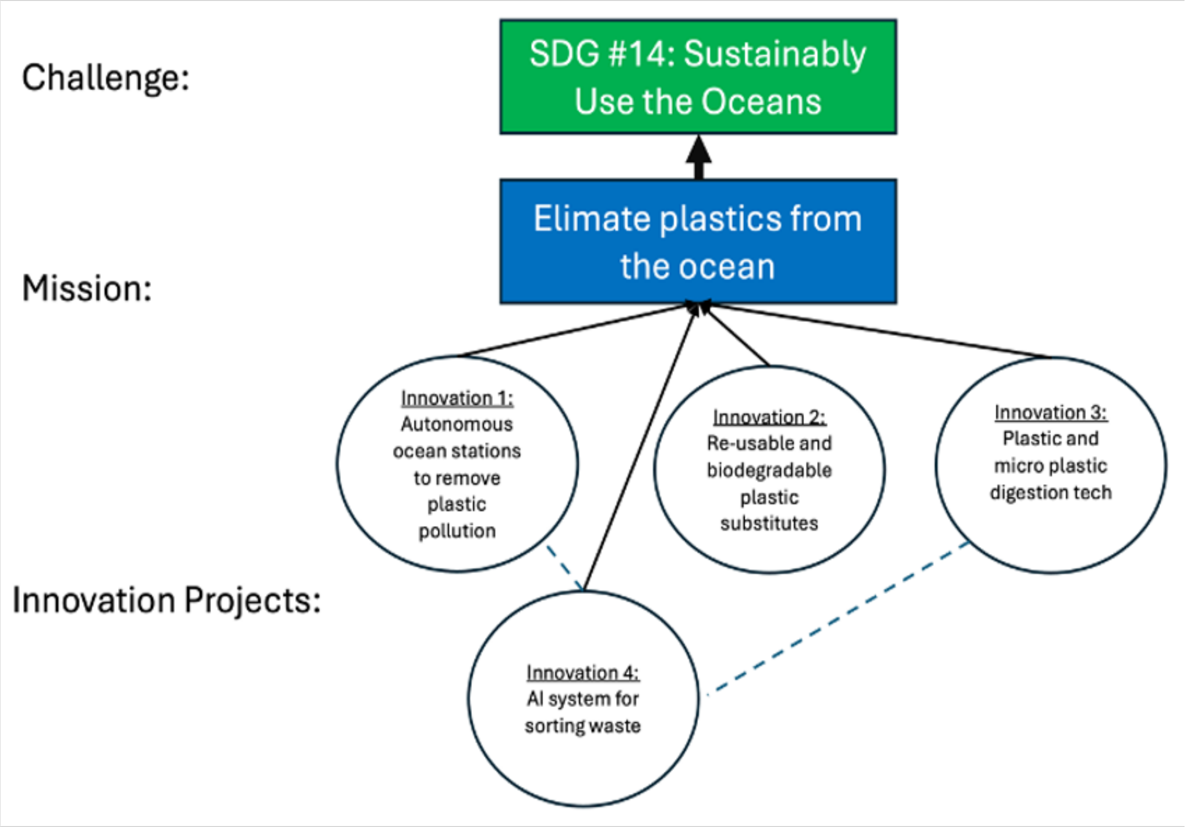
> *"The history of climate change expertise is riddled with weird technological proposals*" (Fressoz, 2024, p.207).

Mazzucato (2018) argues that the government should do more to provide funding for high-risk, high-tech innovation activities and that private finance, such as venture capital, only follow once the fundamental risks in research and development and innovation has been carried. This has led to the concept of Mission-oriented innovation policies. Mission-oriented innovation policies are "systemic public policies that draw on frontier knowledge to attain specific goals, or "big science deployed to meet big problems" (Mazzucato, 2018, p.804).

According to Mazzucato (2018) five criteria for choosing effective missions for mission-oriented innovation policies are i) that they should be bold, inspirational with wide societal relevance - such as tackling climate change; ii) they should have a clear direction: targeted, measurable, and time-bound, such as achieving decarbonisation by 2050; iii) they should be ambitious, focusing on research and innovation across the entire innovation chain, including the interplay between basic and applied research, such as the requirement that climate technology entrepreneurs work have cross-domain knowledge and expertise; iv) they should encourage participation from multiple scientific disciplines, different industry sectors, and a range of actors, including public, private, and civil society organizations; and v) they should be open to different solutions and approaches, rather than relying on a single technology or pathway. This implies that multiple technologies are needed to tackle climate change, including social technologies that will lead to behavioral changes.

To illustrate how the mission-oriented or moonshot approach can be used to catalyze climate technology entrepreneurship, consider the diagram in Figure 13.

Figure 13: The Mission-Orientation Innovation Approach Illustrated



Source: Author's adaptation from Mazzucato (2018, p.812)

Figure 13 uses the example of mission-oriented innovation policies provided by Mazzucato

(2018). The case is of SDG 14, which requires the challenge of the sustainable use of the oceans to be achieved. One important mission to achieve this, is to eliminate plastics from the ocean. For this mission - and other SDG or climate missions to be achieved, various innovation projects can be conceived of. In Figure 13 four such imaginary innovation projects are described, namely for autonomous ocean stations to remove plastic pollution, for AI/ machine learning systems to recognize and help sort plastic waste, for technologies for reducing the use of plastics, including the development of alternative materials, and for digesting plastics in the ocean.

To apply the mission-oriented or moonshot approach on a country level to climate technology entrepreneurship support would require the country to set an ambitious goal (perhaps linked to its Nationally Determined Contribution (NDC) in terms of its UN climate commitment). This becomes the challenge. Then, it needs to identify various missions to achieve this: for instance one mission could be to roll out renewable energy to all rural inhabitants to eradicate energy poverty. The innovations here would be to generate affordable solar, wind and hydro business models, with support from government. In each mission, the setting of targets and the coordination by government and supportive organizations are necessary for implementation, monitoring and feedback.

With respect to the innovation projects that are shown in Figure 13 to make up the key actions within climate action missions, from a climate technology entrepreneurship perspective, governments can provide support through innovation procurement measures Obwegeser and Müller (2018). Innovation procurement refers to public interventions by governments to support the generation and diffusion of innovation through the direct purchase of goods and services Naudé and Dimitri (2021). In the case of climate technology entrepreneurship, a government may simple procurement technologies, existing or non-existing, which it deems necessary to achieve its NDCs. The rationale for governments procuring innovation is that social returns to innovation - especially of climate technology innovations - are higher than private returns, and government-supported innovation policy can help bridge the gap.

The use of innovation procurement specifically for climate action purposes is also referred to as Green Public Procurement (GPP). According to the European Commission (EC)[28] it is defined as ''*a process whereby public authorities seek to procure goods, services and works with a reduced environmental impact throughout their life cycle when compared to goods, services and works with the same primary function that would otherwise be procured.*" This definition indicates that GPP goes beyond climate technology entrepreneurship support, to

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[28] See: `https://green-business.ec.europa.eu/green-public-procurement_en`.

more generally support all climate action initiatives. From the case studies presented on the EC's GPP website, very few are indeed concerned with stimulating entrepreneur to develop new climate technologies.

In the Global South, the use of GPP is still in its infancy. Existing initiatives are reported by UNEP, which supports GPP in Asia through the Asia Pacific GPP Network. Geng and Doberstein (2008) provides a case study of greening government procurement in China.

Related to the idea of "Moonshots" is the more recent notion of "Earthshots" which similarly identifies missions to be achieved. The term Earthshot is used in two primary contexts. The first in the context of the *Earthshot Prize*, which was initiated by Prince William, Duke of Cambridge, in 2019. This is a global environmental prize awarded annually to five individuals or organizations for their contributions to environmental solutions. While the *Earthshot Prize* does not directly promote specific technologies, it recognizes and rewards innovative solutions across various climate technology fields, including renewable energy technologies, energy storage solutions (batteries, hydrogen fuel cells), carbon capture and storage technologies, sustainable agriculture practices, waste reduction and recycling technologies and clean transportation solutions (electric vehicles, hydrogen vehicles). For example, one of the winners of the Earthshot Prize has been the Kenyan entrepreneurial start-up of d.light, which provides clean and affordable energy solutions to communities lacking reliable access to electricity.

A second context of the Earthshot is the US Department of Energy's 2021 *Energy Earthshot Initiative*, which has several ambitious goals to accelerate the development and deployment of clean energy technologies. Table 5 summarizes the targets and the envisioned climate technology outputs that are needed.

Despite the popularity of the Mission-oriented approach in some government circles, that there have been pertinent criticisms against the approach[29].

As discussed by Caverley (2023), the theoretical underpinning of the idea that the government should steer and fund innovation came from economist Kenneth Arrow - long before Mazzucato. In his paper "Economic Welfare and the Allocation of Resources for Invention," Arrow (1962) argued that without government intervention, even a perfectly competitive market would supply less innovation than what was "socially desirable", in other words, the government must fund basic innovation because the private sector would not do enough of it (Arrow, 1962, p.619).

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[29] This section on the shortcomings of the mission-oriented approach is taken from Naudé (2024b).

Table 5: Energy Earthshots and Climate Technologies

Technology	**Need/Description**
Clean Hydrogen	Reduce the cost of clean hydrogen to $1 per kilogram to enable its widespread use as a clean fuel.
Long Duration Storage	Develop affordable grid-scale energy storage solutions that can store energy for 10+ hours to balance renewable energy supply and demand.
Carbon Negative Technologies	Develop technologies to remove carbon dioxide from the atmosphere and ocean to mitigate climate change.
Floating Offshore Wind	Advance floating offshore wind technology to harness the vast potential of offshore wind energy in deeper waters.
Enhanced Geothermal	Develop technologies to extract more energy from the Earth's heat, reducing reliance on fossil fuels.
Industrial Heat	Reduce emissions from industrial processes, such as steel-making and cement production, which are major contributors to greenhouse gas emissions.
Clean Fuels and Products	Develop alternative sources for carbon-based products, such as fuels and materials, to reduce reliance on fossil fuels.
Affordable Home Energy	Reduce the upfront costs of energy efficiency upgrades to make homes more affordable and sustainable.

Source: Author's compilation based on US Department of Energy, 2021

Subsequent scholars have qualified Arrow's argument, pointing out that private firms do engage in substantial basic scientific research to generate innovations and that they have important private incentives to do so (Czarnitzki and Thorwarth, 2012; Rosenberg, 1990); that the impact of government R&D on economic and productivity growth was much less than business R&D (Baily, 2003; Sveikauskas, 2007), and moreover that government funding of basic research (R&D) may distort private innovation - even crowding-out private R&D (Kealey, 2008; Rosenberg, 1990). Worse, mission-oriented policies may incentivize "weird technological proposals" and like "net zero 2050 scenario's that nobody believes in anymore, [may] have the collateral effect of marginalizing other futures" (Fressoz, 2024, p.208).

Moreover, it has been argued that the mission-oriented, or moonshot approach is ill-suited to a world facing a myriad of crises. The original Moonshot approach of President J.F. Kennedy worked when it had a single mission to land a person on the moon. This is not the challenges that climate change and ecological overshoot poses.

An editorial in *Nature Magazine* in 2019 emphasized that the mission-oriented approach to the challenges faced by the world is less than ideal for addressing complex problems. It used the example of climate change, pointing out that addressing it "will require not just money and expertise, but also reconciliation of competing political ideologies, especially in richer countries; satisfaction of demands for equity from poorer countries; and recognition of the citizen voice" (Editorial, 2019).

5 Will AI Save Climate Technology Entrepreneurship?

Progress made in Artificial Intelligence (AI) over the past fifteen years poses opportunities and challenges both for entrepreneurship, for innovation and technology, and for climate change. AI is therefore a cross-cutting issue affecting all the dimensions of climate technology entrepreneurship. It is therefore one of the current trends affecting climate technology entrepreneurship that is expected to have growing impact in future.

The questions, for present purposes, that are most relevant are:

- How will AI affect the nature and impact of entrepreneurship?
- How will AI affect the nature of technology and innovation?
- How will AI affect climate change?

The rest of this section will try to provide answers.

5.1 How will AI will affect the nature and impact of entrepreneurship?

According to Fossen et al. (2024) AI will affect entrepreneurship directly and indirectly. Direct effects will be through AI affecting entrepreneurial uncertainty, entrepreneurial opportunity, entrepreneurial decision-making and entrepreneurial performance. Indirectly, AI will affect entrepreneurship through labor markets and entrepreneurial ecosystems. All of these effects are relevant for climate technology entrepreneurship. From the discussion in Fossen et al. (2024) several implications can be highlighted.

First, AI can help climate technology entrepreneurs in opportunity identification and validation. Climate tech entrepreneurs can use AI to sift through climate data, scientific research, market trends, and consumer behavior to identify promising opportunities for innovation. This can help them develop solutions targeting specific climate challenges, optimize resource use, and predict the impact of climate-related events. Entrepreneurs can use AI to forecast weather patterns, predict energy demand, and improve the efficiency of solar and wind power generation. AI can also help entrepreneurs assess and quantify carbon emissions across various sectors and identify the most impactful areas for carbon offsetting initiatives.

Second, AI can help climate technology entrepreneurs to enhance decision making and reduce uncertainty. This is because AI can help climate tech entrepreneurs make more informed investment decisions by analyzing market trends, assessing risks, and predicting the potential return on investment for various climate solutions.

Third, AI can help climate technology entrepreneurs to optimize the use of resources like energy, water, and raw materials, enabling climate tech entrepreneurs to develop more sustainable and efficient solutions. For instance, AI can be used to model various climate change scenarios and assess potential risks for climate tech ventures, helping entrepreneurs develop more resilient strategies.

Fourth, AI can help climate technology entrepreneurs by improving their performance and impact. This could for instance be by integrating AI into climate technologies themselves, creating "smart" solutions that can adapt to changing conditions and optimize performance. Examples include AI-powered smart grids, precision agriculture systems, and intelligent transportation networks. It could also be done by using AI to help climate tech entrepreneurs monitor the impact of their solutions in real-time, providing data-driven insights for continuous improvement and adaptation.

Fifth, AI systems can help connect climate tech entrepreneurs with investors, researchers, policymakers, and other stakeholders, fostering collaboration and knowledge exchange within the ecosystem, and make climate tech ventures more attractive to investors and talent seeking to work on cutting-edge solutions to pressing global challenges.

5.2 How will AI will affect the nature of technology and innovation?

AI has the potential to significantly boost innovation, acting as both a powerful tool for accelerating traditional innovation processes and, more profoundly, as an innovation in the method of innovation (IMI) itself. According to Almeida et al. (2024) there are several ways in which AI can enhance the efficiency and effectiveness of innovation, and hence boost the innovative capacity of climate technology entrepreneurs.

The first is that AI can help climate technology entrepreneurs to automate the discovery of new climate technologies and climate solutions. For instance, AI can automate tasks in the research and development (R&D) process, such as data analysis, experimentation, and even the generation of novel concepts.

The second is that AI can help climate technology entrepreneurs to by augmenting their entrepreneurial abilities. AI can act as an assistant to human innovators, providing them with insights, predictions, and recommendations based on vast datasets that would be impossible for humans to process manually.

The third is that AI can help climate technology entrepreneurs to innovate by helping them to more efficiently access and use existing knowledge on climate change and technology. AI can analyze and organize existing knowledge, identifying connections and patterns that might be missed by human researchers. This ability to leverage the "standing-on-shoulders" effect can accelerate the development of new technologies and solutions by building upon the work of predecessors. An example of this is that of *ChatClimate*[30] - a conversational AI prototype trained on the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6). *ChatClimate* can help entrepreneurs navigate the world of climate science by providing access to reliable climate data and by providing accurate and up-to-date information(Vaghefi et al., 2023).

AI's potential goes beyond simply speeding up existing methods of innovation. It has been argued that AI represents a fundamental shift in in how entrepreneurs innovate, making it an innovation in the method of innovation (IMI). AI as such may be a potential general purpose technology (GPT). Examples of such potential innovations in the method of innovation include the expansion of the problem and solutions spaces that climate technology innovators face. For instance, generative AI, particularly Large Language Models (LLMs), can generate

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[30] See: `https://www.chatclimate.ai`.

novel research questions and potential solutions that might not have been considered by human researchers. This ability to explore a wider range of possibilities allows for more creative and innovative solutions to complex challenges. Furthermore, AI as IMI accelerates the innovation process, enabling faster cycles of experimentation, learning, and improvement, leading to a more rapid pace of technological advancement. This may be crucial for the fight against climate change, where time is of the essence (Almeida et al., 2024).

5.2.1 How will AI affect climate change?

AI will have both positive and negative impacts on climate change, and as the discussion here concludes, it is likely that the negative impacts may overshadow the positive impacts.

AI help fight climate change and help achieve the SDG 13 (Climate Action). According to Vinuesa et al. (2020) AI can improve the understanding and modeling of climate change, it can help optimize the operation of smart grids, integrating renewable energy sources like solar and wind power more efficiently. AI can also be used to design and operate energy-efficient buildings and transportation systems. AI furthermore used to identify and implement energy-saving measures in various sectors, from industrial processes to household appliances, and AI can play a role in monitoring and managing environmental impacts such as deforestation trends, carbon emissions, and track climate change mitigation efforts using data from satellites and other sources.

There are, however, growing concerns about AI's negative impacts on climate change and the environment. The most important of these are about the high energy consumption for AI applications: The training of complex AI models, require massive computational resources. The compute needed to train state-of-the-art (SOTA) AI models is growing approximately ten times faster than GPU performance per watt, resulting in a large and rising carbon footprint. The International Energy Agency (IEA) predicts that the electricity consumption from datacentres (where AI systems are hosted) will double between 2022 and 2026, requiring as much energy as a country such as Japan (Dolby, 2023). And a single query on GenAI consumes 2,9 watt-hours, around ten times more than a Google search (Coskun, 2024).

For instance, a single training run of OpenAI's GPT-3 language model, using NVIDIA's V100 GPUs, would take around 355 GPU years and generate 223,920 kg CO_2 equivalent if the cloud provider (Microsoft Azure) was based in the USA (Cowls et al., 2023). Projections suggest that the electricity demand from information and communication technologies

(ICTs), including AI, could rise to 20% of global electricity demand by 2030, a huge increase from the current 1% (Vinuesa et al., 2020).The ICT sector is estimated to account for 1.8 to 3.9 percent of global carbon emissions - comparable to that of the global aviation industry (van der Ven et al., 2024). This is estimated to grow to 23% of global emissions by 2030 (Cowls et al., 2023).

A related environmental concern is the severe water needs of AI. From training LLMs to deploying them for globally, AI consumes vast amounts of freshwater, both directly and indirectly. By 2027, AI data centres will require almost 7 billion cubic meters of water, more than that of Denmark in a year (Gordon, 2024). The water needs of AI stem from two primary sources: operational water and embodied water. Operational water encompasses the water used for cooling data centers and generating the electricity that powers them. Embodied water, on the refers to the water consumed during the manufacturing process of AI's essential hardware, particularly the chips and servers. Semiconductor fabrication requires ultrapure water for various stages, and manufacturing facilities also use water for cooling purposes. The discharge water from these processes often contains toxic chemicals, demanding additional treatment before reuse. It has been estimated that training a large language model like GPT-3 can consume millions of liters of water, including a significant amount for on-site cooling. The inference stage, where deployed models process requests, also contributes to water consumption, with estimates suggesting GPT-3 consumes the equivalent of a 500 ml bottle of water for every 10-50 responses, depending on the data center's location and time of operation. Furthermore, projections indicate that the global AI demand in 2027 could require 4.2 – 6.6 billion cubic meters of water withdrawal, exceeding the annual water withdrawal of several countries (Li et al., 2023).

In addition to its high energy and water needs, there is also rising concern that AI will generate exorbitant amounts of electronic waste (e-waste) (Iqbal, 2024). This is due to the short lifespan of hardware used in generative AI, in particular graphics processing units (GPUs) which are central in genAI / LLMs. According to Wang et al. (2024) generative AI applications alone could add 1.2 million to 5 million metric tons of e-waste by 2030. The consequences of this e-waste surge includes environmental contamination, health risks for e-waste workers (most are in the Global South) and loss of valuable resources, including precious metals and rare earth elements. The recovery of these presents an entrepreneurial opportunity.

While AI can impact negatively on human health through environmental pollution such as e-waste, its negative environmental impacts can also have negative impacts on human health. For instance, given that most of the energy for training and operating large AI models demand is still generated from fossil fuel power plants, this results in emissions of fine particulate matter (PM2.5), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2). These air pollutants are directly and causally linked to a range of severe health issues, including: premature mortality, lung cancer, asthma, heart attacks and cardiovascular diseases, strokes and cognitive decline. It is estimated that USA data centers alone could contribute to approximately 600,000 asthma symptom cases and 1,300 premature deaths in 2030, with an associated public health cost of over $20 billion annually (Han et al., 2023).

Another concern is that AI-driven disinformation can manipulate public opinion which could lead to polarization on critical issues like climate change, making it even more difficult to implement effective policies and achieve consensus on climate action (Vinuesa et al., 2020).van der Ven et al. (2024) warns that the combination of technologies such as social media and generative AI contribute to the proliferation of false or misleading information about climate change. They point to the fact that social media can be be effectively exploited by vested interests, like the fossil fuel industry, to spread climate denial, sow doubt about scientific consensus, and portray climate action as a threat to personal freedoms. This could be exacerbated given that LLMs, trained on vast amounts of unfiltered data, can inadvertently reinforce existing biases and misinformation.

Finally, van der Ven et al. (2024) makes a case that a growing reliance on generative AI, particularly LLMs, may hinder the world's ability to develop innovative solutions to the climate crisis. They argue that the danger lies in becoming overly dependent on AI for problem-solving, potentially atrophying the parts of human brains crucial for creative and forward-thinking approaches. Moreover, because LLMs are trained on historical data, it may bias their recommendations toward incremental solutions, ill-suited for the urgent need for transformative climate action.

In conclusion, for Heinberg (2024) AI poses so much more threats to the environment and climate change that he concludes

> "*Artificial intelligence is an energy guzzler we managed to live without until very recently; perhaps it's best if we bid it a quick farewell.*"

6 Concluding Remarks

The challenges of climate change and ecological overshoot represent a significant threat to the habitability of the planet. Human economic activity is releasing enormous amounts of greenhouse gases, mirroring historical mass extinction events. The world is already experiencing warming exceeding 1 degree Celsius above pre-industrial levels, moving towards exceeding potentially catastrophic climate tipping points. Furthermore, humanity's demand on ecosystems already exceeds the planet's bio-capacity, indicating a state of ecological overshoot where resource consumption and waste production outstrip the Earth's regenerative capabilities.

Climate technology entrepreneurship is widely hoped to play a crucial role in addressing these challenges. These entrepreneurs can drive the development, adoption, and adaptation of climate technologies aimed at mitigating greenhouse gas emissions, helping societies adapt to climate change impacts, and decoupling economic activity from resource use. Their innovations are essential for the energy transition away from fossil fuels, for building societal resilience to environmental disruptions, and for eradicating energy poverty. For instance, they can develop renewable energy sources, improve energy efficiency, create sustainable agriculture practices, and advance carbon capture technologies. The need for these solutions is particularly acute in the Global South, which is more vulnerable to climate change impacts.

However, the paper emphasized that climate technology entrepreneurship is no panacea for climate change and ecological overshoot. Several reasons underpinning this conclusion were elaborated.

First, the magnitude of the mitigation challenge is immense, with significant energy, overshoot, and resilience climate technology gaps. The required scale and speed of technological innovation and diffusion may be insurmountable. As (Fressoz, 2024, p.208) remarks, no-one believes in net zero 2050 scenarios anymore - the challenge is just too overwhelming.

Two, the Jevons Paradox suggests that increased efficiency in resource use due to technology can lead to an increase in overall resource consumption, not a decrease. The Jevons Paradox is particularly relevant for the still-to-be-achieved energy transition, where improvements in energy efficiency, and innovations in renewable energy has not lead to a decline in total fossil fuels used. Even if renewable energy could substitute for fossil fuels, the pressure on the environment will not necessarily disappear. Physicist Tom Murphy[31] has asked

> "*what magnificent things would we do with everlasting copious energy? As an excellent guide, we can ask what amazing things have we done with the recent bolus of energy from fossil fuels? Well, in the course of pursuing material affluence, we have eliminated 85% of primeval forest, made new deserts, created numerous oceanic dead zones, drained swamps, lost whole ecosystems [...] and initiated a sixth mass extinction with extinction rates perhaps thousands of times higher than their background levels—all without the help of* CO_2 *and climate change [...] These trends are still accelerating.*"

Three, climate technology requires significant resources for its creation, potentially exacerbating the demand for material extraction and ecological overshoot. Renewable energy technologies in particular rely on critical minerals with their own environmental and geopolitical challenges.

Four, current policy support mechanisms such as entrepreneurial ecosystems and mission-oriented policies have significant shortcomings and may not be adequately focused or resourced to address the specific needs of climate technology entrepreneurs. Notably, the pursuit of high-growth entrepreneurship through existing ecosystems can have a net negative environmental impact - indicators of entrepreneurial ecosystems were found to be negatively correlated with indicators of a healthy environment.

Artificial Intelligence (AI), the new general purpose technology, while offering potential benefits for innovation and efficiency, was show to suffer from limitations - including the Jevons Paradox. Moreover, AI also presents considerable additional risks to climate change, due to its high energy and water consumption, e-waste generation, and potential for spreading (climate) disinformation.

Therefore, while climate technology entrepreneurs have a potentially important role to play beyond pursuing profits in the "green" economy, relying solely on technological solutions without broader societal changes, policy interventions, and a consideration of ecological limits, is unlikely to be sufficient to overcome the climate and ecological crises.

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[31] See: `https://www.resilience.org/stories/2024-02-21/inexhaustible-flows/`

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