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Climate change, technological revolutions and affluence: combining evolutionary and limits-to-growth theories

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Abstract

This paper analyzes the relationship between climate change, technological change and affluence. Our expected contribution is to provide a deeper conceptualization of technological change, while taking into account ecological limits, justice and democratic concerns. To this end, we analyze and try to combine evolutionary theories of long-run economic development and limits-to-growth theories, i.e., post-growth and degrowth. We suggest that technological change, even if directed by government policies in the "right directions", is unlikely to rapidly reduce global emissions. Hence, a significant reduction in global affluence is as necessary as a faster low-carbon transition in order to limit climate change, stay within ecological limits and achieve a more just transition. We also suggest that the low-carbon transition can be conceptualized as an ecological technological revolution, which can originate a new phase of economic development through major qualitative changes of socio-economic systems in dominant technologies, sectors, firms, institutions and societal values. Finally, we propose that a cap on affluence can be conceptualized as a technology cap, which can accelerate and shape a low-carbon transition by activating two processes. The first is an endogenous process of co-evolution or cumulative causation between minimalist demand and investment in ecological technologies. The second is a process of debate and democratic definition of an ecological technological paradigm, which can enable socio-institutional actors to act as exogenous unlocking factors. Both these processes, and the forces that shape them, should enable the qualitative evolution of socio-economic systems towards ecology, without necessarily produce their quantitative growth.

Keywords: Climate change; Technological revolutions; Affluence; Long-run economic development; Ecological technological revolution; Technology cap.

JEL Classification: Q50 - O33 - O11

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1. Introduction

The negative impacts of climate change are mounting much faster than scientists predicted less than a decade (Tollefson 2022). The atmospheric concentration of carbon emissions has crossed the critical threshold beyond which the "safe operating space for humanity" is not guaranteed, and the same goes for other important “planetary boundaries” (Rockström et al. 2009, Steffen et al. 2015). To avoid the most negative impacts of climate change, a very rapid reduction of global emissions is necessary (IPCC 2022). The literature on the Kaya identity[2] shows that global emissions depend on three main (not independent) contributors: global population, global production and consumption, also called affluence (GDP per capita), and technological change, i.e., technological improvement and adoption. A key gap in knowledge is how these different drivers of emissions can be mitigated to different extents and in different settings (IPCC 2022).

The gap in knowledge is especially about technological change as it deeply impacts emissions, but in multiple, contrasting and often unpredictable ways. On the one hand, technological change is widely considered as the main driver of emissions reduction, basically for its potential to replace fossil-fuel technologies with low-carbon technologies, which allows decoupling affluence from emissions and would enable a more sustainable growth. Technological change can also decouple affluence from emissions by increasing energy efficiency, but this has contrasting effects on global emissions because of the rebound effect. On the other hand, technological change is, indirectly, the main driver of emissions growth as it is the most important source of growth in productivity, production and affluence (GDP per capita). And since current socio-economic systems remain mainly based on, and locked-in, fossil-fuel technologies, affluence remains strongly coupled at global level with emissions.

A vast literature shows that environmental technologies can effectively reduce emissions and the environmental impact of production (see e.g., Bianchini et al. 2023). However, the literature is much less clear on the speed and directionality of this process, i.e., on the rates and directions of technological change that are necessary to limit global warming at acceptable levels. This is a major problem because, if we exclude to importantly intervene on population growth, then either technological change will enable to rapidly reduce emissions, basically by quickly unlocking socio-economic systems from fossil-fuel technologies, or a significant reduction in global affluence will be necessary to limit climate change. Conversely, if the rate of technological change will be rapid enough and in the “right directions”, then the need to reduce affluence in order to limit climate change can be eased. To our knowledge, this tradeoff between technological change and affluence has received no attention by the literature.

In this paper, we analyze the relationship between climate change, technological change and affluence. Our expected contribution is to provide a deeper conceptualization of technological change, based on theories of technological revolutions and long-term economic development, while taking into account ecological limits, justice and democratic concerns. As far as we know, in existing climate change models, ranging from mainstream IAMs to evolutionary agent-based models[3], technological change is not modeled as a technological revolution, i.e., a process of creative destruction that can originate a new phase of economic development through major qualitative changes of socio-economic systems in dominant technologies, sectors, firms, institutions and societal values. Conversely, formal models of technological revolutions – evolutionary models of structural change and long-run economic

[2] See IPCC (2022) for a review of this literature.

[3] See IPCC (2022) for a review of climate-energy-economy models, including IAMs. For climate change evolutionary agent-based models see Safarzyńska et al. (2012), Lamperti et al. (2018), Lamperti et al. (2020).

development[4], GPTs models[5] and mainstream models of creative destruction[6] – are not extended to include environmental concerns and the most recent works in the field focus rather on AI as a possible GPT candidate for an emerging revolution[7]. As a result of these gaps, the low-carbon transition is not conceptualized and modeled as a possible technological revolution. Therefore, the processes and forces that may drive major qualitative changes of technologies and socio-economic systems towards ecology are not sufficiently understood. Only a few historical and sociological studies on technological revolutions include in their analysis environmental concerns, namely techno-economic paradigms (Perez 2010, 2016) and sustainability transitions (Markard et al. 2012, Schot and Kanger 2018), but they do not address the above-mentioned tradeoff between technological change and affluence.

To contribute filling these gaps, we analyze, under the lens of tradeoff between technological change and affluence, two theoretical approaches: evolutionary theories of long-run economic development and limits-to-growth theories, which include post-growth and degrowth. The first approach (Schumpeter 1942, Nelson and Winter 1982, Dosi 1982, Freeman and Perez 1988, Perez 2010, Nelson et al. 2018) highlights the processes and forces that drive major qualitative changes of technologies and socio-economic systems. Moreover, it analyzes the endogenous and exogenous factors that can shape paradigm-shifts, new technological revolutions and new phases of economic development. The second approach (Kallis et al. 2012, Weiss and Cattaneo 2017, Jackson 2019, Jackson and Victor 2019, Hickel and Kallis 2020, Hickel et al. 2021) highlights the necessity of limiting global affluence and the quantitative growth of economic systems in order to mitigate climate change and respect planetary boundaries. In addition, it integrates justice and democratic concerns in its analysis of climate change. Finally, on the basis of this analysis, we try to combine both theorical approaches and discuss the proposed concepts of ecological technological revolution and technology cap.

Our study suggests that technological change, even if directed by government policies in the "right directions", is unlikely to rapidly reduce global emissions. Hence, a significant reduction in global affluence is as necessary as a faster low-carbon transition in order to limit climate change, stay within ecological limits and achieve a more just transition. We also suggest that the low-carbon transition can be conceptualized as an ecological technological revolution, which can originate a new phase of economic development through major qualitative changes of socio-economic systems in dominant technologies, sectors, firms, institutions and societal values. Finally, we propose that a cap on affluence can be conceptualized as a technology cap, which can accelerate and shape a low-carbon transition by activating two processes. The first is an endogenous process of co-evolution or cumulative causation between minimalist demand and investment in ecological technologies. The second is a process of debate and democratic definition of an ecological technological paradigm, which can enable socio-institutional actors to act as exogenous unlocking factors. Both these processes, and the forces that shape them, should enable the qualitative evolution of socio-economic systems towards ecology, without necessarily produce their quantitative growth. The rest of the paper is organized as follows. In Sections 2 and 3, we review evolutionary and limits-to-growth theories, respectively. In Section 4, we first analyze both theories in light of the tradeoff between technological change and affluence, then we discuss the proposed concepts of ecological technological revolution and technology cap. Section 5 concludes.

[4] Saviotti and Pyka (2004, 2013), Caiani et al. (2014), Lorentz et al. (2016).
[5] Bresnahan and Trajtenberg (1995), Helpman and Trajtenberg (1994), Carlaw and Lipsey (2006).
[6] Aghion and Howitt (1992)
[7] Aghion et al. (2017), Trajtenberg (2019), Martinelli et al. (2021).

2. Evolutionary theories of long-run economic development

In our view, evolutionary theories of long-run economic development (Schumpeter 1942, Nelson and Winter 1982, Dosi 1982, Freeman and Perez 1988, Perez 2010, Nelson et al. 2018) are important to better understand the potential of technology to rapidly reduce emissions as they explicitly focus their analysis on technological evolution, i.e., the rates and directions of technological change. In this perspective, these rates and directions are largely determined by the emergence and diffusion of new technological paradigms and technological revolutions, which, together with new institutions and societal values, characterize a new phase of long-run economic development. Further, these theories analyze the endogenous and exogenous factors that can shape paradigm-shifts, technological revolutions and phases of economic development, thus highlighting the processes and forces that can drive major qualitative changes of technologies and socio-economic systems.

2.1. Technological paradigms, technological revolutions and long-run economic development

According to evolutionary theories, rates and directions of technological change evolve, in analogy with biological evolution, through processes of variety creation and selection. Variety creation in biological evolution is caused by genetic mutations that originate new species, while in evolutionary economics is represented by the creation of new knowledge, technologies (products and processes of production), firms, sectors, institutions and societal values. Selection, which in biological evolution is operated by the natural environment, in evolutionary economics is operated by the market and, more in general, by the socio-economic system. The first evolutionary result of these processes of creation and selection is that, in analogy with Darwin's notion of the survival of the fittest, some knowledge, technologies, sectors, firms, institutions and societal values will survive and expand in their relative importance, while others are will decline, as showed by Fisher (1930) replicator equations (Silverberg and Verspagen 1995). The second evolutionary result is that "the average fitting function" continuously changes over time with the relative population weights (Silverberg and Verspagen 1995). Both these results enable the quantitative and qualitative evolution of socio-economic systems.

This process of continuous change, however, is not smooth over time, rather, it is punctuated by technological discontinuities, and, therefore, it is cyclical. At some point in time, variety creation and selection originate a new technological paradigm (Dosi 1982), which is defined in analogy with Kuhn's scientific paradigm. According to Kuhn (1970), science evolves in a cyclical way rather than in a linear one, and cyclicality is determined by the emergence and decline over time of new scientific paradigms, which, after a phase of scientific revolution (e.g., Copernican revolution), replace previous paradigms, becoming the dominant ones (e.g., geocentric versus heliocentric paradigm). Similar to scientific paradigms, a technological paradigm is primarily a new cognitive framework or a new heuristic, that is, a radically new vision of "how to do things" based on common scientific, engineering and organizational principles shared by a community of practitioners (Dosi 1982). This new cognitive framework aims at solving technological problems that respond to general, but clear political or social needs. As an example, the semiconductor technological paradigm was deeply influenced by the need of the US government to miniaturize electronic components for military objectives linked to the World War II and the Cold War (Epicoco 2013). The result of this new vision is the gradual emergence and then the rapid growth of a set of radically new knowledge, technologies and sectors, which, after some time, become the dominant ones.

The concept of technological paradigm applies at technological or sectoral level, also called meso-level (e.g., the semiconductor technology or sector). When a set of radically new technologies (e.g., semiconductors) come about in cluster with other sets of interconnected radically new technologies (e.g., computers, software, telecoms, Internet), a technological revolution may emerge at macro level (e.g., the ICTs revolution). For a detailed analysis of the relationship between meso and macro level see Dopfer et al. (2004), but here it is worth to mention that, according to evolutionary theories, the meso level is the fundamental unit of economic evolution, while the macro level essentially adapts itself to changes introduced at meso level and constrains these changes (Dopfer et al. 2004). Technological revolutions have been defined as clusters of interrelated and mutually supporting radical technologies that have the capability of initiating new leading sectors and a widespread impact on existing sectors, destroying some and rejuvenating others (Perez 2010). Each technological revolution is therefore a process of creative destruction (Schumpeter 1942) involving the rise and come to dominance of new knowledge, technologies, sectors, firms, institutions, societal values, as well as the decline of older ones, in analogy with the first evolutionary result illustrated above. In analogy with second evolutionary result, "the average fitting function" continuously changes over time.

The succession over time of technological revolutions, via processes of creative destruction, is at the origin of the process of long-run economic development, which, in the Schumpeterian perspective, refers to both quantitative and qualitative changes of socio-economic systems. Quantitative changes refer to long-run economic growth: its increasing trend and its long-run fluctuations around the trend. Qualitative changes refer to changes in dominant technologies, industrial sectors (structural change), firms, institutions, and societal values. In the words of Schumpeter (1942): "The carrying into effect of an innovation involves not primarily an increase in existing factors of production, but the shifting of existing factors from old to new uses". These qualitative changes are the most important ones for our perspective since, all together, define a new phase of long-run economic development, which includes the organization and structure of firms, the role played by governments, the political, financial and educational system, the industrial relationships system, societal values, norms and behaviors, as well as human attitudes towards the nature.

2.2. Endogenous and exogenous factors of long-run economic development

In sum, according to evolutionary theories, rates and directions of technological change are largely determined, via processes of variety creation and selection, by the emergence and diffusion of new technological paradigms and technological revolutions. In turn, technological revolutions are at the origin, via processes of creative destruction, of the process of long-run economic development and, therefore, of major qualitative changes of socio-economic systems. It is important to add that this is not a technologist or determinist perspective. On the contrary, endogenous and (relatively) exogenous factors may importantly influence paradigm-shifts, technological revolutions and phases of economic development (Epicoco 2021).

The main endogenous factor is a process of co-evolution[8] between investment in technologies and demand. This is based, on the one hand, on the different productivity gains generated by dominant technologies (i.e., the dominant technological paradigm) over its lifecycle, and, on the other hand, on continuous multiplier and accelerator feedback effects between investment in technologies and demand (Dosi et al. 2010) that cause a cumulative amplification of any initial change of investment in technologies. The productivity gains generated by investments in dominant technologies over its lifecycle produce a surplus income that drives demand growth (the multiplier effect), while adaptive

[8] Co-evolution arises when two variables mutually influence each other so that changes in one of them induce corresponding changes in the other (Saviotti and Pyka 2013). In other words, two evolving domains coevolve if they causally influence each other (Almudi and Fatas-Villafranca 2021).

expectations on demand growth push investments in dominant technologies (the accelerator effect). This process of cumulative causation generates a succession of cumulative upward and downward spirals, thus providing a micro-founded explanation for the succession over time of technological revolutions and associated major qualitative changes of socio-economic systems (Epicoco 2021). The process is endogenous because it arises from the tendency of certain economic actors (typically new firms) to invest in radically new technologies when the dominant ones no longer produce enough expected profit gains. And profit gains typically decline after some time because of market saturation and the existence of diminishing returns of innovation.

Exogenous or non-market factors include historical events, pure technical factors and different socio-institutional actors, including political, scientific and economic organizations, as well as various forms of communities (Epicoco 2021). Historical events and pure technical factors may exert an important role on the process of economic development because the process of economic evolution has itself an "essentially historical character" and is inherently path-dependent (David 1985). Therefore, temporally remote events, including happenings dominated by chance elements rather than by systematic forces, can exerted important influences upon the final outcome (David 1985). Here, technological evolution is the consequence of the unique, contingent and sequential characteristics of historical events and lock-in phenomena[9] in which a system can be trapped. This basic dynamic is intertwined with different forms of dynamic increasing returns that magnify historical events: the more a particular technology is employed, the greater its attractiveness relative to its alternatives[10] (David 1985, Arthur 1994). When a technology becomes dominant, the economic system faces a cost of switching to an alternative technology and the system may be trapped in a socially undesirable, and even less efficient, "region". This is the case of the carbon lock-in: current socio-economic systems are locked-in carbon-based technologies, in particular large fossil-fuel energy systems, and seem to be unwilling to pay the cost of switching to alternative, ecological, technologies and energy systems.

Socio-institutional actors can accelerate or delay the emergence of a new technological revolution by promoting its dissemination and assimilation in society or by acting as a deterrent to change (Freeman and Perez 1988). This, according to Epicoco (2021) would explain why these actors can influence the timing and the economic impact (i.e., the rate of economic growth) of a technological revolution. In addition, socio-institutional actors can participate to the processes of variety creation and selection (Dosi 1982) whose outcome will determine the "winning" technological paradigm. This can have an important role in determining the winning institutions and societal values that characterize each phase of economic development, especially when endogenous factors, i.e., declining profits of dominant technologies, push firms to search profits in radically new technologies. It is during these phases of technological ferment that the technological problems and the cognitive framework of the future paradigm are defined through a complex process involving competition among different core technologies and sectors, economic and political interests, societal values.

[9] Lock-in phenomena are defined as the entry of a system into a trapping region (David 1985)

[10] Increasing returns may have different sources, including network and coordination externalities, technological complementarities, learning effects and cumulative properties of technologies.

2.3. Green digital revolution, transition to green growth and the "entrepreneurial state"

According to evolutionary theories, technological change and the factors that shape it, in particular government policies, represent the main lever for enabling a green or sustainable development, that is, for ensuring economic growth while addressing climate change, environmental degradation, and other social goals. Based on historical analyses on techno-economic paradigms, Perez (2016) proposes that we may currently be at the beginning of the "golden age" of the technological revolution based on digital technologies and Al. However, Perez et al. (2022) also emphasizes that this revolution will be a green digital revolution, that is, environmentally and socially sustainable, only if government policies will induce innovation and behavior in that direction. From a complementary perspective, Lamperti et al. (2018, 2020) use a Schumpeterian and Keynesian agent-based model to analyze the transition to a green, sustainable growth in presence of climate damages. The study reports much larger climate damages than those projected by standard IAMs and finds that transitions from a brown to a green energy system might endogenously happen, but the likelihood of such events is particularly small and depends on exceptional technological breakthroughs. This result justifies the importance of direct innovation policies aimed at creating radically new knowledge.

In light of these considerations, evolutionary theories emphasize the need for a strong governance of the ongoing revolution or transition. Market mechanisms and market-based policies (carbon taxes and subsidies for environmental technologies) have low probabilities to rapidly decouple economic growth from emissions (Lamperti et al. 2020) and, more in general, are not sufficient "to shape the technological revolution, guide markets with the new paradigm, and give direction for the best socio-economic outcome" (Perez et al. 2022). Hence, rather than fixing market failures or leveling the playing field and pick up the winner, governments are called upon to be an "entrepreneurial state" and respond to major social needs for which private technological investments are insufficient through "mission-oriented innovation policies" (Mazzucato 2016, 2018) or direct innovation policies (Dosi et al. 2023). These policies "imply an active of role of the public sector in shaping the rates and directions of innovative activities" by the creation of public research-oriented firms diffusing technologies along specific trajectories and the funding Public Research Labs conducting basic research to achieve radical innovations (Dosi et al. 2023). Government policies here are especially important because radical technologies are technically and commercially very risky. Therefore, given the uncertainty and time-horizons of expected returns, they are either too costly or simply impossible to finance by the private sector. Government, instead, can provide patient and steady funding not tied to short-term investment returns and its engagement in low-carbon technology demonstration signals support for businesses willing to take the investment risk (Mazzucato 2016, 2018).

3. Limits-to-growth theories

In this paper, we call "limits-to-growth theories" both post-growth and degrowth (Kallis et al. 2012, Weiss and Cattaneo 2017, Jackson 2019, Jackson and Victor 2019, Hickel and Kallis 2020, Hickel et al. 2021), and, without going into the details of the definitions and eventual differences between the two theories, we hope to focus on their general common points. These theories, in our view, are important because propose a less developed, but more critical vision of technological change. As a consequence, to limit climate change, stay within ecological limits and achieve a more just transition, they consider it necessary limiting global affluence and the quantitative growth of economic systems. Further, these theories integrate democratic concerns in their analysis of climate change.

3.1. Technological change, limits to global production and affluence

Limits-to-growth theories criticize the central idea of green growth that technological change will enable to decouple economic growth from emissions and the increasing use of biophysical resources (energy and raw materials) quickly enough to prevent climate breakdown and biodiversity collapse (Hickel and Kallis 2020, Slameršak et al. 2026). Hence, projections for increased energy and resource consumption are considered as incompatible with the biophysical boundaries of the Earth. According to limit to growth scholars, the lack of empirical evidence for a fast decoupling at global level of emissions from GDP per capita demonstrates that technological change has been insufficient and inappropriate as it has not been fast enough, has not led to the type of innovations that reduce environmental pressure and has failed to displace existing undesirable technologies (Parrique 2021). Here, technological change is rather viewed as the main source of climate change and environmental degradation. Eco-efficiency and leaps to more sustainable substitutes are criticized because have led, in many cases, to an overall increase of consumption via rebound effects (Jackson 2019). Green technologies are considered as increasingly shaped by the vested interests of large international corporations "who effectively promote false solutions to environmental problems" (Kerschner et al. 2018) through eco-efficiency, eco-innovation and green consumerism.

Slameršak et al. (2026) also criticize existing mitigation scenarios since they rely solely on accelerating technological change as mitigation lever, assuming that it will improve at historically unprecedented rates. Existing scenarios are criticized also because they assume unfeasible and risky large-scale carbon sequestration, as well as that the global deployment of renewable energy, electrification and storage will be sufficient to meet the high energy demand of high-income countries. Finally, Slameršak et al. (2026) point out that limiting global production is not considered as a potential mitigation lever by most scenarios; on the contrary, lower-growth scenarios are associated with higher mitigation challenges (e.g., high population growth) and slower technological change, which makes them incompatible with the goals of the Paris Agreement.

Limits-to-growth scholars often frame ecological limits in terms of planetary boundaries (Rockström et al. 2009, Steffen et al. 2015), an approach that defines and quantifies nine planetary boundaries within which humanity can operate safely, ensuring the current Earth system functioning[11]. Crossing these boundaries increases the risk of generating abrupt or irreversible human-induced environmental changes on a global scale. According to limits-to-growth theories, to ensure compliance with planetary boundaries or returning to the safe operating space as soon as feasible, it is necessary to reduce to sustainable levels material and energy throughput, i.e., global production (Kikstra et al. 2024, Edwards et al. 2025). Global production, in turn, should be reduced through a considerable reduction of global affluence and profound structural changes of economic systems, which imply the scaling back of sectors deemed ecologically or socially harmful (e.g., fossil-fuels, nuclear energy and chemicals, weapons) and the expansion, where required, of socially necessary forms of production like renewable energy, public services, healthy and nutritious food, efficient and affordable housing, public transport (Slameršak et al. 2026). Reducing global affluence, that is, limiting consumption of affluent individuals and regions, would limit or reduce the quantitative growth of global production, while structural changes would modify the composition of global production.

[11] The boundaries are: Climate change, Novel entities, Stratospheric ozone depletion, Atmospheric aerosol loading, Ocean acidification, Modification of biogeochemical flows, Freshwater change, Land system change, Biosphere integrity.

According to limits-to-growth theories, the main reason why global affluence should be limited is justice, at national and international level. It is well known that consumption of affluent individuals and regions is the main responsible of emission growth and excess resource use. Conversely, poorest individuals and regions, both within and between countries, which contribute marginally to global emissions and resource use, are disproportionately affected by climate impacts (IPCC 2022). To reduce these inequalities, limits-to-growth scholars propose a lifestyle of sufficiency or voluntary simplicity, i.e., a lifestyle aimed at minimizing environmental impacts by reducing energy and material demand (Fitzpatrick et al. 2022). According to Slameršak et al. (2026), sufficiency can be defined as a corridor between consumption floors, where human needs are satisfied universally, and consumption ceilings, where economic activity remains within safe ecological limits. Measures to reduce consumption that overshoots sufficiency ceilings include maximum consumption standards, sustainable consumption corridors[12], and different forms of caps, e.g., on income, wealth, resource use, emissions and pollution.

Also, different redistribution measures within and between countries are proposed. Within countries, it is proposed to explore a range of "fair" economic inequality, e.g., a ratio of 5:1 between the income of the top 1% and the bottom 10% (Slameršak et al. 2026). Between countries, the objective is to achieve international convergence in material and energy use by scaling it down in high-income nations and expanding it in low-income nations (Edwards et al. 2025). For example, Hickel (2020) bases on the justice principle that all countries should have equal access to atmospheric commons in per capita terms, which is defined as a fair share of the safe global carbon budget consistent with the planetary boundary of 350 ppm atmospheric CO_2 concentration. Then, he quantifies each country's share of responsibility for global emissions in excess of the boundary, finding that, as of 2015, the Global North was responsible for 92% of excess emissions, while most countries in the Global South were within their boundary fair shares[13].

A second reason for limiting global affluence, according limits-to-growth scholars, is the existence of "social limits to growth" (Daly 2014) of socio-economic systems. These limits refer to empirical studies showing that wellbeing has rapidly diminishing returns with overall consumption, so that increasing consumption beyond a certain level does not substantially increase wellbeing and may even harm it (Costanza et al. 2014). Hence, limits-to-growth theories question the sustainability of more economic growth in already high-income nations and argue that, rather than GDP growth, access to specific goods and services that support human need satisfaction is what improves wellbeing (Edwards et al. 2025).

3.2. Creative destruction, democracy and convivial technologies

In sum, according to limits-to-growth theories, "technological change that propelled economic growth over the last two centuries is no longer socially and environmentally sustainable or desirable" (Pansera et al. 2019, Kallis et al. 2012). Rather, these theories advocate a conscious minimization of the use of technology in our lives (Kerschner et al. 2018) and propose a combination of efficiency measures and public investment in decarbonization (Edwards et al. 2025). Efficiency measures refer to "feasible technological change", including minimal reliance on highly uncertain technologies such as NETs, strict energy efficient standards, retrofit programs for buildings, mandatory warranties and right

[12] Sustainable Consumption Corridors propose minimum consumption levels to ensure decent living and maximum thresholds to preserve resources for current and future generations (Gough 2020, Fuchs et al 2021).

[13] Related propositions are: global north targets faster climate mitigation and ends net appropriation of resource from Global South, technology transfer and patent wavers from actors in Global North, reparation for colonial and ecological debt, support for just transition in Global South (Edwards et al. 2025).

to repair to avoid planned obsolescence. Public investment in decarbonization refers to investment in public travel infrastructures and in community-owned renewable energy systems. The association made by most mitigation scenarios between slower economic growth and slower technological change (i.e., slower innovation in mitigation technologies and lower energy efficiency) is criticized by arguing that economic conditions for rapid technological change can be achieved through targeted investment, irrespective of trends in aggregate output (Slameršak et al. 2026).

Limits-to-growth theories also consider that, in the context of creative destruction, innovation is the most important means to overcome the law of diminishing returns of innovation and, therefore, to ensure capital valorization, capital accumulation and the same reproduction of the capitalist system (Robra et al. 2023). On the other hand, the process of capital valorization is considered to impose its logic on science and technology, definition of needs, consumption, and organization of work (Gorz 2012). The dominant view on innovation, including that of evolutionary and Schumpeterian scholars, is considered highly uncritical as it prioritizes capital valorization, i.e., for-profit innovation, over societal needs and therefore does not question goals, purposes and values of innovation (Walsh 2021).

In light of these considerations, limits-to-growth theories advocate a considerable reduction of the role of markets in setting the rate and direction of technological change. Correspondingly, they propose to expand the role of public debate, democratic decisional processes and local communities in technological choices. In the words of Gorz (2012): "The point is to subject economic and technical development to a pattern and orientations which have been thought through and democratically debated; to tie in the goals of the economy with the free public expression of felt needs, instead of creating needs for the sole purpose of enabling capital to expand and commerce to develop". Technological sovereignty, a concept that is often used to indicate these proposals, involves, as an example, moratoria on potentially dangerous geo-engineering practices and biogenetics, regular citizen audits to decide whether or not to introduce a new technology, restructuring social media from a private to a common or public good, repurposing military facilities to produce sustainable and socially useful products (Fitzpatrick et al. 2022).

With respect to innovation, limits-to-growth theories argue that its fundamental purpose should not be increasing profits and productivity to foster economic growth, but rather the creation of use-value, that is, socially useful production that seeks to fulfil societal needs (Robra et al. 2023). Also, innovation is seen as important to enable sufficient provisioning for need satisfaction, while reducing demand for resources, energy and land (Slameršak et al. 2026). In this context, the goal is to focus on the non-economic drivers of technological change, or non-profit innovation, and develop criteria or attributes for the design, evaluation and governance of technology (Kershner et al. 2018). The concept of conviviality, originally proposed by Illich (1973), is the most cited attribute. Convivial tools are technologies that enable socially and ecologically beneficial practices, e.g., preserve or enhance ecosystems, enable users' autonomy and control, disrupt unequal power relationships, and are robust and durable (Vetter 2018). Convivial renewable energy systems, community-owned or operated (Fitzpatrick et al. 2022), low-tech devices, zero-energy developments, and organic farming are examples of convivial technologies, but there are also communities organized around high-tech devices, e.g., Fairphone, fab labs, digital commons and peer-to-peer production (Kerschner et al., 2018). With respect to digital technologies, apart from the concerns about biophysical limits to technological development, concerns focus on the fear that communities and individuals are losing control over the governance of technological development, the fear that digitalization increasingly pervades practices and visions, the conditions of disconnection and isolation that digital technology can create (Pansera et al. 2019).

4. Combining evolutionary and limits-to-growth theories

In this Section, we first analyze evolutionary and limits-to-growth theories under the lens of what we call tradeoff between technological change and affluence: either technological change will enable to rapidly reduce emissions, basically by quickly unlocking socio-economic systems from fossil-fuel technologies, or a significant reduction in global affluence will be necessary to limit climate change. Then, on the basis of this analysis, we try to combine both theories and discuss the proposed concepts of ecological technological revolution and technology cap.

4.1. Tradeoff between technological change and affluence

As discussed in Section 2.3, evolutionary theories advocate a green digital revolution or twin transition, i.e., a strong governance of the ongoing AI revolution to make it environmentally and socially sustainable (Perez 2016, Perez et al. 2022). Strong governance, via mission-oriented projects and direct innovation policies, is necessary because market-based policies have low probabilities to rapidly decouple economic growth from emissions (Lamperti et al. 2020). If we put it in terms of the tradeoff between technological change and affluence, in our opinion, this position implies that technological change, if directed by government policies in the “right directions”, can decouple affluence from emissions rapidly enough to limit global change at acceptable levels. As a consequence, a reduction of global affluence is not considered necessary to meet ecological goals. While this position differs significantly from the market-based solutions proposed by mainstream economics, we believe it tends to overestimate, albeit to a lesser extent than mainstream economics, the potential of technology to rapidly decouple affluence from emissions.

In agreement with limits-to-growth theories, we believe existing empirical and theoretical evidence more than sufficient to consider that future rates and directions of technological change are unlikely to rapidly decouple affluence from emissions, even if directed by government policies in the “right directions”. And, like limits-to-growth theories, we think that keeping deny this evidence can lead to very dangerous consequences. The atmospheric concentration of emissions has already crossed the critical threshold beyond which the "safe operating space for humanity" is not guaranteed, and the same goes for the other important “planetary boundaries” (Rockström et al. 2009, Steffen et al. 2015). It is also well documented that the negative impacts of climate change are mounting much faster than scientists had predicted (Tollefson 2022) and that path-dependency problems, with ensuing lock-ins, hamper economic systems to rapidly shift to renewable technologies and energy systems. Unless there is a technological breakthrough, the occurrence and outcomes of which are by definition highly unpredictable, technological change has low probability to rapidly reduce emissions.

Long-run empirical evidence also shows that, for over half a century, worldwide growth in affluence has continuously increased resource use and pollutant emissions far more rapidly than these have been reduced through better technology (Wiedmann et al. 2020). And, even in the last decade, despite more or less serious efforts of governments, technological change was able to reduce emissions by improving energy efficiency and carbon intensity, but these gains were lost and emissions kept growing because of growth in affluence and population (IPCC 2022). Likewise, theoretical evidence seems to show that “the historical pace of technological change is still insufficient to achieve a fast transition to a low-carbon energy system” (IPCC 2022) and that, to meet ecological goals, the low-carbon transition needs to occur faster than previous transitions (IPCC 2022). In the same evolutionary climate change models, the likelihood of an “endogenous transition from a brown to a green energy system” (Lamperti et al. 2020) is particularly small and depends on exceptional technological breakthroughs, which justifies the importance of direct innovation policies aimed at creating radical new technologies.

While government policies are undoubtedly necessary to achieve the low-carbon transition, we believe they may prove insufficient to achieve it with the speed needed to prevent climate breakdown. In our perspective, unlocking socio-economic systems from dominant fossil-fuel technologies requires a shift in the dominant technological paradigm. A paradigm-shift is typically a long and complex process involving the creation of new “varieties" and strong competition among different core technologies and sectors, economic and political interests, societal values. Although government policies may play a key role in accelerating and shaping this process, its outcome, i.e., “who will win the competition and when”, remains highly unpredictable because historical and chance elements, pure technical factors, different forms of increasing returns and various socio-institutional actors can all exert important influences upon the final outcome (Section 2.2).

If technological change is unlikely to rapidly reduce emissions, then, consistently with the tradeoff between technological change and affluence, we believe that a significant reduction in global affluence is as necessary to limit climate change as a faster low-carbon transition. Consumption of affluent households worldwide is by far the strongest determinant and the strongest accelerator of increases of global environmental and social impacts (Wiedmann et al. 2020). According to IPCC (2022), the global 10% wealthiest consumers contribute about 36-45% of global GHG emissions. If global affluence is defined as the 10% wealthiest consumers, then a significant reduction in their consumption should allow a significant and relatively rapid curb of emissions. This, in turn, should contribute significantly to mitigating climate change, ensuring safer conditions more quickly, and reducing the need for a transition that may not be as fast as necessary. A second important reason to reduce global affluence is justice or equity, as highlighted by limits-to-growth theories. Since two-thirds of affluent consumers live in high-income regions (IPCC 2022), a considerable reduction in global affluence should favor a more just transition as it should reduce economic inequality between high-income and low-income regions, which are the least responsible of emission growth, but suffer the greatest impact of climate change. As reported by IPCC (2022), “economic inequality and climate change are deeply intertwined at national and international levels: failing to address climate change may exacerbate national and international inequalities in income and wealth, while large economic inequality can hinder the transition, especially in low-income countries”.

Finally, from a wider perspective, we see the problem of climate change and environmental degradation as a clear signal indicating the need to limit and select technology growth in order to leave more physical space for the natural environment. Broadly speaking, technology, defined as the set of all products and production processes "created" by humans, can be seen as the expression of a distinctive creative attitude of the human species[14]. Since their origin, inventing and creating ever more sophisticated tools and techniques (from the first stone tools and techniques for using fire) has been the distinctive answer of humans to the adversity of nature, i.e., competing species and resource scarcity. In that sense, technological change stretches the limits to growth imposed by natural adversity and partially liberates humans from the constraints of the nature (Ricardo 1951, Bergson 1909). This power to create machines and machines that make other machines (Bergson 1909) enabled humans first to survive against natural adversity and then to become the dominant species. Since the

[14] In the words of Bergson (1909): “If we could shed all pride, if, in defining our species, we adhered strictly to what history and prehistory present as the constant characteristic of humankind and intelligence, we might not say Homo sapiens, but Homo faber. Ultimately, intelligence, considered in what appears to be its original purpose, is the ability to create artificial objects, particularly tools for making tools, and to endlessly vary their manufacture”

Industrial Revolution, however, technology growth has accelerated sharply, leading to the progressive accumulation of technology in the natural environment and the corresponding reduction in the physical space left for nature. The accumulation of technology, concentrated in a minority of affluent individuals and regions, has now reached the point of threatening the very existence of the Earth and its living species as we know them. Technology, the expression of humankind's liberation from natural constraints, has turned to be the primary constraint on nature and the human species itself, which is part of it. In our view, a significant reduction in global affluence could help limit the physical space occupied by technology in order to expand that of nature and achieve a new balance between technology and nature.

4.2. Ecological technological revolution and paradigm-shift

As discussed in Section 3.2, limits-to-growth theories consider that technological change prioritizes capital valorization and economic growth over wellbeing and human needs. As such, technological change is seen as the main means of ensuring capital valorization and accumulation, as well as the very reproduction of the capitalist system. This view of technology seems to us more critical, but much less developed than that of evolutionary theories. More particularly, our impression is that limits-to-growth theories lack a holistic theoretical framework to analyze the processes and forces that drive major qualitative changes of socio-economic systems. As a consequence, in our opinion, these theories tend to underestimate the potential of technology in mitigating climate change and enabling major changes. As highlighted by evolutionary theories, technological changes, in particular major changes like technological revolutions, in addition to being the main source of quantitative growth of economic systems (growth in productivity and affluence), are also the main driver of major qualitative changes of socio-economic systems. These changes in dominant technologies, sectors, firms, institutions and societal values, all together, characterize a new phase of economic development. In our perspective, the low-carbon transition requires precisely these major qualitative changes and, therefore, needs major technological changes in selected directions.

The low-carbon transition requires the rapid replacement of at least a part of the global energy system with another, i.e., the replacement of at least a part of worldwide fossil-fuel technologies and energy systems with low-carbon technologies and energy systems. Fossil fuels still dominate the global energy mix with a share of about 80%, while renewables, despite their growth, account only for about 15% (IEA 2021). In our understanding, the scale and speed of the required changes suggest that the low-carbon transition can be usefully conceptualized, and possibly modeled, as a technological revolution, which, by definition, is a rapid replacement of dominant technologies via processes of creative destruction. More specifically, we propose to conceptualize the low-carbon transition as a technological revolution based on selected ecological technologies, i.e., an ecological technological revolution. This, following Section 2.1, can be defined as a cluster of interrelated and mutually supporting radical ecological technologies that have the capability of initiating new leading sectors and a widespread impact on existing sectors, destroying some and rejuvenating others. Compared to a green digital revolution based on AI or twin transition, an ecological technological revolution should enable to faster unlock socio-economic systems from fossil-fuel technologies as it should allow to focus research and investment efforts on ecological technologies rather than on competing ones.

In addition, the proposed conceptualization is useful because it allows us to analyze the processes and forces that can accelerate and shape an ecological technological revolution. This analysis can shed new light on the processes and forces that can accelerate and shape a low-carbon transition, which also should contribute to faster unlock socio-economic systems from fossil-fuel technologies.

First, evolutionary theories highlight that each technological revolution is the result of a paradigm-shift and requires the definition of a new technological paradigm (Section 2.1). Therefore, a process capable of accelerating and shaping a low-carbon transition should promote both the shift to an ecological paradigm and the definition of its main features. The definition of a technological paradigm is a process of creation and selection emerging from a community that shares common scientific, engineering and organizational principles. The result of this process should be, in this context, the definition of a set of general, but clear ecological needs to which the paradigm has to respond, an ecological heuristic, i.e., a common vision of "how to do things", a set of core ecological technologies and sectors. The technological paradigm of AI, although probably not yet well defined, seems to respond to the need of "mechanizing human thinking activities" (Iori et al. 2022), which seems rather distant, and indeed in competition with the need of an ecological paradigm.

Second, evolutionary theories highlight that paradigm-shifts, new technological revolutions and new phases of economic development result from a complex interaction of endogenous and exogenous factors (Section 2.2). Therefore, in Section 4.3, we analyze the factors that can accelerate and shape an ecological technological revolution, identifying an endogenous process of co-evolution between minimalist demand and investment in ecological technologies, and an exogenous process of democratic definition of an ecological paradigm. Both these processes, and the forces that shape them, should enable the qualitative evolution of socio-economic systems towards ecology, without necessarily produce their quantitative growth.

4.3. Technology cap, democracy and market

As discussed in Section 4.1, we consider it necessary a cap on global affluence in order to mitigate climate change, stay within ecological limits and achieve a more just transition. In this section, we suggest that, if we define technology broadly as all existing and potential products and processes of production, a cap on affluence can be conceptualized as a technology cap, that is, a limit, voluntary or induced by some form of legal cap (e.g., maximum consumption standards, sustainable consumption corridors), to the amount of technologies to be consumed, produced, developed and adopted. The first advantage of the proposed conceptualization is that, in this way, a cap on affluence can be more easily analyzed in the framework of evolutionary theories of long-run economic development. In this context, the lifestyle of sufficiency advocated by limits-to-growth theories can be conceptualized as consumption and production choices in tune with a minimalist perspective or heuristic, which aims at minimizing the impact of human activity on the nature through a more conscious and selective use of technologies. This heuristic, based on high tastes for nature rather than for consumption and profit, is opposed to that of economic agents that aim at maximizing consumption and profit. The aggregate demand (consumer, investment and government spending) resulting from such a heuristic, or from a legal cap on global affluence, is here called minimalist demand and implies an increase in demand for selected ecological products and production processes, as well as, a reduction in demand for affluent and less useful products and production processes.

As discussed in Section 2.2., the co-evolution between demand and investment in technologies is the main endogenous process driving long-run economic development. If so, a minimalist demand has the potential to activate an endogenous process of co-evolution with investment in ecological technologies that can accelerate and shape a low-carbon transition. An increase in demand for selected ecological products and production processes stimulates investment in selected ecological technologies, which, in turn, stimulates demand growth for selected ecological products and production processes. The result of this process of cumulative causation should be major qualitative changes towards ecology in dominant technologies, firms, sectors, institutions and social values. Although this process may also cause a growth of global demand and production, this effect should be compensated, at least partly, by the reduction in demand for affluent and less useful products and production processes, which should lead to a reduction of global demand and production. In this way, the process of co-evolution between minimalist demand and investment ecological technologies can enable the qualitative evolution of socio-economic systems towards ecology, without necessarily produce their quantitative growth, i.e., growth of consumption, production and affluence.

The second advantage of using the concept of technology cap is that, according to our definition, it consists in limiting not only the technologies to be consumed and produced, but also those to be developed and adopted. Therefore, in this context, establishing a cap on affluence would also explicitly require the definition of an ecological technological paradigm that can guide choices about future rates and directions of technological change. As discussed in Section 2.2, in addition to endogenous factors, there are also exogenous or non-market factors that can influence paradigm-shifts, new technological revolutions and phases of economic development. We have also observed that, among these factors, socio-institutional actors can accelerate and shape the emergence of a new revolution by both promoting its diffusion into society and participating in the processes of creation and selection the outcome of which will determine the "winning" paradigm". Here we suggest that this process of creation and selection can be made more collective and democratic by creating spaces of debate and decisional processes on the main features of an ecological paradigm. This would enable different socio-institutional actors to participate in the process of definition of the new paradigm and, in this way, to act as exogenous unlocking factors, in that capable of accelerating and shaping an ecological technological revolution. Hence, in this context, socio-institutional actors can accelerate and shape a low-carbon transition in three ways: by shifting their consumption choices towards a minimalist heuristic and demand, by promoting their diffusion throughout society and by participating in the process of definition the new ecological paradigm.

In addition, a more collective a democratic definition of an ecological paradigm is important, in our view, to achieve a more democratic transition. A democratic definition of a technological paradigm is, in its essence, a debate on the directions of technological and economic development to be prioritized, postponed or neglected. The objective of these spaces is to help societies to democratically discuss and establish whether accelerating technology use and development in certain directions of change, while reducing or banning it in other directions. As such, a technology cap is thought of as a tool for a democratic political economy of technological change. Its final aim is to achieve a more democratic transition by partly replacing market decisions on technological change with democratic debate and decisional processes, as advocated by limits-to-growth theories. However, here democratic debate and decisional processes explicitly act as factors of creation and selection of future directions of technological and economic development, partly replacing markets and profits in this role. The final result of this process should be higher rates of technological change and production in some directions and slower or zero rates of technological change and production in other directions, with uncertain impact on aggregate growth. Therefore, like the process of co-evolution between minimalist demand and ecological technologies, also the process of democratic definition of an ecological paradigm can enable the qualitative evolution of socio-economic systems towards ecology, without necessarily implying their quantitative growth.

5. Conclusions

This paper analyzes the relationship between climate change, technological change and affluence with the aim of providing a deeper conceptualization of technological change, while taking into account ecological limits, justice and democratic concerns. To this end, we analyze evolutionary and limits-to-growth theories under the lens of what we call tradeoff between technological change and affluence: either technological change will enable to rapidly reduce emissions, basically by quickly unlocking socio-economic systems from fossil-fuel technologies, or a significant reduction in global affluence will be necessary to limit climate change.

In agreement with limits-to-growth theories, we believe existing empirical and theoretical evidence more than sufficient to consider that future rates and directions of technological change are unlikely to rapidly reduce emissions, even if directed by government policies in the "right directions", as proposed by evolutionary theories (Perez 2016, Lamperti et al. 2020). Therefore, we suggest that a significant reduction in global affluence is as necessary to limit climate change as a faster low-carbon transition. If global affluence is defined as the global 10% wealthiest consumers, which are responsible of about 36-45% of global emissions (IPCC 2022), then a significant reduction in their consumption should allow a significant and relatively rapid curb of emissions. Further, since two-thirds of wealthiest consumers live in high-income regions (IPCC 2022), a significant reduction in global affluence should favor a more just transition as it should reduce economic inequality between high-income and low-income regions, which are the least responsible of emission growth, but suffer the greatest impact of climate change. Finally, from a more general perspective, we think that a significant reduction in global affluence could help societies to achieve a new balance between technology and nature. However, key obstacles to such a measure are the economic interests of affluent individuals and regions. Likewise, affluent consumption is structural in both government economic policies and corporate business models (Dubuisson-Quellier 2022). Even so, Koliofotis (2022) suggests that affluent consumption has not evolved as a sexually selected mating strategy, rather it is the result of the evolution of a culture that rewards this type of consumption. In this case, affluent consumption could be reduced as a result of the evolution of a culture that does not reward this type of consumption.

We also suggest that the low-carbon transition can be usefully conceptualized, and possibly modeled, as an ecological technological revolution, i.e., a technological revolution based on selected ecological technologies. Evolutionary theories highlight that technological revolutions are at the origin of major qualitative changes of socio-economic systems: changes in dominant technologies, sectors, firms, institutions and societal values, which, all together, characterize a new phase of economic development. If so, an ecological technological revolution can importantly shift pathways of economic development towards ecology. Compared to a green digital revolution based on AI or twin transition (Perez 2016, Bianchini et al. 2023), an ecological technological revolution should enable to faster unlock socio-economic systems from fossil-fuel technologies as it should allow to focus research and investment efforts on ecological technologies rather than on competing ones. In this context, a process capable of accelerating and shaping a low-carbon transition should promote both a shift towards an ecological technological paradigm and the definition of its main features, i.e., ecological needs and heuristic, core ecological technologies and sectors. We think that, while the needs to which the new paradigm has to respond may be sufficiently general and clear (e.g., net-zero emissions), the new heuristic and the community from which it has to emerge are not yet established. Different visions of ecology – probably not yet well defined, but corresponding to different core technologies, sectors, political and economic interests – are in competition among each other's, as well as with dominant and emergent paradigms (e.g., fossil-fuels and AI). It is worth to mention that, after a phase of competition, the dominant paradigm, once installed, embodies strong prescriptions on the directions of technological change to pursue and those to neglect (Dosi 1982). Hence, the paradigm that will "win the competition" will likely profoundly affect future directions of technological, economic and social development.

Finally, we propose that a cap on affluence can be conceptualized as a technology cap, that is, a limit (voluntary or induced by some form of legal cap) to the amount of technologies to be consumed, produced, developed and adopted. In our view, there is a growing awareness in the literature of the key role of reducing affluence and inequality to mitigate climate change, stay within ecological limits, and achieve a more just transition[15], as also shown by the recent emphasis of IPCC (2022) on demand-side solutions such as demand reduction, changes in lifestyles and social norms. However, the relationship between changes in demand induced by a cap on affluence and changes in technology, as well as the implications of these changes for economic development are not yet well understood. In our perspective, based on evolutionary theories of long-run economic development, a technology cap can accelerate and shape a low-carbon transition by activating two processes. Both these processes, and the forces that shape them, should enable the qualitative evolution of socio-economic systems towards ecology, without necessarily produce their quantitative growth. The first is an endogenous process of co-evolution or cumulative causation between minimalist demand, i.e., the aggregate demand resulting from cap on affluence, and investment in ecological technologies. The second is a process of debate and democratic definition of an ecological technological paradigm, which can enable socio-institutional actors to act as exogenous unlocking factors. Evolutionary theories highlight that the emergence of a technological paradigm is the result of a process of variety creation and selection involving mostly non-market or exogenous actors, like governments, universities and other socio-institutional actors (Dosi 1982). Here we suggest that this process of creation and selection can be made more collective and democratic by creating spaces of debate and decisional processes on the main features of an ecological paradigm.

Hence, in this context, socio-institutional actors can accelerate and shape a low-carbon transition in three ways: by shifting their consumption choices towards a minimalist heuristic and demand, by promoting their diffusion throughout society and by participating in the process of definition the new ecological paradigm. A democratic definition of a technological paradigm is, in its essence, a debate on the directions of technological and economic development to be prioritized, postponed or neglected. The aim is to clarify the political and economic interests at play, make more conscious technological choices and focus investments on more shared directions. As such, a technology cap is thought of as a tool for a democratic political economy of technological change. Its final aim is to achieve a more democratic transition by partly replacing market decisions on technological change with democratic debate and decisional processes, as advocated by limits-to-growth theories. However, here democratic debate and decisional processes explicitly act as factors of creation and selection of future directions of technological and economic development, partly replacing markets and profits in this role.

To conclude, this study suggests that evolutionary and limits-to-growth theories can be usefully combined to better understand how to stay within ecological limits and accelerate a more just and democratic transition. Evolutionary theories may give an important theoretical contribution to form that holistic approach that is widely considered necessary to achieve the low-carbon transition. Limits-to-growth theories highlight the necessity of limiting global affluence and the quantitative growth of economic systems to stay within ecological limits and achieve a more just transition. Further, they integrate democratic concerns in their analysis of climate change. This is an explorative study and

[15] See for example Florian et al. (2019), Wiedmann et al. (2020), EEA (2021), ADEME (2022), Dubuisson-Quellier (2022).

much further research is needed to cope with its limitations. One possible direction of research could focus on developing climate change models and scenarios that model the low-carbon transition as an ecological technological revolution. Secondly, models could explicitly include a form of technology cap and simulate the endogenous and exogenous processes it can activate. Finally, it could be tested the impact of these processes on the quantitative and qualitative evolution of socio-economic systems.

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