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Article

Anthropocene futures: Regeneration as a decarbonization strategy

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Abstract: In the context of the Anthropocene, and in the face of an unprecedented climate crisis generating 20 billion tonnes of CO_2 annually, this study critically examines the transition from a 'grey' economy based on fossil fuels to a 'green' and regenerative economy, proposing two interrelated strategies: the transformation of terrestrial and agricultural systems to enhance natural carbon sequestration (including halting deforestation, regenerative agriculture and sustainable livestock systems), and the restructuring of global social metabolism (promoting reduced consumption, circular economies and renewable energy). The analysis emphasizes that this transition will require unprecedented global cooperation and bold government policies and will face significant challenges such as resistance from entrenched interests and global inequalities; however, the expected benefits—including a stable climate, healthy ecosystems and a sustainable economy—justify the necessary efforts, framing this transformation not just as a technical challenge but as an ethical and ontological imperative to move from an extractive relationship with the planet to a co-creative role that ensures intergenerational prosperity and planetary health.

Keywords: green economy; zero-net; carbon; sustainability; development

1. Introduction

This study critically examines how the transition to a regenerative economy can accelerate the process of global decarbonization in the era of human dominance. This era, also known as the Anthropocene and considered by many experts to be a new geological epoch, represents a turning point in Earth's history. It is characterized by the impact of human activity in shaping the future of the planet. Anthropogenic actions have now decisively influenced Earth's systems, altering natural processes and leaving an indelible mark on the geological record [1–4], driven primarily by exponential human population growth and rising per capita consumption [5], factors operating in a context of unprecedented global hyper-connectivity [6,7]; This interconnectedness, facilitated by information and communication technologies, has not only transformed economic dynamics, but has permeated all spheres of human activity and its interaction with the natural environment, reconfiguring economic, cultural, political, ecological and social aspects on a planetary scale [8,9]. The biosphere is at the epicenter of this convergence of transformative forces and is experiencing abrupt and potentially irreversible changes in global ecological systems [10,11], manifested in accelerated biodiversity loss, changes in global climate patterns, disruptions in fundamental biogeochemical cycles, and widespread land degradation and expansion of drylands.

The Earth's evolution is being reconfigured in the face of humanity. Humanity's insatiable appetite for progress is eroding the planet's biosphere, pushing it beyond its regenerative limits [12,13]. This onslaught is manifesting itself in a three-act tragedy:

First, the overexploitation of renewable sources of life; second, the depletion of Earth's finite resources; and third, the erosion of ecosystem resilience. As we push against these planetary boundaries, we find ourselves in a race against time, challenged to redefine our relationship with the only stage we have ever known: Earth.

Current projections show a worrying outlook for the near future. If current trends in population growth and consumption patterns continue unchecked, human demand for resources and ecosystem services is projected to exceed the planet's regenerative capacity by 100% by 2050. The pressure on natural resources goes beyond the extraction of raw materials. It also affects the ability of ecosystems to absorb the waste we produce, a crucial process for sustaining modern lifestyles [14]. Without nature's capacity to regenerate, our consumption patterns would become unsustainable in the long run, accelerating the ecological collapse that threatens both the natural environment and the societies that depend on it [15], a perspective that underscores the urgency of implementing radical transformations in our economic, technological and social systems; developing and deploying clean technologies; promoting green lifestyles; intensifying conservation and ecological restoration efforts; and strengthening global environmental governance mechanisms. This era therefore represents both an unprecedented challenge and a unique opportunity to redirect the course of human civilization towards a sustainable and equitable future, requiring a deep understanding of the interconnectedness of Earth systems that must catalyze a radical transformation in our relationship with the world, guided by the principles of sustainability, equity and respect for planetary boundaries.

A global paradox is unfolding with intensity: while science urgently calls for a reduction in emissions of climate-changing gases, especially carbon dioxide (CO_2), society is at an ideological crossroads. For decades, the Intergovernmental Panel on Climate Change (IPCC) has warned of a bleak future. But this scientific urgency is colliding with skepticism and short-term economic priorities. At the heart of this controversy is a key question: Are CO_2 levels a valid indicator of societal progress? This debate divides nations, particularly in countries such as the United States, where environmental sustainability is often overshadowed by economic growth [16]. The reluctance to prioritize CO_2 reduction over immediate economic interests reflects not only political myopia, but also the deep contradictions in our development model. As the world approaches a climate tipping point, reconciling progress and sustainability has never been more urgent or challenging [17]. This attitude reflects a dichotomy in global perceptions of decarbonization: while some countries see it as an opportunity for sustainable development, others see it as a threat to their economic growth [18,19].

The reluctance of the United States to fully commit to global decarbonization targets is deeply rooted in the capitalist development model that underpins the global economy. This model, which prioritizes endless profit generation, finds its strongest advocate in the U.S. From this perspective, economic interests often outweigh the urgent need for environmental action. International alliances forged by the US tend to be driven by common interests rather than principles of reciprocity. This economic-centric approach helps explain the country's reluctance to take decisive action to address the climate crisis at this critical juncture in history [17].

Despite these political and economic challenges, scientific projections underline the seriousness of the situation. According to Lashitew and Mu [17], even with the implementation of effective mitigation policies and the development of emission-negative technologies [20], global warming is likely to exceed 3 °C by the end of the 21st century. This scenario underscores the urgency of a paradigm shift in development thinking and the need for a robust global commitment to decarbonization that transcends short-term national interests in favor of long-term planetary sustainability.

On the cusp of an unprecedented climate crisis, humanity stands at a crucial crossroads that requires a radical transformation of our economic and social systems, moving from a "grey" economy based on fossil fuels and unsustainable practices to a "green" and regenerative economy, a transition that is not merely an option but an imperative necessity to ensure the survival and prosperity of future generations, offering a hopeful vision of a sustainable future amidst increasingly alarming climate projections that underscore the urgency of taking drastic action to reduce carbon emissions [21].

A regenerative economy, unlike the current extractive model, seeks not only to minimize environmental damage but also to restore and regenerate ecosystems, based on fundamental principles such as circularity, which aims to design production and consumption systems that eliminate the concept of 'waste' by mimicking the closed cycles of nature; biomimicry, which draws on natural processes to develop efficient and sustainable technologies and systems; a complete transition to clean and renewable energy sources; and, last but not least, a sustainable development policy, which is based on the principles of subsidiarity and proportionality.

The adoption of this regenerative economic model promises to accelerate the decarbonization process through several interlinked pathways [22]: First, clean energy innovation, driven by massive investment in renewable energy technologies, not only reduces direct emissions but also catalyses a virtuous circle of innovation that makes these technologies increasingly efficient and affordable, while decentralising energy production through microgrids and community energy systems can further accelerate this energy transition; second, industrial transformation, through the adoption of circular economy principles, can significantly reduce emissions associated with raw material extraction and waste management, revolutionising production processes with technologies such as additive manufacturing (3D printing) and the development of new biodegradable materials; third, regenerative agriculture, including practices such as agroforestry and holistic grazing management, not only reduces emissions associated with industrial agriculture, but also sequesters carbon in the soil, transforming agricultural fields from emission sources to carbon sinks; fourth, reinventing transport systems by prioritising electric public transport, active mobility and zero emission vehicles can reduce emissions from the transport sector, one of the largest contributors to climate change; and fifth, implementing sustainable building techniques and policies and energy retrofits in existing buildings not only reduces operational emissions, but also addresses the emissions embodied in building materials.

In order to achieve the proposed objective of this study, a qualitative approach was adopted, using documentary analysis as the main investigative tool. The research methodology was designed to ensure both depth and breadth in understanding the interrelationships between the Anthropocene and decarbonization processes in the contemporary global context [23]. The bibliographic search strategy was systematically structured around three interrelated thematic axes: the concept of the Anthropocene and its implications, decarbonization processes and strategies, and the dynamic interrelationship between these two phenomena. This framework allowed for a comprehensive exploration of how the Anthropocene has influenced the context of decarbonization and its far-reaching global consequences. The search process was guided by selected keywords covering the full range of relevant concepts, including "Anthropocene", "decarbonisation", "grey economy", "green economy", "regenerative economy", "climate change" and "public policy".

To ensure a comprehensive and up-to-date review, the research drew on a range of high-quality sources. The main academic databases consulted included Wiley, SpringerLink, Elsevier, MDPI and BMC, which provided access to a wide range of academic materials, including peer-reviewed articles, academic books and book chapters. In addition, to incorporate practical policy perspectives, the study included an extensive review of reports and policy documents from relevant international organizations, accessed through their official platforms.

The documentary analysis process was rigorous, involving an initial review of 120 documents, of which 93 were finally selected on the basis of their relevance, quality and significant contribution to the research objective. These selected documents were systematically categorized into three main thematic groups: i) Conceptualization and implications of the Anthropocene (32 documents): This category focused on theoretical foundations, environmental and social implications, and historical development of the Anthropocene concept; ii) decarbonization processes and strategies (38 documents): These materials covered technical and technological aspects, policy frameworks, implementation strategies and economic implications of decarbonization efforts; and iii) systemic analysis and integration (23 documents): This group focused on the links between the Anthropocene and decarbonization, future scenarios and policy recommendations.

The research process, conducted over six months from February to July 2024, allowed for a detailed and reflective examination of the literature. This extended period facilitated the identification of patterns, emerging trends and key findings that underpin the study's conclusions. The systematic approach enabled an understanding of the interactions between the Anthropocene and decarbonization processes, revealing critical perspectives on their mutual influence and implications for current and future global environmental governance. The approach adopted not only facilitated the identification of current knowledge and gaps in the field [24], but also allowed for the development of new perspectives on the complex relationship between the Anthropocene and global decarbonization efforts.

2. Problematisation around the Anthropocene and decarbonisation

In this study, problematization is understood as a process in which an idea, situation or concept that is generally taken for granted is critically examined in order to reveal its underlying complexity and to challenge established assumptions. This approach, mainly used in academic and philosophical contexts, does not necessarily seek to solve a problem, but rather to understand it in its full depth, taking into account multiple perspectives and uncovering hidden power relations.

The Anthropocene is emerging as a political concept, coined to draw attention to the scale of anthropogenic impact on a planetary scale. This term not only highlights physical changes in the global environment, but also raises fundamental questions about human agency and ethical responsibility in the context of contemporary life [25]. This phenomenon did not emerge as a result of deliberate planning, but rather as an unforeseen consequence of the industrialization of human societies [26]. This marks a crucial shift in the dynamics between humanity and the Earth system. Throughout history, meaningful human engagement with the geological forces of the planet has occurred only on a few exceptional occasions. Among these rare examples, the Montreal Protocol stands out as the most cited case [27], demonstrating the potential for coordinated global action to mitigate anthropogenic impacts on systems. This precedent underscores the possibility of positive human intervention on a global scale, offering a glimmer of hope in the context of contemporary environmental challenges.

In this framework of the Anthropocene, a sustainable development perspective is presented as an imperative that goes beyond conventional policies and requires a profound social transformation. In this context, the concept of agency becomes crucial and emerges as the central axis for catalyzing and implementing the necessary transformations. These transformations are aimed not only at limiting global warming to manageable levels, but also at achieving the wide range of goals set out in the SDGs, from eradicating poverty to preserving ecosystems. In this sense, the notion of agency goes beyond the mere capacity for individual or institutional action. It implies a reconceptualization of collective responsibility and global governance that recognizes socio-ecological systems [28]. This holistic approach is fundamental to addressing the complexity of the challenges of the Anthropocene, which require unprecedented cooperation across nations, sectors and disciplines.

Humanity’s ability to influence the biosphere is redefining the limits of its existence. This global human agency manifests itself in heterogeneous ways that vary considerably across individuals and social groups, adding to the complexity of managing its impacts and potential. Otto et al. [29] argue that in order to achieve efficient resource use and sustainable ecosystem management—whether global, regional or local—it is imperative to intervene and improve existing social institutions. While it is undeniable that social institutions undergo renewal throughout history, the assumption that these changes can be directed or imposed by external agents can be questioned. The dynamics of institutional change often emanate from the very social groups that constitute and sustain them, responding to their changing needs, values and aspirations.

This critical inquiry examines the multifaceted nature of human agency within the global decarbonization paradigm, exploring its latent potential and inherent constraints. It aims to cultivate a more comprehensive understanding of global metamorphosis, acknowledging the intricate web of interconnections that drive this transformative process. By examining humanity’s collective capacity to shape planetary outcomes, the analysis seeks to bridge theoretical abstractions with pragmatic implementations, thereby enriching the discourse on anthropogenic influence in the Anthropocene era. Under this premise, it is argued that to generate adequate problematizations of decarbonization, it is essential to adopt a social-ecological systems perspective. This approach recognizes the complex interdependencies between human and natural systems and allows for a holistic and nuanced view of the challenges and opportunities presented by the transition to a regenerative society [30]. Linkages require addressing both sociopolitical challenges and ecological limits [31]. The relationship between socio-political problems—such as socio-economic inequality, resource conflicts, weak governance, unsustainable economic development models, environmental injustice, nationalism, populism and resistance to change—and ecological constraints—such as climate change, biodiversity loss, water scarcity, soil degradation and pollution—is undeniable. Social problems such as inequality and conflict are intertwined with environmental crises such as climate change and resource scarcity [31]. The current development model, focused on unlimited growth and intensive exploitation, has exacerbated these problems, disproportionately affecting vulnerable communities. Achieving a sustainable future requires a comprehensive approach that combines social equity with environmental sustainability. This means adopting an equitable development model, strengthening environmental governance, investing in renewable energy and promoting international cooperation. In this context, decarbonization is essential to mitigate climate change and ensure a fair and equitable future for all.

Applying a social-ecological lens to decarbonization analysis requires recognition of the complex interactions between social, economic and environmental spheres. This approach requires recognition of the multiple temporal and spatial dimensions within which these systems operate while identifying critical nodes where strategic interventions can have maximum impact. It is imperative to anticipate the potential spillover effects of policy implementation and to promote adaptive, flexible strategies for managing global change. Recognizing the close relationship between sociopolitical challenges and ecological limits, we can better anticipate cascading effects across scales and sectors. This approach not only illuminates the complexity of decarbonization efforts, but also highlights the delicate balance between human ingenuity and ecological constraints in shaping our future. Decarbonization as a global imperative requires not only technological innovation and bold public policies, but also a deep understanding of the socio-ecological dynamics that underpin our production and consumption systems.

Throughout the millennia of human history, our species has been inextricably intertwined with the natural world. From the earliest hunter-gatherers relying on the bounty of the land for sustenance to modern conservationists striving to protect the Earth's fragile ecosystems, humanity's relationship with nature has been a constant thread in our collective history. However, with the advance of civilization, population growth and technological development, this relationship has gradually turned into a dynamic of exploitation and degradation of the natural environment. The ecological footprint, as introduced by Wackernagel [32], provides a sophisticated framework for measuring the impact of human activities on ecosystems. This approach shows that virtually all daily activities—from bathing, eating, commuting, working and studying—contribute to the emission of CO_2, thereby exacerbating the climate crisis.

In this sense, significantly reducing CO_2 concentrations is a challenge that goes beyond simple technical or legislative adjustments. It would require a radical change in the lifestyles of modern societies [33], a profound change in the status quo that governs our forms of production and consumption [33]. The reality, however, is that most people are unwilling to make such profound changes. Despite awareness of the destructive implications of the current model of development and the social metabolism that sustains it [33], contemporary societies tend to prioritize comfort, consumption and economic growth over environmental sustainability.

The discussion of decarbonization as a pathway to sustainable development is proving to be utopian under current societal metabolic conditions [33]. The scale of change required to achieve real decarbonization goes beyond mere technology or public policy, as it affects the very foundations on which our economies and lifestyles are built. Without a profound restructuring of the global socio-economic system and a fundamental rethinking of human priorities, decarbonization remains an unattainable goal under current circumstances. This phenomenon was first observed by William Stanley Jevons in the 1860s in his studies of coal consumption. His studies documented how savings from efficiency gains in industrial operations were reinvested in ways that expanded overall production, resulting in increased coal use. This dynamic came to be known as the Jevons Paradox [34]. Only through radical rethinking and transformative collective action will it be possible to build a future where development is not in constant conflict with the planet's ecological limits.

3. Anthropocene

The precise onset of the Anthropocene remains a matter of considerable debate. However, environmental changes associated with atmospheric gas fluctuations provide geological markers that are synchronous and globally distributed, allowing their identification on annual to decadal time scales. These markers are fundamental to establishing the Global Stratigraphic Boundary Point (GSSP) of the Anthropocene. The first proposed GSSP marker is a marked change in atmospheric methane levels more than 5000 years ago, although the lack of additional stratigraphic correlations precludes a definitive conclusion [35].

Two main dates have been proposed for the start of the Anthropocene. According to Lewis and Maslin [26], the first is 1610 and the second is 1964. The choice of 1610 attributes the beginning of this new geological epoch to the effects of the conquest of the Americas, trade routes and the rise of coal burning. This perspective highlights social issues such as the unequal power dynamics between different societies, the consequences of economic expansion and the globalization of trade, while underlining humanity's increasing dependence on fossil fuels. The European conquest of the Americas is cited as an important example of how human activities can set in motion large-scale processes that are difficult to predict. Instead, the 1964 selection shifts the narrative to an era of elite-driven technological advances that have threatened the sustainability of the planet. The development of military technology, from spears to nuclear weapons, highlights the concept of "progress traps", where technological advances do not always guarantee long-term benefits. The progress trap is an economic and social phenomenon in which technological and productivity advances paradoxically do not always translate into substantial improvements in quality of life or overall well-being. This concept suggests that progress can have side effects such as increased expectations, increased competition, rapid obsolescence of skills and inequality in the distribution of benefits. In essence, it argues that economic and technological development should be evaluated not only in terms of growth or efficiency, but also by considering its holistic impact on society and human welfare [36].

The concept of the Anthropocene encompasses unprecedented, planet-wide changes driven by social transformations. It highlights the underlying social forces responsible for global change and reveals the tensions between generalized narratives of human impact and interpretations rooted in specific historical, political and cultural contexts [37]. These contrasts reflect the complexity of understanding and addressing human impacts on the planet and underline the need for multidimensional approaches to meet the challenges of the current era. The Earth system is an intricate web of interconnected components, each influencing the others in a dynamic of interactions [38]. This complex socio-ecological system comprises physical, chemical, biological and social elements that shape the current state and future trajectory of the planet. The four main components of the Earth system—atmosphere, biosphere, hydrosphere and geosphere—interact synergistically to regulate the functioning of the planet [39]. These components provide essential services such as climate regulation, food production and the provision of natural resources. For example, the climate system regulates temperature, precipitation and atmospheric circulation, while the biosphere provides ecological services such as nutrient cycling and biodiversity [40–45]. The complexity of the Earth system results from the multiplicity of processes operating at different scales and levels of organization [8]. Humans, as an integral part of this system, constantly interact with and influence these components. These interactions can lead to adaptive processes, change and, in many cases, uncertainty about the future of the system. The ability of humans to alter these natural components highlights the importance of understanding the system, where any action on one component can have unpredictable consequences on the rest, affecting both the balance of the planet and the well-being of its inhabitants.

The burgeoning global population, combined with prevailing patterns of consumption, has been the driving force behind the profound and rapid changes facing the planet today [6]. Globally, these changes are having a devastating impact on various aspects of the natural and social environment. One of the main impacts is accelerated deforestation, a process that is rapidly reducing forest cover in many regions of the world, affecting both ecosystems and the communities that depend on them [46]. This is compounded by the intensive use of agrochemicals, which not only degrades soils and pollutes water sources, but also seriously affects the health of the animal, plant and human species that inhabit these areas [47]. Another major consequence of these global changes is the loss of biodiversity. Species are disappearing at an unprecedented rate, altering ecosystems and disrupting the ecological balances that are fundamental to the functioning of the planet [48]. At the same time, we are witnessing a growing loss of ancestral knowledge, the knowledge accumulated over generations that has enabled indigenous cultures to live in harmony with nature. Modernization and globalization have eroded this knowledge, replacing it with technologies and practices that are more efficient in the short term, but unsustainable in the long term [49]. In addition, conflicts and wars, often linked to access to increasingly scarce natural resources, have intensified in various parts of the world, exacerbating humanitarian and environmental crises [50]. The continued overuse of fossil fuels remains a major contributor to climate change, releasing huge amounts of greenhouse gases that exacerbate global warming [51]. This is compounded by land-use change, where natural areas and agricultural land are constantly being converted into urban and industrial areas, fragmenting habitats and further affecting ecosystems [52].

In this context, the Anthropocene emerges as a reflection of this new human-dominated geological epoch. Today, this epoch is characterized by the global environmental crisis, which is not limited to a single aspect but encompasses a wide range of interconnected problems. The globalized world is immersed in a market logic that prioritizes economic growth over environmental sustainability. This economic model has absorbed and subsumed the natural world, treating it as an infinite resource to be exploited without regard for the long-term consequences. A global society governed by parametric rationality, a logic based on the optimization of economic parameters that seeks to maximize efficiency and growth within a framework that largely ignores environmental limits [53]. This narrow focus on indicators such as GDP, production rates and consumption overlooks critical measures of environmental well-being, ecosystem health and social equity. The balance between human development and planetary sustainability has thus been profoundly altered, creating a crisis that requires an urgent overhaul of our economic, social and environmental systems to avoid even greater collapse in the future.

The above scenario underlines the need to change the way humanity interacts with the planet, to rethink the social metabolism. The Anthropocene, together with its wide interdisciplinary circulation, has generated a diversity of narratives about global change and possible futures [54]. The term has allowed discourses to emerge that range from deeply disturbing visions to hopeful perspectives. The focus on human agency has shifted from predominantly catastrophic narratives of global environmental change to new, empowering stories of action. This shift is based on the recognition that societies, which are now more globally interconnected, have the potential to decisively influence the Earth system. Despite the uneven contributions of different societies to global change, and the disproportionate benefits that certain regions or groups derive from Earth system changes, the Anthropocene highlights the growing interconnectedness of individuals and societies [55]. This global interconnectedness has given humanity a significant and growing influence within Earth system processes [38].

The narratives of the Anthropocene reflect a diverse panorama of approaches that, far from being limited to categorizing the phenomenon, seek to rethink the future and its interactions in a context of global innovation and transformation [38,56]. From a naturalistic perspective, science and technology are presented as fundamental tools for managing environmental change [8], while the post-nature narrative reconfigures the relationship between culture and the environment, blurring their traditional boundaries and suggesting a future in which coexistence is reinvented [57,58]. The eco-catastrophe narrative, in turn, confronts us with the risks of inaction in the face of possible collapse and highlights the ambivalent power of innovation to both alleviate and exacerbate crises [59]. Finally, the eco-Marxist vision profoundly challenges the dynamics of capitalism that perpetuate resource exploitation and promote inequality, suggesting that any move towards true sustainability must address and transform current economic structures [60,61]. These narratives represent the complexity of the Anthropocene and project radically different futures where innovation becomes the linchpin of survival or collapse. In this context, new narratives need to be rethought to guide new processes of restoration and improvement of natural and social systems [62–64].

The emerging narrative on the Anthropocene must move beyond conventional typologies to an approach that not only acknowledges the magnitude of anthropogenic change, but also embraces the idea of "technological co-evolution" between natural and human systems. In this vision, humanity is no longer merely an agent of environmental disruption, but part of a dynamic web of interdependence in which technology and biology are intertwined in unprecedented ways. The future cannot be seen as a mere extension of today's problems, but as a space for the creation of a new planetary pact in which the boundaries between the natural, the artificial and the human dissolve in awareness and cooperation. Here, innovation is not simply a resource to mitigate crises or drive growth, but the vehicle through which the very foundations of life on Earth are redesigned. This narrative suggests that the key to navigating the Anthropocene is not to avoid catastrophic tipping points, but to anticipate and generate new forms of symbiosis between civilization and planet, where technology functions to restore lost balances, generate biodiversity and expand human capabilities without depleting resources. The challenge, then, is not just technological or social, but philosophical: It is about redefining what it means to thrive in a world co-created by humans and nature, and how to steer innovation towards a harmonious convergence between the two spheres.

If we were to start from an emerging narrative of "technological co-evolution" between natural and human systems, the future would be radically different from current projections, with a profound transformation in our relationship with the planet and our own technologies. Instead of seeing ourselves as mere stewards of natural resources, we would be co-creators in a system where nature and technology interact synergistically, with humanity playing a more balanced and responsible role in this interaction. In this future, technology would not be seen as a tool to exploit or mitigate, but as an extension of natural processes, designed to integrate and adapt to the biological and geological cycles of the planet. Cities, for example, would no longer be islands of asphalt and concrete separated from nature, but would become "urban ecosystems" where the infrastructure is literally alive: Buildings that regenerate air, harvest water and promote biodiversity, integrated into smart grids that interact with the surrounding ecosystems. Agricultural systems would be based on biomimetic processes inspired by natural ecosystems, managing resources, reducing waste and regenerating rather than degrading soils and in livestock systems, the inclusion of methane inhibitors in livestock feed and the use of microalgae and insects for manure treatment [65,66]. The reduction of methane emissions in livestock systems can be achieved through the implementation of several complementary technological strategies [65]. First, methane inhibitors, such as 3-nitrooxypropanol and cottonseeds, are incorporated into animal feed to block methanogenic bacterial enzymes in the rumen, achieving a 20%–40% reduction in emissions without compromising animal productivity [67]. In parallel, manure treatment can be optimized through the use of microalgae [68], which consume nutrients in the manure as they grow, reducing methane emissions while producing biomass that can be used as fertilizer or animal feed, as well as purifying water and capturing CO_2 during photosynthesis. In addition, the use of insects such as the black soldier fly (Hermetia illucens L.) allows manure to be processed efficiently, accelerating the decomposition of organic matter and reducing the period of methane emission while transforming the waste into protein-rich biomass that can be used as food, achieving a reduction in odours and total waste volume [69].

The economies of the future would operate within a logic of regenerative abundance rather than extractive exploitation. Digital technology and artificial intelligence would be used not only to optimize resource use, but also to create new forms of wealth based on environmental restoration and ecological value creation. The concept of ‘progress’ would be redefined, not in terms of material expansion, but as the ability to coexist in dynamic equilibrium with the planet. Evolution would no longer focus exclusively on the ability to dominate the environment, but on how we adapt and evolve alongside it, creating a new global ethic based on cooperation between species, technological systems and ecosystems. The boundaries between the human, the natural and the artificial would be blurred, giving rise to new forms of hybrid life that combine the biological and the technological in symbiosis. This future is not without its challenges. Political and social decisions would be crucial to ensure that technological co-evolution does not perpetuate inequalities or create new ones. But with an ethical and critical vision, this path would lead us to a world in which humanity, instead of being a threat to the planet, becomes an agent of regeneration and coexistence, building a future in which flourishing means evolving alongside the natural environment, not at its expense.

4. Decarbonisation

Decarbonization is the comprehensive process of reducing man-made CO_2 emissions to a net zero state and is a cornerstone of the global strategy to combat climate change. This multi-faceted approach involves transformations in the energy, transport, industry and land-use sectors, driven by technological innovation, policy interventions and evolving market dynamics. It aims to limit global temperature rise in line with international climate agreements, which will require a profound transformation of economic models and energy systems. This transition presents both significant challenges and opportunities, promising to reshape economies, labor markets and societal norms as the world moves towards a sustainable, low-carbon future. Decarbonization is therefore not just a technical endeavour, but a fundamental redesign of human activities in balance with the Earth’s climate system.

To understand the scale of the decarbonization challenge, it’s important to examine the historical context of CO_2 emissions. The global concentration of carbon dioxide in the Earth’s atmosphere has risen sharply since the start of the Industrial Revolution in the late 18th century, the period that marked the beginning of large-scale industrialization, when atmospheric CO_2 levels were around 280 parts per million (ppm). This was a natural balance that had remained relatively stable for thousands of years. However, human activity, mainly through the burning of fossil fuels, deforestation and land-use change, has drastically disturbed this balance.

Currently, the concentration of CO_2 in the atmosphere will exceed 424 ppm by 2025 [70], an increase of more than 51% over pre-industrial levels (**Figure 1**).

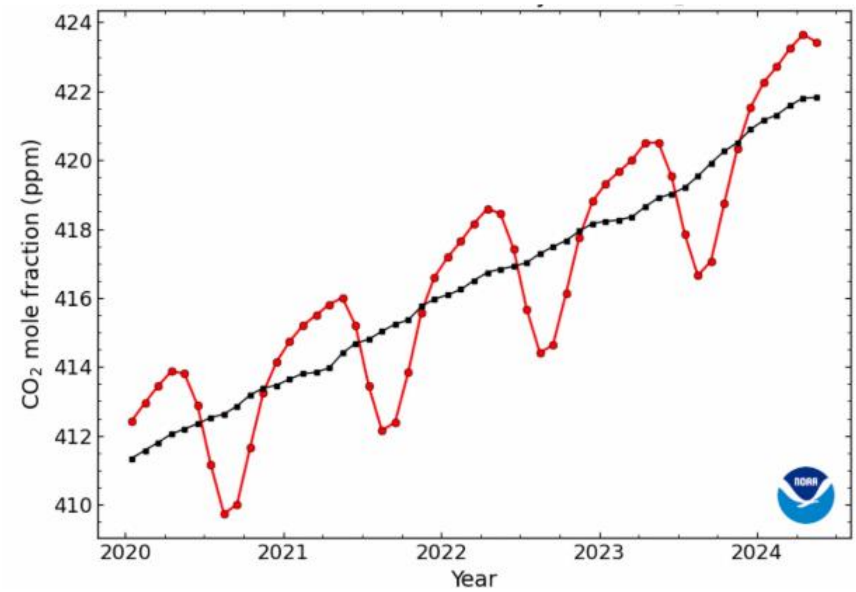

Figure 1. Global CO_2 concentration in ppm, 2025.

Source: [70]. Available in: https://gml.noaa.gov/ccgg/trends/global.html

The escalating concentration of CO_2 in the atmosphere poses a formidable challenge to global climate stability. With levels rising at an unprecedented rate of around 2.7 parts per million (ppm) per year (**Figure 2**), the scientific community has sounded the alarm about the potential consequences of unchecked carbon emissions. The IPCC has identified a critical threshold of 450 ppm atmospheric CO_2 concentration, which corresponds to a 2 °C increase in global temperature above pre-industrial levels [71]. Exceeding this threshold could trigger severe and irreversible climate change impacts, threatening ecosystems and human societies worldwide.

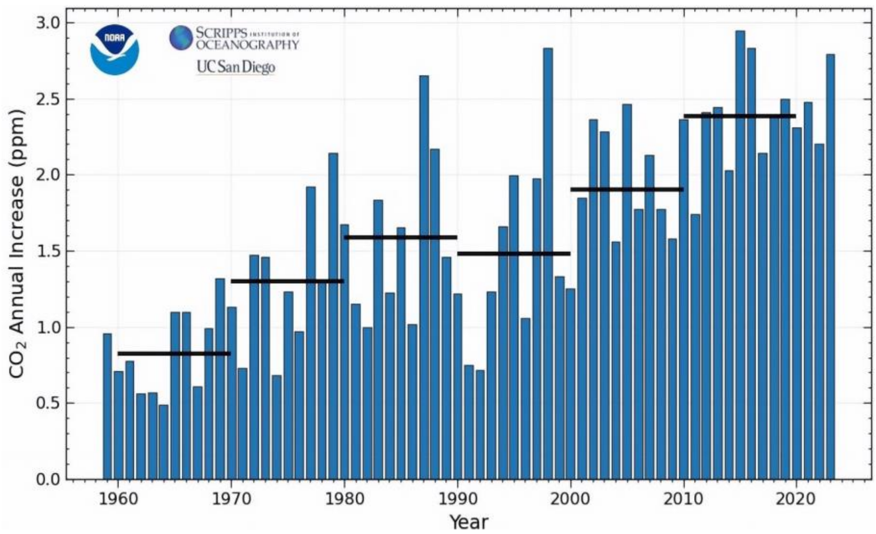

Figure 2. Annual global increase of CO_2, 2025.

Source: [70]. Available in: https://gml.noaa.gov/ccgg/trends/gl_gr.html

In response to this looming crisis, the international community has mobilized. The Paris Agreement on climate change, negotiated under the United Nations Framework Convention on Climate Change, represents a pivotal moment in global cooperation. Nations around the world have pledged to reduce greenhouse gas emissions, recognizing the urgent need for collective action to mitigate climate change. However, the persistence of rising CO_2 levels, coupled with the complexity of the transition to a low-carbon economy, suggests that emissions reduction alone may not be sufficient. This realization has brought the concept of decarbonization to the forefront of climate change strategies. Decarbonization aims not only to halt the upward trend in atmospheric CO_2, but also to stabilize concentrations at a level that avoids the most severe impacts of climate change.

Achieving this ambitious goal will require a two-pronged approach. First, CO_2 emissions must be drastically reduced across all sectors of the economy. This means transforming energy systems, industrial processes and consumption patterns to minimise carbon footprints. Second, and equally important, is the implementation of technologies and practices that can capture and sequester carbon already in the atmosphere [71].

Carbon dioxide removal (CDR) technologies and strategies have thus emerged as a critical component in the fight against climate change [72]. These range from nature-based solutions such as reforestation and soil carbon sequestration to more advanced technological interventions such as direct air capture and enhanced weathering. Integrating these CDR approaches into comprehensive climate action plans is becoming increasingly important as we seek not only to reduce future emissions, but also to deal with the legacy of past carbon pollution. The urgency of this dual approach cannot be overstated. As we continue to witness the effects of climate change - from extreme weather events to rising sea levels—the need for immediate and decisive action becomes ever more apparent. By combining aggressive emissions reductions with proactive carbon removal, we can hope to stabilise the Earth's climate system and protect the planet for future generations.

4.1. Background

Climate change has emerged as one of the world's most critical environmental challenges following two key milestones: the United Nations General Assembly's resolution 43/53 of 6 December 1988, which recognized climate change as a "common concern of mankind", and the subsequent adoption of the United Nations Framework Convention on Climate Change at the historic Earth Summit in Rio de Janeiro in 1992 [73]. In this context, global governance has developed mechanisms for cooperation to address climate change, including in particular the Montreal and Kyoto Protocols and the Paris Agreement.

4.1.1. Montreal protocol

The story of chlorofluorocarbons (CFCs) provides a compelling parallel to the earlier controversy over dichlorodiphenyltrichloroethane (DDT), highlighting the complex relationship between scientific innovation and environmental consequences. Both chemicals initially represented groundbreaking advances, offering promising solutions to everyday problems and industrial challenges. CFCs were long hailed as almost miraculous compounds. These seemingly inert and harmless molecules found widespread application in various industrial and domestic sectors. Their versatility and apparent safety led to their integration into numerous products and processes, from refrigerants and aerosol propellants to cleaning solvents and foam-blowing agents. However, much like DDT two decades earlier, the initial enthusiasm for CFCs was tempered by growing scientific evidence of their harmful environmental effects. In the 1970s and 1980s, researchers began to uncover the role of CFCs in depleting the stratospheric ozone layer, which shields the Earth from harmful ultraviolet radiation. This discovery led to a paradigm shift in the way these chemicals were perceived and regulated.

The international response to the ozone depletion crisis culminated in the Montreal Protocol on Substances that Deplete the Ozone Layer, signed in 1987. This agreement was a watershed in environmental governance, demonstrating the ability of the global community to unite in the face of a common ecological threat. The Protocol's success in phasing out ozone-depleting substances has been widely hailed as one of the most effective international environmental treaties to date. Similarly, growing awareness of anthropogenic climate change towards the end of the 20th century led to the adoption of the Kyoto Protocol in 1997. This agreement, under the United Nations Framework Convention on Climate Change, aims to reduce greenhouse gas emissions and mitigate the effects of global warming. The parallel between CFCs and DDT, and the subsequent global responses to ozone depletion and climate change, illustrate several important lessons: i) the potential for unintended consequences of technological innovation, particularly when deployed on a global scale; ii) the critical role of scientific research in identifying environmental threats and informing policy decisions; iii) the importance of international cooperation and governance in addressing transboundary environmental issues; and iv) the capacity of global society to mobilize and take decisive action when faced with clear scientific evidence of environmental harm.

These historical examples underscore the complex interplay between scientific discovery, technological progress, environmental impacts and global governance. They serve as a powerful reminder of the need for precautionary approaches in the development and deployment of new technologies, as well as the continuing need for robust international frameworks to address global environmental challenges.

As we continue to grapple with today's environmental challenges, including the ongoing threat of climate change and emerging concerns such as microplastic pollution, the lessons of the CFC and DDT sagas remain highly relevant. They underscore the importance of maintaining vigilance, fostering scientific inquiry and supporting international cooperation in our ongoing efforts to protect the global environment and ensure a sustainable future for all. The versatility of CFCs has transformed many aspects of modern life. At home, they revolutionized refrigeration and air conditioning, making household appliances not only more efficient but also safer and more reliable. In industry, CFCs enabled the production of foams for a wide range of applications, from comfortable cushions to innovative food packaging and highly effective insulation. In addition, their use in aerosols greatly increased the efficiency and practicality of these products [74]. However, the perception of CFCs as harmless substances was challenged by scientific advances. Groundbreaking research revealed an unexpected and alarming facet of these molecules: their chemical reactivity under the intense ultraviolet radiation conditions of the stratosphere. This discovery revealed the destructive potential of CFCs for the ozone layer, which is essential for protecting life on Earth from harmful solar radiation.

The discovery of the Antarctic ozone hole through satellite observations in the 1980s marked a pivotal moment in environmental science and policy. These satellite measurements provided irrefutable visual evidence of the devastating effects of chlorofluorocarbons (CFCs) on the Earth's atmosphere [75,76], offering a global perspective on ozone depletion that had previously been unattainable. The powerful images of the ozone hole not only consolidated scientific consensus, but also raised public awareness and catalyzed international action. This visual data played a crucial role in the negotiations that led to the Montreal Protocol, demonstrating the power of advanced technology in environmental monitoring and its ability to influence global policy. The case illustrates how clear, objective evidence can overcome skepticism, drive public engagement and accelerate cooperative global responses to environmental threats. It also set a precedent for the use of satellite technology to address other global environmental issues, underscoring the critical role of comprehensive monitoring systems in identifying, understanding and mitigating complex Earth system processes. These images not only provided critical scientific evidence, but also acted as a catalyst for global public awareness and political action. The revelation of the harmful effects of CFCs is an example of how advancing scientific knowledge can challenge long-held assumptions and reveal the unintended consequences of seemingly beneficial technological innovations. The evolution of global environmental governance, particularly in addressing the threats posed by chlorofluorocarbons (CFCs) and rising CO_2 emissions, provides a compelling narrative of international cooperation, scientific advocacy, and the complexities of balancing development and environmental protection.

The case of CFCs illustrates the critical importance of continuous and rigorous assessment of technologies and substances introduced into our environment. It also highlights the need for coordinated international responses to global environmental threats. In the face of considerable opposition and scientific uncertainty [76], environmentalists emerged as the leading voice in the global campaign to ban CFCs. Their persistent efforts culminated in the signing of the Montreal Protocol in 1987 [29], a landmark achievement in international environmental governance.

The Montreal Protocol, ratified by every nation on earth, set a clear path for eliminating the production and consumption of ozone-depleting substances [77]. This agreement is widely regarded as a triumph of international cooperation and evidence-based policy-making, demonstrating the potential for global action in the face of a common threat. However, the implementation of the Montreal Protocol revealed unforeseen challenges [78]. The CFC issue was perceived primarily as a problem of rich countries, leading to difficult and protracted negotiations. Developing countries, which had contributed minimally to the accumulation of CFCs in the atmosphere, rightly sought to expand their use of these compounds, particularly for refrigeration [79]. To address this imbalance, the Protocol's authors introduced the innovative principle of "common but differentiated responsibilities", recognizing the unequal burden of responsibility between developed and developing countries [29].

This principle allowed for a nuanced approach: Developed countries would immediately reduce their use of CFCs by 50%, while developing countries were allowed a 15% increase. Although these measures were intended to benefit developing countries, instances of corruption under the Protocol led in some cases to uncontrolled CFC consumption [80], highlighting the challenges of implementing global environmental agreements.

Rising CO_2 emissions were a second major global concern, again requiring coordinated international action.

4.1.2. Kyoto protocol

The adoption of the Kyoto Protocol in the late 1990s, which entered into force in 2005, marked a turning point in international climate policy by establishing a historic precedent for the differentiation of responsibilities among nations. This international agreement, based on the principle of "common but differentiated responsibilities", explicitly recognized that developed economies, as the main emitters and historical contributors to the accumulation of greenhouse gases since the industrialization era, should assume greater responsibility for reducing emissions [81]. The Protocol's architecture not only established differentiated mitigation commitments, but also established an innovative framework for international cooperation by requiring developed countries to provide additional financial resources and facilitate technology transfer to developing countries, recognizing that global participation in the mitigation effort would require substantial support to redress the imbalance in capabilities among countries and to ensure an equitable transition to a low-carbon economy [82].

The Kyoto Protocol established a framework to drive the transition to a low-carbon economy through three fundamental mechanisms [83]: the Clean Development Mechanism (CDM), which allowed developed countries to invest in emission reduction projects in developing countries while generating emission reduction certificates; Joint Implementation (JI), which facilitated cooperation between developed countries to implement joint projects and share technologies; and Emissions Trading (ET), which established an international carbon market and created economic incentives for emissions reductions. This transformative framework affected national economies by requiring developed countries to set binding emission reduction targets and develop mitigation policies while providing developing countries with access to finance and technology transfer for sustainable projects [83]. Sectoral transformation was particularly evident in three key areas: the energy sector, with significant momentum for renewable energy and energy efficiency; the industrial sector, through the adoption of clean technologies and process optimization; and the financial sector, through the creation of new financial instruments and carbon markets.

However, these mechanisms and their application were flawed due to a confluence of critical factors that undermined their global effectiveness [84]. The CDM suffered from an uneven geographical distribution that favoured large emerging economies such as China and India while marginalising less developed countries, as well as problems of additionality and excessive bureaucracy that discouraged small and medium-sized projects. JI was hampered by problems in verifying emissions reductions, lack of transparency and limited participation, while ET faced structural challenges such as initial over-allocation of permits, extreme volatility in carbon prices and lack of coordination between systems. These specific problems were compounded by broader systemic deficiencies, including the absence of the United States as one of the world's largest emitters, the exclusion of developing countries from binding commitments, inadequate science-based reduction targets, and the lack of effective compliance and sanction mechanisms. This set of limitations demonstrated the weaknesses of the Protocol's top-down approach, which did not adequately take into account specific national circumstances and capabilities, and ultimately led to a fundamental rethink, embodied in the 2015 Paris Agreement, which adopted a more flexible and bottom-up approach to addressing the global climate challenge.

4.1.3. Paris agreement

The Paris Agreement represents an unprecedented milestone in the global fight against climate change, establishing a robust and dynamic international framework for coordinated climate action [85]. This historic pact structures a system in which each nation makes specific commitments to reduce its greenhouse gas emissions through Nationally Determined Contributions (NDCs), instruments that reflect each country's unique capabilities and circumstances. The architecture of the agreement rests on several key pillars: a periodic review system that drives the progressive increase in climate ambition; rigorous transparency mechanisms for monitoring and reporting emissions; comprehensive adaptation strategies that prioritize the needs of developing countries; and a climate finance framework that facilitates the mobilization of resources. The inclusion of market mechanisms and the emphasis on international cooperation catalyze the transition to a decarbonized economy.

Conferences of Parties (COPs) have emerged as the primary forum for materializing and strengthening these climate commitments [86]. COP21 in Paris marked a turning point by setting concrete targets to limit global temperature rise. Each subsequent conference has contributed significantly to the framework for climate action [86]: COP24 developed the operational rulebook for the Paris Agreement, COP26 consolidated specific commitments to reduce coal use and deforestation, while COP27 launched an innovative fund to address climate-related loss and damage. The recent COP29, to be held in Baku, Azerbaijan, in 2024, represents significant progress in the practical implementation of previous commitments. The establishment of a new climate finance target to mobilize $300 billion per year by 2035 is an example of growing ambition to support developing countries. The conference deepened the dialogue on a just energy transition, recognising the urgent need to ensure that the transition to a green economy equitably benefits all sectors of society and upholds workers' rights.

Despite the innovative and ambitious nature of the Paris Agreement, the persistence of rising emissions in some developed countries reveals deep contradictions between international commitments and national realities [85]. While the Agreement established an unprecedented framework through NDCs, periodic reviews, transparency mechanisms and adaptation strategies, effective implementation has faced significant obstacles. The evolution of the COPs, from the historic COP21 in Paris to the recent COP29 in Baku, has shown remarkable progress in terms of commitments and climate finance. However, the gap between commitments and concrete actions persists due to several factors: Resistance from fossil fuel dependent industries, lack of political will to implement structural changes, prioritization of short-term economic interests over long-term climate goals, and disparities in implementation capacity between developed and developing countries [85]. The voluntary nature of commitments under the Paris Agreement, while facilitating broader global participation, has also allowed some countries (such as the US, Russia, India and China) to continue to increase emissions without facing consequences, highlighting the limitations of a system that fundamentally relies on political will and international pressure to be effective [85].

The evolution of international environmental agreements, from the Montreal Protocol to the recent COP29, has revealed lessons of mistrust and fragmentation in global environmental governance [87]. Science has demonstrated its ability to drive global environmental policy even in the face of uncertainty and resistance, while the effectiveness of international cooperation in addressing transboundary environmental problems has often been indifferent [88]. The incorporation of the principle of "common but differentiated responsibilities" into these legal frameworks has emphasized the importance of integrating equity and development needs into global environmental governance, allowing for the inclusive and effective participation of all nations. The evolutionary nature of this governance is evident in how the experience and lessons learned from pioneering agreements such as the Montreal Protocol have enriched and shaped the development of subsequent treaties, from the Kyoto Protocol to the Paris Agreement. These agreements, while often politically ineffective, have established precedents for the design of robust implementation and compliance mechanisms [87].

5. Anthropocene in transition: The decarbonisation paradigm

Human activities, particularly the use of fossil fuels for energy, have profoundly altered the composition of the atmosphere, significantly increasing the concentration of greenhouse gases (GHGs). These gases have the unique ability to absorb infrared radiation and re-emit it back to the Earth's surface, a natural process known as the greenhouse effect, which is essential for sustaining life on our planet. However, the disproportionate increase in GHG concentrations due to human activity has accelerated the rise in global temperatures, a phenomenon known as anthropogenic global warming.

It's important to recognize that GHGs have been present in the Earth's atmosphere since the formation of the planet. However, the onset of the Anthropocene epoch has witnessed unprecedented changes in GHG concentrations. From an analytical point of view, GHGs can be divided into two main groups: (i) anthropogenic GHGs, which are directly produced or amplified by human activities such as the burning of fossil fuels, deforestation and various industrial processes; and (ii) natural GHGs, which are emitted by the planet's inherent systems, including oceans, volcanoes and the decomposition of organic matter. This classification allows us to address two related but distinct challenges. Anthropogenic GHGs continue to pose a significant threat to global climate stability, despite international governance efforts embodied in agreements such as the Montreal Protocol (focused on protecting the ozone layer) and the Kyoto Protocol (aimed at reducing GHG emissions).

Implementation and enforcement of these agreements have been uneven and, in many cases, insufficient to counter the accelerating pace of emissions. Controlling natural greenhouse gases presents even more complex challenges. Emissions of nitrous oxide (N2O) and methane (CH4) are increasing at an alarming rate due to several factors: i) the thawing of permafrost in Arctic regions, releasing large amounts of previously trapped methane; ii) the intensification of forest fires and biomass burning, both natural and man-made; iii) the expansion of livestock activities, particularly cattle farming, which is a major source of methane; and iv) industrial processes in developing countries, where environmental regulations are often less stringent or poorly enforced.

The interaction between anthropogenic and natural greenhouse gas emissions creates a feedback loop that exacerbates global warming. For example, as human activities raise atmospheric temperatures, permafrost thaws, releasing more methane and amplifying the warming effect. This complex interaction underlines the need for a comprehensive approach to climate change.

International efforts to reduce greenhouse gas emissions have had mixed results. While the Montreal Protocol has been largely successful in phasing out ozone-depleting substances, which are also potent greenhouse gases, the Kyoto Protocol and subsequent agreements have faced significant challenges in achieving widespread compliance and meaningful reductions in carbon dioxide emissions.

The disparity in industrial development and environmental regulations between developed and developing countries further complicates global efforts to reduce GHG emissions. As developing countries pursue economic growth, they often rely on carbon-intensive industries and less stringent environmental standards, offsetting reductions achieved in more developed economies. To effectively address the complex issue of GHG emissions and their impact on the global climate, a multi-faceted approach is required: i) Strengthening and broadening international agreements to include both developed and developing countries, with mechanisms for technology transfer and financial support, ii) Investing in research and development of clean energy technologies to reduce dependence on fossil fuels, iii) Implementing policies to protect and restore natural carbon sinks such as forests and wetlands, iv) developing and deploying carbon capture and storage technologies to reduce emissions from existing industrial processes; v) promoting sustainable agricultural practices to reduce methane emissions from livestock and nitrous oxide emissions from soil management; and vi) increasing public awareness and education on the impacts of climate change.

These factors create a positive feedback loop in which global warming accelerates the release of more natural greenhouse gases, which in turn increases warming. The complexity of this situation requires a multi-faceted approach that addresses both the reduction of anthropogenic emissions and the mitigation of the effects of climate change. This means not only deploying clean and efficient technologies, but also protecting and restoring ecosystems that act as natural carbon sinks, such as forests and oceans. It is also essential to strengthen international cooperation to ensure that developing countries can adopt sustainable industrial practices without compromising their economic growth. This could include the transfer of clean technologies, increased financial support for adaptation, and the implementation of public policies that incentivize the transition to a renewable, low-carbon economy. Addressing the greenhouse gas challenge in the Anthropocene requires a deep understanding of the complex interactions between human and natural systems, and a sustained global commitment to implement effective and equitable solutions.

However, these problems are compounded when it comes to the main greenhouse gas: CO_2, which accounts for 70% of greenhouse gases. CO_2 is at the forefront of the greenhouse gases driving climate change, with both anthropogenic and natural sources and effects. On the anthropogenic side, CO_2 is primarily produced by the combustion of fossil fuels, including oil, natural gas and coal, which form the backbone of global energy systems. Conversely, natural CO_2 emissions result from complex Earth system processes, in particular permafrost thawing and ocean dynamics.

The challenge of mitigating CO_2 is multifaceted. Even if we succeed in controlling 45% of anthropogenic CO_2 emissions [89], the remaining 55%—a consequence of the social metabolism of global society—will continue to exert a significant influence on the Earth system. When natural CO_2 emissions are included, the potential future scenario becomes alarmingly catastrophic [25].

According to the National Oceanic and Atmospheric Administration [70], while land plants and the world's oceans collectively absorb approximately half of the 40 billion tonnes of CO_2 pollution generated annually by human activities, atmospheric CO_2 levels continue to rise at an alarming rate. Historical data reveals a consistent acceleration in atmospheric CO_2 concentration, starting from an average annual increase of 0.8 ppm in the 1960s, doubling to 1.6 ppm in the 1980s, briefly stabilizing at 1.5 ppm during the 1990s, then rising to 2.0 ppm in the 2000s, and ultimately reaching 2.7 ppm per year in the most recent decade [70,71].

This accelerating trend underlines the growing imbalance between CO_2 emissions and the Earth's capacity to absorb them and highlights the urgency of mitigation efforts. The challenge is compounded by the long-lived nature of CO_2 in the atmosphere. CO_2 can persist for hundreds if not thousands of years [90], meaning that today's emissions will continue to influence climate well into the future. This persistence underlines a critical point: Stabilizing climate change requires reducing net CO_2 emissions to zero. If we emit more CO_2 than nature can absorb in its sinks (mainly oceans and forests), atmospheric CO_2 concentrations will continue to rise, exacerbating global warming. This reality has several important implications: i) Urgency of action: The accelerating rate of CO_2 increase emphasizes the need for immediate and drastic emission reductions; ii) Holistic approach: Addressing anthropogenic emissions alone is not enough. We must also consider strategies to enhance natural carbon sinks and possibly develop technologies to actively remove CO_2 from the atmosphere; iii) Long-term perspective: Given the atmospheric longevity of CO_2, climate mitigation strategies must take a multi-generational perspective and consider impacts well beyond the immediate timescale; iv) Balance between emissions and sinks: Achieving net-zero emissions requires not only reducing emissions, but also increasing the capacity of natural and artificial carbon sinks; v) Global cooperation: The transboundary nature of CO_2 emissions and their impacts requires an unprecedented level of international cooperation and coordinated action; vi) Technological innovation: Developing and scaling up technologies for carbon-neutral energy production and carbon capture and storage will be critical to achieving emission reduction targets; and vii) Ecosystem conservation: Protecting and restoring natural carbon sinks, such as forests and oceans, is essential to maintain the Earth's capacity to absorb carbon.

From a practical perspective, three cases are analyzed: The economies of Saudi Arabia, Chile and Italy, which are striving to implement circular and regenerative economy principles in their territories, each with its own approach and challenges. In the case of Saudi Arabia [91], its strategy is framed by the Saudi Green Initiative (SGI), which aims to reduce emissions by 2060. An analysis based on the Leontief input-output model examines the economic criteria needed to achieve low-emission targets and identifies potential sources of finance for green projects. The study, which is aligned with the country's Vision 2030, forecasts growth in the green bond market of 15% by 2030 and 30% by 2060, equivalent to around $14 billion and $39 billion respectively. Annual GDP growth of 2.6% by 2030 and 2% by 2060 is forecast, with the creation of more than 23 million new jobs. For its part, Chile [92] has implemented initiatives such as the Circular Economy Roadmap, although it faces several obstacles. The main challenges include cultural resistance, limited public awareness, insufficient professional training, growing consumerism and inadequate technological infrastructure outside metropolitan areas. However, the country has strengths such as a sound regulatory framework, commitment to international environmental agreements and a growing interest in sustainability among the young population. The mining, agriculture and tourism sectors offer opportunities for implementing the principles of a regenerative economy. Italy [93], on the other hand, has focused its strategy on circular economy innovation and multisectoral network contracts as a solution to the problem of common natural resources. Research shows that circular economy innovation can improve the efficiency of investments in natural resource regeneration, while network contracts create a legal framework that prevents coordination failures and increases the effectiveness of individual willingness to act cooperatively. This approach provides original solutions to the 'tragedy of the commons' by combining circular economy and governance systems that take into account the heterogeneity of stakeholders.

The uniqueness of these cases lies in their different approaches to socio-environmental transition, each deeply rooted in its specific context and territorial reality. Saudi Arabia emerges as a paradigmatic case of transformation as it moves from an oil economy to a more sustainable model. Its strategy rests on two fundamental axes: economic diversification and the implementation of sophisticated green financial instruments that seek to catalyse this transition without compromising economic development. The Chilean case illustrates the paradox characteristic of emerging economies whose productive base depends on natural resources. The country faces the inherent tension between its traditional extractivist matrix and its growing sustainability aspirations, creating systemic frictions that require innovative and adaptive solutions. From its position in Southern Europe, Italy brings an innovative perspective to the debate. Its approach is characterised by the privileging of collaborative governance and the development of sophisticated mechanisms for the management of common goods, materialised in multi-sectoral network contracts that facilitate the transition to a circular economy.

This confluence not only suggests a global recognition of the urgent need to transform production systems in the face of the challenges of the Anthropocene, but also demonstrates the diversity of possible paths towards this common goal. The differences in their approaches also underline the impossibility of applying a single, universal solution and highlight the crucial importance of adapting circular and regenerative economy strategies to local contexts and the specific institutional capacities of each territory. This mosaic of approaches suggests that the transition to regenerative economic models in the Anthropocene will require a sophisticated articulation between financial innovation, cultural transformation and new governance frameworks, adapted to the socio-economic and environmental realities of each region [28].

6. Conclusion and strategies for a decarbonised future

6.1. Conclusion

The results of the analysis show that the transition to a decarbonized global economy faces enormous challenges. However, the transition from grey to green through a regenerative economy is not just a climate change mitigation strategy, but a pathway to a prosperous, just and sustainable future. Accelerating this transition requires a coordinated effort between governments, businesses and citizens. By applying the principles of a regenerative economy, we have the opportunity not only to avoid the worst effects of climate change, but also to build a more liveable and equitable world for all forms of life. However, the increasing concentration of CO_2 in the atmosphere reflects the global capitalist model, which continues to drive massive resource consumption, as evidenced by the brief dip in emissions observed during the COVID-19 pandemic, which was quickly reversed with economic recovery. Mitigating the 20 billion tonnes of CO_2 we produce each year requires urgent and coordinated global action. The complex interplay between anthropogenic and natural sources of CO_2, coupled with the long-lived nature of the gas in the atmosphere, presents a formidable challenge to climate change mitigation. Addressing this issue requires a multifaceted approach that combines aggressive emission reductions, enhancement of natural carbon sinks, technological innovation and global cooperation.

6.2. Strategies for a decarbonised future

Two key, interlinked strategies are proposed to address this challenge. The first is to transform land and agricultural systems to increase their natural capacity to absorb carbon. This includes halting deforestation, promoting regenerative agriculture and developing sustainable livestock systems. The second strategy is to restructure the global social metabolism, which would involve reducing consumption, promoting a circular economy, accelerating the transition to renewable energy, and rethinking economic growth in terms of sustainability rather than the infinite accumulation of wealth. Such an approach would require a profound rethink of social and economic values and unprecedented global cooperation. Resistance from entrenched interests and global inequalities in responsibility and development are major obstacles, but the scale of the climate crisis demands radical change. To achieve this, it is essential that governments implement bold and visionary policies that drive green innovation and foster international cooperation. This transition will not be easy or linear, but the benefits—a stable climate, healthy ecosystems, resilient communities and a sustainable economy—fully justify the effort required. In moving towards this future, we must embrace a holistic vision that integrates the environmental, economic and social, creating a world where human prosperity and planetary health are mutually reinforcing and ushering in a new era in human history.

The analysis leads to an ethical and ontological debate by articulating the narrative of the Anthropocene and regenerative economics as a philosophical and practical paradigm. Beyond the proposed decarbonization strategies, it introduces the need to redefine human progress in a context where planetary boundaries are inescapable. It proposes an innovative approach based on technological co-evolution, in which human technologies integrate with natural cycles to promote planetary symbiosis. It also shows how historical patterns of CO_2 emissions, and their acceleration reveal the urgency of adaptive, intergenerational solutions, emphasizing that the challenge is not merely technical but intergenerational. This approach transforms our relationship with the planet, moving from an extractive logic to a co-creative role in building a regenerative system.

Finally, it is recommended to strengthen policies for sustainable land use and regenerative agriculture, as well as to redesign economic models toward a circular and regenerative economy.

First, strengthening land use and regenerative agriculture policies requires the establishment of a comprehensive policy framework that prioritises the conservation of critical ecosystems and the transition to regenerative agricultural practices, based on three interrelated strategic pillars: The implementation of strict measures to halt deforestation through satellite monitoring systems, effective sanctions and the creation of community-managed protected areas; the development of a robust system of incentives for the adoption of sustainable technologies in agricultural production, including smart agriculture, efficient irrigation systems and integrated pest management; and transforming livestock production into low environmental impact systems through manure treatment, which can be optimised through the use of microalgae that consume nutrients from manure as they grow, reducing methane emissions while producing biomass that can be used as fertiliser or animal feed, as well as purifying water and capturing CO_2 during photosynthesis. In addition, the use of insects such as the black soldier fly would allow manure to be processed efficiently, accelerating the decomposition of organic matter and reducing the period of methane emissions. To encourage these practices, a comprehensive support framework must be put in place, including differentiated economic incentives, technical assistance programs, innovative financing mechanisms and participatory monitoring systems, to ensure that this transformation is inclusive, equitable and directly benefits rural communities, indigenous peoples and family farmers, thereby improving rural livelihoods, strengthening food security and building more resilient food systems that respond to current and future challenges in the global agricultural sector.

Second, the transition to a circular and regenerative economy requires a profound rethinking of current production and consumption systems, as well as the principles that underpin the concept of economic progress. This approach proposes the creation of regulatory and economic frameworks that encourage practices aimed at reducing the consumption of resources, promoting the recycling of materials and prioritising the use of renewable energy.

To achieve this transformation, it is essential that governments play a central role in implementing specific policies and measures. These include introducing carbon taxes that reflect the true environmental cost of emissions, providing subsidies to encourage the development and deployment of clean technologies, and negotiating international agreements that ensure equity and promote effective global cooperation. This transition is not only a technical one, but also a cultural and conceptual one, as it requires a redefinition of economic progress beyond unlimited growth to prioritize human well-being, ecosystem resilience and long-term sustainability. By adopting a circular and regenerative model, societies can move towards a future where economic development is in harmony with planetary boundaries and the needs of the natural environment.

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