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Review

Embracing a diverse approach to a globally inclusive green energy transition: Moving beyond decarbonisation and recognising realistic carbon reduction strategies

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ABSTRACT

The green energy transition is aimed at mitigating the impact of climate change. Yet, the current emphasis on 'green' is narrowly centred around decarbonisation, or CO_2 reduction, often side-lining the roles of other gases, such as sulphur hexafluoride (SF_6) and PCF-14 (CF_4), which have a respective 24,300- and 7380-times higher global warming potential than CO_2 on a time horizon of a century. In addition, any energy transition is a complex affair that simultaneously impacts the environmental, economic and social systems, with significant system-level interactions. For example, the material requirement for renewable energy is known to be substantial, at a factor of 15 times greater than natural gas-based energy for offshore wind generation, and almost 7 times greater for solar. The resulting increased competition for materials is reducing the appetite for global collaboration. In addition, the global capacity to deploy renewable energy technology or participate in climate change mitigation is geographically variable and no single solution is universally viable. This study examines an expanded definition of 'green' energy and proposes a beyond-decarbonisation approach that is more comprehensive and globally inclusive, in pursuit for a sustainable transition. The increased diversity of our approach promises advantages such as heightened global collaboration, diminished geopolitical tension, improved energy access, expanded market opportunities, and socio-environmental co-benefits. Strategies pivotal to this approach involve understanding the role of carbon-based energy systems in the transition, amplifying renewable resources, augmenting cross-sector energy efficiency, implementing effective carbon markets, and integrating nature-based as well as carbon removal technologies. Moreover, it is imperative to implement all-cost and all-benefit monitoring and evaluation systems to optimise existing decarbonisation methods systematically. This could entail the use of composite metrics that normalise the gain in climate change mitigation against economic, social or environmental metrics. Addressing societal apprehensions requires a focus on pragmatic and fair outcomes, geopolitical stability, market impacts, developmental objectives, effective public engagement, and recognition of the role of enterprises. Policymakers are important in fostering global synergy by implementing policies that encourage international collaboration, investment, enterprise engagement, institution fortification, and cross-sector policy integration.

1. Introduction

The drive to mitigate climate change while simultaneously striving for a sustainable future has reached a critical juncture. This urgency is highlighted by decadal trends (Montzka et al., 2011) in greenhouse gas (GHG) emissions and their impacts on environmental and human well-being (Fawzy et al., 2020; Liu et al., 2023). Increasing levels of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other GHGs is thought to affect our climate system, promoting temperature changes, extreme weather events, sea-level elevation, and biodiversity loss (Montzka et al., 2011). Beyond environmental disruptions, these changes potentially can affect governance stability, global food security,

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water resources, human health, and socio-economic stability.

Decarbonisation is emblematic of efforts to mitigate against climate change, because it is the most vociferously communicated element in global climate mitigation strategies. It involves an unprecedented shift away from fossil fuel-based energy infrastructure towards renewable alternatives such as wind, solar, and geothermal power, alongside a heightened emphasis on bolstering energy efficiency. While important, an excessive focus on decarbonisation, e.g., 'decarb-centrism'—might inadvertently overlook other essential contributors to environmental degradation and societal disparities, because both environmental and social systems are complex and geographically variable (Papadis and Tsatsaronis, 2020). Addressing these challenges demand a comprehensive, multi-faceted approach that extends beyond 'decarb-centrism'.

A holistic approach to climate change is needed to account for interactions of complex systems, such as the environmental, social and economic systems. This class of approaches include balancing system-wide trade-offs (e.g., Collier et al., 2013; Merad et al., 2013), explicit considerations of systemic interactions and interdependencies (e.g., Mendoza and Clemen, 2013; Wang et al., 2013), and reframing the problem to derive solutions from different perspectives (e.g., Jennings et al., 2013; Scanlon et al., 2013). A holistic approach is more likely to ensure a globally inclusive green energy transition, because it explicitly avoids narrow framings of the problem and seeks a more balanced approach to address systemic effects across environmental, social, and economic systems (Mukund and Kabra, 2023). Consequently, it is possible to seek solutions that prioritise sustainable development, resilience, and equity in confronting the multi-faceted challenges posed by climate change (Mendoza and Clemen, 2013; Grasso and Rodrigues, 2022). Thus, this holistic approach which makes a wider attempt to acknowledge the role of decarbonisation, while addressing its more profound implications is here termed the 'true green energy transition'. The true green energy transition represents a substantive shift from incumbent carbon-intensive energy sources, such as fossil fuels, to sustainable, renewable, and ecologically sound alternatives.

Solutions to the true green energy transition minimally encompass the deployment of renewable energy technologies, GHG emissions reduction, and energy efficiency promotion. Crucially, it requires systemic restructuring beyond mere source substitution, considering social equity, economic viability, environmental impact, and enduring sustainability objectives (Smith et al., 2023). Envisioning this transition demands comprehensive systemic alterations in energy systems—integrating renewables, enhancing energy efficiency, and prioritising social equity. This is a systemic transition extending beyond superficial adaptations and requires understanding of the social, economic and environmental systems' interactions and independencies (e.g., Mendoza and Clemen, 2013; Wang et al., 2013).

This study examines a diversified approach to effectuating a system-type solution that aims to achieve a globally inclusive green energy transition, surpassing the confines of conventional decarbonisation strategies. Its primary aim is to offer a comprehensive understanding of the intrinsic challenges and potential pathways toward realising a sustainable future that transcends existing limitations. Moreover, this research endeavours to unravel the intricate dynamics of GHG emissions, reframing the perspective of what constitutes truly 'green' energy sources. Specifically, the research objectives are multidimensional. Firstly, it involves conducting an exhaustive analysis to grasp the multi-faceted challenges and opportunities inherent in transitioning towards a globally inclusive green economy. This assessment extends beyond the narrow scope of decarbonisation, emphasizing the necessity for systemic changes, integration of renewable energy, and measures fostering sustainability, resilience, and social equity. Additionally, it seeks to delve deeply into the complexities of GHG dynamics, meticulously evaluating their impact on climate change and sustainability. This includes a nuanced examination of various GHGs and their implications in reshaping the understanding of green energy sources. Finally, the study aims to provide actionable insights and evidence-based recommendations. These recommendations are tailored to guide policymakers and stakeholders, facilitating an effective, comprehensive, and equitable transition towards sustainability, and addressing environmental, social, and economic dimensions.

The significance of this research lies in its broad-reaching implications. By addressing urgent global needs with a holistic sustainability approach, it offers guidance crucial for policymakers in formulating effective and balanced policies. This helps to ensure that climate change mitigation is more sustainable. Furthermore, by focusing on social equity and economic viability, this research aims to alleviate disparities accentuated by environmental challenges, striving to foster a transition beneficial for diverse communities worldwide. Additionally, through its contributions to academic knowledge, this study aims to bridge gaps in current literature, offering comprehensive insights into the 'true green energy transition'. Ultimately, this study aspires to fill critical knowledge gaps, steering actions towards achieving a sustainable, low-carbon future, thereby playing a pivotal role in guiding policy formulations, and fostering a global transition aligned with environmental sustainability, social inclusivity, and economic growth.

2. The green transition: rethinking the focus on CO_2

2.1. Understanding greenhouse gases (GHGs)

To grasp the green transition's implications, understanding various GHGs and their climate impact is vital. GHGs such as CO_2, CH_4, N_2O, and fluorinated gases trap heat, causing the greenhouse effect. GHGs such as sulphur hexafluoride (SF_6) and PCF-14 (CF_4) have a respective 24,300- and 7380-times higher global warming potential (GWP) relative to CO_2 over a 100-year timescale (IPCC, 2021). The GWP takes into consideration of the absorption of infrared radiation by a given gas, the time horizon of interest of the effect, and the atmospheric lifetime of the gas. However, CO_2 remains the focus of decarbonisation efforts not because of its impact (e.g., GWP multiplied by volume fraction or carbon dioxide equivalent) but because of its emitted volume and other factors. Specifically, CO_2 represents 73.1%, CH_4 17.7%, N_2O 6.6%, and F-gases (including HFCs, CFCs and SF_6) 2.6%, of GHG emissions in the year 2020 (Climate Watch, 2023). Globally, CO_2 emissions have increased 6.2 times since 1950 (6 Gt in 1950 compared to 37 Gt in 2022; Liu et al., 2023; Friedlingstein et al., 2023). Emissions have slowed in the past few years but have not yet peaked. A comparison of major GHGs (CO_2, CH_4, N_2O, and fluorinated gases) in terms of emission sources, potential impacts, and reduction strategies is detailed in Table 1. Despite lower concentrations, non-CO_2 GHGs profoundly impact climate and requires proportionate attention (Montzka et al., 2011). To holistically mitigate GHGs, it is vital to recognize sources, plan reduction measures, and integrate with CO_2 strategies.

2.2. CO_2 versus other greenhouse gases: why the focus on CO_2?

Anthropogenic CO_2 emissions stem from fossil fuel combustion, deforestation, cement production and land-use changes (Fig. 1; Table 1). Globally, anthropogenic CO_2 emissions have historically dominated GHG emissions. In 2022, global energy-related CO_2 emissions surged to 37 Gt, a 2 Gt rise from the COVID-19-induced low in 2020 (Liu et al., 2023; Friedlingstein et al., 2023). Despite these fluctuations, the breakdown of sectoral CO_2 emissions remained consistent. Notably, power contributed 39.3%, industry 28.9%, ground transportation 17.9%, residential 9.9%, international bunkers (shipping, aviation) 3.1%, and domestic aviation 0.9% of total CO_2 emissions (Liu et al., 2023). Remarkably, power sector emissions grew by 423 Mt. In contrast, industry sector emissions decreased by 102 Mt. Within the power sector, electricity and heat generation rose by 1.8% (261 Mt), driven by a 2.1% increase in coal use for electricity and heat (224 Mt), primarily in Asian developing countries. Adopting clean energy technologies (wind, solar, hydro) and electric vehicles averted an extra 550 Mt CO_2 release (IEA,

Table 1
Comparison of major greenhouse gases: emission sources, impacts, and reduction strategies (IPCC, 2021; IEA, 2022; Liu et al., 2023).

Criteria	CO_2	CH_4	N_2O	Fluorinated gases (e.g., HFCs, PFCs, SF_6)
Emission sources	Combustion of fossil fuels	Agricultural activities (e.g., enteric fermentation, rice cultivation)	Agricultural activities (e.g., use of synthetic fertilisers)	Various industrial processes (e.g., refrigeration, semiconductor manufacturing)
	Deforestation	Oil and gas production	Industrial processes (e.g., nylon production)	Electrical transmission and distribution equipment
	Industrial processes	Waste management (landfills)	Biomass burning	Use in consumer products and aerosols
Potential impacts	Long-lasting in the atmosphere, contributing to global warming and climate change	High global warming potential (approx. 25 times that of CO_2 over a 100-year period)	Significant greenhouse gas with a high global warming potential (approx. 298 times that of CO_2 over a 100-year period)	Potent greenhouse gases with high global warming potentials (hundreds to thousands of times more potent than CO_2)
	Ocean acidification	Contributes to tropospheric ozone	Destroys stratospheric ozone, contributing to ozone depletion	Contributes to global warming and climate change
	Alters ecosystems	Affects agricultural yields	Impacts nitrogen cycling and ozone balance	Persistent in the atmosphere
Emission reduction strategies	Transition to renewable energy sources	Improved livestock management	Enhanced nitrogen use efficiency	Phase-out or reduction of usage
	Energy efficiency improvements	Methane capture from landfills	Reduced use of synthetic fertilisers	Adoption of alternatives with lower global warming potentials
	Carbon capture and storage (CCS)	Biogas recovery from waste	Sustainable land management practices	Improved equipment design for reduced emissions

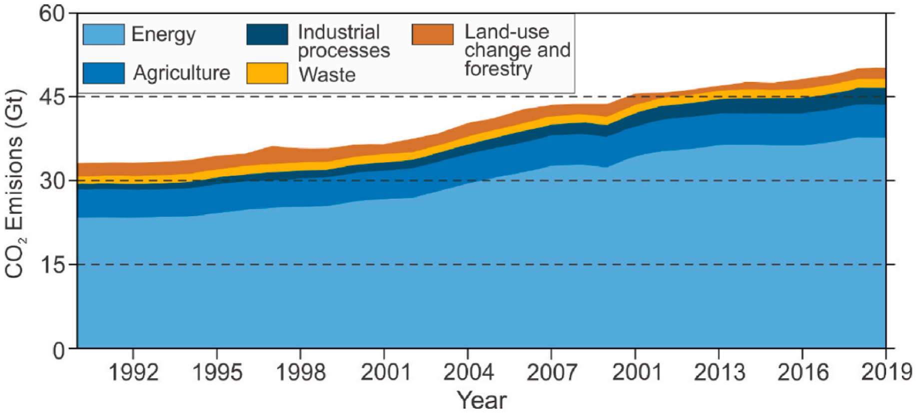

Fig. 1. Historical CO_2 emissions from various sectors and sources. Data from Climate Watch (2023).

2022). CO_2 growth in 2022 notably lagged behind global GDP growth (3.2%), signalling a return to the trend of decoupling emissions and economic growth disrupted by the sharp 2021 emissions rebound.

The emphasis on CO_2 finds basis in intrinsic factors such as its atmospheric longevity, cumulative impact on climate, and historical prevalence in GHG records. Notably, CO_2 persists for centuries in the atmosphere, significantly affecting warming over time (Archer et al., 2009; IPCC, 2021). This attribute makes CO_2 pivotal in shaping long-term climate results (Archer et al., 2009). Additionally, the cumulative nature of CO_2 implies that its historical and current emissions continue to shape climate dynamics (IPCC, 2018). Extrinsically, focusing on CO_2 offers advantages: 1) it reduces the governance and management of intricate socio-economic and natural systems to a single facet; and 2) it serves as a proxy and integral measure of numerous human activities (Table 1). Consequently, addressing CO_2 is seen as indispensable in the green energy transition. It is unsurprising that decarbonisation has become a focal point of research and policy (Liu et al., 2023). Nonetheless, recognising the practicality of a systemic approach is crucial, which minimally involves addressing other GHGs in tandem (Hazboun et al., 2020; IPCC, 2019).

2.3. Redefining ‘green’ for holistic sustainability

The ‘green’ concept now centres on decarbonisation, yet true systemic sustainability surpasses CO_2 reduction. To realise an inclusive and sustainable green transition, redefining ‘green’ is imperative. Thus, embracing a comprehensive approach encompassing diverse environmental and social factors is necessary (Mishra, 2012). Broadening the ‘green’ scope entails gauging the holistic impact of human actions on the environment and society. These span activities countering biodiversity loss, ecosystem degradation, air/water pollution, and social disparities (Papadis and Tsatsaronis, 2020; Keynejad et al., 2021). Enriching the ‘green’ definition incorporates various environmental and social indicators. This enables assessing the real sustainability of an approach or technology, leveraging system-level dynamics for an enduring green shift. It also offers more metrics for evaluating progress. A natural extension is assessing mineral and productivity chains, curbing carbon externalisation across these chains. For example, renewable energy tech, deemed ‘green’ for low CO_2 emissions, carries environmental and social impacts in production and disposal (Fritsche et al., 2021). This comprehensive view encompasses the entire lifecycle, guiding choices to mitigate negative impacts.

Furthermore, an extended ‘green’ perspective should address social equity. Equitably distributing green transition benefits globally is vital (Bullard and Wright, 1993; Papadis and Tsatsaronis, 2020). It involves providing renewables to low-electricity communities, offering green sector jobs to marginalised groups, and involving local communities in decisions. Ethical dimensions must be integrated into policies, acknowledging the unequal distribution of climate and environmental impacts (McCauley et al., 2019). A holistic ‘green’ grasp encompasses ecosystem effects such as biodiversity and resource sustainability (Esfahbodi et al., 2023). Safeguarding habitats and endorsing sustainable agriculture bolsters ecosystem resilience, carbon sequestration, and ecosystem services. This redefinition also weighs trade-offs and unintended consequences. Bioenergy, while CO_2-reducing, can intensify deforestation via large-scale monoculture plantations. A system-wide perspective aligns ‘green’ strategies with achievable and locally beneficial sustainable development goals (SDGs) (Kronenberg et al., 2021; UN, 2015).

3. Limitations and challenges associated with decarb-centrism

3.1. Increased reliance on the mineral value chain

Efforts to lessen reliance on the fossil fuel value chain, unfortunately, escalate dependence on the mineral value chain (Fig. 2). In a scenario where renewable energy dominates global supply, mineral value chain activities across various commodities are projected to surge beyond current rates, possibly by orders of magnitude (e.g., Kleijn et al., 2011; Michaux, 2021a, b). The geopolitical significance of this shift hinges on how extensively this reliance transfer unfolds. In particular, contentions tied to mineral resource distribution and consumption is magnified compared to that of fossil fuels (e.g., Zhang et al., 2023 and references therein), which ironically, can lead to a system-type response in the form of an increased desirability of fossil fuels (e.g., war-induced price surge of coal to nearly 8 times prior pricing; Banya, 2022). The mineral demand surge has already transformed energy-related mineral commodities into a seller’s market, which is promoting the rise of resource nationalisation and domestic vertical integration (Zhang et al., 2023). Consequently, assuming equivalence between current and future needs, an all-encompassing global energy shift would reshape power dynamics, state relations, conflict vulnerabilities, and socio-economic and environmental drivers of geopolitical instability (McLaren, 2018; Zhang et al., 2023).

Notably, the mineral value chain is already experiencing a substantial upswing, supported significantly by fossil fuels (Fig. 3; McLellan et al., 2012). Globally, this fossil fuel reliance is unlikely to fully yield to energy alternatives in the near future because of sheer material and energy needs (Michaux, 2021a, 2021b) and resource extraction realities (Igogo et al., 2021). Extraction to beneficiation frequently transpires in remote, confined and/or harsh environments (Ghorbani et al., 2023), demanding machinery of proven strength, resilience, and endurance (e.g., extreme temperatures, shocks, humidity, chemicals) (Igogo et al., 2021; Mateus and Martins, 2021). Moreover, current ‘green’ research and development primarily focus on material downstream applications. The energy density, infrastructure, value chain, and motive technologies of fossil fuels hold a clear advantage in ensuring steady and reliable productivity throughout the mineral value chain, which is ironically important for enabling decarbonisation. Consequently, within a period marked by substantial fossil fuel and renewable energy utilisation, the mineral value chain inherits global geopolitical, economic and otherwise intricacies from both sectors (Zhang et al., 2023), adding further complexity to the overall landscape (Thompson, 2022).

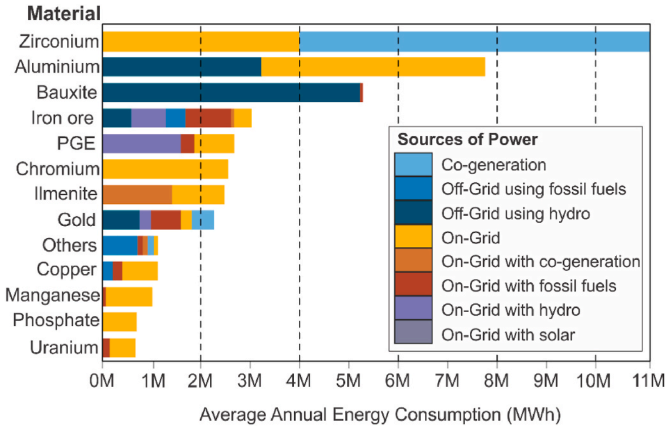

Fig. 3. Annual energy consumption of material production in sub-Saharan Africa. Data from World Bank (2014). Note that on-grid power generation is dominated by fossil fuels. PGE corresponds to platinum group elements.

3.2. Technological and infrastructure constraints

In the pursuit of decarbonisation, there is recognition of the barriers or hindrances posed by technology and infrastructure (Alexander and Gleeson, 2018; Newell, 2019), which is geographically variable (Power et al., 2016). Renewable energy technologies, such as solar and wind, still grapple with limitations (Michaux, 2021a, 2021b). These limitations are indirectly related to physical and material limitations of the Earth (e.g., the quantity of ore that meets economic or energetic thresholds to extract), the capabilities of the mineral value chain (e.g., its rapid expansion in support of renewable energy), and the unknown time that is required to achieve the next meaningful technological breakthrough (e.g., battery chemistry and material substitutions). Notably, the intermittent nature and variability of renewable sources, with the exception of nuclear power, present challenges in ensuring a consistent and reliable energy supply (Fig. 4; Smith et al., 2005). Furthermore, energy storage technologies, including batteries, remain in a state of evolution, necessitating substantial and resolute strides to effectively store energy at a societal scale and tackle the intermittent renewable energy dilemma (Worku et al., 2022). This challenge intensifies at higher latitudes, where prolonged energy intermittency results from seasonal insolation fluctuations (Fig. 4; Liou, 2002). Consequently, storage infrastructure must address not just daily variations but multi-month fluctuations, further complicated by heightened energy demand and ambient temperature conditions during low insolation periods, such as for interior and battery heating (Luo et al., 2022).

Moreover, the current energy infrastructure and supply, primarily tailored for fossil fuel systems, might necessitate significant overhauls, modifications, or replacements to integrate renewable energy sources seamlessly (Le Billon and Kristoffersen, 2020; Igogo et al., 2021). As

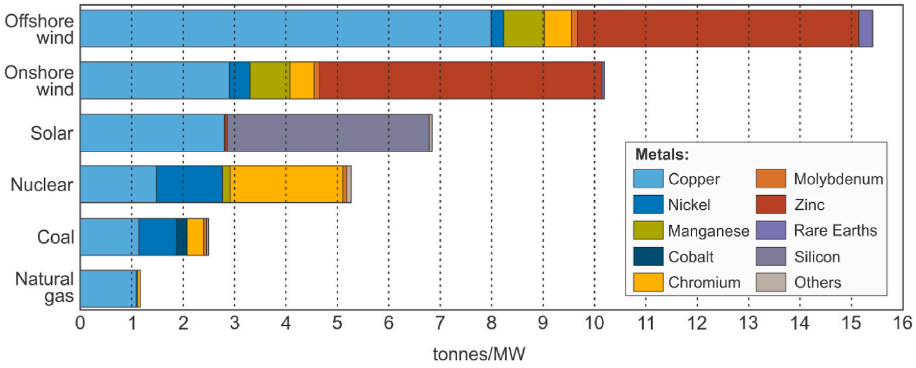

Fig. 2. Metals (in metric tonnes) required for various clean and traditional energy-generating technologies (megawatt). Data from IEA (2021).

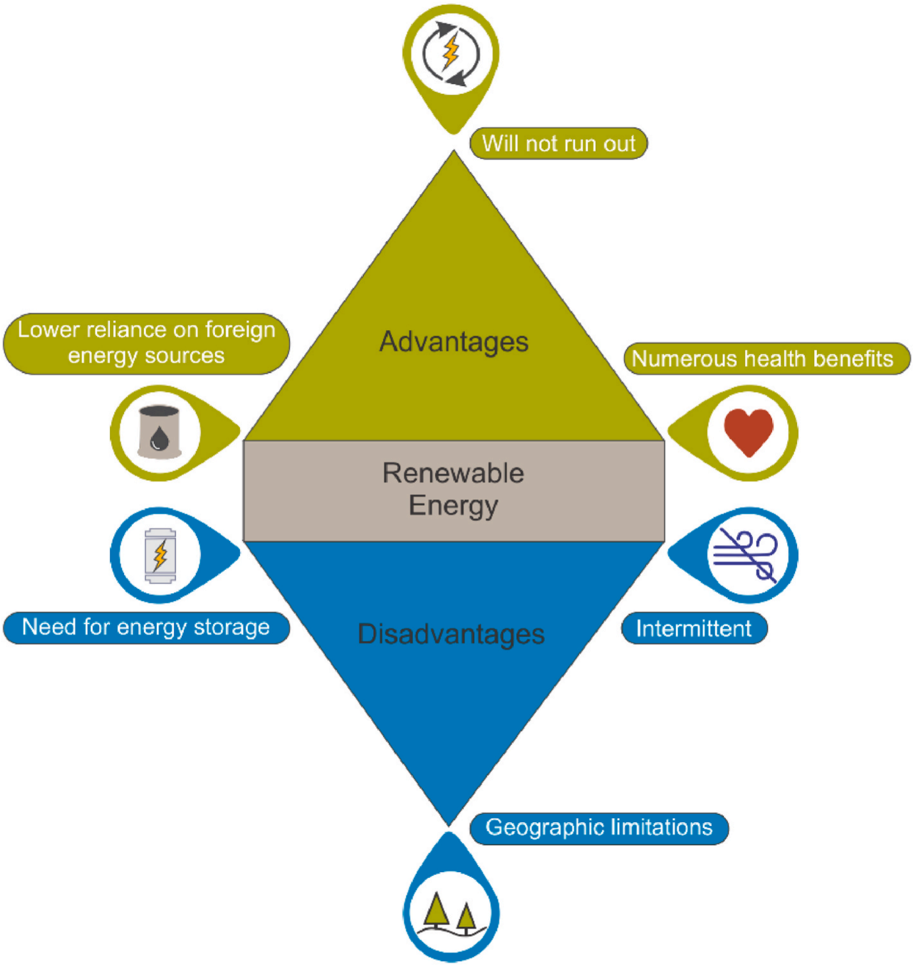

Fig. 4. Advantages and disadvantages of renewable energy. Fossil fuels as an energy source would have the opposite advantages and disadvantages to those of renewable energy. Figure inspired from EnergySage (2023).

fossil fuel consumption wanes, a greater share of energy distribution will shift onto electrical grids, urging meticulous planning and execution of grid expansion and maintenance. This encompasses revamping and expanding grid infrastructure, transmission lines, and storage facilities to accommodate the upswing in renewable energy deployment (Jacobson et al., 2017). However, establishing new infrastructure encounters challenges involving land use, permitting, and community consent (Rosnes, 2008). Fossil fuel-related infrastructure tends to be centralised and compact, situated away from populated zones, because its generation facilities are sparse and transmission at high voltages permit distant power transport.

Conversely, renewable energy infrastructure, particularly solar and wind, occupy larger areas due to their lower energy density, potentially yielding decentralised or federated grid systems (Le Billon and Kristoffersen, 2020; European Commission, 2023a). It is no longer rare to witness roof-top solar installations, which attest to the portable but also intrinsically decentralised nature of renewable power generation. Practicality, and a desire for energy autonomy, is promoting the rise of a decentralised energy infrastructure (Juntunen and Martiskainen, 2021 and references therein). Moreover, increased electrification could lead to elevated electricity transport losses (because by Ohm's law, losses are to a first order, proportional to consumption and transport distance), necessitating decentralised energy grids (e.g., Weinand et al., 2023 and references therein; European Commission, 2023a) or novel solutions (Wei et al., 2018 and references therein). Consequently, conventional solutions, such as high-voltage alternating-current infrastructure might not align with either a decentralised energy setup or emerging solutions (e.g., ultra-high voltage direct current), necessitating swift and massive infrastructure evolution for effective green energy distribution (European Commission, 2023a).

3.3. Economic implications and transition costs

Efforts centred around decarbonisation carry profound energy and economic repercussions, along with associated transition costs (Wang and Lo, 2021; Thurbon et al., 2023). Significant upfront investments are required that span fossil fuels, renewable energy infrastructure, energy storage systems, and grid infrastructure (Mulvaney, 2020; Lazard and Youngs, 2021). These costs can pose formidable challenges, particularly for developing regions or countries constrained by financial resources, potentially amplifying existing economic disparities (Fig. 5; Papadis and Tsatsaronis, 2020; Luderer et al., 2022). For example, although solar energy has become more affordable, decentralised (e.g., roof-top) installations are still costly in developed nations and typically unaffordable in developing or underdeveloped nations. It is imperative to establish mechanisms facilitating affordable financing access, international collaboration, healthy competition, and technology transfer to bolster decarbonisation in developing nations (Sovacool et al., 2023).

Additionally, transitioning to a low-carbon economy can lead to job losses in high-carbon sectors, such as the conventional fossil fuel and related sectors. Workers in coal mines, oil refineries, manufacturing, and carbon-intensive domains might confront unemployment and financial adversity. This is partly mitigated by the indispensable role of fossil fuels in powering the mineral value chain, potentially leading to heightened

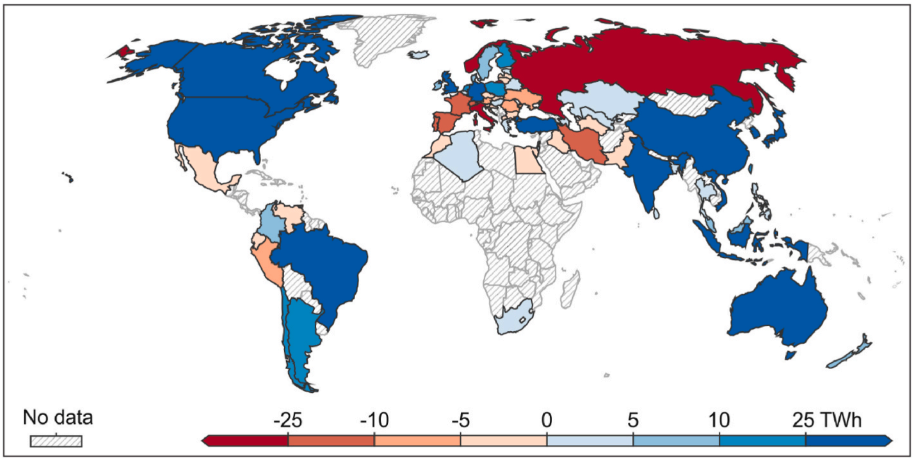

Fig. 5. Annual change in renewable energy generation globally in 2022. Figure taken and modified from Our World in Data (2023).

fossil fuel demand due to enhanced chain productivity (Green and Healy, 2022; Thurbon et al., 2023). The extent of this phenomenon hinges on the pace of activity increase across the mineral value chain. Ensuring an equitable transition that supports affected workers through retraining initiatives, job placement services, and social safety nets becomes pivotal (Abram et al., 2022). Balancing cooperation and mutual scrutiny between governments, industry players, and labour unions are likely key to alleviating the social and economic repercussions of the transition (Abram et al., 2022).

A significant economic consequence of the energy transition is the substantial preparedness gap between Global North and Global South countries (Fig. 5). The Global North boasts comprehensive infrastructure, energy self-sufficiency, and considerable foreign influence. This contrast underpins the formation of expansive mineral-consuming alliances, collaborating to secure energy-transition minerals and metals. Notable examples include the European Union's Critical Raw Material (CRM) Act and the intent to establish cooperative trade alliances (European Commission, 2023b). These moves, however, are increasingly met with geopolitical counteractions. Resource nationalisation is witnessed, exemplified by Chile's lithium case (Villegas and Scheyder, 2023). Vertical integration is also occurring (e.g., Indonesia's nickel sector, Widiatedja, 2021). These are system-type effects at the geopolitical level that originate from the rise of self-sufficiency in primarily the Global North (Zhang et al., 2023).

3.4. Socio-political acceptance and resistance

Realising a successful energy transition hinges on securing economic and socio-political approval, and empirically persuading stakeholders to overcome resistance (Papadis and Tsatsaronis, 2020). Challenges might be especially pronounced within the extractive and processing facets of the mineral value chain due to their perception as polluting, ecologically adverse, and conservative entities (e.g., Moffat et al., 2014; Dikgwatlhe and Mulenga, 2023). This lowers investment interest into the mineral value chain, ironically leading to a poorer outcome. Resistance to decarbonisation can arise from public perception of it as detrimental to their livelihoods or traditions, which can include land displacement (e.g., Bose, 2023; Gukurume and Tombindo, 2023). Apprehensions over job losses and economic turmoil can fuel resistance, necessitating effective communication, education, and public engagement for mitigation (Gareiou et al., 2021; Chipangamate et al., 2023). Raising public awareness and employing targeted communication strategies could be instrumental in shaping public perception. Engaging communities, stakeholders, and policymakers through dialogue, addressing concerns, and integrating diverse viewpoints facilitates consensus-building and smooth policy implementation (Leach et al., 2010; Chipangamate et al., 2023). Involving local communities in decision-making processes, such as renewable energy projects, fosters social acceptance and equitable outcomes (Schelly et al., 2019; Igogo et al., 2021). Lastly, deriving tangible and sustainable benefits to local communities is probably the most important factor, by the principle of reciprocity, to ensure an equitable and sustainable electrification.

These challenges are exacerbated by multi-national, large-scale mining companies operating on a non-local scale. Cost-benefit analyses are very different to large corporations. Disruptions to local socio-environmental conditions might be justifiable for economic gains as mere business externalities (Johnston et al., 2021). Incidentally, the entry of foreign-owned mining entities, especially with government affiliations, may be wielded and perceived as geopolitical moves. This is more prominent in centralised as opposed to market economies, because the Capitalist Peace theory would not be applicable, even if it is debatable (e.g., Mansfield, 2021). Additionally, reconciling contrasting customary and statutory traditions within stakeholder engagement is crucial to ensure that the energy transition's societal advancement is not inadvertently 'colonial' in nature or perception (e.g., Huntington and Marple-Cantrell, 2021). Definitions of 'green' must be geographically harmonised with local needs and contextual considerations.

3.5. Potential disruptions to existing industries

Decarbonisation can potentially unsettle prevailing industries and supply chains (Alexander and Gleeson, 2018; Newell, 2019), especially those deeply reliant on fossil fuels (Power et al., 2016). With increasing success of renewable energy, the demand for fossil fuels would decline, inevitably, if not immediately. This transformation carries substantial multi-scaled and multi-sectoral economic implications for nations heavily reliant on fossil fuel exports, including coal and natural gas, as well as businesses functioning in these sectors (Lazard and Youngs, 2021; Wang and Lo, 2021). The curtailment of oil earnings could unsettle national budgets and economic stability for oil-exporting nations (Mulvaney, 2020). To pre-empt potential adverse outcomes, proactive steps are imperative to diversify economies shackled by fossil fuel dependency and create novel prospects. Market investments in commodities serve as a cornerstone for industry stabilisation, generating whole markets, economies, and employment avenues. Amid labour market shifts, fresh sectors could emerge, bolstered by economic diversification and supporting industry transitions (Power et al., 2016; Alexander and Gleeson, 2018; Newell, 2019). This approach might involve investing in renewable energy infrastructure, fostering innovation and research, and sustaining investments into the renewable energy sector (Diaz-Rainey et al., 2021).

Furthermore, the adoption of renewable energy sources could usher in new players and dynamics within energy markets, potentially reshaping geopolitical relations and trade flows. Nations rich in renewable energy resources could ascend as key global energy stakeholders, influencing energy market dynamics and trade trajectories (Sheng et al., 2022). This shift might prompt countries to re-evaluate energy security strategies, exploring fresh avenues for collaborative energy sector initiatives (Green and Healy, 2022). Governance and industry leaders should anticipate and navigate these potential upheavals. Strategies such as 'just transition plans', emphasizing the well-being of affected workers and communities, hold the potential to alleviate social and economic repercussions of industry disruptions (Bumpus and Liverman, 2018). This entails endorsing retraining and reskilling initiatives, forging fresh job openings in emerging sectors, and erecting social safety nets to safeguard vulnerable individuals and communities during the transition.

4. The role of carbon-based energy systems in the green transition

While carbon-based energy systems have been significant contributors to GHGs emissions, they play a vital role in the green transition. By leveraging their advantages, such as reliability, existing infrastructure, and economic benefits, as well as implementing strategies to accelerate the transition, such as setting realisable targets, investing in research and development, and advancing energy efficiency, it is possible to facilitate a smoother and faster shift towards renewable energy sources (IPCC, 2021). These advantages and strategies are comprehensively outlined in Table 2.

5. Advantages of a globally inclusive approach

A universal definition of a 'globally inclusive approach' towards energy transition does not exist. Here, we provide a pragmatic (functional) definition, based on the idea of global inclusivity, which stipulates that participation in global initiatives should always be possible, despite pervasive geographical differences. In this definition, we acknowledge geographical differences (e.g., socio-economic status or resource availability) and a diversity of approaches that could be theoretically undertaken in pursuit of climate stewardship. Consequently, in our definition, a more globally inclusive approach is one that accepts a greater diversity of approaches, such that more people can participate internationally in climate stewardship (and other) activities. Therefore, a globally inclusive approach in the global energy transition should empirically result in a more inclusive outcome along any measurable societal dimension (e.g., economy). A globally inclusive approach can provide multiple benefits such as additional collaboration, access to diverse renewable energy resources, market opportunities, and social and environmental co-benefits, which are further discussed below. Thus, a globally inclusive approach to the energy transition offers several significant advantages in addressing decarbonisation and beyond, geopolitical realities, and climate change.

5.1. Collaboration and shared responsibility

A globally inclusive approach encourages collaboration among nations in recognising that the green energy transition requires cooperation (UNFCCC, 1992; Mukund and Kabra, 2023) and resource competition degrades cooperation (Zhang et al., 2023). Countries can share knowledge, resources, and best practices, thus accelerating the transition (IEA, 2021). Collaboration can lead to the development of innovative solutions, technologies, and policies that are more effective and efficient in reducing GHG emissions (Stanton et al., 2016). For example, the International Solar Alliance, a collaborative initiative between solar-rich countries, aims to promote solar energy deployment through knowledge sharing, capacity building and investment facilitation (International Solar Alliance, 2022). Furthermore, a shared

Table 2
Advantages, opportunities, and strategies for carbon-based energy systems in the green energy transition.

Aspects	*Components*	*References*
Advantages and Opportunities of Carbon-Based Energy Systems. Carbon-based energy systems, such as fossil fuels, fuelled civilisation and economic growth. Despite emissions, they provide benefits and opportunities in the green transition.	*Reliability and Energy Security.* Carbon-based energy systems provide unmatched reliability and energy security. Unlike intermittent renewable sources, they offer consistent and stable energy supply, meeting baseline demands even during high-consumption periods. *Existing Infrastructure and Expertise.* Carbon-based energy systems' infrastructure offers a chance to integrate cleaner technologies, accelerating the transition to greener alternatives and driving innovation. *Economic Benefits and Job Creation.* Transitioning to cleaner energy systems can drive economic growth by fostering new industries, such as renewables and energy efficiency, while preserving the economic benefits of the carbon-based energy sector. *Integration with Renewable Energy Sources.* Carbon-based energy systems pave the way to a low-carbon future by combining with renewables. Pairing fossil fuel plants with CCS cuts emissions, enabling a gradual shift while securing steady energy provision in the initial stages of renewable implementation.	IEA, 2023; UNEP, 2021; Tour et al. (2010)
Accelerating the Transition through Carbon-Based Energy Systems. Phasing out carbon-based energy systems is the goal, but they can also accelerate the green transition through use of strategies.	*Bridge to a Low-Carbon Future.* Carbon-based energy systems bridge the transition from high-carbon to low-carbon sources. Ambitious emission reduction targets drive the gradual shift from fossil fuels to renewable alternatives. *Phasing Out Fossil Fuels: Setting Ambitious Targets.* Clear and ambitious targets for phasing out fossil fuels are crucial. This involves setting deadlines for coal plant decommissioning, limiting hydrocarbon extraction, and incentivising renewable energy adoption. *Research and Development for CCS Technologies.* Investing in CCS technologies capture and stores CO_2 emissions from power plants and industries, and is thus crucial for reducing the carbon footprint of carbon-based energy systems.	IEA, 2023; Dubey and Arora (2022); IPCC, 2021; IRENA, 2019a, b
Advancing Efficiency in Carbon-Based Energy Systems. Enhancing carbon-based energy system efficiency reduces emissions and maximises energy utilisation.	*Improving Fuel Efficiency and Combustion Technologies.* Enhancing energy conversion efficiency in carbon-based systems reduces emissions. Advanced combustion technologies, such as combined cycle turbines, increases efficiency and lowers emissions.	IEA (2023)

(*continued on next page*)

Table 2 (*continued*)

Aspects	*Components*	*References*
	Energy Management and Grid Integration. Integrating smart energy management systems with carbon-based energy systems optimises energy utilisation and reduces waste. Effective monitoring and control thus align energy supply with demand, minimising excess capacity and energy losses. *Utilisation of Waste Heat.* Carbon-based energy systems generate waste heat during production. By utilising combined heat and power (CHP) or district heating, waste heat can be captured, enhancing efficiency, and reducing emissions by eliminating separate heating or cooling systems.	
Ensuring Environmental Considerations. In the green transition, prioritising environmental considerations and minimising negative impacts when using carbon-based energy systems is vital.	*Implementing Stringent Emission Regulations.* Governments can enforce emission regulations for carbon-based energy systems, setting limits on pollutants and mandating emission control technologies to mitigate environmental impact. *Investing in Environmental Protection and Restoration.* Allocating resources to environmental initiatives mitigates the impacts of carbon-based energy systems. This includes reforestation, habitat restoration, and pollution control measures to preserve ecosystems and biodiversity. *Carbon Pricing and Market Mechanisms.* Carbon pricing mechanisms, such as taxes or cap-and-trade, incentivize emission reduction. They assign value to carbon emissions, promoting cleaner technologies and transitioning to low-carbon energy systems.	IEA, 2023; UNEP, 2021; IPCC, 2021; Tour et al. (2010)
Transitioning Beyond Carbon-Based Energy Systems. While carbon-based energy systems act as a bridge to a low-carbon future, investing in and transitioning to cleaner energy sources is crucial for long-term sustainability goals.	*Scaling up Renewable Energy Deployment.* Expanding renewable energy sources reduces reliance on carbon-based systems. This involves increasing capacity, improving storage, and enhancing grid integration for a sustainable energy supply. *Advancing Energy Storage Technologies.* Efficient energy storage technologies address renewable energy's intermittency challenge. They enable higher integration into the grid, reducing reliance on carbon-based backup power sources. *Promoting Energy Efficiency and Conservation.* Energy efficiency and conservation reduce reliance on carbon-based systems. This includes efficient building standards, appliances, transportation, and conservation practices. *Investing in Research and Development for Clean Technologies.* Investing in research and development is crucial for advancing clean technologies and sustainable energy solutions. This includes research on renewables, energy storage, carbon capture and sustainable transportation.	IEA, 2023; IRENA, 2019a

responsibility approach promotes burden-sharing, ensuring that all nations contribute to global efforts in proportion to their capabilities (Bulkeley et al., 2014).

5.2. Competition, geopolitics, and energy security

A globally inclusive approach encourages beneficial competition, and harnesses it as a pivotal catalyst for enhancing productivity and sustaining the transition process (De Wildt et al., 2020; Grasso and Rodrigues, 2022). This ensures that efforts are rewarded in proportion to their outcomes, stimulating continued transition momentum. At the national level, competition should mirror market dynamics to prevent adverse geopolitical consequences such as resource nationalisation or supplier-consumer cartels (Smith et al., 2023; Mukund and Kabra, 2023). This signifies a shift from ideological stances to pragmatic drivers within the mineral value chain, much akin to the evolution observed in the fossil fuel industry (Arbatli, 2018). This transformation steers international interactions from ’desires’ to ‘feasibility’, thus anchoring geopolitics.

By leveraging the principles of the Capitalist Theory, redirecting the green transition towards the market reduces conflicts (Mukund and Kabra, 2023). Market openness, a cornerstone of Kantian peace, forms a foundation for peaceful relations, and resource trade can transpire on material and monetary terms rather than through coercion, armed forces or politics (Russett et al., 1998). Market competition creates effective separation of green energy from governance, leading to less politicised and more economically-driven global interactions. Additionally, markets lack direct military instruments for exerting geopolitical control, decreasing the impact of material competition (Smith et al., 2023; Mukund and Kabra, 2023). Although an in-depth exploration of utilising decarbonisation to bolster global geopolitical stability is beyond this study's scope, it is pivotal to conceive the energy transition as part of a broader peace engineering effort in a complex system context (Kröger, 2023). The potential for geopolitical conflicts arising from resource competition necessitates a profound exploration.

5.3. Access to diverse renewable energy resources

A globally inclusive approach empowers countries to tap into the diverse array of renewable energy resources scattered worldwide. Varied regions host distinct potentials for solar, wind, hydro, geothermal, and other renewable sources. Through international collaboration and trade, nations can access this rich spectrum, alleviating the challenges tied to intermittency, and reinforcing energy reliability (IRENA, 2020). The Desertec initiative, for instance, envisions harnessing renewable energy from North Africa and the Middle East's deserts to provide clean electricity to Europe (Desertec Foundation, 2023). By broadening their energy mix, nations can diminish reliance on fossil fuels, enhancing energy system resilience and fortifying energy security (Karekezi et al., 2012). Energy supply diversification significantly reverberates in stabilising geopolitics concerning raw material provision, as it entails diversifying raw materials themselves (Mukund and Kabra, 2023). This physical and commodities diversification stabilises the energy transition process and its accompanying geopolitical landscape. A diversified material landscape along the mineral value chain introduces more degrees of freedom. This, in turn, augments the system's capacity to absorb changes during stress periods (e.g., supply droughts) and averts abrupt, drastic events such as conflicts (Lazard and Youngs, 2021; Wang and Lo, 2021). Consumer-centric countries of raw energy materials already recognize this, exemplified by the European Union's diversified approach for CRMs (European Commission, 2023b).

5.4. *Market opportunities, economic growth, and prosperity*

An all-encompassing global approach to energy transition births substantial market openings, and propels economic growth and well-being (De Wildt et al., 2020; Smith et al., 2023). Economic dynamism spanning the mineral value chain is poised to surge as the energy transition unfolds. This surge presents ample opportunities for individuals displaced by traditional sector job losses. The shift towards renewable energy necessitates substantial investments spanning infrastructure, research, development, and manufacturing. This investment spurs job creation facilitates upward career mobility, catalyses innovation, and nurtures the growth of clean energy industries. According to the International Renewable Energy Agency (IRENA), the renewable energy sector employed 11.5 million individuals worldwide in 2019, projected to burgeon to 42 million by 2050 (IRENA, 2019a). Through collective adoption of this transition, nations may establish themselves as vanguards in the global green economy, drawing investments and gaining a competitive edge in burgeoning sectors (Government of Canada, 2022). Furthermore, deploying renewable energy can yield long-term energy cost reductions, augmenting economic competitiveness and energy affordability (IRENA, 2020, 2021).

Artisanal and small-scale mining (ASM) serves as a pivotal supplier of several energy transition minerals. ASM, driven by dire livelihood options, absolute and relative poverty, and other socio-economic forces, is significant in providing minerals such as cobalt, copper, and tantalum (e.g., Hilson and McQuilken, 2014). The escalating economic allure of diverse commodities suggests that ASM would swiftly venture into novel niches, as evidenced by tantalum and cobalt. ASM's contribution as a major provider of numerous energy transition metals, such as 25% of the world's tin and a substantial 60% of tantalum supplies, underscores its significance (Schütte and Näher, 2020). ASM's projected growth and its potentially underappreciated role in the green energy transition evoke varying anticipation levels. Given the livelihood dependency of the ASM sector, estimated at around 150 million lives (Fritz et al., 2018), a globally inclusive strategy ensures adequate recognition of ASM's green transition contribution. This, in essence, means that a considerable and relatively disadvantaged population would encounter a substantial economic advancement and prosperity.

5.5. *Social and environmental co-benefits*

A globally inclusive approach to energy transition delivers a multitude of societal and environmental advantages, extending beyond decarbonisation's core tenets. Pivoting towards green energy sources substantiates air quality enhancement, curbs pollution-induced health challenges, and alleviates the healthcare burden (WHO, 2023). For instance, a study conducted in the United States projected that transitioning to renewable energy sources would avert thousands of premature deaths and yield billions of dollars in healthcare savings annually, provided living conditions remain consistent throughout and after the transition to green energy. This could concurrently impact the pharmaceutical sector's economic activity during the transition.

Renewable energy initiatives concurrently foster the evolution of rural landscapes, generating employment prospects and nurturing social inclusivity (Clara et al., 2023). These projects often necessitate localised labour engagement, cultivating job opportunities and economic expansion in communities traditionally leaning on fossil fuel industries. Moreover, community-driven renewable energy endeavours empower societies, propelling energy sovereignty and ameliorating energy scarcity (IRENA, 2020).

Furthermore, the integration of ecosystem conservation and restoration into energy transition strategies take on a pivotal role in safeguarding biodiversity, conserving natural resources, and bolstering climate adaptation endeavours (De Wildt et al., 2020; Grasso and Rodrigues, 2022). Renewable energy deployment aids in mitigating habitat destruction and fragmentation tied to extractive industries, thus minimising ecosystem disruptions and protecting vulnerable species (IPBES, 2019). Nature-oriented solutions such as landscape greening, reforestation, and ecosystem rehabilitation augment carbon sequestration and resilience against climate change, playing a substantial role in meeting climate adaptation goals (Di Sacco et al., 2021). Through a globally inclusive lens, nations not only transition their energy systems, but also embrace an array of social and environmental benefits. These ancillary benefits positively impact public health, foster sustainable development, and contribute to ecosystem and biodiversity preservation, in line with the Paris Agreement and the United Nations SDGs (UN, 2015).

6. The role a diverse approach in adopting an earth-centric resource philosophy

In concordance with the public acceptance of climate change mitigation, a comprehensive and diverse approach is necessary. While there are no system-type recipes to success, because climate engineering is unprecedented, a more holistic approach is more likely to be effective than an overly narrow or reductive one. While decarbonisation is a partial solution, it is important to acknowledge the need for more complete, and therefore, more effective solutions (Table 1).

6.1. *Renewable energy deployment and innovation*

Expanding renewable energy mixture is part of the overall solution. The widespread adoption of renewable energy technologies reduces GHG emissions, diversifies energy sources, potentially enhances energy security, and has the potential to stimulate economic growth through job creation and innovation. For example, solar and wind technologies have decreased in manufacturing and deployment costs by 85% and 55%, respectively (2010–2019), making them more competitive with fossil fuels (IRENA, 2021; IPCC et al., 2022). Continued research and development in renewable energy technologies can further increase performance, reduce costs, and increase global accessibility (IRENA, 2019a).

6.2. *Energy efficiency and conservation measures*

Improving energy efficiency and implementing conservation measures across sectors are essential elements to mitigate climate change. Energy efficiency involves reducing energy consumption while maintaining or improving the desired outcomes, such as lighting, heating, and/or transportation (Fig. 6). Significant emissions reductions can be achieved by implementing energy-efficient technologies, practices, and behavioural changes across sectors. Energy efficiency contributes to decarbonisation goals, leads to cost savings, enhances energy security, and promotes sustainable development. For instance, implementing energy-efficient technologies and practices in buildings can reduce energy demand and lower GHG emissions (IEA, 2021a). Policies and incentives, such as carbon credits, encouraging energy efficiency investments and behaviour changes can amplify its impact (IEA, 2021a).

Policies and incentives play a crucial role in driving energy efficiency improvements. Governments can implement regulations, standards, and labelling schemes that promote energy-efficient products and buildings.

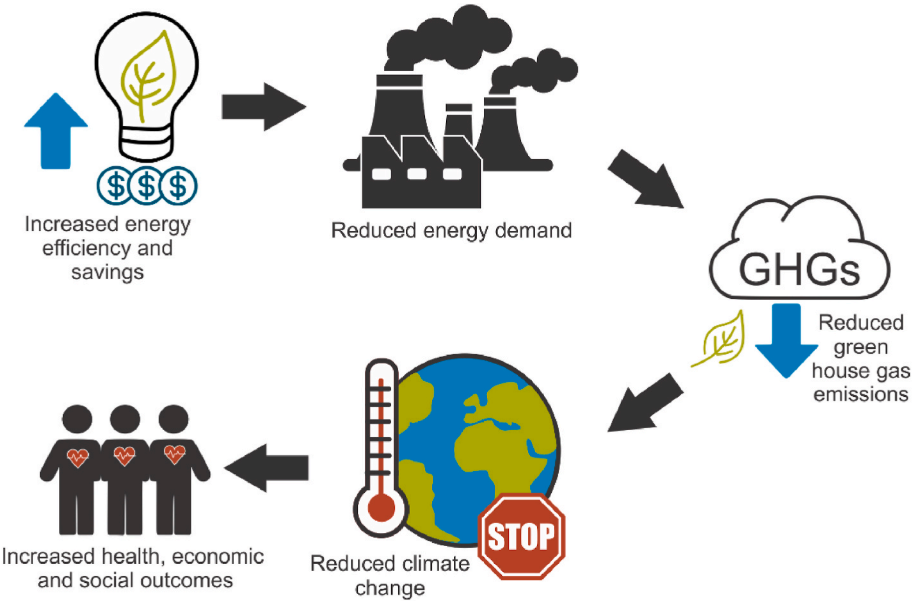

Fig. 6. Advantages of increased energy efficiency. Changes made to improve energy efficiency (e.g., appliances and buildings) requires less energy resulting in savings. Energy-efficient appliances and buildings result in a reduction in energy demand from fossil fuels, which in turn leads to a reduction in greenhouse gas emissions, reduced climate change, and improved human health, economics, and social outcomes.

Financial incentives, such as tax credits or subsidies, can encourage individuals and businesses to adopt energy-saving practices. Public awareness campaigns and educational initiatives can also be important in fostering behaviour changes and promoting energy conservation (IEA, 2022, 2023).

6.3. Carbon pricing and market-based mechanisms

Market-based mechanisms harness complex-system dynamics to catalyse the emergence and implementation of solutions. Channelling investments into the market towards cost-efficient renewable energy technologies and related innovations should be considered a main driver of the green energy transition. This realm encompasses both formal and informal economies, and corporate social responsibility with the former concentrating on value augmentation and practicality, and the latter aiming to rectify ethical concerns associated with the former. Investments in the mineral value chain and clean energy technology, particularly within the research and development sphere, can yield enduring advantages. Markets beyond quaternary economy, such as the carbon trade market (including carbon taxes or emissions trading systems), offer economic incentives to curtail GHG emissions (Fig. 7; Papadis and Tsatsaronis, 2020). However, this must be implemented democratically to be ethically acceptable, and these types of mechanisms should not override primary or secondary economies, because those are fundamentally more supportive of the energy transition. By assigning a monetary value to carbon emissions, these market-based mechanisms nudge enterprises and individuals toward adopting cleaner technologies and modifying behaviours (Bölük and Kaplan,

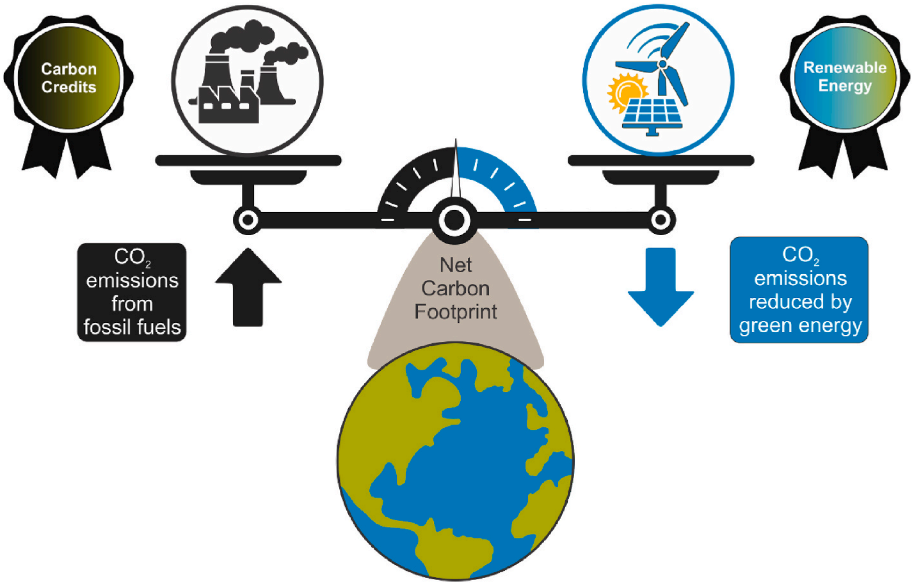

Fig. 7. Use of carbon credits to offset greenhouse gas emissions towards renewable energy and the intricate balance between traditional fossil fuels and renewable energy generation towards the green energy transition.

2022; Stavins, 2003). Carbon pricing stimulates innovation, eases the transition to low-carbon alternatives, and generates revenue for sustainable initiatives (Fig. 7). For instance, a World Bank study underscores that carbon pricing can efficiently drive emissions reduction while concurrently providing government revenue (Clara et al., 2023), although there does not seem to be any system-type studies focused on the costs. Pragmatic implementation of carbon pricing mechanisms can foster equitable conditions and spurs collaboration across nations (IMF, 2019). Although the exact baseline living standards that would be equitably pursued is unspecified. Consequently, a greater shared responsibility is to ensure that carbon pricing is attuned to each nation's capacity and willingness, to ensure that higher orders of economies do not hinder the progress of developing countries, which are pre-occupied with establishing primary and secondary economies (Bulkeley et al., 2014).

6.4. *Nature-based solutions and carbon removal technologies*

Nature-based solutions wield substantial prowess in curbing carbon emissions and bolstering carbon sequestration. This strategy acknowledges carbon's natural role as an atmospheric enhancer for Earth's greenery, akin to an aerial fertiliser (Zhu et al., 2016; Yang et al., 2023). This is because life is carbon-based and many plants respond positively to increased atmospheric carbon content (e.g., Buitenwerf et al., 2012; Kgope et al., 2010). Natural solutions encompass initiatives such as reforestation, afforestation, and safeguarding forests, wetlands, coastal habitats, and grasslands (e.g., Duncanson et al., 2023). Notably, forests are prominent carbon sinks (Di Sacco et al., 2021; Yang et al., 2023). Diverse ecosystems are equally impactful, including mangroves, peatlands, and seagrasses, which harbour immense carbon sequestration potential (IPBES, 2019). These strategies not only amass carbon while furnishing ecological, biodiversity, and societal perks, but also effectuate considerable local temperature reductions (Li et al., 2023). They also demand minimal ongoing human management and anthropogenic energy inputs (because they are solar powered), unlike other carbon removal technologies (e.g., CCS). As a result, the administration of nature-based solutions tends to be less carbon-intensive than managed alternatives. Capitalising on these solutions enables policymakers to forge natural and ecologically sound blueprints that tackle the challenges of the green energy transition, geopolitical dynamics, and climate change. Executing nature-based solutions may entail strategic, scientific, and social considerations to assure their durability and efficacy over the long term (e.g., Di Sacco et al., 2021).

Unnatural or synthetic strategies primarily focus on carbon removal, such as direct air capture (DAC) and CCS. DAC involves isolating CO_2 directly from the atmosphere via specialised technologies. Conversely, CCS captures CO_2 emissions from industrial processes or power plants, consigning them underground or re-purposing them elsewhere. These innovations wield the potential to curb atmospheric CO_2 and advance carbon neutrality, while minimising detrimental emissions. However, these technologies are in nascent stages and require substantial anthropogenic input such as energy, and grapple with technical and financial hurdles necessitating solutions for scalable deployment (Papadis and Tsatsaronis, 2020). It is pertinent to note that these advanced solutions, while effective in capturing carbon, do not contribute to ecosystem enhancement or biodiversity, as they essentially isolate carbon from the biosphere completely, eliminating desirable outcomes such as afforestation or crop cultivation. This implies that other environmental initiatives such as forestry and agriculture are not synergized.

7. Evaluating the effectiveness of current approaches

It is essential to evaluate the effectiveness of current approaches in achieving sustainable and inclusive outcomes if geoengineering would become a pragmatic and manageable task. This evaluation must be empirical and objective, whose outcome is important to ensure sustainable climate change mitigation while other important issues are not overshadowed and nor are new issues created. This evaluation should go beyond decarb-centrism and explore diverse approaches towards a green transition. One requirement is to consider a broader range of factors and re-evaluating the definition of 'green'.

7.1. *Monitoring and evaluation systems for the green transition*

Comprehensive evaluation of the effectiveness of current approaches necessitates robust monitoring and evaluation systems. These systems should capture various system-level indicators, particularly those of interconnectivity and interdependency, including environmental, social, and economic aspects and their inter-relationships. Key metrics for evaluation that already exist include GHG emissions reduction, energy efficiency improvements, job creation, technological advancements/investments, social equity, and environmental conservation (UNEP, 2019; Janoska, 2019). System-level metrics are a matter of research and requires system-wide indicators that are sensitive to a diversity of approaches beyond those specific to carbon. However, some of these metrics do not measure outcome but instead effort, which makes them ineffective for feedback to guide system engineering. Additional all-cost and all-benefit metrics are needed to ensure that the overall state of the world is accounted for, and, therefore, fixation does not occur for a particular metric to the detriment of others. For instance, composite metrics that normalise climate change mitigation outcome (e.g., reduction of GHGs through projects or approaches) by the current economic cost to benefit ratio may be effective to assess total economically feasible deployment potential. Similarly, energy efficiency normalised by lifecycle GHG emission is likely to be useful to evaluate transition progress. These metrics could be crafted after a more holistic approach towards climate change mitigation becomes more generally accepted. Ideally, a performance measurement framework should exist that measures the impact on climate change with respect to economic activity in the sector.

Implementing such monitoring and evaluation systems requires collaboration among various stakeholders, including governments, international organisations, research institutions, and civil society (IPCC, 2018). These systems should be transparent, accountable, pragmatic, and adaptable to evolving challenges and emerging opportunities. By regularly monitoring progress and evaluating the outcomes of current approaches, policymakers and stakeholders can make informed decisions, identify areas for improvement, and ensure an effective green energy transition.

7.2. *Positive effects of the current approach*

While acknowledging previous limitations and challenges, it is important to highlight the positive impacts of the decarb-centric approach to addressing climate change. Efforts to decarbonize the global economy have led to notable progress in renewable energy technologies, energy efficiency, and sustainable practices across sectors (IEA, 2021). The reduced costs of renewables such as solar and wind power have bolstered their competitiveness and accessibility, enabling at least a partial shift away from fossil fuels (IRENA, 2019a; IPCC et al., 2022). This has made renewable energy more affordable and shifted its deployment from centralised plants to more grassroots applications such as rooftop solar panels. This shift supports the decentralisation of electrical grids, fostering a gradual evolution of our energy infrastructure (Chen et al., 2020; European Commission, 2023a). The embrace of green energy tech has spurred innovation, generating jobs, economic growth, and new industries (UNEP, 2020). This transition has also yielded environmental co-benefits—better air quality, reduced water pollution, and enhanced biodiversity conservation (IPBES, 2019). The focal point of decarbonisation has engaged researchers, policymakers, and citizens in scholarly, socioeconomic and political debates, which assisted the public in understanding climate issues and mitigation strategies. Global awareness has spurred international collaboration and shared responsibility (UNFCCC, 2015), fostering trust, market competition, cooperation, and momentum for transformative change.

7.3. *Inclusive definition of green: towards a holistic assessment*

To effectively assess system-type approaches, it is vital to embrace a comprehensive and diverse definition of ‘green’ encompassing a wide array of sustainable practices. This permits a system-type definition of ‘green’. This definition, moves beyond CO_2 reduction to encompass other GHG emissions (Table 1), resource conservation, circular economy principles, biodiversity protection, and social fairness (Fig. 8; Rosenzweig et al., 2018). This means that any action correlating with positive outcomes across various global/regional indicators (e.g., socio-economic or ecosystem indicators) could qualify as inherently ‘green’. A green economy should also encompass basic concepts of discounting and investment, which implies that there should be mechanisms to deduce when an immediate action is favourable or when an upfront cost (e.g., investment or carbon emissions) is necessary to achieve a long-term gain. This would promote investment into the mineral value chain, whose activity is critical to climate change mitigation. Inclusivity should also factor in fairness and justice. Shifting to a green economy must not worsen subsistence or conflicts, or unfairly burden any community, because otherwise, green would become connotated with poverty and become unsustainable. Evaluations need to assess differential outcomes, guaranteeing that advantages and prospects are justly distributed throughout society (Fig. 8; UNDP, 2021). Performance assessments made with a broad perspective is more likely to capture actual changes in the environment and would better direct policymakers, stakeholders, and researchers in honing strategies, addressing drawbacks, and plotting a course toward a globally inclusive transition to green energy.

8. Addressing potential criticisms and concerns

8.1. *Equity and just transition considerations*

To achieve a globally inclusive approach, justice and equity are important. The burden of climate change mitigation should not disproportionately fall on vulnerable populations, such as developing nations or small businesses. Otherwise, decarbonisation would be viewed unfavourably as a type of economic subjugation, detailed in Table 3.

Table 3
Key aspects of social equity and a just transition in a global green energy transition.

Key aspects	Description	References
Social equity	Policies and initiatives, on average, should aim to prioritise equitable outcomes. This involves supporting and assisting affected communities, facilitating job transitions, and creating new employment opportunities. For example, studies have shown that communities with higher levels of social capital and inclusive decision-making processes have a greater success in transitioning to renewable energy sources. Additionally, access to affordable and green energy should be ensured for all, particularly for underserved regions and disadvantaged communities.	Roberts et al. (2018)
Just transition	A just transition framework should be implemented, acknowledging potential disruptions to workers and industries that are reliant on fossil fuels. It involves supporting affected workers through retraining programs, facilitating job placements in clean energy sectors, and providing financial assistance. Activities across governments, industries, and labour unions are necessary to ensure a fair and inclusive transition process. The International Labour Organisation (ILO) has highlighted the importance of just transition policies to protect workers’ rights and promote social justice during the energy transition.	ILO (2015)

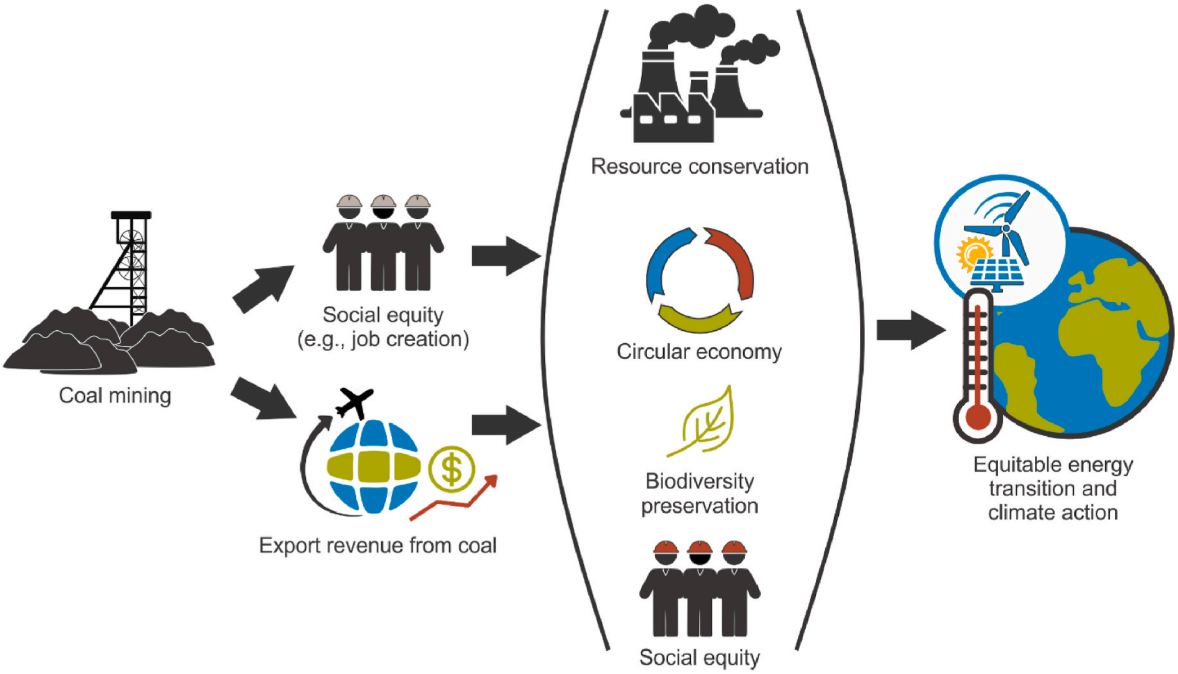

Fig. 8. Inclusive approach to a green energy transition. Here, South Africa, which heavily relies on coal for energy, jobs, and revenue is taken as an example. The energy transition should extend beyond decarbonisation and should promote resource conservation, circular economy, biodiversity preservation and social equity to reach an equitable energy transition and climate action.

8.2. *Geopolitical and trade implications*

The green energy transition has geopolitical and trade implications that need to be considered to maintain stability and encourage cooperation among nations:

- Energy interdependencies: The green transition can reduce dependence on fossil fuel exporters, altering existing geopolitical dynamics. Countries relying on fossil fuel exports may face economic challenges that may be existential in scope, requiring careful transition management. Diversification of energy sources and fostering partnerships for renewable energy development can mitigate potential geopolitical tensions arising from shifting energy landscapes. For instance, the European Union's efforts to diversify its energy sources through renewable energy imports and domestic production aim to enhance energy security and reduce dependence on single suppliers (European Commission, 2023c).
- Trade relations: The green transition may lead to changes in global trade patterns, particularly in the energy sector. Countries rich in renewable mineral resources may become key players in energy exports, potentially reshaping trade relationships and creating new economic opportunities. It is crucial to ensure fair trade practices, open markets, and promote international cooperation to avoid trade disputes and foster global energy security. The World Trade Organisation (WTO) ensures a rules-based and transparent global trading system for energy products and services (WTO, 2023).

8.3. *Interplay between climate and development goals*

Addressing climate change and advancing SDGs are interconnected processes that require a synergistic systemic approach:

- Co-benefits: Green transition efforts can contribute to sustainable development by creating new jobs, fostering innovation, and improving public health through reduced pollution, where they do not negatively affect other SDGs. Renewable energy deployment and energy efficiency measures can simultaneously address climate change and support socio-economic development, particularly in developing countries. For example, renewable energy projects can create employment opportunities and enhance rural electrification, improving socio-economic development (IRENA, 2019b).
- Trade-offs and prioritisation: Balancing climate change mitigation goals with other development priorities can pose challenges. Policymakers and investors should carefully assess and prioritise actions that align with both climate and development objectives. This involves considering context-specific factors, such as energy access, poverty alleviation, and food security, to ensure a balanced and mutually reinforcing approach. Trade-offs may arise when pursuing climate change mitigation measures that potentially impact other development goals. For instance, expanding renewable energy projects could involve land use changes affecting agricultural activities or biodiversity conservation efforts (Oatley, 2021). Policymakers must conduct comprehensive assessments and engage in multi-stakeholder dialogues to identify potential and long-term trade-offs and develop strategies that maximise co-benefits and minimise negative impacts. Prioritisation is also important in reconciling climate and development objectives. It requires understanding the specific needs and circumstances of different regions and sectors, and the relationship between the economic and energy systems. For example, in areas with limited access to electricity, prioritising energy access using renewable energy solutions can simultaneously contribute to climate goals and support development outcomes (Overland, 2019). Similarly, integrating climate resilience measures into infrastructure development projects can enhance adaptive capacity and reduce vulnerability to climate change impacts (IPCC, 2018).

Principle-based frameworks, such as the United Nations SDGs, provide a set of dimensions for balancing climate and development priorities. The SDGs emphasise the interconnectedness of various goals and the need for integrated approaches to ensure sustainable development (UN, 2015). Policymakers can use these frameworks as guidance in prioritising actions and identifying synergies between climate and development objectives.

8.4. *Public engagement and communication strategies*

Effective public engagement and communication strategies are essential for building public support, fostering cooperation, and addressing multi-faceted concerns related to an inclusive green transition. These strategies and their implementation have been detailed in

Table 4
Strategies for effective public engagement and communication in an inclusive green transition.

Strategies	Description	References
Education and awareness	Increasing public awareness about the urgency and significance of a diverse and inclusive green transition. Educational campaigns, targeted outreach, and open dialogues can improve understanding and highlight the advantages and disadvantages of the transition. Objective information must be available to support informed decisions by individuals, communities, and businesses. For instance, the Intergovernmental Panel on Climate Change (IPCC) regularly communicates scientific findings and assessments to inform policymakers and the public.	IPCC, 2021, IPCC et al., 2022
Stakeholder engagement	Involving stakeholders, including civil society groups, businesses, and local communities in decision making. Encouraging meaningful engagement allows for a range of perspectives, promoting ownership and trust. Platforms such as multi-stakeholder forums and public consultations enable collaborative policy design, ensuring diverse voices are acknowledged and included.	UNEP (2019)
Tailored messaging	Effective communication involves tailoring messages to various audiences. Climate change impacts differ based on location, socio-economic status, and culture. Adapting messages to resonate with specific groups boosts relevance and engagement. For instance, stressing health benefits to healthcare professionals or framing climate action as economic growth for business leaders.	Leiserowitz et al. (2009)
Building trust	Establish trust with the public and stakeholders. Transparency, integrity, and inclusivity in decision-making are key. Open dialogue, addressing concerns, and integrating feedback build trust and legitimacy. Trusted messengers such as local leaders, scientists, or community representatives enhance credibility and promote acceptance of inclusive green transition efforts.	Moser and Dilling (2004)
Collaboration with media	Media engagement is vital for sharing information, sparking public discourse, and rallying support. Cultivating journalist relationships, sharing accurate data, and showcasing diverse solutions through media coverage can magnify communication impact. Prioritising balanced reporting, accurate science representation, and avoiding misleading balance is crucial.	Boykoff and Mansfield (2008)

Table 4. By employing effective public engagement and communication strategies, policymakers can foster public understanding, create consensus, and mobilise collective action.

8.5. The role of enterprises

Effective strategies to climate change mitigation should make explicit recognition of the role of enterprises. Productivity across the primary and secondary economies are particularly important to ensure a steady supply of raw and processed materials that are necessary to sustain material needs of climate change mitigation (World Bank, 2017; Sovacool et al., 2020). Leveraging the market to encourage competition is likely to result in an abundance of economically viable, and therefore, pragmatic solutions. Promoting the market to find solutions to climate change or sustainability will likely dampen global contention for CRMs and stabilise international relations, which fosters for more collaborative responses to a collective problem (Poast, 2019). Enterprises can also evolve to become more proactive in their practices by picking and choosing from a greater diversity of approaches, by fundamentally adopting a broader definition of 'green'. For example, while CCS is out of the scope for many small-to medium-sized businesses, natural solutions are likely to be highly affordable, from the active participation in afforestation to achieving carbon-circularity in source materials or produced goods. Larger enterprises will likely play a lead role, because they can invest in substantially larger projects, including technology transfer to underdeveloped regions, conservation through sustainable resource management practices, and improving business efficiency to reduce resource consumption (Bester, 2022). Strategic implementation to encourage enterprise participation includes: 1) a reduction in regulatory burden, to facilitate the participation of smaller and medium-sized businesses; 2) incentivising a diversity of 'green' practices and environmental transparency; and 3) incentives to technology transfer, healthy competition and innovation.

9. Policy implications and recommendations

9.1. Fostering global cooperation through policy frameworks

Governments should establish robust and pragmatic policy frameworks to promote a diverse and globally inclusive approach to the green transition. These frameworks should encourage collaboration, knowledge sharing, and technology transfer among nations (Fig. 9). Partnerships, joint research initiatives, and best practice exchange are key components. Policies directed toward broadening the definition of 'green' should include the activities of the mineral value chain, in recognition of its necessity and upfront carbon costs in exchange for a greater benefit in the long term. Similarly, policy should exist to incentivize and sustain other enterprises and sectors that are practicing a diversity of approaches beyond decarbonisation towards sustainability and/or climate change mitigation. Policies to enhance global cooperation is pivotal for addressing climate change and implementing the energy transition, because scientific and economic collaboration is key to solving a planetary-scope problem. Policy frameworks promoting collaboration can facilitate the sharing of scientific knowledge, technological advancements, and policy experiences among countries. This collective effort can expedite renewable energy technology deployment and overcome shared challenges (IRENA, 2020). The IRENA exemplifies such a global cooperation, facilitating knowledge exchange in renewable energy.

9.2. Mobilising investments, enterprise activity and financial mechanisms

Multi-sectoral mobilisation, including those of international financial institutions and relevant enterprises should bolster the shift toward renewable and green energy technologies. This entails creating favourable investment climates, implementing green finance mechanisms, and channelling funds toward sustainable infrastructure development. Adopting a broader definition of 'green' and seeking solutions beyond decarbonisation, and a willingness to incur short-term investments in exchange for a bigger long-term gain is necessary for the minerals industry to be recognised as a major contributor to climate change mitigation and sustainability. Enterprises should be recognised for their

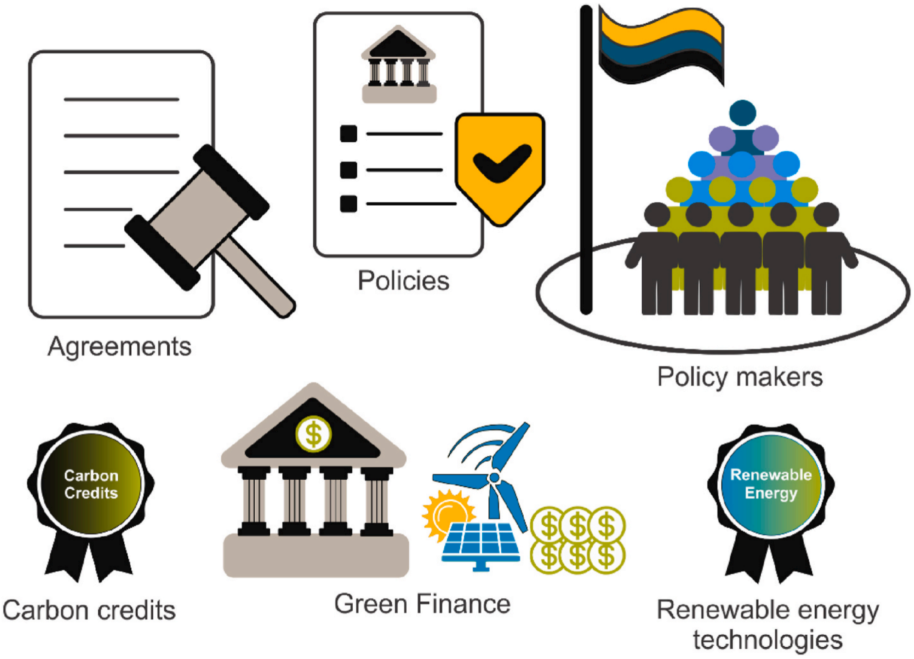

Fig. 9. Policy makers can create a more inclusive environment by creating frameworks, policies, and agreements to enable an approach-diverse and equitable green energy transition. Such policies can include green financing, carbon credits and renewable energy technologies.

efforts through financial incentivisation, such as funding research and development, or economic activity proposals with a diverse approach to climate change mitigation or adaptation. Deploying renewable energy technologies and supporting requisite infrastructure demands substantial investments and enterprise participation. Stable, transparent, and certain policies can foster investment climates by setting clear renewable energy targets and providing incentives such as feed-in tariffs or tax breaks (Papadis and Tsatsaronis, 2020; IRENA, 2018). An emphasis should be on small-to medium-sized enterprises, since this constitutes a disadvantaged group that is also responsible for economic and social mobility in developing countries. This group is also critical to the success of the energy transition by providing the capacity for both mitigation implementation and generation of new approaches, technologies and ideas. International financial institutions, such as the World Bank, can allocate funding and devise tailored financial products for developing countries. Green bonds and climate funds can mobilise private capital for sustainable investments and technology transfer (Climate Bonds Initiative, 2021; Green Climate Fund, 2021).

9.3. *Strengthening international institutions and agreements*

Efforts should reinforce international institutions, interdependence and agreements governing climate change and the green energy transition. This creates a peaceful and necessary condition to facilitate economic collaboration. This involves enhancing effectiveness and accountability of existing bodies, exploring reform opportunities, and fostering coordination among pertinent international entities. The UNFCCC and its subsidiary bodies provide a platform for climate-related negotiations and cooperation. Fortifying these institutions enhances their capacity to facilitate dialogue, collaboration, and achievable climate action (UNFCCC, 2021). Exploring reform possibilities can yield more effective governance structures. Coordination among international bodies is vital to prevent redundancy, promote coherent policy approaches, and maximise global initiatives' impact. Coordination between UNFCCC, the International Energy Agency (IEA), and the World Trade Organisation (WTO) can yield an integrated approach to the green energy transition (WTO, 2023; UNFCCC, 2021). Trade of material goods can facilitate the participation in green energy value chains, therefore reducing geographical disparities through gains of trade.

9.4. *Coherent policy integration across sectors*

Policymakers must ensure policy coherence between the energy transition and other sectors such as transportation, industry, agriculture, and urban planning. This requires holistic approaches, cross-sectoral collaboration, and integrating sustainability considerations into decision-making at all levels to permit a longer and more system-type planning horizon. Integrated policies addressing energy, transportation, industry, and more are vital for sustainability, if they are also pragmatic and empirical. Cross-sectoral collaboration identifies synergies, identifies trade-offs, and enhances policy effectiveness. Policymakers should foster dialogue, collaboration, and stakeholder engagement to develop integrated solutions. Sustainability assessments, economy, and scientific evidence should inform policy development. The EU's Green Deal integrates climate goals across sectors, fostering cross-sectoral collaboration and sustainable practices (European Commission, 2019). Integrated policies amplify energy transition strategies' efficacy, promoting climate-development goal synergy for a resilient future.

10. Conclusion and outlook

Global efforts are directed towards mitigate climate change while simultaneously striving to maximise sustainability. This study proposed a diversified approach that aims to achieve a globally inclusive green energy transition which surpasses conventional decarbonisation strategies. First, this study detailed the role of CO_2 in the green energy transition while highlighting the need to consider other impactful GHGs. Current decarbonisation efforts present several challenges, namely, an increased reliance on the mineral value chain, technological and infrastructure constraints, socio-economic implications, among others. Furthermore, we also detailed the often-overlooked role that our current carbon-based energy system needs to play in the transition. By embracing a more system-type perspective, the proposed beyond-decarbonisation approach takes into account economic, environmental and social factors, effectively expanding the definition of 'green' to encompass a spectrum of considerations. To this end, we detailed and explored various advantages that include increased global collaboration potential, decreased material competition, improved energy access, heightened economic opportunities, and socio-environmental co-benefits. Strategies to implement this approach include amplifying renewable energy deployment and innovation, increasing energy efficiency and environmental stewardship activities, implementing efficacious carbon pricing mechanisms, integrating nature-based solutions and carbon removal technologies. We then present an overview of strategies needed to evaluate and thus optimise the effectiveness of current decarbonisation methods. Finally, addressing societal apprehensions requires a focus on fair outcomes, geopolitical stability, market impacts, developmental objectives, and effective public engagement. Policymakers play an important role in fostering global collaboration, mobilising investments, strengthening institutions and cross-sector policy integration.

Going forward, reducing the reliance on carbon-based fuels and embracing green energy will be vital for accomplishing the green energy transition. Furthermore, optimizing carbon-based fuel efficiency through innovative technology and engineering will be equally important. Thus, investments in research and development for better fuel technology and methods should also be considered. This holistic approach will help the shift to cleaner energy and could also help tackle emission concerns.

No approach is without weakness. Several challenges remained to be explored in order to find suitable solutions. Future work will undoubtably need to: 1) investigate and propose system-level metrics to assess the effectiveness of all approaches; 2) consider global collaboration complexities such as technology transfer mechanisms; 3) consider the potential of innovative technologies on the green energy transition, especially with regards to energy storage and digitalisation; 4) evaluate the potential of CO_2 conversion into useful products that can derive circular economic and environmental outcomes directly from the carbon cycle; and 5) encourage the implementation of diverse approaches to address geographical diversity to maximise the likelihood of success for an inclusive green energy transition.

CRediT authorship contribution statement

Yousef Ghorbani: Writing – original draft, Investigation, Conceptualization. **Steven E. Zhang:** Writing – original draft, Investigation, Conceptualization. **Glen T. Nwaila:** Writing – review & editing, Writing – original draft. **Julie E. Bourdeau:** Writing – review & editing, Writing – original draft, Visualization. **Derek H. Rose:** Writing – review & editing, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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