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The Spectrum of Implications of Decarbonization on Sustainable Development

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ABSTRACT

Decarbonization is essential for addressing climate change, but it has wide-ranging implications for sustainable development. This paper examines the spectrum of implications of decarbonization on key areas of sustainable development, such as poverty reduction, job creation, food-water-energy systems, ecosystems, and biodiversity. It highlights both opportunities and challenges, including the need to balance environmental goals with social equity and economic stability. The analysis shows that careful planning and targeted policies are required to address regional disparities, land-use conflicts, and job transitions. By aligning decarbonization efforts with sustainable development goals, this paper argues that the energy transition can support a fairer, more resilient, and prosperous future for all.

KEYWORDS

climate action, energy policy, sustainability, nexus approach, policy coherence.

INTRODUCTION

In 2015, two major milestones were achieved in global sustainability efforts: the launch of the United Nations (UN) Sustainable Development Goals (SDGs) [1] and the establishment of the Paris Agreement [2]. These initiatives, widely endorsed and ratified by UN Member States, marked a significant step forward in international collaboration on sustainability and climate action. The SDGs represent a holistic framework comprised of 17 objectives, that address key economic, environmental and challenges that stand on the path to sustainable development. On the other hand, the main goal of the Paris Agreement is to "strengthen the global response to climate change, reaffirm the goal of limiting global temperature increase to well below 2 degrees Celsius, while pursuing efforts to limit the increase to 1.5 degrees". In essence, the Paris Agreement is closely tied to SDG 13: Climate Action, and requires countries to submit Nationally Determined Contributions (NDCs) every five years in which they state their climate goals, but also the specific policies and measures (PAMs) they intend on implementing to achieve those goals.

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While climate change mitigation and sustainable development are historically seen as district fields, the implications of decarbonization extend far beyond the reduction of greenhouse gas (GHG) emissions [3]. The transformation of energy systems, industries, and economies required to achieve net-zero emissions has profound consequences on sustainable development—both positive and negative. Addressing these implications is critical to ensuring that decarbonization contributes to a just and equitable global transition, leaving no one behind. The absence of inclusive policies exposes the energy transition to the risk of social resistance from certain socio-demographic groups and to "revenge of places that don't matter" [4].

Energy systems are at the heart of this transition and its decarbonization requires a complete overhaul of energy generation, distribution, and consumption patterns [5]. This in turn interacts with core aspects of sustainable development such as poverty alleviation, job creation, and the protection of ecosystems and biodiversity. These interactions are complex and highly context-dependent, influenced by regional differences in resource availability, economic development, and governance structures [6].

This paper explores these themes by examining the wide-ranging implications of decarbonization on sustainable development. It considers the socio-economic, environmental, and governance dimensions of this transition, focusing on key topics such as poverty and inequality, job creation, the food-water-energy nexus, ecosystem impacts, and policy coherence. The analysis highlights both opportunities and challenges, emphasizing the need for tailored, context-specific strategies to maximize synergies and mitigate trade-offs. By addressing these dimensions holistically, this paper aims to contribute to a deeper understanding of how decarbonization can support a sustainable and inclusive future.

FRAMEWORKS FOR EVALUATING THE DECARBONIZATION-SUSTAINABILITY NEXUS

Many studies explore the interactions between decarbonization efforts and the SDGs [7], highlighting the need for their careful consideration [8]. Policymakers welcome systematic approaches that break down these complexities. An example of such an approach is the seven-step scale introduced by Nilsson et al. [9], which contains seven possible types of interactions. The scale ranges from (+3) to (-3), with (+3) indicating a highly positive interaction and a strong synergy and (-3) indicating a highly negative interaction and strong trade-off, as shown in Fig. 1. While it can be used at any level, it is particularly effective at mapping the synergies and trade-offs between the 169 SDG targets, making it easier to identify points of collaboration and competition and simplifying the development of coherent policies and measures relevant to sustainable development. This scale has been later used by Nerini et al. [10] to evaluate the connections between climate action and the SDGs. The analysis in [10] underscores the impacts of not mitigating climate change, stating that the changing climate could undermine the achievement of 72 targets across 16 SDGs. This aggravates existing challenges related to poverty, wellbeing, food, energy and water availability and health. However, their analysis also identifies synergies between climate action and 134 targets across all SDGs, which notably outweigh the identified trade-offs (34 targets across 12 SDGs).

Inspired by [9] and [10], Gjorgievski et al. [11] introduce an additional step in which the synergies and trade-offs are quantified with aggregate score. The quantification exercise has been implemented for the energy, heating and building sectors in North Macedonia [11]. As the proposed approach is suitable for stakeholder engagement, Gusheva et al. [12] also implement it to evaluate how climate policies in the waste management sector contribute to sustainable development. Gusheva et al. share how the identification of the synergies and trade-offs, as well as their quantification, can be co-developed with external stakeholders [12]. A common denominator in the findings within this body of literature is that the synergies tend to outweigh the trade-offs, but that the latter can have a large impact, particularly in cases where their long-term consequences are not adequately addressed. For example, hydropower dams, while improving energy generation and water supply, can disrupt ecosystems and affect agricultural productivity long-term. The literature further identifies gaps in current methodologies, particularly in the modelling of SDG interlinkages. While many studies focus on historical data, there is limited exploration of future projections and the transboundary impacts of SDGs [13]. Transboundary spillovers—where one country's policies affect the SDG progress of neighbouring countries—are particularly important in environmental contexts, where regional cooperation is essential for managing shared resources like water and air quality. Additionally, the issue of intergenerational spillovers emphasizes the need to account for long-term environmental and social impacts, particularly in relation to climate change. These concepts suggest that current research methodologies may overlook the broader, more distant impacts of policy decisions.

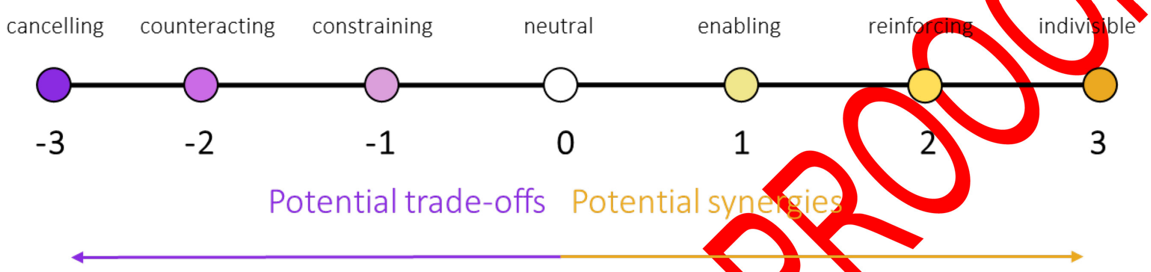

Figure 1. Seven-step scale proposed by Nilsson et al. [9]

The simplicity of these approaches makes them highly useful when engaging stakeholder, discussing policy coherence issue and communicating key points from the complex landscape of the energy transition. At the same time, the simplicity comes at a cost, as it somewhat compromises the ability of these approaches to rigorously quantify the interactions beyond the seven-steps. As reviewed by Beltrami et al. [14] different composite post-GDP indicators can be used for this purpose, such as the Human Development Index, Index of Sustainable Economic Welfare, Happy Planet Index, Measured Economic Welfare index, Index of Sustainable Economic Welfare, Genuine Progress Indicator, Inclusive Development Index, Sustainable Prosperity Index and others. Beltrami et al. [14] further modify the Sustainable Prosperity Index and apply it to study all EU countries under different scenarios. Their findings show that energy self-sufficiency of countries can improve sustainability performance.

SYNERGIES AND TRADE-OFFS

The importance of integrated, systems-based approaches is emphasized in the literature to better understand and manage the interaction within the energy sector [15] and between the energy sector and other sectors [16]. Energy system models and integrated assessment models (IAMs), are gaining traction for their ability to assess the synergies and trade-offs across various sectors, providing policymakers with a more comprehensive understanding of the potential outcomes of different policy choices [11]. However, the models still face challenges in capturing uncertainties, particularly in relation to transboundary and intergenerational effects, which are critical for accurate assessments of SDG progress [17] [18].

The output of these models can be used to simultaneously evaluate the implications of decarbonization on multiple SDGs. In [19] it is found that decarbonization pathways based on wind and solar energy are more effective at reducing the negative health impacts than energy transition pathways that are not based on renewable energy. They also lessen ecosystem damage and fossil resource depletion, though they require more critical mineral extraction. In the EU, early decarbonization reveals synergies with health and agriculture but also trade-offs with poverty, hunger, and economic growth, necessitating corrective policies [20]. The IAM community's Shared Socioeconomic Pathways (SSP), based on five socio-economic narratives, were evaluated by six IAMs to assess energy, land use, and emissions.

The authors of [21] show that mitigation costs and societal impacts depend heavily on socioeconomic and policy assumptions, highlighting the need for more detailed research. This section reviews the estimates of synergies and trade-offs between decarbonization, and SDGs obtained from various computational models, some of which are shown in Fig. 2.

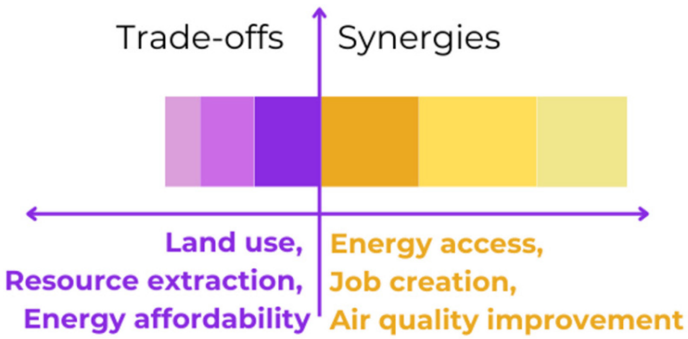

Figure 2. Synergies and trade-offs between decarbonization and SDGs

Health and wellbeing

The 2023 Lancet Countdown report on health and climate change [22] highlights the health co-benefits of decarbonization. Analyzing the benefits of sustainable development pathways in nine countries, it sheds light on the potential for significant health co-benefits of climate action in the form of reduced air pollution-related deaths, diet-related deaths and deaths due to physical inactivity. Similar results are found in found in [23], which use the Global Change Assessment Tool (GCAM) and the Fast Scenario Screening Tool (FSST) to quantify the global health co-benefits from decarbonization. The authors conclude that between 2020 and 2050, premature mortality can be reduced between 17-23% by following global mitigation pathway that is aligned with the Paris Agreement.

While there are multiple mitigation measures that offer substantial health co-benefits, phasing-out of coal power stands out as one of the most significant. Described as a "no-regret" option in [24], phasing out coal yields health benefits that outweigh the costs associated with early coal plant closures. Lower-GDP countries are disproportionately impacted by the negative health effects of coal. As air pollution health problems reduce economic productivity and life expectancy, countries with low GDP can potentially lose up to 8% of GDP [25]. Thus, early decarbonization is especially beneficial in emerging economies, such as India and China, where the net economic benefit from health co-benefits and the costs of coal plant shutdowns could reach up to 0.5% of GDP, respectively [26]. Access to electricity and clear cooking also plays an important role for improving health and wellbeing in low-income countries, especially in women. Results from international panel data spanning over 26 years and 155 demographic and health surveys reveals that clean electricity and cooking, together with improved education positive impact women's wellbeing, empowering them in their reproductive choices, which is often reflected in falling birth rates [27]. At the European level, co-benefits from reductions in PM2.5 due to air quality policies and stringent climate mitigation could offset at least 85% of the costs of climate policy [28]. Similar findings are supported by analyses of individual countries such as China [29][30], South Korea [31] and North Macedonia [32], among others.

Poverty and inequality

The 3.5 billion people (44% of the global population) that live with less than 6.85$ per day [33] will probably be among those who are disproportionately affected by the negative impacts of climate change [34]. While this damage can probably be minimized by rapid climate action [35], most climate models indicate that there is an intrinsic conflict between climate action and short-term poverty reduction. In other words, the cost of climate change mitigation will mostly be borne by the poorest [36]. This trade-off, together with the growing energy demand in developing countries and their struggle to raise capital [37] leads to an important conundrum – those that need climate change mitigation the most are also those who can least support it. There are two subproblems to address with regards to this issue.

Firstly, it is worth reviewing how lifting people out of poverty impacts climate change. Income and energy consumption are positively correlated – populations that are economically better off also consume more energy. As a result, lifting people out of poverty requires building reliable energy infrastructure that will serve their growing energy needs. But to what extent would this affect global emissions? In [38] the authors explore how eradicating global poverty impacts the global GHG emissions, assuming all new demand is met by generation with emissions intensity equivalent to historical trends. Interestingly, their results reveal that alleviating extreme poverty, which is defined based on the international poverty line of US $2.5 per day, would increase global GHG equivalent emissions by only 4.9% of the GHG emissions released in 2019. However, the authors note that increasing the poverty line also increases the environmental impact. These results emphasize the importance of supporting developing countries to avoid lock-in with fossil fuel infrastructure and adopt renewable energy. Achieving climate and poverty reduction goals requires comprehensive policies tailored to each country's economic and social structures [39]. Key lessons include the need for broad investment in physical and human capital, strong social protection, and international financial partnerships. Low-income countries face higher investment needs, and global collaboration is essential for navigating the low-carbon transition [40].

It is equally important that climate action does not impair the economic wellbeing of people. Climate policies that mandate technology bans, carbon pricing or other instruments can be regressive in that they asymmetrically burden those with lower incomes [41]. Addressing this concern, Ram et al. [42] share counter arguments to Afful-Dadzie's criticism [37], stating that the transition to 100% renewables by 2050 is not only realistic, but an imperative for of developing countries to *leapfrog into a sustainable future*. The authors compare energy transition to the leapfrog in the telecom industry, when many developing countries skipped landlines and moved straight into using mobile phones [42]. One specific policy recommendation that can support this transition is the so-called carbon tax recycling. Carbon tax recycling essentially refers to distributing the total collected carbon tax, equally to all people, regardless of their income [36]. Using the NICE model to account to economic inequalities, the authors of [36] illustrate that achieving a 2°C compatible scenario, yields notably improvements well-being and reductions in inequality and poverty, when carbon tax recycling is implemented. The rationale for this idea is that in low-income countries, fossil fuel consumption is predominantly associated with wealthier individuals. So, while the costs are paid by the richest citizens, the equal per capita tax refunds progressively improve the wellbeing of the bottom quintiles in the income distribution. In line with this finding, a global comparative analysis of poverty and distributional effect of carbon pricing finds that "mitigating climate change, raising domestic revenue and reducing economic inequality are not mutually exclusive, even in low- and middle-income countries" [43].

Job creation

An important question pertinent to the energy transition is whether decarbonization creates more jobs than it destroys. The jobs in the energy sector can be classified as direct, indirect and induced. Ram et al. [44] estimate that a global decarbonization of the electricity sector should create 14 million jobs by 2050, raising the total number of direct jobs from 21 to 35 million. When also accounting for the heat, transport and desalination sectors, this global number of jobs grows from 57 million in 2020 to nearly 134 million by 2050 [45]. This finding is justified given that $1 million spent on renewables or energy efficiency creates about 7.49 and 7.72 full-time equivalent (FTE) jobs, respectively, while only 2.65 FTE jobs in fossil fuel industries [46].

In the case of the US, the energy transition is estimated to support the creation of 3 million jobs in the 2020's and 4-8 million jobs in the 2040's [47]. While "boom-and-bust" cycles are expected in the labour market, the Mayfield et al. [47] estimate that the jobs created by the energy transition offset the ones lost by the phase-out of fossil fuels. Building on this work, Mayfield et al. [48] also find that even applying inclusive labour and procurement policies, such as local procurement preferences, unionization, minimum wage standards and gender equality, incurs only a small additional cost which does not significantly affect the leading role of solar and wind energy in the energy transition. They also argue that these incurred cost premiums can potentially be counterbalanced by improvements in labour productivity.

In China, Zhang et al. [49] find that clean energy generation growth of 1% can lead to about 0.013 % employment rise. In absolute numbers, this is equivalent to 0.12-4.13 mil jobs by 2030 and 5.89-9.66 mil. jobs by 2060 in China. While less optimistic, conceptually similar results are obtained by Gou et al. [50] who use the TIMES model and an input-output assessment of the employment implications of the energy transition in China. They find that a new power generation system would create between 1.56-2.20 mil. jobs in China compared to a business-as-usual scenario by 2060, while Ram et al. [44] estimate around 33 mil. jobs by 2050, when jobs related to heating, transport and desalination are included.

For Europe, Fragkos et al. [51] estimate that if the EU follows a transition pathway compatible with the targets outlined in the EU Winter Package, it should expect 3.62 mil. energy supply side jobs to be created by 2050. These numbers are aligned with Ram et al. [44] who conclude that 3.37 mil. jobs should be created by 2050 in Europe's electricity sector, with solar energy playing a significant part. They also find that the job creation increases to 15.5 mil. jobs if the heating, transportation and desalination sectors are considered along with the electricity sector. Using GCAM, portfolio analysis and Mote Carlo simulation to account for uncertainty, the assessment of Koasidis et al. [52] results in lower estimates – between 0.88-1.43 mil. job-years in Europe created by 2030. The studies also diverge in their conceptual findings. Compared to Ram et al. [44], Koasidis et al. [44] find that wind generation, biofuels and small nuclear generation will have the greatest impact on job creation. Nevertheless, the key message, that the energy transition has a net positive impact on jobs, is further reiterated by other country level findings for the Netherlands [53] and Italy [54] and a comprehensive review of Hanna et al. [55].

However, there are distributional nuances that cannot be captured by aggregate numbers. For example, despite the net-positive job creation on aggregate during the 1995-2009 energy transition of the EU, 6 of the 27 EU Member States were worse-off. Regional disparities were also found in the Chinese case, with jobs shifting from Middle to East China and leaving coal-dominant regions worse-off [49]. To address this challenge, the energy transition should be based on concepts of *distributional fairness and address vulnerabilities*, which in nature are geographically concentrated [56]. This often requires dealing with place-based power struggles and challenging corruption, as shown by the experiences in South Africa [57]. At an individual level, the energy transition leads to job uncertainty for many workers. Analysing micro-data from over 130 million work profiles, Curtis et al. [58] report that less than 1% of workers leaving carbon-intensive jobs move into green employment. In general, older workers and those without university degrees tend to switch from one carbon-intensive job to another within the fossil fuel sector. Furthermore, some authors argue that accounting for both direct and indirect jobs, the energy transition would lead to a loss of 4.45 million jobs globally [59]. The divergence of these findings is an indication of the complexities that need to be anticipated and the need for further research on the topic.

Water-energy-food nexus

The water-energy-food (WEF) nexus refers to the interconnectedness of water, energy and food systems, highlighting the complex relationships and trade-offs that exist among these resources [60], as shown in Fig. 3. As global populations grow and climate change exacerbates resource scarcity, understanding and optimizing these interconnections becomes essential for achieving sustainability and reducing carbon emissions. The concept of the WEF nexus emphasizes that energy production, food security, and water availability are not isolated sectors but rather interdependent systems [61] – energy is required for food production and water management, while food and water systems also influence energy consumption patterns [62]. This interdependence requires a holistic approach to resource management, where decarbonization efforts in one sector can have significant implications for the others. One example of this are certain alternative fuels, such as biofuels [63]. In the example of biofuel production, Delucchi [64] calls for policies for sustainable biofuel production, since "conventional agricultural practices will *not* mitigate the impacts of climate change and will exacerbate stresses on water supplies, water quality, and land use, compared with petroleum fuels".

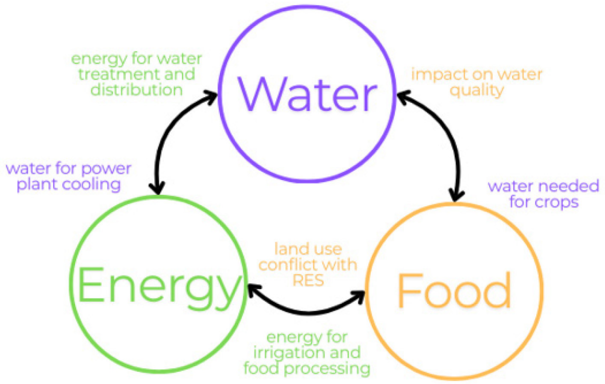

Figure 3. Illustration of water-energy-food nexus

The trade-offs withing WEF systems are strongly emphasized in the developing world. By 2050, African energy and water demands are expected to increase by 80% and 55%, respectively, while meeting food needs will require agricultural production to grow by approximately 50% compared to 2017 levels. With the continent's population continuing to rise rapidly, these trends pose significant risks to the security, access, and availability of water, energy, food, and ecosystem resources [65]. To address this, Apeh et al. [65] highlight the need for integrated, cross-sectoral planning aligned with the SDGs, supported by coordinated governance, especially in transboundary water management. They note that effective implementation requires strengthened institutional cooperation, harmonized data sharing, and inclusive stakeholder engagement. Advancing technical and scientific capacity through targeted education, local expertise development, and involvement of think tanks are also seen as essential for evidence-based policymaking. Digital tools, such as the one described by Pulighe et al. [66], combined with water diplomacy and regional collaboration, are some of the tools that can be used to addressing these resource interdependencies.

Water availability and electricity generation are highly interconnected. Stunjek et al. [67] study the impact of water availability on power generation, evaluating various water stress indices for the electricity generation fleet in the Balkan Peninsula. In that direction Farfan et al. [68] note that water scarcity may significantly affect not just the reliability of hydropower plants, but also of thermal power plants based on coal, gas or nuclear energy. They find that approximately 65% of global generating capacities depend directly on freshwater for cooling or energy generation, with low-resiliency capacities expected to increase from 9% in 2020 to over 24% by 2030 under various scenarios. The authors conclude this by using a novel method which incorporates water stress scores for individual power plants. This bottom-up approach, based on matching thermal and hydropower plants with regional water stress projections assesses the risk to generating capacities based on water availability.

On the other hand, renewable energy can be used to tackle some of the challenges of the WEF nexus. Desalination offers a cost-effective way to reduce water shortages, especially in remote islands where tourism exacerbate the challenge of freshwater scarcity. Stunjek et al. [69] present a framework for optimizing integrated water-energy systems tailored to small-scale islands with distinct seasonal variability. Their work advances conventional methods by employing a mixed-integer linear programming (MILP) model to determine optimal capacities for renewable energy sources and battery energy storage, while simultaneously integrating water supply infrastructure through reverse osmosis desalination and water storage, hence emphasizing the role of power-to-water solutions. Placing solar PV generation on hydro reservoirs and lakes is another measure with co-benefits, improving water retention in reservoirs, tackling water scarcity, enhancing the productivity of hydropower plants, while also increasing PV module efficiency due to passive cooling [70]. Similarly, agrivoltaics – co-locating PV generation on agricultural land are gaining traction a potential solution to the land-use conflict for electricity and food, by providing increased land use efficiency and income diversification for farmers. Deploying renewable energy sources in this manner can reduce greenhouse gas emissions while also ensuring that energy-intensive agricultural practices become more sustainable [71]. While promising, both floating and agriculture PV come with their challenges, ranging from policy uncertainty to increased O&M costs. Nevertheless, these concepts emphasize that renewable energy and innovation can contribute to overcoming the opposing goals of different societal sector by providing synergies and co-benefits.

Ecosystem and biodiversity impact

Like other infrastructure project that involve mining, landscape adaptation, processing and manufacturing [72], the rapid production and installation of net-zero energy technologies will inevitably impact local ecosystems and biodiversity [73]. Therefore, it is crucial to minimize impacts through adequate planning. Renewable energy sources can have some negative impacts on local ecosystems and biodiversity. For instance, throughout their lifecycle, PV power plants can contribute to the depletion of the ozone layer and water toxicity, biomass can lead to abiotic depletion, global warming, acidification, and eutrophication, while wind power can have potential impacts on human toxicity and terrestrial ecotoxicity [74]. Out of these energy sources, bioenergy poses the highest risk, especially in tropical areas, while wind and solar energy have lower negative impacts, as noted by Santangeli et al. [75]. Recognizing these challenges is important to ensure that the net-zero energy transition does not negatively affect agriculture, life on land or life in water.

However, it is also very important to highlight that the net-zero energy transition accelerates the phase out of fossil fuels, whose negative environmental impacts are far more severe [76], as they pose greater risks to biodiversity [77] and require more mining [78]. For example, an evaluation of China's energy transition shows that the uptake of renewable energy not only reduces biodiversity risk but also increases economic complexity [79], leading to multiple benefits of the net-zero energy transition.

Renewable energy sources have a lower spatial energy density compared to fossil fuels [80]. This makes renewable infrastructure more land-use intensive, which may eventually lead to an overlap between conservation areas and renewable energy projects. The latter challenge is emphasized in the work of Rahbein et al. [81] which identified a total of 2,206 fully operational renewable energy facilities and an additional 922 facilities under development that are within the boundaries of conservation areas. Analyzing the American Weste, Patankar et al. [82] find that while the potential for renewable energy is vast, only less than 4% of the solar potential and less than 17% of the wind potential is good quality and cost-effective. Within these potential sites, <53% solar and <83% wind sites demonstrate developmental risks, indicating an increased potential for conflict over land. In a similar analysis of 11 Western U.S. states suggests that not considering land availability in energy planning may increase uncertainties and the challenges of reaching climate targets [83]. In Europe, the network of conservation areas which are legally protected spans over 18% of Europe's area. Case studies of a hydroelectric dam in Portugal and a tidal barrage in the UK demonstrate that the EU's strict biodiversity protection laws can prevent approval of large renewable energy projects, raising legal tensions that may impact both the rule of law and nature conservation efforts [84]. Rather than prompting deregulation, these challenges call for an informed global debate on balancing biodiversity and climate policies. Following this development, it is reasonable to expect that as the energy system becomes more climate neutral, the value of land increases [85]. This highlights the need for careful planning to mitigate negative effects and promote biodiversity conservation alongside renewable energy development [86].

TOWARDS GREATER POLICY COHERENCE

Policymakers face the challenge of ensuring horizontal and vertical policy coherence for sustainable development. Horizontal coherence involves aligning policies across sectors and government levels, while vertical coherence focuses on coordination from local to international governance. Both are essential for addressing the interconnected nature of sustainable development. Frameworks like the EU and OECD's Policy Coherence for Sustainable Development (PCSD) promote collaboration across public, private, and civil society stakeholders, thus enhancing horizontal coherence [87], while integrating environmental considerations, such as linking climate adaptation and development policies, is also considered very important [88]. However, sometime the policies that are most adequate are also most difficult to implement, since they require changing practices that are deeply rooted in economic and cultural traditions. Such is the case of agriculture practices and nitrogen pollution [89]. Nitrogen pollution has grown into a major challenge, because the nitrogen can react with almost any compound, thus aggravating not only climate change, but also air and water pollution and biodiversity loss [90]. Hence, policymakers are faced with the "carrot vs. stick" dichotomy, where traditional market-based policies penalize polluters financially and information-based approaches that encourage pollution reduction by leveraging consumer demand for environmentally friendly products [91]. Guo et al. [92] found that both command-and-control and market-based approaches are effective for GHG emissions reduction. They found, however, that command-and-control approaches achieved this goal by stimulating technological innovation, while market-based approaches achieved it through affecting consumption preferences.

Vertical coherence, on the other hand, ensures that national policies align with local needs and international commitments, such as the 2030 Agenda. Mechanisms for communication, participatory governance, and frameworks like the WEF nexus enhance policy integration and resource management [93]. Normative coherence further supports sustainable development by addressing trade-offs between policy objectives and ensuring equity. Participatory approaches are vital for resolving conflicts and incorporating stakeholder perspectives [94].

Frontiers for future research

While the literature on the implication of decarbonization on sustainable development is vast, there are areas that have received less attention and could be improved.

For example, refining and comparing various post-GDP indicators and evaluating indirect effects, including rebound impacts and socio-economic co-benefits, can contribute to a more thorough assessment of sustainability [14]. This opens new avenue for research in the field of indicators on sustainable development.

Furthermore, the works studying the impact of decarbonization on labour mostly focus on aggregate national number of jobs that are created or lost. However, the reviewed literature provides limited insight into the geographic and sectoral dimensions of job creation in the low-carbon energy transition. Future research should not only examine the displacement and substitution of employment in high-carbon sectors, but also address the spatial distribution of job losses and gains—factors that aggregate figures alone cannot capture.

Jobs, along with land use, GHG emissions, resource availability and other aspect of sustainability are endogenously integrated in IAMs. On the other hand, when energy system models are used to assess decarbonization scenarios, the questions related to sustainability are evaluated ex-post, based on the outputs of least-cost optimization or scenario simulations. One frontier for future research can be the endogenizing of sustainability constraints and goals in energy systems models. This would make energy system models more comparable to IAMs, while preserving their temporal and spatial resolution advantages.

Finally, the climate-economy interactions go beyond productivity and the labour market. Climate goals can disrupt trade dynamics and market dominance, shifting the focus in energy-related global trades from energy fossil fuel resources to minerals and technologies (PV generators, wind generators, batteries etc.). With this perspective in mind, the nexus between trade conflict and decarbonization has been significantly less studied. On that account, Block et al. [95] call for a new research agenda that will bring together the existing scattered evidence, improve quantitative tools to understand how conflict affects emissions, and explore ways to ensure that mitigation efforts stay on track even in the face of conflict.

CONCLUSION

The decarbonization of energy systems is crucial for mitigating climate change and achieving global sustainability goals. However, its wide socio-economic and environmental implications, require a holistic and integrated approach to ensure that this transition supports the broader objectives of sustainable development. As discussed in this paper, decarbonization presents both opportunities and challenges that must be carefully navigated to maximize synergies and minimize trade-offs across multiple dimensions.

On the socio-economic front, decarbonization can drive job creation and economic growth, particularly in renewable energy and related sectors. However, these benefits are unevenly distributed and must be complemented with proactive policies that manage workforce transitions, address inequalities, and support underserved communities. Similarly, while renewable energy can enhance energy access and alleviate poverty, the affordability and equity of clean energy systems must remain a central point within decarbonization strategies.

The environmental implications of decarbonization are equally complex. Transitioning to low-carbon energy systems reduces greenhouse gas emissions and mitigates climate change impacts, but it also introduces challenges related to land use, competition with agricultural land, and biodiversity conservation. Many works argue that even with this in mind, the potentially negative implications of decarbonizing energy systems are smaller than the environmental harm of a fossil fuelled society.

Finally, the governance of decarbonization requires fostering policy coherence across sectors and scales. Integrated planning and multi-stakeholder collaboration are essential to align decarbonization with sustainable development goals, ensuring that policies are inclusive, equitable, and effective. Lessons from successful case studies underscore the importance of balancing competing priorities, leveraging innovative funding mechanisms, and embedding social and environmental safeguards into policy frameworks.

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