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SPECIAL FEATURE: ORIGINAL ARTICLE

Accelerating Actions for Leveraging a Climate-Neutral, Sustainable Society

Beyond synergies: understanding SDG trade-offs, equity and implementation challenges of sectoral climate change mitigation options

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Abstract

Mitigation actions needed to achieve the ambitions of the Paris agreement to limit global temperature rise to 1.5 °C or below 2 °C have to align with sustainable development. In the near term, this implies a better understanding of context-specific challenges in integrating sustainability with climate policies during the designing, planning, implementation and financing stages. Through a review of selected studies across regions, this paper draws out conclusions focussing on mitigation–sustainable development goal (SDG) trade-offs, with implications on costs and equity for different development contexts. Studies show that trade-offs depend on how the option is implemented and at what scale; mitigation options such as afforestation, biomass production and digitalisation are examples of this. Some options could also result in significant adverse environmental impacts as in the case of battery waste and raw material resources for electric vehicle (EV) or air pollution associated with compact urban development. We find the most important factors influencing equity include unequal access (e.g. urban green spaces and public transportation), high costs (e.g. EV) and financial constraints. Major knowledge gaps include (i) limited empirical evidence of SDG-related trade-offs associated with scaling up mitigation options, (ii) limited understanding of the extent to which benefits are experienced by different groups, (iii) an understanding of the extent to which local context was considered when assessing mitigation–SDG interaction, including the engagement of stakeholders and (iv) synergies and trade-offs associated with cross-sectoral policies. The paper recommends ex-post analysis of detailed and place-based cases that document how synergies and trade-offs emerged and how these were addressed.

Keywords SDGs · Synergies · Trade-offs · Climate change mitigation

Introduction

To limit global warming in line with the Paris agreement requires rapid and very wide global participation in greenhouse gas (GHG) emission reductions, and this can only be achieved if climate policies are embedded in a broader

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sustainable development policy framework (UNFCCC 2015; IPCC 2022a). In practice, it means that GHG emission reduction policies have to align- or at least not counteract sustainable development-related policy goals. A myriad of topics emerges from this challenge including the need for integrated assessment of several policy objectives for mitigation options and issues related to the planning, implementation and financing of integrated sustainability and climate policies.

Mitigation is critical to sustainable development, and mitigation actions can deliver a range of sustainable development outcomes. At the same time, mitigation policies could entail trade-offs with some development objectives as the ones included in the UN2030 agenda for sustainable development including 17 sustainable development goals (SDGs) (United Nations 2015). Chapter 17 and Figure SPM.8 of IPCCs WGIII report included a qualitative mapping of potential synergies and trade-offs between the SDGs and mitigation options based on inputs from the sectoral chapters (IPCC 2022a; Denton et al. 2022). Chapter 3 of the same report (Riahi et al. 2022) included a similar assessment based on global and national integrated assessment models. A key message from these assessments is that there are many synergies between mitigation options and SDGs, few trade-offs, and in a number of cases, *both synergies and trade-offs*. In this paper, we use 'mixed evidence' to refer to the interactions that show (i) both synergies and trade-offs and (ii) trade-offs.

Sectoral mitigation options and their interlinkages with SDGs

The sectoral assessment of synergies and trade-offs between mitigation options and meeting the SDGs in Denton et al. (2022) arrived at the following conclusions:

Energy-sector options demonstrate mixed evidence (30 out of 57 interactions, see Fig. 1) with several SDGs, especially with SDG 2 (zero hunger) in relation to land use for bioenergy crops, wind and solar energy and other energy supply options. The same is the case for hydropower due to land use conflicts and impact on fisheries. Potential trade-offs in relation to SDG 6 (clean water and sanitation) can occur due to high water consumption for some options. Rivalry about water resources could emerge from bioenergy crops and bioenergy with carbon capture and storage (BECCS), as well as from cooling water demand from various power supply options.

In the agriculture, forestry and other land use (AFOLU) sector, mitigation options are very closely linked to the SDGs and offer mixed evidence (28 out of 105 interactions), particularly in relation to SDG 2 (zero hunger). The assessment of the AFOLU mitigation options emphasises that the synergies and trade-offs are very context- and scale-dependent, depending on how measures are carried out, for example, in relation to the enhanced production of renewables needed to replace fossil fuel-based products. Trade-offs are particularly a risk with large-scale applications of afforestation projects, bioenergy crops and other land-consuming activities, and especially, if not adapted to local circumstances, there are adverse implications for food security, livelihoods and biodiversity.

In urban areas, several mitigation options have synergies with the SDGs and in a few cases can result in mixed evidence (44 out of 171 interactions), depending on the specific urban context (Fig. 1). Actions taken in the building sector can have mixed evidence such as the economic impacts in the energy sector associated with reduced energy demand and lower energy prices, and with energy-efficiency investments, and the fostering of innovation and improvements in labour productivity.

The mitigation options in the transportation sector are assessed as having synergies with SDG 1 (no poverty) and SDG 3 (good health and wellbeing) mainly due to improved air quality, with exceptions in relation to pollution from biofuels and the risks of traffic accidents. Synergies are also assessed in relation to SDG 7 (affordable and clean energy), SDG 8 (decent work and economic growth) and SDG 9 (industry, innovation and infrastructure). 10 out of 58 interactions between mitigation options and SDGs show mixed evidence. There may be potential trade-offs with SDG 2 (zero hunger) in the transportation sector if the production of biofuels takes land away from food production (Fig. 1).

In the industrial sector, energy efficiency, material recycling and electrification create increased employment and business opportunities related to SDG 8 (decent work and economic growth), but material-efficiency improvements could reduce tax revenues. Carbon capture and storage (CCS) and carbon capture and utilisation (CCU) applied in industry can increase emissions of some air pollutants such as particulate matter, nitrogen oxides and ammonia, and production costs could increase due to higher energy consumption (Fig. 1). 7 out of 31 interactions in this sector show mixed evidence.

The impacts on SDGs of mitigation scenarios were assessed by Chapter 3 of IPCC WGIII (Riahi et al. 2022) based on integrated assessment models implemented at global and regional scales. Though several synergies were found, it was also highlighted that limiting global warming to 1.5 °C could imply trade-offs in terms of increasing food prices, population at risk of hunger and population relying on solid fuels. The assessment also highlighted that mineral resources could be under pressure and that a habitat loss could potentially emerge if mitigation policies were carried out narrowly and not integrated with sustainable development policies. For instance, bioenergy demand should be reconciled with food, water, biodiversity and competition

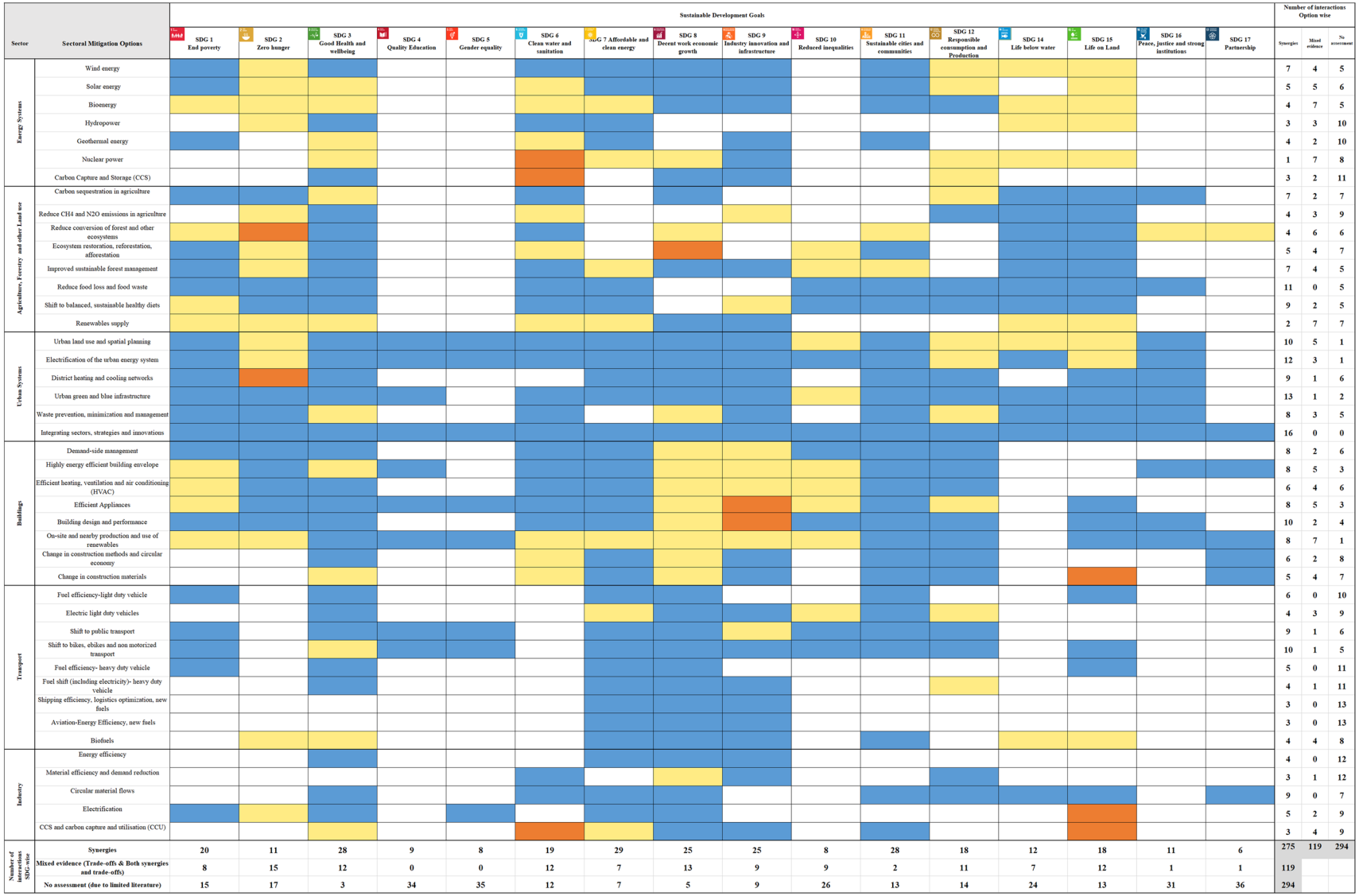


Fig. 1 Synergies and trade-offs between mitigation options and the SDGs. Blue cells indicate synergies, orange cells indicate trade-offs, yellow cells imply both synergies and trade-offs and white represent "no assessment"; the numbers in the last three columns and last three rows denote the number of interactions—mitigation option wise and SDG wise, respectively. Note 1: the synergies and trade-offs reported rely on what has been addressed in the underlying studies, and white cells does not imply that there could be no interactions, it means the assessment of interaction could not be done due to limited literature. Note 2: see IPCC WGIII Chapter 17 Supplementary material for more information Denton et al. (2022) Source: Based on Halsnæs et al. (2022)

for land and should be supported by a range of policies and technologies related to agricultural intensification, dietary changes, open markets, biotechnology and other options to avoid trade-offs. The importance of policies to support the capture of SDG synergies with mitigation policies is also emphasised by Cohen et al. (2021) based on a mapping of SDG relationships with mitigation options in countries' Nationally Determined Contributions (NDCs), which concluded that it could be very beneficial to further link SDGs and mitigation policies.

Nerini et al. (2019) reviewed synergies between climate action and 134 targets across all SDGs and concluded that there are approximately four times more synergies than trade-offs (only 34 targets across 12 SDGs) between climate action and the delivery of the SDGs. Those trade-offs nevertheless have the potential to block climate action—or conversely other development gains making the case for strong governance structures and policy coordination. Similar observation can be made using the open access data behind the Figure SPM.8 of IPCC (2022a). It can be observed that 275 out of 397 interactions identified in the underlying studies reviewed are related to synergies, and 119 out of 397 interactions show mixed evidence (Fig. 1). Existing literature discusses synergies at a great length but misses out on the other two interactions both synergies and trade-offs, and only trade-offs—which means missing out on 30% of the interactions. The sectoral studies and the review of the integrated assessment models for global, regional or national scenarios by IPCC (2022a), Cohen et al. (2021) and Nerini et al. (2019) reach similar conclusions despite different scaling focus and methodological approaches.

Existing literature focuses on approaches or methodologies to understand mitigation–SDG linkages, and assessment of interactions with national and sectoral policies (Nerini et al. 2019; Di Lucia et al. 2022; Cohen et al. 2021). There is, however, limited literature that does an in-depth analysis of identifying and understanding trade-offs as a basis for understanding how those can be resolved or minimised through integrated policies, which also partly explain the small share of trade-offs in interactions identified in Fig. 1. There are methodological challenges to understanding trade-offs, especially how these manifest in different contexts, what actions were taken to address these and whether these were successful. A key missing aspect in the existing literature on trade-offs is how the mitigation interventions impact equity and how this is related to implementation policies. Costs and finance are also central in relation to implementation policies in order to capture synergies and avoid trade-offs between mitigation options and SDGs, but these are only sparsely addressed in the literature on mitigation–SDG linkages. This paper, therefore, delves deeper into understanding the interactions between equity, finance, costs and implementation challenges, in relation to mitigation options, which could have synergies as well as trade-offs.

The paper reviews studies that focus on potential trade-offs between mitigation and SDGs, and how these can be overcome in policy design and implementation. Among the several trade-offs evident in the literature, equity impacts of climate actions are important in relation to policy implementation. For example, earlier studies have shown that climate action can enable and reinforce building prosperous, equal and peaceful societies, and equity is an important component in building strong, functioning and capable institutions, and is closely related to sustainable development aspects such as poverty reduction, welfare and jobs (IPCC 2018). However, climate action can also exacerbate equity issues if improperly implemented (Roy et al. 2022). Bowen et al. (2017) highlight that win–win in terms of only synergies are difficult to achieve and trade-offs related to equity, justice and fairness are important to address as part of an integrated approach to implementation. Howe et al. (2014) in a review of over 1000 case studies on ecosystem services and trade-offs show significant gaps in the literature, including a limited geographic distribution of case studies and highlight the importance of considering the reasons for the trade-offs.

In this backdrop, this paper contributes to the literature in two key aspects: (1) examines carefully selected mitigation interventions and their trade-offs with SDGs while specifically understanding their impacts on equity; and (2) highlights key issues related to policy implementation matters with a specific focus on how studies have assessed equity, costs and stakeholder perspectives in relation to implementation and policy coordination issues for a number of sectoral mitigation options. By doing so, the paper moves the knowledge closer to how options in practice can be implemented.

Methodology

Our starting point is the IPCC AR6 categorisation of sectoral mitigation options and SDG interlinkages assessed in IPCC (2022a). We focus on selected mitigation options for a more detailed examination based on the following three main vetting criteria: (i) options where mixed evidence (only trade-offs or both synergies and trade-offs) were identified in IPCC (2022a); (ii) case studies where the potential implementation of specific mitigation options was addressed and where aspects of trade-offs related to equity, costs and finance were included; and (iii) studies from diverse contexts and countries at different development stages.

A focussed literature search is conducted based on the sectors and mitigation options included in Fig. 1 that match the aforementioned vetting criteria, using a combination of search terms including the name of options, "SDG" and "equity". Equity is here defined as the principle of being fair

and impartial, and a basis for understanding how the impacts and responses to climate change, including costs and benefits, are distributed in and by society in more or less equal ways in accordance with the IPCC Glossary (IPCC 2022b).

The resultant studies were then filtered to identify mitigation options and related studies which included a detailed in-depth discussion of the mitigation option and its synergies and trade-offs with SDGs. Studies which demonstrate mixed evidence were included. After reading the articles, we shortlisted key studies for a particular option which would include an in-depth discussion of implementation challenges and equity issues. Detailed summaries were recorded from each study for synergies and trade-offs, costs and equity. Finally, we looked for and reported implementation—the conditions necessary for implementation but more importantly if there was evidence of or recommendations on enabling conditions that could affect the implementation.

Sectoral assessment

Based on the review, we identified the following mitigation options for more in-depth review in the paper: afforestation and biomass production in the AFOLU sector; electric vehicles (EVs) and public transport in the transportation sector; urban green areas and planning in the urban systems sector; electrification with renewable energy in the industry sector; and digitalisation as a cross-sectoral option. For each sector with extended assessment, we both include our own assessment and the results from other assessments of these sectors.

AFOLU

Afforestation

Several synergies with SDGs have been identified (IPCC 2022a, b) relating to afforestation in the literature: for example, income to forest community/villagers (SDG 1), improved regional soil quality (SDG 2), health benefits due to cleaner air (SDG 3), improved quality and availability of water (SDG 6), potential cooling effects in surrounding cities (SDG 11), may provide shelter from predators and food for life below water (SDG 14) and beneficial for biodiversity (SDG 15) (Denton et al. 2022; Nabuurs et al. 2022). However, very-large-scale afforestation has trade-offs with SDGs due to increased competition with agricultural land, leading to increased food prices affecting food security (SDG 2) (Denton et al. 2022; Kreidenweis et al. 2016).

The synergies and trade-offs vary with the species of trees used, the scale of implementation and the region of implementation (Kim et al. 2021; Peprah 2017). Our literature review helped in identifying some real-life examples of how implementing afforestation projects created opportunities and challenges. Kim et al. (2021) reported four afforestation projects, one in South Korea and three others funded by South Korea in other countries: China, Mongolia and Kazakhstan. These projects provided several region-specific ancillary benefits, thereby increasing regional socioeconomic resilience such as recruiting local low-income individuals, and eco-refugees, opening education centres and providing forestry-related education and training. The major challenge identified is inadequate data collection that would help in quantitative analysis. In 2014, financial incentives (such as establishment expenditure, maintenance premium and afforestation premium) were introduced in Poland to encourage afforestation in low-yield agricultural farmland which is under 10 ha (Źróbek-Różańska et al. 2014). However, farmers do not always prefer investing in afforestation as this is a long-term investment that could potentially be impacted by various uncertainties (e.g. fire) or changes in forest policy. They tend to make investment decisions by weighing an investment in afforestation vs in other assets (like the real estate market) because of profitability.

A study in Ghana (Peprah 2017) found that the success of afforestation (in terms of redeeming land degradation) depends on the species of plant used in swamplands. This study also highlighted that for this project, the host communities received almost zero social and economic benefits as it was outside the clean development mechanism (CDM). Dasgupta and Srikanth (2021) reported that in India, the intergovernmental fiscal transfers for forests by indirectly incentivising the subnational entities for maintaining land under forests have not resulted in desired outcomes as the social, cultural and economic values for communities were not incorporated. Therefore, the paper recommended the involvement of forest communities in such projects and creating a knowledge pool from existing projects which can be used to implement such international policies around the world.

Biomass production

In the context of climate and energy policies, researchers and policymakers (e.g. in India and Chile) are advocating a circular economy. In AFOLU, therefore, the focus is on using agricultural waste/by-product as a (renewable) energy raw material. Biomass production/supply can fetch additional income (SDG 1), provide food and wood products (SDG 2), improve water balance (SDG 6) and enhance energy security (SDG 7) (IPCC 2022a). However, if done at a larger scale, and without considering local circumstances, it can lead to competition with land resources and can have an adverse impact on food security (increasing food prices), biodiversity and livelihoods (Humpenöder et al. 2018; IPCC 2022a). Our focussed literature search helped in identifying some case studies that discuss the barriers to scaling up

a biomass market, role of government in the deployment of the biomass energy sector and scenario studies that try to understand the impacts of large-scale biomass production on natural resources.

In Poland, Roszkowska and Szubska-Włodarczyk (2022) interviewed more than 300 farm owners and found that 94% of them use biomass from their own farms for their own needs such as compost, field manure and livestock feed. Only 15% indicated their interest in cultivating energy crops and the reasons stated are: lack of profitability and lack of assurance of buyers. Other concerns shared by the farm owners include no guaranteed collection system, no organised biomass transport system to buyers and lack of knowledge/information about innovative ways of using biomass for energy. This paper points out that if biomass buyers organise the logistics themselves, then farm owners will be willing to sell.

Choi et al. (2019) evaluated the impact of increasing biomass demand in the European Union (EU) to meet emission reduction targets in 2050 on food and land prices and found that crop yield improvement and cultivation of biomass crops on marginal land may help in reducing food price hike, but increase in land prices is inevitable because the availability of marginal land is very small in the EU. This can also increase investment cost of crop establishment and biomass transportation cost. Scenario analysis, using global land use models, suggests that complementary measures are needed to reduce trade-offs (such as deforestation, CO_2 emissions from land use change, nitrogen losses, unsustainable water withdrawals and food prices) arising from large-scale biomass production. Such complementary measures include forest and water protection schemes, agricultural intensification and improved fertilisation efficiency (Humpenöder et al. 2018).

A recent study (Kevser et al. 2022) explored the long-term relationship among biomass energy investment, financial development and economic growth in 15 African and Asian countries (Cameroon, Democratic Congo, Tanzania, Nigeria, Haiti, Nepal, Togo, Mozambique, Ivory Coast, Niger, Kenya, Cambodia, Myanmar, Zimbabwe and Republic of Congo) and found that investment in biomass energy can increase economic growth and financial development. In line with these findings, the paper recommended creating new energy policies to support biomass investment. In India, around 60% of the land is under agriculture (World Bank Data 2022). Therefore, massive agricultural residues are produced. However, the primary residues are used as fertiliser and animal feed, but the secondary residues can be used as biomass feedstock for power generation. Kumar et al. (2015) reported that 511,041.39 kt/year feedstock is available for power generation. Transportation of biomass on a daily basis is still a challenge as the cost of transportation is too high for poor farmers. Singh et al. (2020) suggested a few strategies to support implementation such as the government creating machinery for transporting biomass, creating markets and innovating financial models. Government of India has been promoting biomass-based power plants and technologies (biomass gasifiers) that use locally available biomass through various policies and incentives (including capacity building through biogas development training centres), and the subnational governments are taking leadership in bagasse cogeneration projects (Ministry of New and Renewable Energy 2013).

Table 1 highlights how afforestation and biomass production influence aspects related to costs, equity and SDGs.

Transportation

Electric vehicles

Electric vehicles (EVs) powered by low-carbon electricity are a key mitigation strategy for the land transport sector. Several studies that have assessed the health impacts of mitigation policies concluded that large benefits could be generated by reduced air pollution (SDG 3), particularly in urban areas from using cleaner energy technologies and fuels (Riahi et al. 2022), creation of jobs associated with EV supply chain and associated infrastructure building (SDG 8), reducing oil import dependence in some contexts and decarbonisation in the long term from low-emission electricity production (SDG 7) (Dhar et al. 2018; Jaramillo et al. 2022). Electric vehicle deployment has advanced in several countries and is increasing in others. Our literature review shows that in countries/regions where upscaling ("diffusion" stage of transition) is already taking place, the challenges are very different from the countries/regions where EV is still in the "emergence" stage.

In US cities where the "diffusion" of EVs is taking place, the main challenges faced are high upfront costs, range anxiety and inadequate charging stations. Romero-Lankao et al. (2022) highlight that EV diffusion generates a rural–urban divide in the US as the wealthier population is likely to have both plug-in and non-plug-in hybrid EVs, and more access to charging stations in cities, while for the rural/ex-urban population, the detrimental factors are the high upfront cost of plug-in EVs, less access to charging infrastructure and range anxiety as people have to travel longer distances. Hardman et al. (2021) highlight that EV charging infrastructure is not equitably dispersed and more low-cost charging stations are needed in lower income residential areas. In addition, incentives provided do not incorporate equity aspects in their design, as sometimes more incentives are given to higher income buyers. Sheldon (2022) found that in the USA, lower income households (annual income < 25,000 USD) may have to spend more than 50% of their household budget on vehicle ownership costs, including fuel, maintenance,

Table 1 Implications of afforestation and biomass production on SDGs, costs, equity and implementation challenges

Aspects	Afforestation	Biomass production
Equity	Host communities may not get any social and economic benefits (Peprah 2017)	If local food prices increase, it can lead to food insecurity for the marginalised, esp. women (Beuchelt 2016) Commercial biomass activities are often male centric, so income increase may not benefit women (Beuchelt 2016)
Implementation	Farmers do not always prefer investing in afforestation (Źróbek-Różańska et al. 2014) Need involvement of forest communities (including fund transfer schemes), creating a knowledge pool from existing projects (Dasgupta and Srikanth 2021) Need international/national financing	Farmers perspectives: lack of profitability and lack of assurance of buyers, no organised biomass transport system to buyers (Roszkowska and Szubska-Włodarczyk 2022) Complementary measures—forest and water protection schemes, agricultural intensification and improved fertilisation efficiency helps in reducing trade-offs (Humpenöder et al. 2018) Creating new energy policies to support biomass investment (Kevser et al. 2022)
Costs	Depends on context, varies with scale, period and location	Increase in land prices leading to increased investment cost of crop establishment and biomass transportation cost (Choi et al. 2019) Cost of transportation is too high for poor farmers (Singh et al. 2020; Kumar et al. 2015)
SDGs (trade-offs are indicated)	SDG 2: large-scale/massive afforestation will increase competition with agricultural land, leading to increased food prices affecting food security (Kreidenweis et al. 2016)	SDGs 1, 2 and 15: massive scale implementation, and without considering local circumstances, can lead to competition with land resources and can have an adverse impact on food security (increasing food prices), biodiversity and livelihoods (Humpenöder et al. 2018; IPCC 2022a, b)

insurance and purchase costs, while households with annual income > 150,000 USD may have to spend less than 10%. In the USA, most buyers purchase used EVs due to the high price. Hardman et al. (2021) indicated that even new EVs cannot create an ample supply to provide affordable used vehicles. Risk of battery pack failures also acts as a concern for poor households to buy EVs. Whether EVs are cost saving is still a debate because new studies argue that the high upfront cost may not get partially offset by fuel cost savings (Sheldon 2022).

In countries where "emergence" of EV is taking place, policies are playing a key role. Multiple initiatives are being taken by central and state governments in India and Nepal to create a market for EVs, for example, road tax exemptions, reduced interest on loans for EVs and amendments to existing laws (e.g. Building Bye-Laws, 2016 in India) to allow charging stations in private and commercial buildings (Singh-Patyal et al. 2021). However, there are many technology-, infrastructure- and societal acceptance-related challenges identified in the literature (Table 2). For example, on the technology side—performance (battery range), recharge time and safety (like explosion due to overcharging and heating) are the key concerns. Charging infrastructure located far from home, concerns over unavailability of reliable electricity and power quality in case of in-home charging infrastructure are major concerns for potential EV purchasers. In India, subsidies on EVs have less impact on consumers, and they are more interested to know about the future policy roadmap for EVs and availability of post-purchase maintenance support, and are sceptic about performance efficiency (Goel et al. 2021; Adhikari et al. 2020). Other concerns include high upfront cost, resale value (due to uncertainty over life of batteries) and lack of awareness (unfamiliar with latest technology, lack of understanding about monetary return). At the national level, the concern is more about availability of rare-earth materials (lithium, nickel, cobalt and many other subcomponents) necessary to sustain the EV market and concerns over high import dependency (Dall-Orsoletta et al. 2022). Moreover, there are high chances of increasing inequality across regions for import and export because for EVs, Europe dominates the market, whereas for batteries, Asia is the largest exporter (Dall-Orsoletta et al. 2022).

Existing literature does point out many solutions to reduce the challenges such as providing a public charging system, improving technology to reduce range anxiety, removing knowledge barriers and providing warranties for used PEV batteries. However, the less explored trade-offs relating to electric vehicles include future challenges relating to concern over rare battery materials, managing a large amount of battery waste (Asokan et al. 2023), and international cooperation and partnerships between EV-producing countries and its supply chain partner countries. In addition, in many countries, electric buses are still relatively expensive, and it is important to ensure that this

Table 2 Implications of transport actions (EVs and public transport) SDGs, costs, equity and implementation

Aspects	Electric vehicles	Public transport
Equity	EVs upfront costs and charging infrastructure (not equitably dispersed) (Romero-Lankao et al. 2022; Sheldon 2022) Jobs, health and emission related issues in lithium- and cobalt-rich countries (Dall-Orsoletta et al. 2022) Export–import inequality (Dall-Orsoletta et al. 2022) Rural–urban divide (Dall-Orsoletta et al. 2022) Incentives for electric vehicles do not incorporate equity in their design (Hardman et al. 2021)	High fares or unequal access for some sections of society (Ghosh et al. 2022; Wang et al. 2022; Gössling 2016) Systems favouring private modes can result in excluding certain populations from equal access to mobility (Gössling 2016) Can lead to an increase in spatial division across economic lines (Seo and Nam 2019)
Implementation	Battery disposal–recycling is needed (Dall-Orsoletta et al. 2022) Equity issue can be solved by user-centric strategies (Romero-Lankao et al. 2022) Policymakers may provide purchase-based incentives (Singh-Patyal et al. 2021) Investment in infrastructure is needed (Jaramillo et al. 2022)	Need to incorporate equity dimension in the transport policy framework to account for differentiated transport needs (Ghosh et al. 2022; Roy et al. 2021) Public transportation policies should consider the residential location patterns of different socioeconomic classes (Gössling 2016)
Costs	High upfront cost for buyers New/repurposed infrastructure cost	Low to medium (depends on the system and the capacity)
SDGs (trade-offs are indicated)	SDG 11: EVs still consume a considerable amount of energy and contribute to other external effects such as congestion (Langbroek et al. 2017) SDG 12: material resources and disposal issues for EV batteries (Asokan et al. 2023)	SDG 11: trade-off between public transportation accessibility and housing size in Seoul, Korea (Seo and Nam 2019)

increased cost does not burden any particular section of the population (Jaywant and Kantikar 2022).

Public transport

Public transport is an important strategy for climate change mitigation and equitable distribution of public transportation services is one of the sustainable development goals (SDG 11) (Ghosh et al. 2022; Jaramillo et al. 2022). Efficient mobility including non-motorised transport, electric transport and compact urban development integrated with public transport have been shown to include synergies with health through improved air quality (SDG 3 and 11), both in developed and developing countries (Pathak and Shukla 2016; Ahmad et al. 2017). High-quality and affordable public transport can enhance mobility, especially for low- and middle-income groups, women and marginalised groups, thereby delivering multiple benefits of achieving the goals of education (SDG 4), and access to healthcare, and to employment (SDG 8) (Dhar et al. 2018).

Affordable public transport can deliver SDGs 1, 5 and 10, while high-cost options can exclude certain sections of the population. Seo and Nam (2019) show a trade-off between public transportation, accessibility and housing size in Seoul, Korea—households with less economic stability preferred neighbourhoods with low-cost housing and greater accessibility, while the relatively wealthier residents moved to more attractive neighbourhoods, thereby leading to an increase in spatial division across economic lines. Studies in Bengaluru, India (Ghosh et al. 2022), and in Shanghai, China (Wang et al. 2022), using slightly different methodological approaches show that spatial inequality exists in transport access and highlight the need to estimate and prioritise equity of access and factor this in planning the public transit network.

Issues in transportation equity include concepts of environmental justice, financing infrastructure, unequal active transportation investments, transit fares and issues of gender and safety (Brown 2022). Studies have highlighted issues of equity and justice in the context of private transport where contemporary transport systems tend to prioritise motorised transport, exercising significant environmental and social burdens on sustainable transport modes through increased risks of accidents, exposure to air pollutants and allocation of road space (Gössling 2016). Hansmann Kellia et al. (2022) show that while interventions to improve active transport through behaviour change programmes, pedestrian and cycling infrastructure improvements and increased transit infrastructure or access showed positive health benefits, these did not necessarily enhance health outcomes for the disadvantaged groups (by race, ethnicity or socioeconomic status). A study on bus rapid transit BRT planning in three Canadian cities reflects lack of transparency in decision making and shows that several unbuilt route options would have likely provided greater improvements for equity-seeking groups (Linovski et al. 2022).

Millonig et al. (2022), therefore, call for ensuring that policy measures for reaching climate targets should not be at the cost of exacerbating mobility access. It is possible to

avoid or at least minimise trade-offs (Denton et al. 2022) with a careful understanding of these distributional impacts across different social groups, which should ultimately be incorporated into policy and infrastructure design (Roy et al. 2021).

Urban areas

Evidence shows sustainable cities and human settlements will have to play a key role in both climate mitigation and adaptation efforts (IPCC 2022a). Compact urban development integrated with public transport is shown to have synergies with SDG 3 and SDG 11. However, this could aggravate local environmental issues including congestion, air pollution and noise. Urban green infrastructure has shown strong evidence of benefits to mitigation with co-benefits of health and adaptation. The most widely reported trade-offs include issues around affordability of housing for low-income residents and equitable access to the green spaces (Sharifi 2020). Grabowski et al. (2022) highlighted three important justice issues around urban green spaces: ecological, Indigenous environmental and infrastructural justice.

In addition to the potential synergies between climate policies, transportation and urban structures, greening of cities including urban farming, urban forms and green spaces has also been assessed to have large potential for both mitigation and adaptation.

Chaminuka et al. (2021) interviewed 30 low-income households in Zimbabwe about the potential welfare impacts of urban farming and concluded that synergies between environmental improvements including SDG 13 could be created including income generation and access to food, but access to inputs and extension services are very constrained and a barrier for implementation. Urban farming could create trade-offs in terms of increased air pollution and chemical pollution if not well managed. Altogether, this calls for careful policy support for urban farming to meet sustainable development goals.

There are several examples of engineering options in urban areas, which can meet both mitigation and adaptation policy goals (Senosiain 2020). Case studies from two Spanish cities illustrate how some of the options could be used in real city environments. Specific examples of greening cities for mitigation and adaptation are presented in a review by Haase (2022) which concluded that implementation of greening options meet significant barriers in terms of limited mainstreaming of climate change policies in general city planning, limited finance and access to the options, as well as failures to communicate the benefits of greening the cities.

Global studies based on integrated assessment models concluded that meeting SDGs and equity perspectives could generate many synergies with low-emission mitigation scenarios, but capturing these would require governance across several urban policy domains and integrated policies to ensure that large transformations needed for meeting a 1.5 °C scenario can be implemented jointly with the SDG targets (Kilkis 2022). Scenarios related to urban forms in 15 large urban areas are included in the study.

A general conclusion on the urban studies is that many synergies can be created with climate friendly transportation such as EVs and public transportation, but significant barriers in terms of user costs and investments needed can prevent implementation and can create negative impacts on equity in terms of access (Table 3). Greening of cities similarly can generate synergies between climate policies and SDGs, but changes in urban forms and introducing more green space require governance across several policy domains, and equity issues could also be at stake in relation to access to areas and resources.

Industry

Industry is a very large global GHG emission source, and implementing large GHG emission reductions in this sector

Table 3 Implications of urban actions (green spaces and urban planning) on SDGs, costs, equity and implementation

Aspect	Green spaces	Urban planning
Equity	Affordability of housing in cities can be influenced by green spaces (Sharifi 2020)	Equity can be a concern if not explicitly addressed. Weak groups can be displaced (Mohtat and Khirfan 2021)
Implementation	Barriers related to finance, accessibility and communication (Haase 2022) Implementation can be hindered due to constraints on inputs to urban farming (Chaminuka et al. 2021)	Land use strategies for mitigation and adaptation can be in conflict if they are not integrated (Xu et al. 2019) Governance aspects need to be integrated in studies in order to capture synergies and avoid trade-offs across several policy domains (Kilkis 2022)
Costs	Costs will depend on land availability (Chaminuka et al. 2021)	Low to medium costs (Xu et al. 2019)
SDGs (trade-offs are indicated)	SDG 3, 11: synergies with income generation and food access of urban farming, but trade-offs with local pollution and safety (Chaminuka et al. 2021)	SDG 3, 11: compact cities can imply increased air pollution, stress, noise and safety issues (Xu et al. 2019)

will require very large investments in electrification, carbon storage, material recycling, energy efficiency and CCS.

Wei et al. (2019) have reviewed recent studies from the US and Europe on the potential for electrification in terms of renewable energy and concludes that there is an enormous potential across several industrial sectors, but there can be a trade-off in terms of high costs compared with a continuation of existing energy and production systems despite that the renewable energy systems considered are not very expensive as such. This is due to many and very significant barriers, which exist in electrification of industry including costs, risk aversion of the industry towards new technologies and the need for supporting equipment and new engineering capacities to enable the electricity use including special needs of high-temperature processes. Other key barriers are heterogeneity of sectors, and missing regulatory policies, which can facilitate the implementation of the renewable electrification options.

Case studies for industries in India similarly show that there are significant barriers to electrification with renewable energy in terms of high investment costs compared with fossil fuel-based systems and high costs of supplementary equipment needed if renewables based systems substitute other existing energy supply (Pal and Hall 2021). Lack of access to capital is a key barrier particularly for small-scale industries (Table 4).

For the user industry, electricity-based technologies invariably require higher initial investment in comparison to fossil fuel-based technologies. For example, initial costs of electric melting/heating furnaces and forklifts are high. In addition, the user may need to pay for augmenting the power connection infrastructure and make space available for additional equipment such as the transformers and panels. This barrier is especially relevant for the large number of small-scale industries who lack investment capital and access to commercial means of finance. This barrier can be overcome by making soft loans available, lowering the cost for power delivery, simplifying the approval process and standardising the required equipment and their specifications.

Bataille (2020) highlights that a combination of policy packages will be required to decarbonise the industry sector, and these would have to differ by the capacity of countries, regional capacities, resources and other circumstances while also recognising the acceptance of stakeholders implementing these.

Digitalisation

Digitalisation, circular economy and sharing economy are significant trends that will affect sustainability in the near future with implications in the medium and long term. Digitalisation can improve services, enhance efficiency and contribute to gender equality (Pérez-Martínez et al. 2023). Mondejar et al. (2021) show that digitalisation can assist in attaining SDGs in different sectors such as (i) food–water–energy nexus, (ii) industry, (iii) citizens' health and wellbeing and (iv) climate change and biodiversity protection. For instance, open-source tools that provide information on ecosystem services and trade-offs can help inform local decisions (Hamel et al. 2021). Digitalisation could also potentially reduce emissions; however, so far, these have made limited contributions to climate change mitigation (Creutzig et al. 2022).

A comprehensive and systematic country-based analysis of the relationship between digitalisation and sustainability indicators found strong synergies with SDGs 1, 3, 4, 6, 7, 9 and 16; medium positive correlation with SDGs 2, 8 and 11; and weak correlation with SDGs 5, 10 and 17 (Pérez-Martínez et al. 2023). The study also finds that digitalisation indicators have a notable trade-off with SDGs 12 and 13 mainly due to air quality emissions related to imports

Table 4 Implications of industry actions on SDGs, costs, equity and implementation

Aspect	Electrification in industry with renewable energy
Equity	Access to finance can be limited in both high- and low-income countries, which can exclude some industries from electrification (Wei et al. 2019; Pal and Hall 2021)
Implementation	Significant barriers are faced for electrification of industry including costs and risk aversion of the industry towards new technologies. Other key barriers are heterogeneity of sectors and missing regulatory policies. The barriers exist in both high- and low-income countries (Wei et al. 2019; Pal and Hall 2021; Bataille 2020)
Costs	High costs associated with transformation from other energy systems to electrification based on study for EU and US (Wei et al. 2019) Electrification with renewable energy is costly compared with fossil fuel-based systems in some countries, e.g. India (Pal and Hall 2021) Electrification requires investments in several parts of the production system and can, therefore, be expensive (Wei et al. 2019; Pal and Hall 2021)
SDGs (trade-offs are indicated)	Many synergies are associated with renewable-based electricity, but costs are a major trade-off (Wei et al. 2019)

and production, energy-related CO_2 emissions, generation of waste including e-waste, overexploitation of resources and impacts on biodiversity. Jones (2018) attributes 0.3% of the global CO_2 emissions to data centres, and the entire Information and Communication Technology (ICT) ecosystem including personal devices, phone-networks and televisions could contribute over 2% of global emissions. Lange et al. (2020) show that despite the energy-efficiency effects, digitalisation in fact causes an increase in energy consumption through direct effects as well as indirect effects of economic growth and better access to services (Table 5). Creutzig et al. (2022) assess impacts of digitalisation on the planetary scale and conclude that in addition to energy consumption and other direct environmental impacts, the indirect and systemic effects of digitalisation are more profoundly reshaping the relationship between humans, the technical landscape and the planet.

Two recent global assessments (IIASA 2019; Denton et al. 2022) concluded that efficiency improvements, reduced resource consumption and new services can support the SDGs, but there were challenges, including in relation to equity, especially low level of access to technologies faced by the least developed and developing countries. The necessary preconditions for successful digital transformation include prosperity, social inclusion, environmental sustainability, protection of jobs and good governance of sustainability transitions. Digitalisation in the manufacturing sector could also provide a comparative advantage to developed countries due to the falling importance of labour costs, while the barriers to emerging economies seeking to enter global markets could accordingly be increased.

Discussion on findings and gaps in the research

The paper takes a deeper dive into the literature on SDG trade-offs and synergies with mitigation actions and goes into further details in assessing mitigation options in cases where there can be mixed evidence with a specific focus on equity, costs, finance and implementation challenges as a supplement to the assessment included in IPCC (2022a). Through evidence from reviews and case studies across a variety of contexts globally, we explore these synergies and trade-offs—specifically, what causes these trade-offs and challenges and what considerations should be taken to reduce or minimise and to avoid trade-offs, as these can act as a barrier to policy implementation. The sectoral studies included in this paper for in-depth analysis identified major barriers in relation to implementation including access to finance as well as costs associated with introducing new technologies in the transportation sector and with new production systems in industry. Regulatory frameworks and integration in comprehensive urban planning were also identified as major implementation barriers. In addition, equity could be at stake due to high costs and limited accessibility to urban green spaces, EVs, and technology access particularly for developing countries or low-income groups within countries.

We find that despite a large number of studies identifying synergies between mitigation actions and SDGs, few studies in effect included an assessment of trade-offs. This is in line with findings from other studies, which show a gap in empirical studies on trade-offs, especially in the global South (Sharifi 2020; Bataille 2020). It is important to recognise that the identification of few trade-offs in studies do not imply that significant trade-offs do not exist despite the high number of studies indicating the potential of mitigation options to deliver synergies on a number of SDGs. We caution against interpreting this result as a guarantee that SDG

Table 5 Implications of digitalisation on SDGs, costs, equity and implementation

Aspect	Digitalisation
Equity	Unequal internet access for countries at different income levels and for different household income levels, can imply that digitalisation excludes some groups from services and markets (IIASA 2019)
Implementation	Structural obstacles need to be acknowledged and adequately managed (Pérez-Martínez et al. 2023) Ensuring responsible digitalisation through design, access and system complexity (Metta et al. 2022) International cooperation to avoid degradation of resources; appropriate choice of computing architecture and design and management of institutions (Creutzig et al. 2022)
Costs	High costs of implementing wide access to the internet (IIASA 2019)
SDGs (trade-offs are indicated)	SDG 3: trade-off between digitalisation and air quality emissions (Pérez-Martínez et al. 2023) SDG 13: energy-related CO_2 emissions (Jones 2018) SDG 12: waste generation (Pérez-Martínez et al. 2023) SDGs 7 and 8: increase in energy consumption as a result of direct impacts as well as through economic growth (Lange et al. 2020)

synergies can always be achieved by implementing specific mitigations options. Here, equity is important, and synergies can vary spatially between countries or even within a city or between groups. At a global level, issues of equity include finance and technology access, for example, in relation to industrial decarbonisation options and digitalisation between countries at different development levels. Some interventions (e.g. digitalisation, public transport and urban green spaces) can deliver synergies with a range of SDGs, but also could potentially increase inequity. These issues arise mainly because of lack of universal access, for example, access to, raw materials, technology and finance among and within countries. At a more local level, equity issues arise as a result of unequal access to infrastructure (e.g. electric vehicle, public transport and urban green spaces). Reckien et al. (2016) identify three dimensions of equity associated with urban climate actions: (i) contextual, (ii) process oriented and (iii) outcome based. The studies identified in the paper do not explicitly address these. For example, there is very limited information on whether and to what extent stakeholders were consulted and the outcomes of such a process.

The direction of interactions (synergies or trade-offs) between mitigation options and SDGs greatly depends on how the measure is adopted locally and at what cost and scale, for example, in the case of afforestation and biofuels - the direction of interaction changes from synergies to trade-offs when applied at scale and there is strong rivalry about, for example, land resources (e.g. afforestation). A general conclusion we found for the AFOLU sector is that before implementing large-scale biomass production/afforestation, it is important to develop policies for regulating trade-offs and negative externalities.

Some mega trends such as digitalisation are already altering patterns of housing, work, travel, consumption and production and have a potential to reduce emissions and improve the wellbeing of humanity. However, digitalisation could also result in increased energy consumption and material consumption and create an unequal world with higher emissions and disadvantaged poorer countries and populations, which might be excluded from international markets due to limited digitalisation. Digitalisation needs to be used and promoted wisely including decisions around computing and institutions to manage data (Creutzig et al. 2022). However, digitalisation is a relatively recent development, and more studies are needed to fully understand its impacts on society.

Some measures are closely linked to others and can potentially provide much higher benefits if jointly implemented (e.g. electric vehicles, public transport and urban planning); however, the literature on combined effects is scarce, and capturing these synergies and avoiding/ minimising trade-offs can call for complex cross-sectoral implementation policies.

Conclusions

While literature on climate action and SDG interlinkages is growing rapidly, there are few robust studies which address implementation aspects and the role of trade-offs in relation to equity, costs, finance, infrastructure and technology access. While equity is a critical enabler of sustainable development, many interventions do not make any impact on improving the status quo and in some cases could lead to more adverse outcomes. We also find that even where synergies are shown, it is not necessary that these benefit the most disadvantaged groups. We, therefore, call for a careful interpretation of SDG synergies and more detailed studies of how trade-offs could show up and be coped with in practical policy implementation.

Results of this study contribute to the existing knowledge on the extent to which trade-offs between mitigation options and the SDGs could act as implementation challenges and based on this recognises that there is a need to go more into details than the currently available studies on how mitigation options potentially could be aligned with meeting the SDGs and to be more context specific on policy implementation rather than what can be addressed in large-scale global and regional modelling studies. Locally based studies could be important in designing implementation policies and removing barriers in terms of costs, finance and equity. Future research needs include more detailed and place-based cases and should also move further beyond assessments of implementation options to review of actual experiences with implementation of mitigation options and how synergies and trade-offs have emerged and been addressed. Results from such studies could better inform our understanding of how to modify local actions, how to capture synergies between mitigation options and SDGs and resolve/ minimise trade-offs.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests and/or conflict of interest/any other competing interests that could have appeared to influence the work of this paper.

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