CLEAN HELPDESK
Climate, Environment and Nature

Cost-effective climate change mitigation in low- and middle-income countries:

Rapid Umbrella Review

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COVER PHOTO:

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Acronyms

AFOLU	agriculture, forestry, and other land-use sector
ASI	avoid–shift–improve
BESS	Battery energy storage systems
BNEF	Bloomberg New Energy Finance
CCS	carbon capture and storage
CIF	Clean Investment Funds (administered by World Bank)
CO_2e	carbon dioxide equivalent
CNG	compressed natural gas
CSP	concentrated solar power
CTF	Clean Technology Fund
ESG	environmental, social and governance
ETS	emissions trading system
FCAS	fragile and conflict-affected states
FCDO	Foreign, Commonwealth & Development Office
FiT	feed-in tariff
GHG	greenhouse gas
G-PV-WT	grid-connected solar PV and wind turbine
GS	Google Scholar
HIC	high-income country
HRES	hybrid renewable energy system
ICE	internal combustion engine
IMO	International Maritime Organisation
IRENA	International Renewable Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LMIC	low- and middle-income country
LCA	life-cycle analysis
LCOE	levelised cost of electricity
NDBs	National Development Banks
NbS	nature-based solution
PBP	payback period
PV	photovoltaic
RE	renewable energy
REDD+	reducing emissions from deforestation and forest degradation
RUR	rapid umbrella review
UNFCCC	United Nations Framework Convention on Climate Change
VGS	vertical green system
WoS	Web of Science

Executive Summary

This rapid umbrella review (RUR) analyses evidence from scholarly and grey literature on the effectiveness and cost-effectiveness of interventions to mitigate greenhouse gas emissions applicable to low- and middle-income countries (LMICs). **It was prepared for the UK's Foreign, Commonwealth & Development Office (FCDO) to inform programming and priority-setting** of the UK's International Climate Finance (ICF) and to provide material for the development of an FCDO Best Buys paper.[1]

While noting that LMICs bear much lower responsibility for greenhouse gas (GHG) emissions on a historical or per-capita basis than HICs, many of the larger and wealthier emerging economies are already globally significant emitters by virtue of their size, and are likely to become more so. They clearly need to continue to pursue economic development and growth to reduce poverty and improve lives and livelihoods. We need to identify innovative and cleaner growth pathways, so that LMICs are able to leap-frog fossil-fuel based investment. A failure to act could lock in fossil fuel use for decades to come.

This RUR **analyses systematic reviews of ex post and ex ante research in six high-emitting sectors and three policy intervention themes.** The team identified evidence based on an agreed protocol, using four academic databases and, to a much lesser extent, AI search engines. The team identified over 1 600 titles, reviewed 377 abstracts and read and extracted information from 63 full papers, after assessing each one for quality. Data was gathered on regional coverage, policies implemented, effectiveness and cost-effectiveness of GHG mitigation and delivery of other sustainability goals. Comparisons were made of discounted financial savings and costs over time per tonne of carbon saved.

The table below shows the six high-emitting sectors and the three policy intervention themes that were used to assess the mitigation strategies discussed in the literature we reviewed.

Summary of climate mitigation measures reviewed:

	No regrets	Low-hanging fruit	High impact, but up-front capital	Key risks
SECTORAL MEASURES				
Agriculture	Changing diets to reduce meat and dairy			Appropriate measures hard to generalise because of micro-climates
Climate-smart urban development	Mandatory energy efficiency labels	Retrofits, net zero buildings	Densification of cities. Metro systems	

1 The 'Best Buys' documents are distillations of the knowledge generated by academic research into digestible summaries, categorising interventions by how cost-effective they are according to the evidence, and how strong that evidence is.

	No regrets	Low-hanging fruit	High impact, but up-front capital	Key risks
Industry	Energy-efficient blast furnaces, waste-derived fuel	Using fly ash in cement kilns	Segregating solid waste to ensure appropriate treatment	Markets for a green hydrogen-based industry are unproven
Natural Climate Solutions		High-income countries' businesses paying for carbon nature/ offsets (voluntary or compliance)	Protected areas, wetlands restoration	Monitoring required to ensure savings delivered
Renewable Energy	Solar and solar hybrid for distributed generation	Utility-scale solar and wind in many countries	Battery storage, transmission, distribution	
Transport	Real-time information for public transport passengers	Fuel switching from petrol, diesel, and marine to compressed natural gas (CNG), micro-mobility	Electrifying transport and charging infrastructure	Grid decarbonisation does not keep pace with transport electrification
POLICY MEASURES				
Carbon pricing	Introducing carbon pricing schemes that better reflect externalities	Reducing energy subsidies		No consensus on superiority of carbon tax vs emissions trading systems (ETSs)
Finance & Markets	Creating demand for green investment (via an understanding of greenium) to reduce the cost of finance	Feed-in tariffs	Loan guarantees	Need to ensure the finance instrument creates additionality
Just Transition		Integrating social considerations into environmental/ energy projects	Social protection policies and workforce development	

Many no-regrets opportunities were found to mitigate carbon at minimal cost. These typically rely on changing behaviour through information or education, using energy more efficiently, implementing fuel replacement measures, or introducing regulatory reforms. Examples include changing diets to reduce meat and dairy consumption; replacing end-of-life energy-inefficient capital equipment with more efficient alternatives (for example, replacing blast furnaces with electric arc furnaces); using refuse-derived fuels; mandating energy-efficiency labels on consumer electrical appliances; and providing bus passengers with real-time information about schedules to increase utilisation rates.

There is substantial low-hanging fruit across the economy. For example, substituting clinker with fly ash, a waste product, can reduce the greenhouse gas emissions of cement production by 30–80% and reduce the quantity of waste landfilled. Businesses in high-income countries can buy carbon offset certificates to meet voluntary or compliance emissions reductions targets generated by projects that sequester carbon and provide biodiversity co-benefits. These can work even in fragile and conflict-affected (FCAS) countries like Ethiopia and Democratic Republic of Congo, but attention needs to be paid to monitoring the delivered carbon capture to ensure that it aligns with claimed capture.

Some cost-effective GHG mitigation measures have higher upfront costs but provide valuable co-benefits. Segregated solid waste collection and treatment reduces methane emissions from landfill, enhances recovery of valuable secondary materials like scrap steel, plastic pellets, and compost, and reduces nuisance and litter. Fuel switching in vehicles away from petrol and marine diesel to compressed natural gas (CNG) and electricity requires upfront investment but provides very large health benefits from better air quality. Investment in solar and wind generation in low- and middle-income countries (LMICs) is cost-effective, accounting for 91% of all newly commissioned utility-scale renewable energy projects in 2024. These delivered electricity at a lower cost than the cheapest fossil fuel-fired alternative. But this transformation requires huge investment in transmission and distribution, and storage. In remote locations, on- and off-grid hybrid (mixed fossil and renewable energy) systems cost less than diesel generation over their lifetimes.

There are also many longer-term mitigation technologies that need upfront investment, but whose payback may extend over decades. This is especially true of urban development changes like densification of cities and the development of public transport nodes. It is also true of the creation of electrified mass-transport systems in big cities like metros. Other longer-term solutions include alternative renewable electricity systems like geothermal, solar thermal, and green hydrogen/ammonia-based shipping where the technologies are not yet common.

Two recent global meta-analyses of carbon pricing include estimates from ex post evaluations in China, although evidence from other LMICs is not available. The most comprehensive review, of 80 ex post evaluations of 21 carbon pricing schemes, found that at least 17 of these led to emissions reductions of between 5% and 21%.

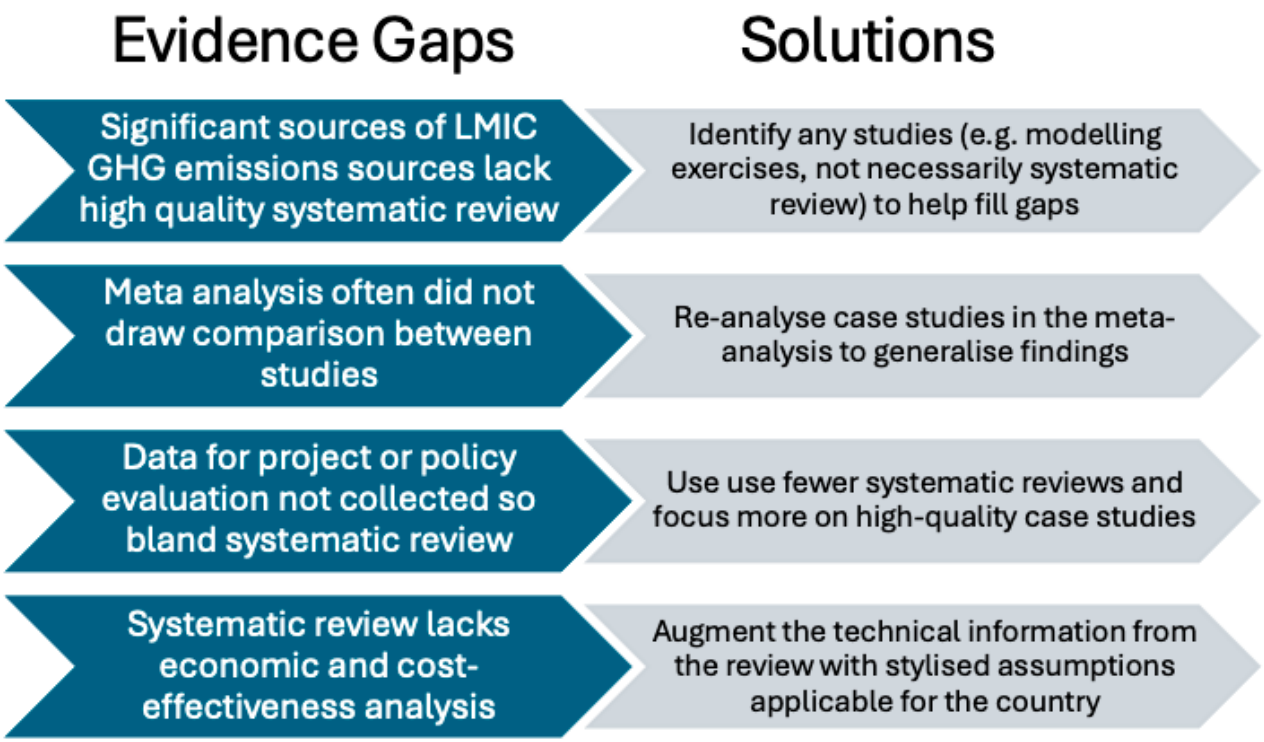
Evidence on the effectiveness of green finance (and associated public incentives to invest in environmentally sustainable projects) in stimulating private investment in mitigation is mixed. Instruments like feed-in tariffs, tax credits, loan guarantees, and National Development Banks have successfully mobilised private finance and increased the quantum of investment. Environmental, social and governance (ESG) disclosure and green bond certification have also increased private flows of green finance but have been less successful at lowering the cost.

The number of systematic reviews we could include was limited for several reasons:

- Many systematic reviews examine only a narrow range of measures, describing the mitigation of some emissions and leaving swathes of other measures in LMICs under-analysed.
- For some interventions, especially those designed to mitigate emissions from agriculture and other natural systems, context is all important: what works in one place may not work in another. Reviewers found it hard to disentangle the effect of technology/policy being assessed from its market/policy environment.
- Some reviews focus on the bibliographic properties of the literature (such as the country or the methodology used) rather than mitigation effectiveness.
- Data suitable for undertaking an ex post evaluation of the interventions was not collected. The lack of information on the counterfactual position sometimes hampered the systematic review.

The figure below shows the solutions we adopted where these issues occurred. These solutions can be adopted in future reviews.

Gaps in the evidence and solutions adopted:



Recommendations for further work

A different goal for the best value exercise might be to locate good quality and timely reviews of technologies effective for greenhouse gas mitigation and not to restrict the search to systematic reviews and ex post studies. A further step would then be needed after the literature review to assess cost-effectiveness, testing sensitivity to prices, grid-carbon intensity, and policy environment. Given the limitations of the evidence base, future research could focus on:

1. Undertaking a highly targeted search of major GHG sources that need transformation in LMICs.
2. Locating research (not necessarily systematic reviews and not necessarily by academics) that identifies a broad technical solution set. These transformations might include alternatives for, say, cement, low-carbon steel, the cooling of homes and offices, low-carbon long distance travel, and segregated solid waste collection and treatment.
3. Analysing the cost and GHG mitigation from deploying these solutions, using stylised assumptions about market prices and supportive policies for selected countries to model locally tailored advice.
4. Include modelled results, even if this analysis is ex ante. Some mitigation interventions cannot be evaluated ex post because they have rarely been trialled yet (for example, policies to reduce meat consumption). Some models have been produced by large teams of experienced scientists familiar with the most reliable evidence available. Their high-quality work should be included even though it is not ex ante.

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1 Purpose and objectives of the research

1.1 Introduction

Low- and middle-income countries (LMICs) are the predominant source of greenhouse gas (GHG) emissions, accounting for 67% of total CO_2 emissions (Ritchie, Rosado and Roser, 2024). While noting that LMICs bear much lower responsibility for GHG emissions on a historical or per-capita basis than HICs, many of the larger and wealthier emerging economies (such as China, India, Brazil and Indonesia) are now globally significant emitters by virtue of their size. It is inevitable that they will become more so, if continuing on their current trajectory.

Nevertheless, there is a clear and immediate need in these countries to continue economic development and growth to reduce poverty and improve lives and livelihoods. Measures to reduce energy-related GHG emissions – such as transitioning to renewable energy, introducing electrified public transport, ensuring energy-efficient industrial processes, and managing GHG from waste and agriculture – improve air quality, reduce urban congestion and production costs, and hence enhance competitiveness. Their adoption means identifying new, innovative, and cleaner growth pathways that will allow LMICs to bypass fossil-fuel-based investment. Cost-effective investment in mitigation technologies allows LMIC development to leap-frog fossil fuel-based power systems and industrialisation. Given the long lifetimes of power and transport infrastructure, it is imperative to switch investment to low-carbon technologies to avoid lock-in to fossil-fuel based technologies. Factoring environmental issues into land use change reduces GHG emissions from soils and biomass, and provides biodiversity gains and rural employment.

A rapid umbrella review (RUR) is an accelerated 'review of reviews', typically undertaken over a few months, that synthesises findings from numerous systematic reviews and meta-analyses on a broad topic. This RUR analyses the scholarly and grey evidence on the effectiveness and cost-effectiveness of interventions that promise to deliver GHG reductions and achieve other goals – poverty alleviation, health, climate resilience, and enhanced equality (detailed in Box 1) – applicable to and drawn from low- and middle-income countries (LMICs). Our review was prepared to inform the production of a Best Buy paper about interventions to reduce GHGs. Best Buy papers are easily digestible summaries of recent rigorous evidence on the effectiveness and cost-effectiveness of interventions. They provide UK officials with evidence on interventions

to help them understand which interventions are most likely to offer value for money and the strength of evidence supporting them.

Box 1: Scope and objectives of this report

Core research question:

- What evidence is there on the effectiveness and cost-effectiveness of interventions in delivering greenhouse gas emissions reductions in low- and middle-income countries, including medium- and long-term emissions reductions, through changing social preferences or production costs?

Supplementary research questions:

- Do these interventions also deliver wider development outcomes especially improved (i) income and consumption levels, (ii) health outcomes, (iii) adaptive capacity and climate resilience, (iv) other environmental impacts?
- Do these interventions impact groups or types of individuals in society differentially especially (i) those living in absolute and/or relative poverty, (ii) women and girls, (iii) other categories of individuals or social groups that are more likely to be marginalised, such as people with disabilities?
- Does the literature discuss differences between regions or nations at different stages of development, including fragile and conflict-affected states (FCAS)?

1.2 Segmentation of the literature

The literature has been categorised into nine themes and sub-divisions (set out in Table 1) developed through discussion between the researchers and officials. Six of the themes are economic sectors that cover major sources of emissions and offer removal opportunities: renewable energy, climate-smart development, natural climate solutions, agriculture, transportation and industry. There is a degree of overlap between some themes (e.g. agriculture and natural climate solutions) and the team used judgment to reallocate material between themes, ensuring that valuable literature was appropriately categorised and not omitted. Three of the themes are policy interventions that facilitate economy-wide decarbonisation: just transition, carbon pricing and climate finance and markets.

Table 1: Nine themes for analysing intervention effectiveness

	Theme*	Sub-divisions**
1	Agriculture	Crop management; Pasture management; Restoring degraded land; Livestock feeding; Rest of food system
2	Climates-smart urban development	Construction and building materials; Sustainable buildings; Green infrastructure; Solid waste; Cities/ Urban scale; Public policies
3	Industry	Iron and steel; Cement and construction; Circular economy; Chemicals; Pulp and paper; Oil, Gas & Energy; Other; Glass; Ceramics; Industrial Policies
4	Natural climate solutions	Financing; Ecosystem restoration, conservation and protection; Policy tools; Prevention of deforestation; Reforestation; Carbon markets (for offsets)
5	Renewable energy	Access; Technology improvements; Feed-in tariffs; Storage solutions; Policy tools; Cost competitiveness
6	Transportation	Fuel; Freight; Passenger; Aviation; Maritime; Demand reduction; Urban planning
7	Just transition	Job creation; Skills development; Alternative employment; Just transition
8	Carbon pricing reforms	Carbon tax; Emissions trading system (ETS)
9	Finance and markets	Cost of capital; Quantity of capital; Standards and environmental, social and governance (ESG) performance; Novel instruments; Financial institutions

Source: *RUR methodology and **authors

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2 Methodology

This section summarises the methodology used in this review. A more detailed description is given in a separate research protocol developed by the research team in conjunction with FCDO.[2]

The approach followed the steps of a rapid umbrella review (RUR), adapting systematic review principles to streamline search, screening and synthesis processes. We sought ex post research into carbon mitigation opportunities useful to the UK government's climate and environmental advisers working on LMIC programmes.

We included systematic reviews and excluded individual case studies. We preferred ex post evidence because it provides more real-world and practical insight into emissions savings and costs compared to modelled or ex ante studies. We also preferred reviews from low- and middle-income countries (LMIC).

2.1 Stages of analysis

The key steps taken were:

- conducting a search to produce a longlist of titles from academic databases, using AI to assist with a grey literature review;
- screening titles using exclusion criteria for out-of-scope research;
- shortlisting articles based on abstracts to identify useful research;
- coding extracted data from shortlisted articles, and appraising quality;
- analysing and synthesising.

Each of these steps is discussed below.

2 Internal document *Introduction to Best Buys v5.docx*

1. Searches

The search built up a comprehensive longlist of literature under the nine themes.

This search followed the population–intervention–outcome–study (PIOS) framework, where the *population* was LMIC case studies, *interventions* were technical solutions or policy measures, *outcomes* were the effectiveness and cost-effectiveness of the GHG mitigation efforts, and the *studies were* peer-reviewed journal articles targeting systematic reviews of ex post studies and grey literature from multilateral organisations.

We targeted reviews with information on the effectiveness and cost-effectiveness of GHG mitigation. In Section 3.2 we explain when and how our analysed systematic reviews deviated from the ex post, LMIC, cost-effectiveness ideal.

The Annexures contain information on the in-scope grey literature, the search terms used for the academic databases, and the prompts used for the AI search.

We undertook searches using three academic databases: Google Scholar (GS), Scopus, and Web of Science (WoS), in accordance with the protocol agreed with the Client. The search engines differ in the way search terms are used. Scopus and WoS only run queries in the Title, Keywords and Abstract fields. Generally fewer than a hundred articles are identified by a typical search. GS queries sift through the entire text of the article, resulting in many thousands of qualifying articles. For some sectors, we supplemented these by using the EBSCO database and the software package 'Publish or Perish' that retrieves and manages Google Scholar output, and by conducting separate targeted searches through specific journals identified as highly relevant for a given sector. The standard search string applied was:

('Systematic review' OR 'meta-analysis') AND ('GHG emissions' OR 'decarbon') AND ('abatement cost' OR 'MAC' OR 'economic analysis') AND ('global south' OR 'low income' OR 'middle income') AND ('theme search term')

Table 2 below shows the theme-specific terms used to supplement the standard shared search terms. Sector-specific deviations from the main search strategy are outlined in Annex 4.
The initial GS searches typically generated more than 15,000 hits; the first 50–100 titles were screened and the relevant ones were retained. The differences among the academic database search engines are discussed later.

Table 2: Specific search terms by intervention theme from the protocol

Intervention theme	Theme search terms
Agriculture	Agriculture, conservation agriculture, climate-smart agriculture, agricultural productivity
Climate-smart Urban Development	Buildings, housing, construction, waste, management
Industry	Industrial decarbonisation, circular economy, resource efficiency, hydrogen, critical minerals

Intervention theme	Theme search terms
Natural Climate Solutions	Natural climate solutions, forestry, ecosystem, land-use, nature-based solutions, ecosystem restoration, conservation, forest conservation, afforestation, reforestation, carbon farming
Renewable Energy	Renewable energy, energy access, energy price, market reform, clean energy, solar, geothermal, biomass
Transportation	Transportation, freight, passenger
Just Transition	Just transition, justice, distribution
Carbon pricing	Carbon pricing, carbon tax, emissions trading
Finance and Markets	Climate finance, public financial management, blended finance, international carbon markets, leverage, mobilisation, blue bonds, green bonds, green finance, nature finance, ocean finance

Adjustments to Google Scholar

Because GS searches the entire text of the article, and not just the article's title, abstract and keywords fields, it generated many thousands of hits, far more than the other academic databases. Articles that appeared at the top of a GS search were only marginally more likely to be relevant than articles that appeared much lower down. The GS algorithm seemingly gave many irrelevant articles a high weight.

We sought to target GS, trying two adjustments: first, using the advanced search facilities to search for specific terms in the title of the article (like 'GHG mitigation' or 'Review') or to constrain the search to specific journals that we knew focused on climate mitigation. This dramatically reduced the number of articles found by the GS search, reducing the number of false positives. However, it did not identify many new articles that we had not already found. The 'Publish or Perish' package proved an easy way of accessing GS's more advanced search facilities. It allows the user to query just the title field or select a particular named publication. This helped to vastly reduce the number of articles reported by GS.

The use of AI and grey literature

Three generative artificial intelligence (AI) search engines were used to identify suitable reviews from the grey literature: Claude, Gemini Deep Research, and Perplexity. We did not use the Large Language Models (LLMs) to summarise or extract information (which would have made the analysis vulnerable to hallucination) but to simply identify suitable literature, i.e., to produce a longlist of formatted articles that conformed to the prompt. We wrote tailored prompts for use in the AI instruments to rapidly scan and identify grey literature. The prompts included definitions of the type of study to include (i.e., ex post, meta-analyses, systematic reviews), geographies (developing countries, low- and middle-income countries), timeframe (since 2015), and a description of each intervention theme. We asked the AI to generate result tables detailing the citations and summarising the studies' results, geographies and DOIs or URLs, to minimise hallucinations. An example of a prompt is provided in Annex 2. For quality assurance, each generated source was checked with a manual search.

The AI searches generally yielded few results (just nine of the total 63). Upon manually reviewing the output of each, we found that Gemini Deep Research was more prone to hallucinating articles that did not appear to exist from our internet searches. As a result, our focus switched to Perplexity and Claude to trawl the grey literature, which provided links to the quoted articles. In general, a high proportion of the reports they identified were relevant.

2. Screening

In our screening stage we combined the outputs from the different search terms and engines into one list, removed duplicates selected by multiple engines or search terms, and then screened out titles not relevant to our project.

There was little overlap in the articles selected by the different databases, even when the same search terms were used. Articles that the search ranked highly in terms of relevance were only marginally more likely to be relevant than those deemed low rank. The use of Boolean operators (AND/OR) and quotation marks ('…') to pick phrases helped refine searches but did not result in a seismic improvement in the targeting of the search.

The screening of titles (and abstracts) involved reading them to eliminate unsuitable articles. Common reasons for excluding studies included if they:

- used common words such as 'transport' in a different sense to what we wanted;
- did not appear to discuss GHG mitigation;
- produced results about the bibliography's characteristics rather than the results of the reviews;
- concerned a single project rather than a systematic review of studies;
- were clearly ex ante or modelled; or
- were unrelated to LMIC countries.

The long- and shortlists of titles and abstracts were independently reviewed by a team member to test if uniform inclusion/exclusion judgements were made across themes.

3. Shortlisting

The titles of the articles often provided too little information about whether or not they should be included in our database. In many cases, the only way to tell if a review met our inclusion criteria was to read the abstract or skim the paper. Some that did not meet the inclusion criteria were included in this report and the accompanying Excel spreadsheet if we felt they offered useful insights.

Although we sought to identify reviews about the *cost-effectiveness of greenhouse gas mitigation interventions,* we found such reviews were rare. Many interesting studies did not discuss the economic/financial aspects of GHG mitigation, focusing only on various measures' effectiveness. We believe there could be two reasons for this: either the underlying literature's focus was on effectiveness rather than cost-effectiveness, or the authors of the systematic reviews found there were too many confounding differences between individual economic analyses in matters such as the price of fossil fuel, the cost of capital, carbon taxes and policy environments, making the underlying economic differences impossible to disentangle.

Although we tried to avoid reviews with large proportions of HIC case studies, we did include some, as so much of the underlying literature was focused on Europe and North America.

4. Extraction and Quality Assessment

The shortlisted reviews were read to extract the information they contained using the data extraction tool developed in Phase 1 of the research. The variables are shown in Table 3. Up to 70 fields of data were sought.

Table 3: Brief description of variables in the coding spreadsheet

Variables	Coverage
Review study background	Title, Author, Type of review, Method
Intervention	Description, Geographic focus, World Bank region
Effectiveness and cost-effectiveness of reducing emissions	Author's judgement of GHG effectiveness, Evidence cited, Quantification, Basis of calculation
Impact on income levels	Positive or negative income impact, Evidence, Scale, Distributional effect
Impact on consumption levels	Positive or negative income impact, Evidence, Scale, Distributional effect
Impact on health outcomes	Positive or negative income impact, Evidence, Scale, Distributional effect
Impact on adaptive capacity, adaptation and climate resilience	Positive or negative income impact, Evidence, Scale, Distributional effect
Impact on other environmental and social objectives	Positive or negative income impact, Evidence, Scale, Distributional effect
Barriers and enablers	Governance or institutional enablers/barriers

We also used the Quality Assessment tool developed in Phase 1 of the project to evaluate the cogency and transparency of the reviews. The tool was designed and signed off by FCDO before the RUR commenced. It was designed to align with the methodology used for the companion adaptation RUR to enhance methodological consistency across these two papers. 'Cogency' was assessed by examining each systematic review's theoretical underpinning: Was a theory being tested, and was a theory of change set out? Was there an assessment of gaps in the literature, and hence a set of research questions? 'Transparency' was evaluated by determining how case studies were selected and whether information was systematically extracted in terms of population, interventions, setting and outcomes. Finally, 'credibility' was assessed by asking, 'How transferable are the findings? Were findings from case studies well integrated?' Annex 5 sets out the questions we asked for assessing quality in more detail.

5. Analysis and Synthesis

Key findings from the papers were pasted into the spreadsheet, with a focus on any overviews or generalised findings from the case studies and reasons for differences between case study results or rationales.

Generally, around ten systematic reviews were read for each theme. These occasionally overlapped with one another but were more typically about different measures. For each systematic review, we sought first to understand the measure or policy being reviewed, the number and geographic spread of the papers included in the systematic review, and why certain papers were excluded.

The following questions were asked about each review:

- What was the geographic spread of the papers reviewed? Were there any salient methodological differences; for example, some ex ante, some ex post? Were there any substantial differences between the scale of projects; for example, one might be a neighbourhood, another at national level.
- How much consensus was there between the papers?
- What were the reasons for differences between papers' findings (local environment, market conditions, unexplained)?
- What was the range of carbon mitigation effectiveness?
- Was there information on the cost-effectiveness of carbon mitigation?
- Did the authors report any findings on other social and environmental benefits?
- Were any interesting figures or quotes also recorded?

Results are written up in Chapter 4 of this report, which sought to

- make general observations about the literature: its strengths, weaknesses and gaps;
- report on the effectiveness of interventions;
- assess the cost-effectiveness of interventions; and
- summarise the findings about other relevant social and environmental issues raised in the studies.

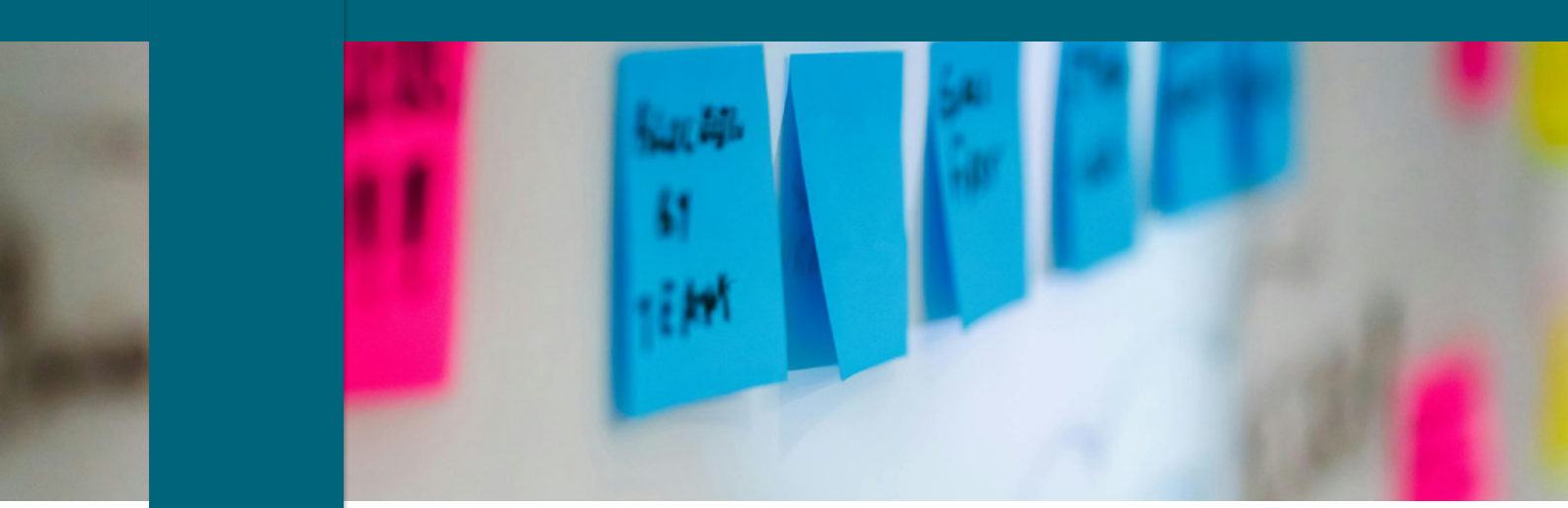


Photo credit: Jakub Zerdzicki via Pexels

3 Landscape of the material reviewed

3.1 Materials reviewed

Altogether, 377 abstracts were read (from a list of 1637 titles). Roughly a quarter of these appeared to meet the criteria for inclusion in our review. Figure 1 shows the three main stages of selection and provides an overview of how the titles from the initial identification by search engine, AI and grey literature website were selected.

Figure 1: Flow chart of stages in review

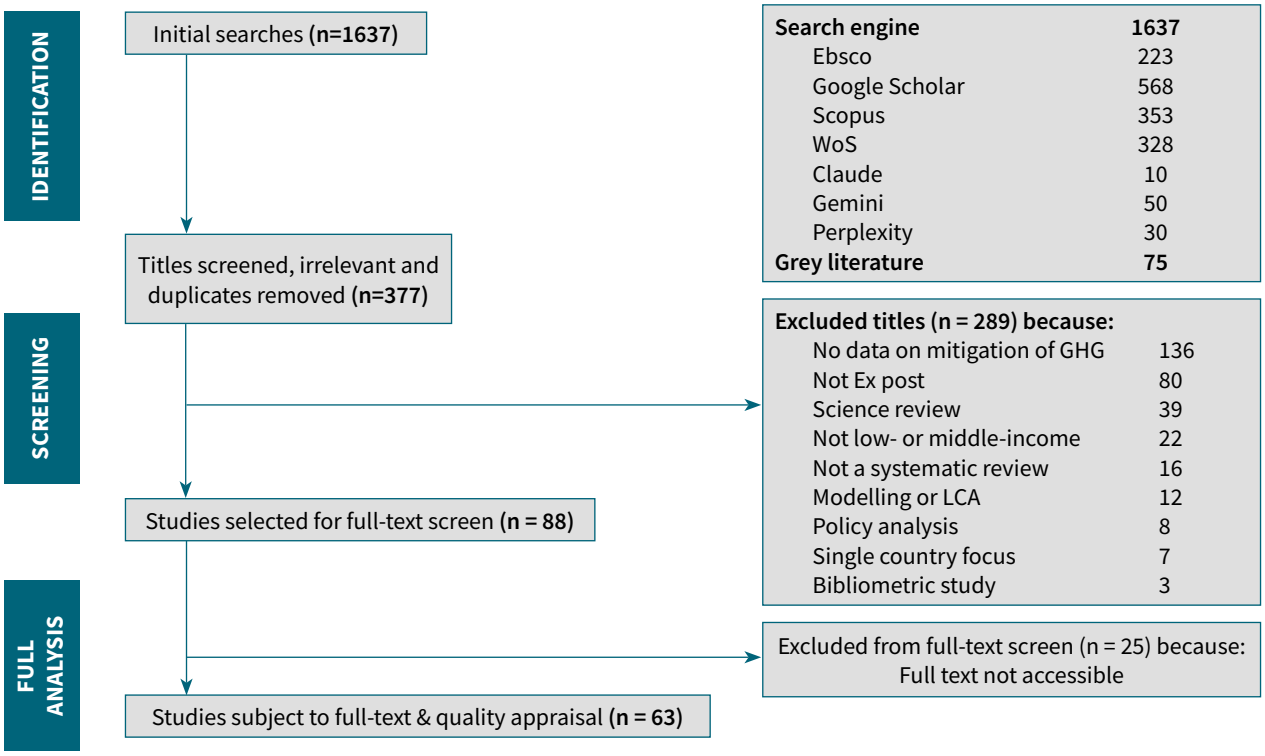


Table 4 tabulates the effectiveness of the different search engines in terms of generating articles for inclusion in our longlist, abstracts that appeared useful, and articles subject to full reviews.

The AI search engines produced shortlists of highly relevant articles, while the academic databases produced longlists, many of which, from the title alone, were clearly irrelevant. The grey literature was identified either by searching the relevant institutional website (e.g. World Bank) or by using the AI tool.

Table 4: Effectiveness of search engines at yielding useful titles

Type	Search engine	Longlist	Abstracts	Full reviews
Academic	EBSCO	223	66	5
	Google Scholar	568	133	24
	Scopus	353	39	4
	Web of Science	328	41	8
AI	Claude	11	11	1
	Gemini Deep Research	50	10	4
	Perplexity	30	15	4
Grey	Grey literature	75	62	13
	Total	**1638**	**377**	**63**

Because Google Scholar's full-text scan for search terms generated so many false positives, only the first 50 or 100 titles and abstracts were evaluated out of the thousands identified. Publish or Perish was also used to target the Google Scholar search, focusing on specific journals or searching just the academic article's title. Prompts were used to focus the AI instruments on the grey literature, but they also uncovered several academic articles. Gemini Deep Research hallucinated many non-existent reports.

Table 5: Numbers of abstracts and full articles read by theme

Theme	Longlist	Abstracts	Full reviews
Agriculture	384	68	8
Climate-Smart Urban Development	266	29	10
Industry	136	24	8
Natural Climate Solutions	99	70	5
Renewable Energy	44	42	7
Transport	234	33	9
Carbon Pricing	296	53	9
Finance & Markets	115	47	4
Just Transition	64	11	4
Total	**1638**	**377**	**63**

We looked at the sub-themes covered by the systematic reviews, as judged from the 377 abstracts that we reviewed. (See Table 1 for a list of the sub-themes.) Table 6 shows the numbers of systematic reviews that covered each sub-theme. The total is greater than 377, as a review could be included in multiple sub-themes. As may be seen, we could not find a suitable abstract for every sub-theme listed in Table 1.

Table 6: Count of systematic reviews by sub-themes of themes from the abstracts reviewed

Agriculture	Rest of food system	Crop management	Pasture management	Restoring degraded land	Livestock feeding		
	14	33	16	3	2		
Climate-smart urban development	Construction and building materials	Sustainable buildings	Green Infrastructure	Solid waste	Cities/Urban Scale	Public policies	
	3	15	1	4	3	0	
Industry	Iron and steel	Cement and construction	Circular economy	Chemical	Pulp and paper	Oil, Gas, Energy Other	Glass, Ceramics
	4	12	1	1	2	4	2
Natural Climate Solutions	Ecosystem restoration, conservation, protection	Policy tools	Carbon markets	Carbon pricing	Prevent deforestation	Reforestation	
	2	6	7	2	4	3	
Renewable Energy	Access	Technology improvements	Feed-in tariffs	Cost competitiveness	Storage solutions	Policy tools	
	7	8	0	13	7	9	
Transport	Fuel	Freight	Passenger	Aviation	Maritime	Demand reduction	Urban planning
	11	15	17	4	10	9	13
Carbon Price	Carbon price						
	14						
Finance & Markets	Cost of capital	Quantity of capital	Standards and ESG performance	Novel instruments	Financial institutions		
	6	4	4	4	1		
Just Transition	Just transition						
	12						

3.2 Systematic reviews of case studies undertaken ex post and ex ante

We sought to identify systematic reviews of initiatives undertaken after their completion (ex post) based on measured outcomes, rather than analyses based on anticipated or modelled costs and benefits (ex ante) to avoid any project promoter bias and to capture unanticipated real-life risks.

Among the 63 articles from which data was extracted, 33 were ex post studies, 16 were ex ante and the remainder were mixed or did not specify (see Table 7). The ex ante studies that included several innovative topics – such as smart grids or green bonds – were not well-suited to ex post analysis. It was disappointing to find so few systematic analyses of ex post studies, which possibly reflects the absence of randomised control trials in climate technologies and policy work.

Table 7: Number of studies undertaken ex post

Theme	Mixed	N	U	Y	Grand Total
Agriculture		3	4	1	**8**
Climate-smart Urban Development		1	4	4	**9**
Industry		1	1	6	**8**
Natural Climate Solutions		3	1	1	**5**
Renewable Energy		2		5	**7**
Transport	1	3		5	**9**
Carbon pricing		2	1	6	**9**
Finance & Markets		1	2	1	**4**
Just Transition				4	**4**
Total	1	16	13	33	**63**

N – No; Y – Yes; U – Unknown; Mixed – both ex post and ex ante

LMIC and region

We sought to identify reviews of LMIC case studies. We did not find any scholarly papers that *exclusively* used LMIC case studies, so drew on those that included LMIC and HIC countries. We also accepted studies with mainly or only HIC case studies where we felt they had validity in LMIC contexts. This was particularly true of interventions like energy efficiency in industries such as steel, where the palette of technologies is similar worldwide (although costs may vary).

This dominance of case studies drawn from HICs, was, in part, a result of the fact that we reviewed only English language systematic reviews, which were themselves based on underlying papers in English and European languages. Hence, our work excludes any case studies in Chinese and other Asian countries that publish in their own languages. More broadly,

researchers from LMIC countries are less likely to publish open access academic papers owing to financial constraints, including author payments, or universities' inability to pay journal access charges. Development banks and UN agencies often explicitly target LMIC countries, but this grey literature typically consists of policy advocacy reports that may include modelled benefits and brief case studies for illustrative purposes.

It is interesting to note that the authors of systematic reviews seldom treated LMIC status as an explanatory variable, if they included non-HIC case studies at all. We believe this reflects the paucity of case studies meeting their inclusion criteria.

Of the 63 studies, the case studies' region was unclear in 25 examples. In 27 cases, the authors sought global examples. Of the studies that named LMIC case studies, the best represented region was East Asia (usually China). In the global studies, MENA, Sub-Saharan Africa and LatAm were less well represented.

Table 8: Regions from which case studies were drawn

Region	Count*
East Asia and Pacific	5
Europe and Central Asia	4
Latin America and the Caribbean	3
Middle East and North Africa	1
South Asia	4
Sub-Saharan Africa	3
Global	27
Unclear	25

**Count can exceed 63 as some studies cover multiple regions*

Cost-effectiveness of interventions

As set out in the inclusion criteria, we sought reviews that included some consideration of cost-effectiveness. Of the 63 review studies examined, 22 included studies that considered the cost-effectiveness of technologies or interventions. These were typically normalised with respect to units of output like per kWh-electricity or per passenger-km. The cost-effectiveness was calculated from the local GHG emissions factor for grid electricity or the internal combustion engine (ICE) vehicle.

No systematic review sought to control and interpret the impacts of economic and policy differences (e.g., cost of capital, feed-in-tariffs) among case studies.

Table 9: Systematic review studies that included case studies with cost-effectiveness

Cost-effectiveness	No	Unknown	Yes	Total
Agriculture			8	**8**
Climate-smart Urban Development (for consistency)	5	2	2	**9**
Industry	1		3	**4**
Natural Climate Solutions	6		2	**8**
Renewable Energy	4			**4**
Transport	7		2	**9**
Carbon pricing	5			**5**
Finance & Markets	3		4	**7**
Just Transition	8		1	**9**
Total	39	2	22	**63**

Sub-themes

A count of the systematic reviews by sub-theme that met our inclusion criteria and that were subjected to full data extraction is given in Table 10. The total is greater than 63, as a review could be included in multiple sub-themes.

For some sub-themes, we found no systematic review articles that met our inclusion criteria. Omissions included construction materials used (under climate-smart development), the pulp and paper sectors (under industry) and feed-in tariffs (under renewable energy). All of these might be considered important carbon mitigation interventions.

Table 10: Count of systematic reviews by sub-theme from the articles extracted

Agriculture	Rest of food system	Crop management	Pasture management	Restoring degraded land	Livestock feeding	GHG gases	Crop or animal
	3	5	1	1	2	0	0
Climate-smart Urban Development (for consistency)	Construction and building materials	Sustainable buildings	Green Infrastructure	Solid waste	Cities/ Urban Scale	Public policies	
	2	4	0	1	1	0	
Industry	Iron and steel	Cement and construction	Circular economy	Chemicals	Pulp and paper	Oil, Gas, Energy Other	Glass, Ceramics
	2	3	0	0	2	3	1
Natural Climate Solutions	Financing NCS	Ecosystem restoration, conservation, protection	Policy tools	Carbon markets	Carbon pricing	Prevent deforestation	Reforestation
	1	1	2	1	0	2	1
Renewable Energy	Access	Technology improvements	Feed-in tariffs	Cost competitiveness	Storage solutions	Policy tools	
	1	2	0	3	1	3	
Transport	Fuel	Freight	Passenger	Aviation	Maritime	Demand reduction	Urban Planning
	2	5	7	2	2	3	5
Carbon Pricing	Carbon price						
	9						
Finance & Markets	Cost of capital	Quantity of capital	Standards and ESG performance	Novel instruments	Financial institutions		
	3	2	0	3	0		
Just Transition	Just transition						
	4						

Photo credit: Nuno Marques on Unsplash

4 Key findings

4.1 Agriculture

Sectors	Mitigation Strategies	Most Effective / Cost effective
Arable farming & livestock rearing	Discourage deforestation	Payments for ecosystem services, research into sustainable farm systems, access to capital for smallholders. These (and other measures) need considerable tailoring to context. Co-benefits: conserve biodiversity, enable global ecosystem functioning
Food supply chains: pre- and post-agriculture	Manure & fertiliser management. Agroforestry. Reduce methane emissions from flooded rice fields and ruminant livestock	Research into sustainable farming systems. Reduce demand for ruminant livestock products
	Change diets among well-off consumers to diets with fewer livestock products. Reduce food loss and waste	Nudge diet choice: education, regulation, taxes and subsidies. Co-benefits: improved health, less demand for agricultural land

This section discusses mitigation options in the agriculture and food supply chains. Land use change from agriculture to forestry is discussed under 'Natural climate solutions'.

Eight articles were reviewed in detail, of 66 initially identified as relevant to mitigating agricultural emissions. Those discarded did not meet the expectations raised in the abstract/ article, chiefly because they failed to include studies evaluating the economic impact of the intervention. Articles in the longlist were mostly scientific and technical papers, including articles on the physical science of mitigation and the potential effectiveness of various methods,

which are precursors to an economic analysis. Most studies identified as useful were carried out by international teams of natural scientists and published in high-ranking journals such as *Nature.* We gleaned useful information from reviewing these articles, as reflected in the analysis below. Authors also said their findings could not be generalised outside the specific place and time they were conducted.

The coverage of sub-topics was uneven – articles about reducing methane emissions from rice paddies and livestock were common, as were articles about the prospects of capturing more carbon in soils. There were major gaps in the systematic studies, which excluded information on interactions between livestock (methane emissions) and soil ecology (carbon sinks), dietary changes, food systems, and food waste emissions.

From the reviewed articles, it became clear that emissions from agriculture and food systems vary, both by source and greenhouse gas. Some 45% of agriculture and food system emissions come from farming and herding; another 21% comes from land use change, and the remaining 34% comes from other parts of the food supply chain. (See Sutton et al., 2024 for a comprehensive review of existing knowledge about emissions from agriculture and the food chain, from World Bank analysis based on data from FAOSTAT, 2023.) The single largest source of emissions is from the (net) conversion of forests to agriculture (18.4%), followed by enteric fermentation by ruminant livestock (17.6%) (ibid).

Perspectives on agricultural emissions are changing. It has long been thought that agriculture, with associated land use changes – especially clearance of forest for fields and pastures – contributes around one fifth of all GHG emissions (Sutton et al., 2024 citing IPCC estimates from 2022). This turns out to be understatement: it is more likely that agriculture and food systems emit some 31% of GHG emissions (Crippa et al., 2021; Tubiello et al., 2022).

Effectiveness

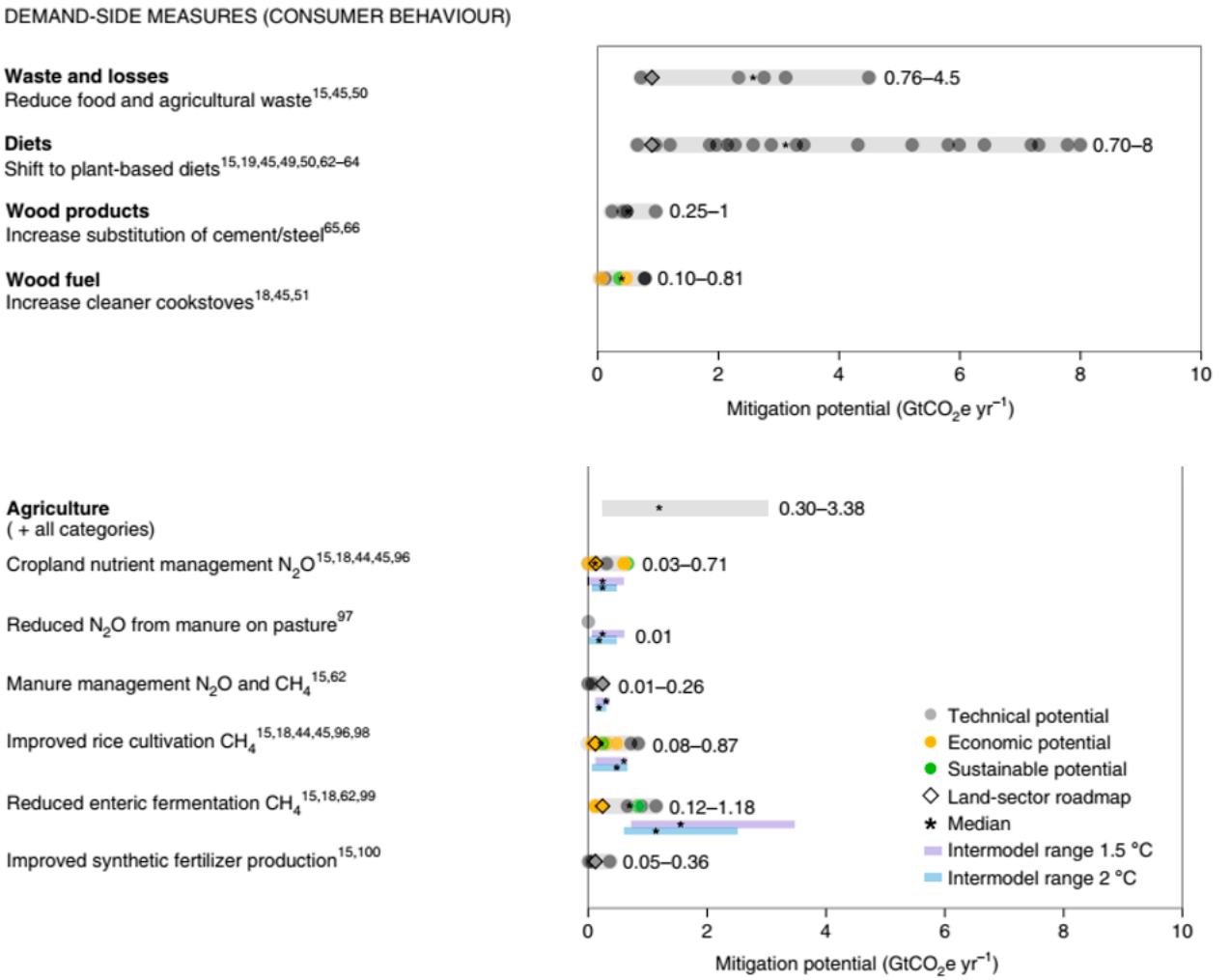
Agriculture and food production involve various processes that cause emissions; at least 17 sources of emissions can be identified (Sutton et al., 2024). Correspondingly, numerous measures can mitigate these emissions. Direct or supply-side measures consist of reducing emissions from fields and herds, largely through cutting methane emissions from ruminant livestock and flooded rice fields; and capturing carbon in soils and biomass through agroforestry, biochar application, etc. (See Figure 2 from Roe et al., 2019, a major scientific review of GHG emissions from agriculture and land). Indirect or demand-side measures to reduce emissions include altering diets and reducing food waste and loss.

Three things stand out from Roe et al.'s (2019) analysis. First, some measures clearly have far more potential than others. On the demand side, these are altering diets and reducing food loss and waste; on the supply side, these are reducing deforestation, afforestation and agroforestry, capturing carbon in soils and plants, and creating bioenergy with carbon capture and storage. These measures dwarf others in their potential to curb net emissions.

Second, the economic mitigation potential of some measures (where benefits exceed costs) can be a small fraction of the technical potential mitigation.

Third, the technical potential for mitigation in agriculture and food varies considerably, perhaps alarmingly: for many measures, the estimated potential varies by more than an order of magnitude (Figure 2).[3] Such extraordinarily wide ranges of potential effectiveness stem from the variations in the operations of natural systems owing to local circumstances of geology and soil, terrain, climate, vegetation, and incidence of insects, bacteria and viruses (pests and diseases). Mitigation measures interact with all these elements. A synthesis of economic analyses across studies is difficult because the effectiveness of a given intervention depends in large measure on the local context.

Figure 2: Mitigation measures for agriculture and food systems



Source: (Roe et al., 2019), after excluding supply side measures – mostly changes in land use, which are discussed under 'Natural climate solutions'.
Notes: Mitigation potentials reflect the full range of low to high estimates from studies published after 2010, differentiated according to technical (possible with current technologies), economic (possible given economic constraints) and sustainable potential (technical or economic potential constrained by sustainability considerations). Medians are calculated across all potentials in categories with >4 data points. Supply-side and demand-side measures are treated separately, as these two categories are not additive.

3 This finding is common in the scientific literature concerning individual measures. Most authors qualify their findings by assigning wide margins of confidence to any estimate of technical potential, let alone economic potential.

What works well in one place may not work as well in another. For example, while it is established that flooded rice fields emit methane, the precise amount depends on several factors. The following extracts make this clear:

> *'The effect of alternate wetting and drying (AWD) on CH_4 (methane) emissions was significantly modified by soil drying level, the number of drying events, mean annual precipitation (MAP), soil organic carbon content (SOC), growth cycle, and nitrogen fertilizer (N) application. Regarding N_2O emissions, mean annual temperature, elevation, soil texture, and soil pH had significant impacts on the AWD effect'*
>
> *(Zhao et al., 2024).*

> *'… emissions [from flooded rice fields] vary markedly, primarily reflecting the impact of management practices. Organic matter additions and continuous flooding of paddies both stimulate CH_4 emissions, whereas fertilizer N application rate is the most important driver of N_2O emissions.'*
>
> *(Qian et al., 2023).*

Fundamental queries can arise with regard to the science behind emissions calculations, such as the volume of methane emissions from ruminant livestock through enteric fermentation. The high reported methane emissions from ruminants are usually measured in controlled conditions. But this ignores the effects of grazing ruminants on rangeland, where short-term methane emissions from the livestock may be offset by long-term carbon captured in grazed soils and plants. Assouma et al. (2019) documented studies that measure the GHG emissions and carbon accumulation in rangelands grazed by Senegal pastoralists over a year; this is a rare example of a synthesis of studies measuring net GHG fluxes *in the ecosystem, not the lab.* These studies found that cattle in pastoral systems on rangelands caused close to net zero GHG emissions, once interactions between livestock and the ecology were accounted for. Scoones (2023) reviews the controversy over emissions from ruminant livestock, questioning the assumption that all ruminants, regardless of the system in which they are raised, are major net emitters of GHG.

One might add that many measures to mitigate agricultural emissions are imprecise, since the skill of farmers in adopting these measures in their land practices makes a great difference. Nowhere are these factors more marked than in capturing carbon in soil and biomass. (Box 2).

Box 2: Capturing carbon in agriculture

Agriculture and forestry, unlike most other sectors, can be net negative carbon emitters by capturing carbon in soils and biomass through afforestation, reforestation, agroforestry, and the restoration of peatlands. The prospect is tantalising; enormous quantities of carbon might be captured, given that soils already store around seven times the volume of carbon that circulates in the atmosphere. Therefore, a small percentage increase in carbon stored in soils could disproportionately reduce atmospheric carbon. However, the prospect is subject to considerable qualifications. The range of estimates of potential mitigation run from 1.1 to 22.7 $GtCO_2e$ (Roe et al., 2019, Figure 4.2)

There are also uncertainties about how much carbon could be captured by different measures in local circumstances; whether the rate of capture can be retained or will decline over time; and the potential for altered land use and management to emit captured carbon. A large body of literature exists on these qualifications, much of it cautioning against naïve optimism over the volume of carbon that might be captured.

Sources: Bieluczuk et al., 2024, Dignac et al., 2017, Don et al., 2024, Frank et al., 2024, Fuss et al., 2018, Kirchbaum et al., 2024, Moinet et al., 2024, Nolan et al., 2021, Obermeier et al., 2024, Qhasa et al., 2024, Tan and Kuebbing 2023, Wang et al., 2023.

Cost-effectiveness

With effectiveness and cost both subject to much variation, high margins of uncertainty apply to the cost-effectiveness of mitigation of emissions from agriculture and food systems. Take, for example, agroforestry: in some cropping systems, the trees detract little from or even add to crop yields, but in other systems, trees and crops compete. Labour costs of agroforestry vary depending on local (shadow) wages. Measures requiring much labour can be cost-effective in the Sahel, but unthinkably costly in rural economies with higher wages, such as Thailand. Modelled cost-effectiveness can remove the influence of such real-life locational and short-term variations in costs and weather, making it easier to identify the underlying agronomic and mitigation efficiencies. It is largely from abstracted models that we find some quite confident rankings of cost-effectiveness, not least in marginal abatement cost curves. However, to provide location-specific advice, these location factors need to be reintroduced.

Some mitigation measures are still only theoretical; hence there can be no ex post observations. For example, governments across the world are extremely reluctant to do anything more than inform and educate consumers about the effects of consuming too much ruminant meat. Any stronger measure, such as taxing meat, may be seen to infringe individuals' rights and choices (even if these choices harm the individual's health and welfare) (Wiggins and Keats, 2014). Enough is known about the elasticities of demand for red meat for the impacts of a tax on red meat to be modelled, even though we have no meat taxes to evaluate.

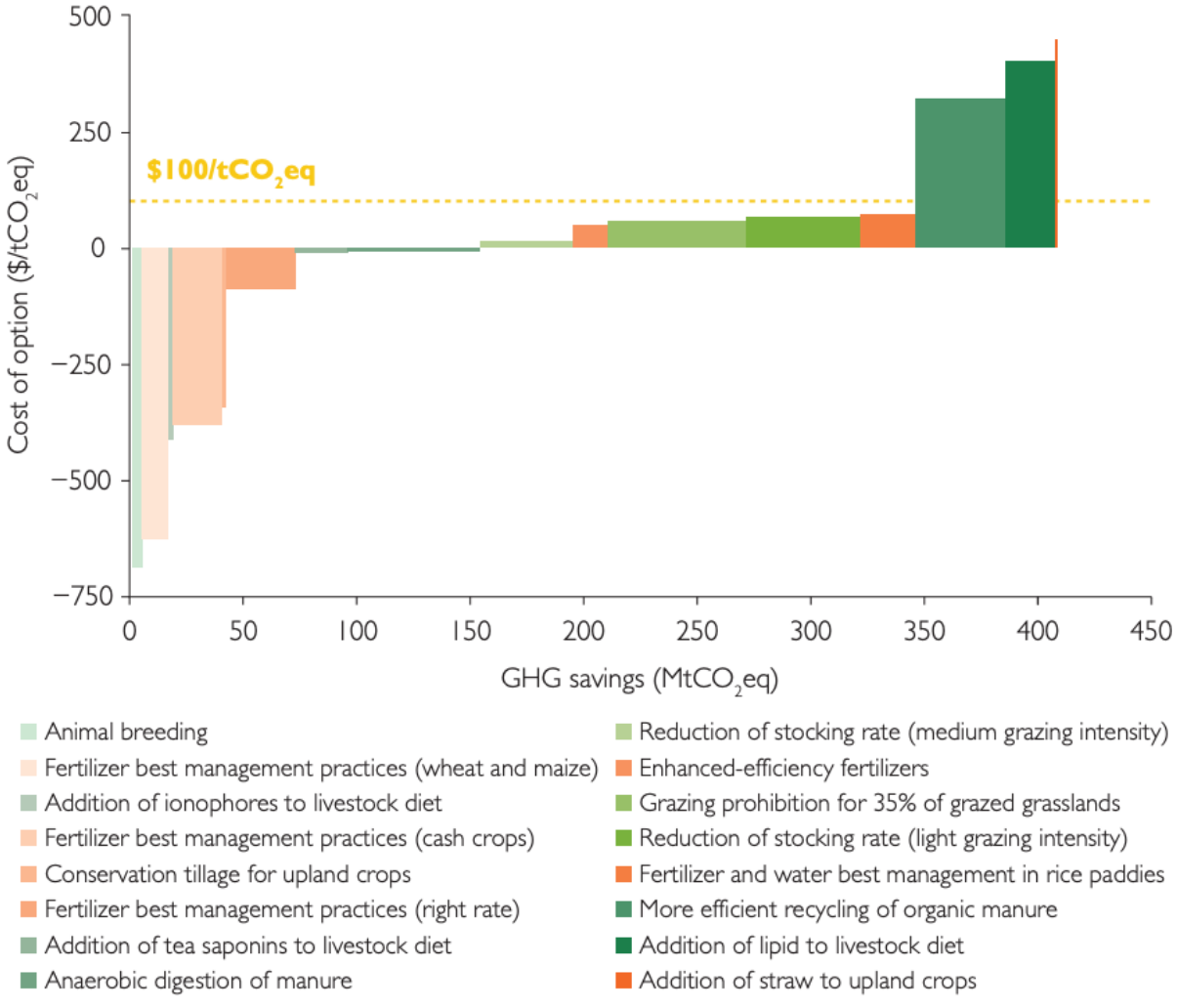
Similarly, some mitigation measures are still experimental, and models allow potential technical breakthroughs to be assessed (see Martin and Vos, 2024, for a review of policy options to mitigate emissions from agriculture and the food supply chain). An example is synthetic foods, produced by precision fermentation. If the cost of producing synthetic dairy products falls below the cost of producing milk from cows, as some observers believe will happen (since costs have been falling over time), most of the world's dairy herds will become redundant, with a potentially massive reduction in methane emissions.

Modelled cost-effectiveness can be instructive in ranking different options across countries.

Figure 3 shows model results for China, India and Bangladesh. The bar's width depicts the effectiveness and its height depicts the cost-effectiveness. Some measures would save money – as much as 75% of the mitigation potential in Bangladesh and 90% in India (Sutton et al., 2024). Cost-effective technical options can differ among countries from the same region and with similar agricultural systems. For example, for China, measures that save money include animal breeding fertiliser management and management of water in rice paddies; in India, cost-saving measures include altering livestock diets, fertiliser management, and use of biogas; in Bangladesh, cost saving mitigation comprises nutrient management, zero tillage, and managing water in rice paddies.

Figure 3: Marginal abatement cost curves for agriculture in China, India and Bangladesh

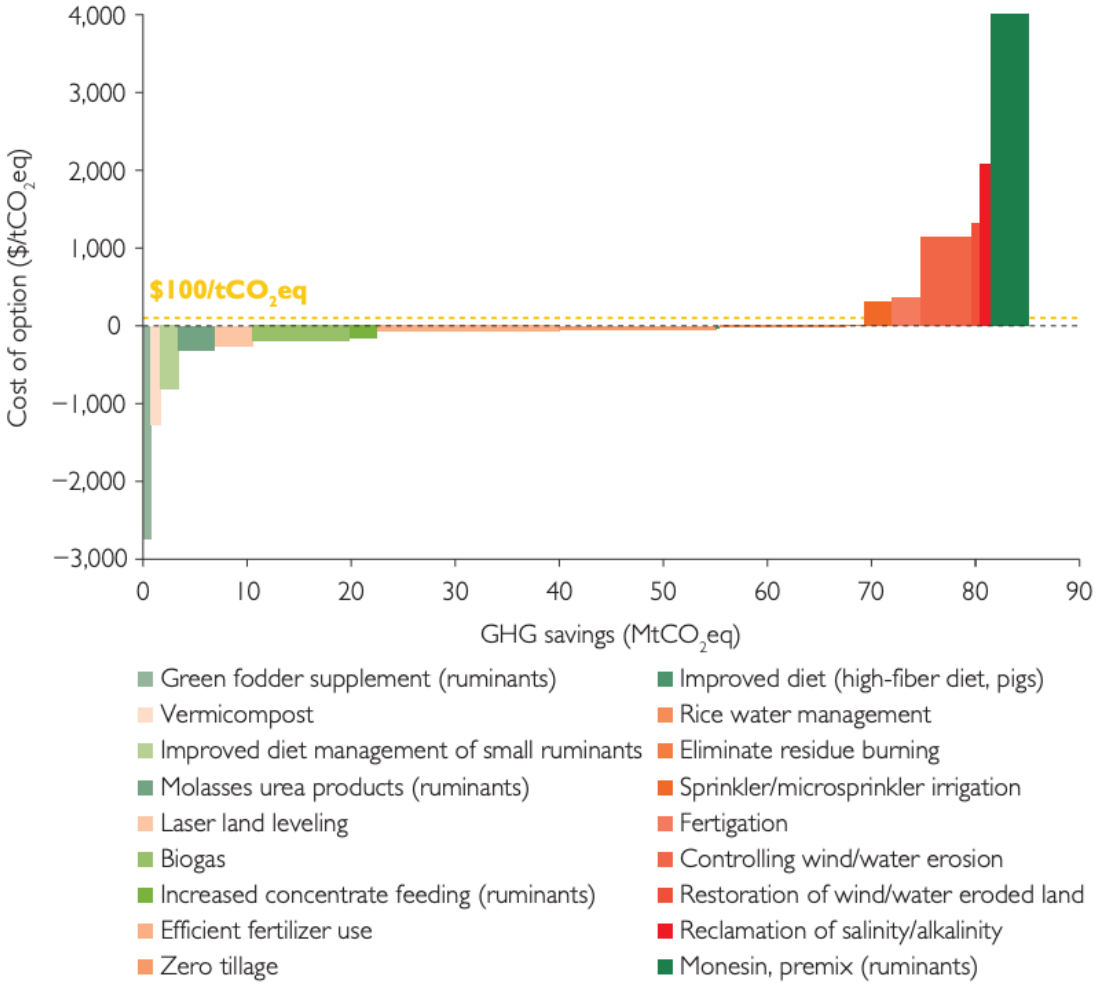
China



Source: World Bank based on data from Nayak et al. 2015.
Note: Figure shows the cost of mitigation options associated with livestock and crop production (represented in shades of green and red, respectively) in relation to the savings in greenhouse gases (GHGs). When arranged from least to most costly along the x-axis these mitigation options, represented as scaled bars, form a "curve" referred to as marginal abatement cost curve. The area of each bar represents the total cost of the respective mitigation option (that is, the volume, expressed in $MtCO_2eq$ on the x-axis, multiplied by the unit cost, expressed in $/tCO_2eq$ on the y-axis). Several mitigation options toward the left of the graph have negative marginal abatement costs—that is, their implementation saves money. Two mitigation options, the least cost-effective, are not represented in the figure to enable visualization: (1) addition of probiotics to livestock diet, $7,080/tCO_2eq$ (tons of carbon dioxide equivalent) and (2) addition of biochar to soil, $5,478/tCO_2eq$. Exchange rate: $1 = ¥ 4.94; $MtCO_2eq$ = megatons of carbon dioxide equivalent; tCO_2eq = tons of carbon dioxide equivalent; ¥ = yuan.

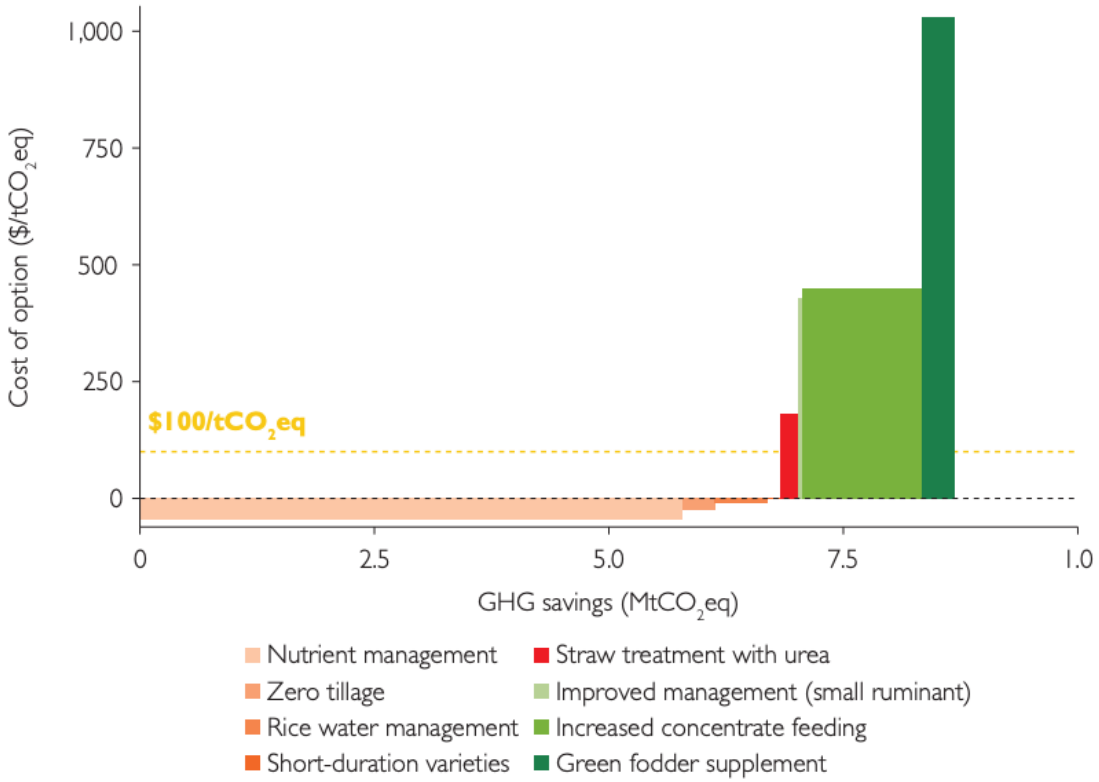
Source: World Bank based on data from Nayak et al., 2015.

India



Source: World Bank based on data from Sapkota et al. 2019.
Note: Figure shows the cost of mitigation options associated with livestock and crop production (represented in shades of green and red, respectively) in relation to the savings in greenhouse gases (GHGs). Three mitigation options—efficient fertilizer use, zero tillage, and rice water management—could deliver more than 50 percent of the total technical abatement potential. One mitigation option, the least cost-effective, is not represented in the figure to enable visualization: reclamation of waterlogged soil, $5,014/$tCO_2$eq (tons of carbon dioxide equivalent). Exchange rate: $1 = Rs 82.67; $MtCO_2$eq = megatons of carbon dioxide equivalent.

Bangladesh



Source: World Bank based on data from Sapkota et al. 2021.
Note: Figure shows the mitigation options associated with livestock and crop production (represented in shades of green and red, respectively) in relation to the savings in greenhouse gases (GHGs). Three mitigation options—nutrient management, zero tillage, and rice water management—are cost-saving. One mitigation option, the least cost-effective, is not represented in the figure to enable visualization: vermicompost, $5,623.7/tCO$_2$eq (tons of carbon dioxide equivalent). Exchange rate: $1 = Tk 106.5; MtCO$_2$eq = million tons of carbon dioxide equivalent; Tk = taka.

Source: World Bank based on data from Sapkota et al. (2021).

Modelled results also show the differences between technical potential and low-cost potential. One estimate shows the technical potential for reducing emissions from agriculture and food systems to be 11 GtCO$_2$eq, but only 3 GtCO$_2$eq is available for under US$100/tCO$_2$eq (Table 3.1, Sutton et al., 2024).

A different approach to questions of cost-effectiveness can be seen in papers that consider not specific mitigation measures, but policy options that would lead to mitigation. For example, Martin and Vos (2024) classify the options as

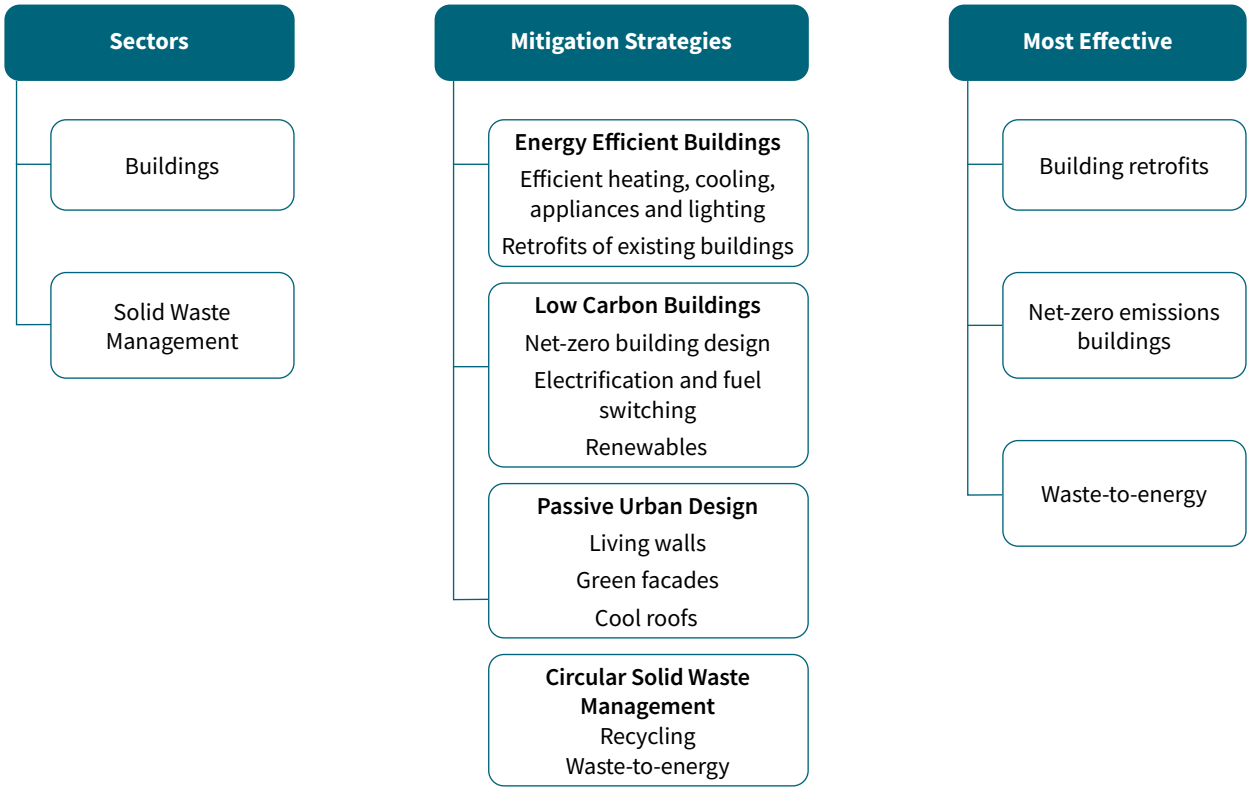
> *'(i) emission tax-based approaches,(ii) repurposing or elimination of agricultural support (iii) regulatory approaches, carbon credits, (iv) innovation-based approaches, and (v) interventions designed to change food demand.'*

Their analysis leads to the conclusion that 'repurposing agricultural support towards R&D on sustainable agricultural intensification could generate major efficiency gains, sharply reduce emissions and improve food security' (Martin and Vos, 2024).

Lee and Ignaciuk (2025) conducted a systematic review of 190 studies of emissions mitigation in agriculture forestry and other land use. They also examined the mitigation effectiveness of policy options in agriculture (such as subsidies, regulatory instruments, and government investment), although only 4% of the 190 studies in their reviewed sample were causal (ex post) econometric policy evaluations. They found that government investments in R&D have an estimated average mitigation potential of 28 tCO_2e per ha per year through improvements in agricultural practices for soil quality, productivity, and breeding programmes, while subsidies targeting environmental goals (such as efficient fertiliser use and application, and producer payments to reduce methane emission intensities in livestock) had a lower potential of 5.3 tCO_2e per ha per year (ibid). The authors qualify their conclusions by noting the importance of local conditions such as climate, topography, ecosystems, land use and farm system specificity. They also observe that policies to reduce emissions may trade off against other policy aims, such as increasing food security.

Savilaakso et al. (2024) conducted a rapid review of programme-level outcomes of nature-based solutions in smallholder agricultural systems in LMICs (i.e., climate-smart agricultural practices, conservation agriculture and agroforestry). The 46 studies on climate-smart agriculture they reviewed found positive impacts of these measures on farmers' yields and productivity, which in some cases led to higher incomes, along with enhanced food security and nutrition through dietary diversity and improvements in soil quality, water use and biodiversity. Education and farm ownership were identified as enablers for the adoption of climate-smart agricultural practices (ibid). The need for context-specific approaches adapted to regional agroecological conditions was highlighted.

4.2 Climate-Smart Urban Development



The systematic reviews on climate-smart (low-carbon) urban development focused on interventions that deliver sustainable or net-zero emissions buildings in their design, construction and use. The literature also included reviews about decarbonising the solid waste sector. There is a sub-section of the literature that looks at urban development and the decarbonisation of cities more broadly.

Many of these studies seek to enhance the thermal energy efficiency of building envelopes through insulation. Effectiveness is expressed in terms of ability to reduce energy consumption, while carbon effectiveness depends on the volume of heating fuel being displaced. Therefore, for a given level of capital investment, an energy-efficiency improvement appears more cost-effective when the underlying fuel source is heating oil rather than natural gas, because heating oil is typically more expensive and more carbon intensive, leading to greater cost savings and emissions reductions per unit of energy saved.

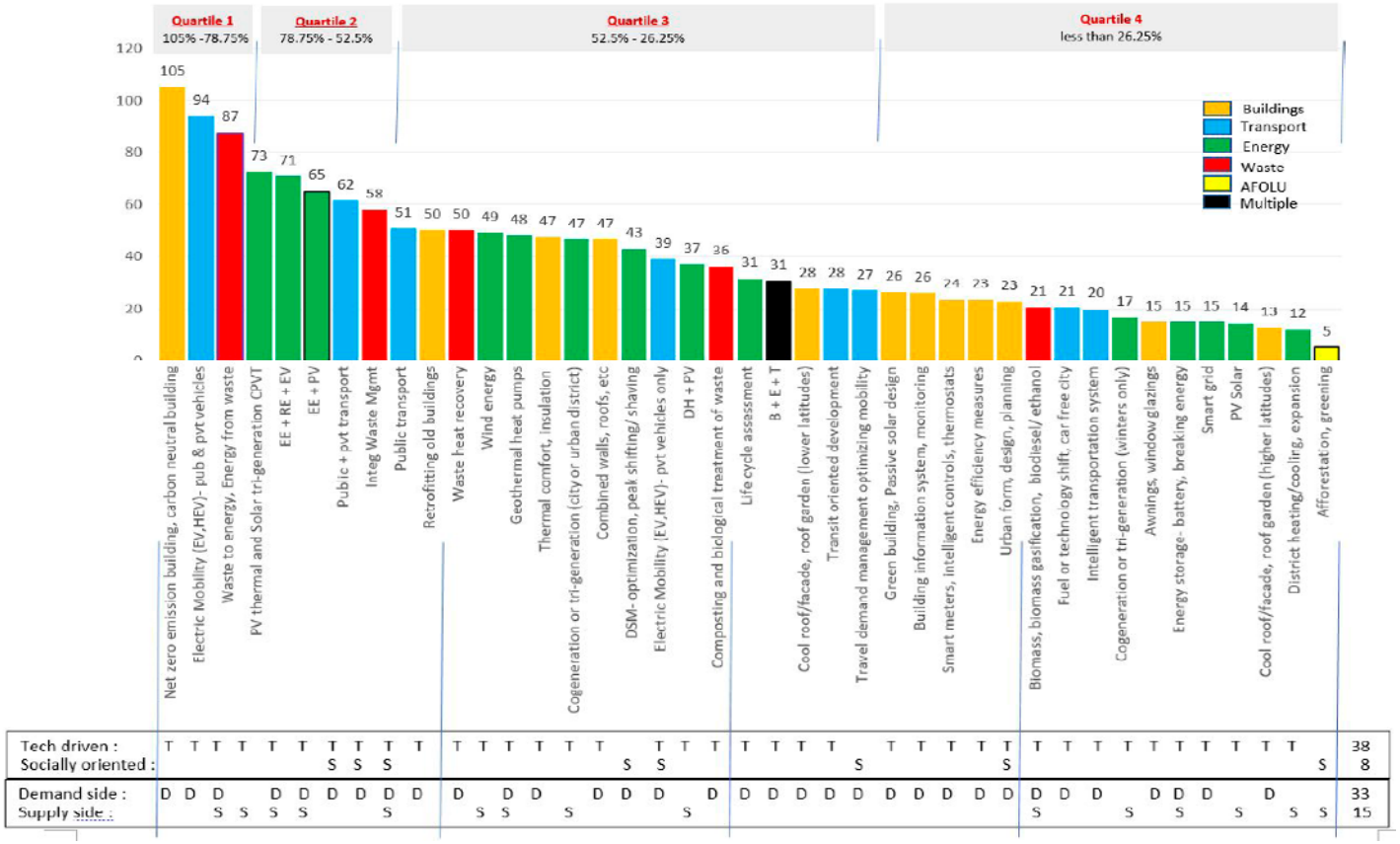
Many of the reviews covered a range of interventions, technologies and strategies that could reduce emissions across the building life cycle – design, construction and use. A few studies conducted detailed assessments of specific interventions, such as different types of green infrastructure, daylighting and lighting retrofits, and cool wall cladding, among others. Both the academic and grey literature were dominated by ex ante studies that used modelling and scenarios to determine the impacts of the various climate mitigation interventions on reducing emissions. As a result, limited ex post studies were identified.

Solid waste collection and treatment was also covered under the buildings theme. Waste management practices in LMICs differ markedly from those in HICs owing to poor source segregation, with sporadic and inefficient collection (<50% for LIC and 50–80% for MIC), low composting, limited use of incineration, and excessive reliance on landfill or dumping (Hoornweg and Perinaz Bhada-Tata, 2012). These differences greatly increase the GHG emissions of waste management and mean that countries fail to exploit the energy and material recovery potentials. HICs typically define a waste management hierarchy that seeks to reduce, recover and recycle ahead of digestion (of organic waste), incineration, and landfill as a last resort. LICs recycle only 16% of their waste, compared to 51% in HICs (Khan et al., 2022).

Effectiveness

Sethi et al. (2020) conducted a meta-analysis of the literature, listing 41 different urban solutions across the building, transport, energy, and waste sectors that could contribute to climate mitigation. The most common interventions included peak shaving or shifting electricity demand, introducing building efficiency measures, retrofitting buildings, installing solar photovoltaic (PV) or photovoltaic-thermal, integrated planning, fuel or technology shifts, waste to energy, and cool roofs, among others. However, most of the case studies were from Europe and China, with less representation from the rest of Asia, Africa and the Americas. Nonetheless, the review found that the building sector had an average mitigation potential of 35%, if one considers 13 climate solutions benchmarked against the business-as-usual (BAU) scenario. The mitigation potential for each solution ranged from 13% (cool roof/façade, roof garden) to 50% (building retrofit) to 105% (net zero emissions buildings).

Figure 4. Mitigation potential of selected building-sector climate interventions relative to a business-as-usual (BAU) scenario



Quartile 1 (105% to 78.75%): Net zero emission building (NZEB), Electric mobility- electric vehicles (EV) & hybrid electric vehicles (HEV)- in public & private vehicles, Waste to energy or Energy from waste (WtE/EfW)

Quartile 2 (78.75% to 52.5%): PV thermal and Solar tri-generation CPVT, EE + RE + EV, EE + PV, Public and private transport, Integrated waste management

Quartile 3 (52.5% to 26.25%): Public transport expansion, Retrofitting old buildings, Waste heat recovery, Wind energy, Geothermal heat pumps, Thermal comfort & insulation, Cogeneration or tri-generation (city or urban district), Combined walls/ roofs, DSM- optimization, peak shifting/ shaving, Composting and biological treatment of waste, Life cycle assessment, Buildings, energy& transport combined solutions (B+E+T), Cool roof/facade, roof garden (lower latitudes), Transit oriented development, Travel demand management optimizing mobility

Quartile 4 (less than 26.25%): Green building, Passive solar design, Building information system, monitoring, Smart meters/ intelligent controls/ thermostats, Energy efficiency measures, Urban form, design, planning, Biomass, biomass gasification, biodiesel/ ethanol, Fuel or technology shift, car free city, Intelligent transportation system (ITS), Cogeneration or tri-generation (winters only), Awnings or window glazing, Energy storage- battery or from breaking energy, Smart grid, PV Solar, Cool roof/facade, roof garden (higher latitudes), District heating/cooling, expansion, Afforestation & greening.

Source: Sethi et al. (2020)

Gouldson et al. (2018) also focused on low-carbon measures, drawing from ex ante studies in the buildings and waste sectors. They highlight that in the building sector, new building heating efficiency measures, heating retrofits, efficiency standards for appliances and lighting, fuel switching, and the use of solar panels in urban areas could save 4.5 $GtCO_2$ emissions by 2050 (Gouldson et al., 2018). Focusing specifically on the building sector, Khan et al. (2024) reviewed the viability and economic sustainability of vertical green systems in buildings, specifically living walls and green facades. They conclude that living walls are more effective than green facades, and that the higher efficiency of living wall systems to capture pollution and reduce emissions compared to green facades could make them a viable option for addressing climate change-related issues in buildings. The evidence was drawn from both HICs and LMICs such as China, Malaysia and Nigeria.

In the waste sector, Gouldson et al. (2018) found that the implementation of recycling programmes and landfill gas capture could save 0.6 $GtCO_2e$. Sethi et al. (2020) found that the waste sector had the greatest average mitigation potential (50%) of five climate solutions. The GHG mitigation potential ranged from 21% with the use of biomass gasification to 87% with waste to energy solutions. A survey of solid waste treatment in India (Gour, Singh and Mandal, 2022) identified the trends of urbanisation, population growth, and a reduction in the organic portion in waste as factors that require a rethink of old recommendations. Even simple source segregation – for instance, by providing street bins with simple colour coding such as green for organic, blue for recyclable and grey for residual – can make it easier to economically exploit the portions for composting, materials recovery and combustion.

Cost-effectiveness

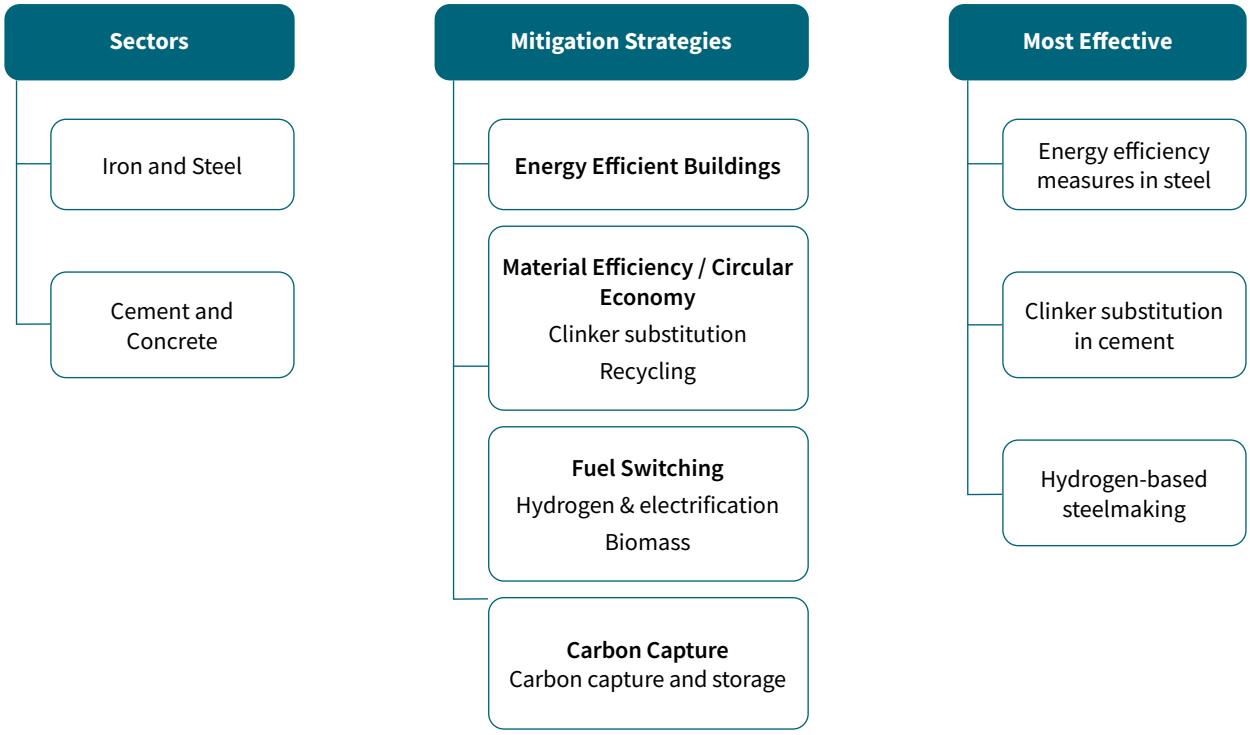
One study noted that there was a lack of consistent data, which made it hard to account for the costs of mitigation options, but the authors noted that they expected costs to vary with situations (Sethi et al., 2020). Similarly, Khan et al. (2024) noted that the potential economic returns of vertical green systems (VGS) are highly context-dependent and require careful consideration of design, installation, operation, and maintenance costs. However, they found that when co-benefits and tax incentives were considered, the VGS's payback period could be as low as eight years. The case studies in Malaysia focused on living walls, finding that the reported benefits included energy savings for a building of US$37 per year in that country.

A report by Graham (2020) more specifically investigated policy drivers for decarbonisation and the costs and benefits associated with their implementation. This author evaluated the most cost-efficient policies, which he defined as the policies that deliver the highest impact with the lowest monetary cost over a given period. The study found that mandatory building energy codes and rating and disclosure with appliance standards were the most cost-efficient options with the highest positive impact. Overall, the most cost-effective regulatory measures included building energy codes and renovation obligations, cost-effective market intervention measures, including public procurement, emissions trading, carbon taxes and grants, and voluntary agreements. The most cost-effective information measures included building energy certificates and labelling, and the most cost-effective advice and leadership measures included information campaigns, knowledge services, and public leadership and capacity building. However, the author notes that the cost-effectiveness and impact value of these measures are dependent on local market conditions (Graham, 2020).

Other themes

Gouldson et al. (2018) found that low-carbon measures in the buildings and waste sectors could help to achieve a range of development priorities, including job creation, improved public health, social inclusion and improved accessibility. It has also been noted that achieving zero-emissions buildings requires the decarbonisation of the energy supply and electricity generation.

4.3 Industry



Most systematic reviews on climate mitigation opportunities in industry focused on a specific and highly carbon-intensive industry, such as iron and steel, cement, concrete, chemicals, ceramics or glass. The most frequently studied industries are iron and steel, and cement and concrete. Each systematic review typically focused on a broad range of technologies or interventions across the entire industry's value chain or across different stages of the industry's production process. For example, in the steel industry, reviews such as Kim et al. (2022) focused on interventions that can mitigate emissions at each stage of the steel production process, which includes raw materials, iron and steel making, the manufacture and use of steel products, and waste and recycling. In the cement industry, reviews such as Griffiths et al. (2023) and Arthur et al. (2025) focused on interventions across pathways, such as energy efficiency, material efficiency, fuel switching and carbon capture.

Some reviews, such as Cantzler et al. (2020), focused on multiple industries and on how one technology or intervention (for example, promoting the circular economy) can be applied to mitigate emissions across each industry. Some studies focused on a specific technology and were forward-looking, investigating how technologies such as carbon capture and storage (CCS)

and green hydrogen, which are not yet widely commercially available, could be utilised. These ex ante studies used models to determine the technologies' effectiveness at reducing GHG emissions. Most were excluded, since our methodology favoured ex post studies. However, some were included in cases where robust ex post evidence was not yet available for a technology and the technology is widely recognised as critical for deep decarbonisation in the long term.

The geographic scope of most of the systematic reviews was global, with many not specifying the country or regional focus. However, as expected, the studies were only able to draw case studies and examples from countries where that industry is prominent; as a result, there are many case studies from China, India and across Europe, with limited mention of other regions. Many of the studies discussed the effectiveness of the interventions in reducing GHG emissions, but did not consider cost-effectiveness or the other impacts.

Effectiveness

The systematic reviews identified industrial decarbonisation solutions that could yield carbon savings across industry sectors. In the iron and steel industry, Kim et al. (2022) reviewed 271 studies, identifying a range of low-carbon interventions, in addition to 86 other potentially transformative technologies. They found that effective interventions in the raw material phase included material substitution and the use of hydrogen from renewable or other low-carbon sources as the reducing agent in the steel making process. This has the potential to mitigate more than 3 $GtCO_2$ annually. The review also found that energy efficiency and the adoption of renewable sources or fuel switching from fossil fuels was effective, and that biomass could replace fossil-based reducing agents, having the potential to decrease CO_2 emissions by up to 50% in the integrated steelmaking process. Among a group of commercially available but not yet widely used energy-saving technologies, coal moisture control and high temperature air combustion can yield financial benefits from energy and carbon savings across multiple levels of the sociotechnical system. It was predicted that the application of these measures could reduce almost half of the CO_2 emissions from the Chinese steel sector, bringing emissions down from 1469 Mt in 2015 to 710 Mt by 2050 (Kim et al., 2022).

Cantzler et al. (2020), whose study focused on the circular economy, found that in the steel sector, recycling presents many opportunities to reduce emissions. Specifically, recycling saves 1.5 kg CO_2e GHG emissions and 1.4 kg iron ore for every 1 kg of steel scrap that is recycled – a reduction of 27% and 10% compared to primary production. Similar savings are available in the cement sector, as the study also found that using waste material for cement and concrete production and the production of 1 ton of marble-based geopolymer green cement paste saves around 54% of CO_2 emissions compared to Portland cement paste (Cantzler et al., 2020).

In the cement and concrete industry, Arthur et al. (2025) found that effective climate mitigation interventions included clinker substitution; the use of fly ash and calcinated clay could reduce carbon emissions by 30–80%; geopolymers and other alternative binders could lower emissions by 20–60% when used with eco-friendly activators; and new CO_2-curing technologies, such as cement-free block systems, could sequester more CO_2 than is released during their production. Orsini and Marrone (2019) also found that there were benefits from the use of alternative materials (such as coal fly ash, granulated slag, silica fume and red clay brick waste) to reduce clinker production, and indicated that these can reduce GHG emissions by 40%. Interventions

such as implementing CCS and increasing the use of renewable energy could reduce emissions by up to 70% and 60%, respectively (Orsini and Marrone, 2019).

Overall, these findings show that a range of effective climate mitigation measures can be applied across different industries' value chains. However, the findings emerge from studies with a global focus, making it difficult to determine which interventions are more suited to particular geographies.

Cost-effectiveness

Several studies indicated that there are compelling decarbonisation innovations that could yield financial benefits from energy and carbon savings. Kim et al. (2022) highlighted that since the iron and steel industry is energy intensive, most measures that reduce energy inputs will result in significant financial savings and social cost savings through a reduction of the negative externalities imposed by coal and natural gas consumption. However, the study notes that even though the benefits are clear, the sector still requires significant initial investment to implement such decarbonisation measures. This study also highlights a list of 14 efficiency measures in the industry that could save between US$0.11 and US$6.27/t of steel (Kim et al., 2022). These include the use of the scrap preheating twin-shell furnace (which saves US$0.11), and thin slab casting, which improves productivity and reduces material losses and could save US$6.27/t. However, while this study took a global focus, the latter data was drawn from the US iron and steel industry, rather than LMICs.

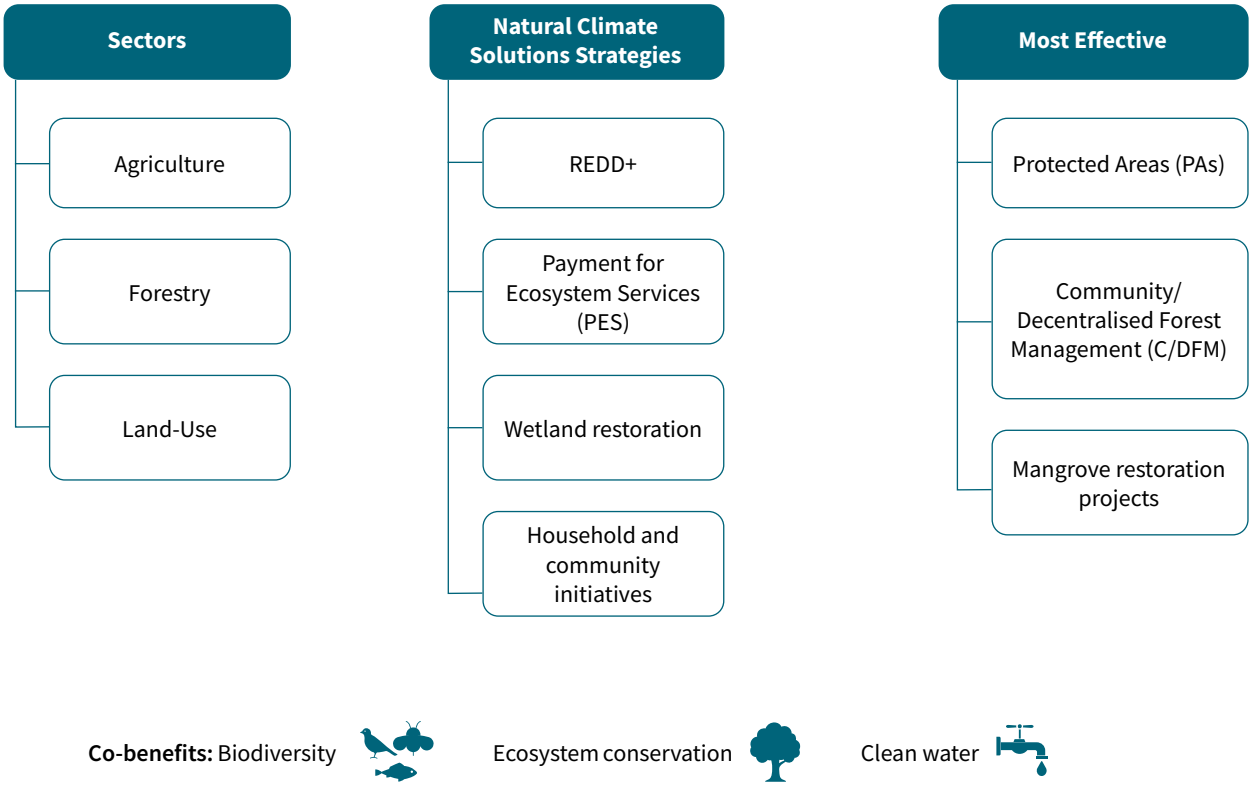
In the cement and concrete industry, Arthur et al. (2025) indicated that clinker substitution is the fastest, lowest-cost climate mitigation lever. Clinker substitution (or the use of supplementary cementitious materials (SCMs)) is a low-hanging fruit and is cost-neutral or low cost, explaining its rapid diffusion. On the other hand, these authors found that the cost-effectiveness of technologies such as CCS is dependent on the trajectory of carbon prices (Arthur et al., 2025). While there was some data on financial savings, there was a lack of data on cost-effectiveness and cost savings per ton of CO_2 emissions avoided. However, Kim et al. (2022) note that hydrogen from renewable or other low-carbon sources is used as a reducing agent in the steel making process and could potentially mitigate more than 3 Gt of CO_2 annually at a cost of less than US$60/t CO_2 mitigated.

While most of the systematic reviews had a global scope and lacked country or region-specific analysis, some insights could be cautiously extended to LMIC contexts. For example, interventions such as energy efficiency improvements, fuel switching to biomass, material substitution, and greater use of recycled material may be particularly relevant for LMICs, as these measures offer both emissions reductions and cost savings with relatively low capital intensity. It was noted that efficiency measures and clinker substitution in the cement sector are low-cost options, which may align well with the capacities of industries in LMICs. More capital-intensive options like CCS or hydrogen-based production may face greater potential barriers in LMICs owing to constraints in infrastructure, financing or technology access, especially as it was noted that the cost-effectiveness of CCS is dependent on countries' carbon prices, and to date there are few carbon pricing policies in LMICs. This highlights a significant gap in the literature and a need for more disaggregated, region-specific and ex ante analysis that considers the cost-effectiveness of mitigation options in LMIC industries.

Other themes

Many of the decarbonisation options identified for industry can also reduce water usage, minimise waste, and yield other positive benefits, such as air quality improvements by reducing air pollutants such as PM2.5[4]. Kim et al. (2022) highlight that in China, the decarbonisation of the iron and steel industry could improve the ecological environment of the Beijing–Tianjin–Hebei region, the Yangtze River Delta region, Henan, and other places that have frequently suffered from pollution haze.

4.4 Natural climate solutions



This section discusses findings from systematic reviews of nature-based interventions that reduce or sequester greenhouse gas emissions. These cover interventions that are bracketed under Agriculture, Forestry, and Other Land-Use sector (AFOLU) in climate negotiations, Payment for Environmental Services (PES), as well as household and community initiatives such as improved cookstoves and the restoration and conservation of coastal and inland wetlands. The academic literature occasionally conflates nature-based solutions with solutions based on agriculture and carbon pricing. A few studies focus on agricultural practices such as regenerative agriculture and conservation agriculture, analysing their effect on soil carbon, crop yield and greenhouse gas emissions. There is also a sub-section of the literature that looks at carbon offsets, specifically evaluating the actual emissions reductions (integrity) achieved by various types of offset projects, including forestry.

4 PM means 'particulate matter'. Thus PM2.5 means particles that are 2.5 µm or smaller in diameter.

The interventions studied largely draw from project-level evidence, although coverage remains uneven across geographies and outcome measures. Ex post evaluations of projects with mitigation outcomes are limited. Many systematic reviews focus on adaptation or resilience outcomes (Maldonado et al., 2020; World Bank, 2023) or enhanced ecosystem management (Su, Friess and Gasparatos, 2021; Nguyen et al., 2020). Other current and emerging literature provides conceptual frameworks and programme evaluations, and on developed countries, although with some limited evidence from FCAS (Ethiopia and Democratic Republic of Congo).

Research methods predominantly involve ex post quantitative evaluations of implemented policies and projects, using quasi-experimental study designs such as propensity score matching (PSM), difference-in-differences (DID), synthetic control methods, and, less frequently, randomised controlled trials (RCTs), to assess ex post outcomes against hypothetical counterfactuals, contrasting them with ex ante estimates (Snilstveit et al., 2016).

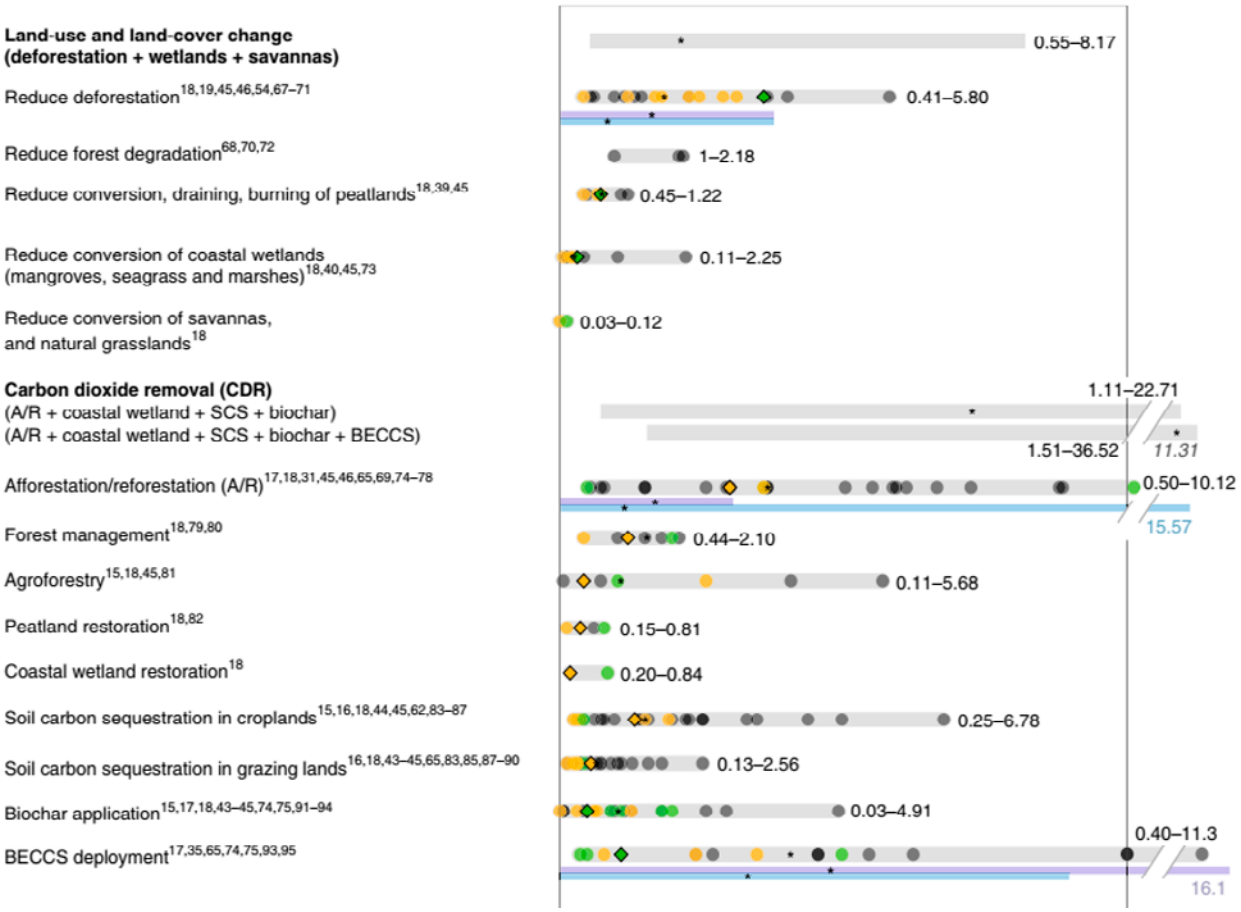
In the longlist of systematic reviews, several topics were discussed that did not meet the inclusion criteria and therefore could not be shortlisted, but their data was worth noting. Among these were many single-country studies, some of which are relevant to the focus on LMICs, including Ghana (Agbotui et al., 2023) and India (Kandpal et al., 2023). For example, Agbotui et al. (2023) calculated the sequestration of traditional cocoa agroforestry systems in four villages in the Eastern Region of Ghana and the theoretical impact of CO_2 emissions rights trading on their profitability, finding that total carbon sequestered in the organic system was 30% higher than in the conventional system, and that CO_2 payments could improve the attractiveness of organic cocoa cultivation for farmers, which can be beneficial for livelihoods and social outcomes. However, owing to the single-country nature of the study, it was not included in the shortlist.

Effectiveness

As seen in Figure 5, avoiding land use changes – above all the conversion of forests, peatlands and wetlands to fields and pastures – can be a highly effective means of reducing GHG emissions or retaining them in the soil or stock of biomass. REDD+[5] (reducing emissions from deforestation and forest degradation) is the collective term for a framework and set of institutions and interventions developed by the UNFCCC, aimed at protecting forests in LMIC countries. These interventions employ various financing and implementation mechanisms.

5 The UNFCCC framework for REDD+ primarily operates through results-based finance, where countries receive payments that are tied to national-level accounting and reporting. Separately, REDD+-related projects also operate in voluntary carbon markets, where they generate tradable carbon credits based on project-level baselines and verified emissions reductions. These credits may be purchased for various purposes, including as carbon offsets, where entities use credits to compensate for their own emissions elsewhere. However, voluntary market REDD+ projects represent one subset of the broader REDD+ landscape and are distinct from UNFCCC-aligned REDD+ programmes, although both aim to reduce deforestation.

Figure 5: Mitigation measures from land use change and carbon sequestration



Source: Roe et al. (2019).
Notes: Mitigation potentials reflect the full range of low to high estimates from studies published after 2010, differentiated according to technical (possible with current technologies), economic (possible given economic constraints) and sustainable potential (technical or economic potential constrained by sustainability considerations). Medians are calculated across all potentials in categories with >4 data points. Supply-side and demand-side measures are treated separately as these two categories are not additive.

Probst, Toetzke and Kontoleon (2023) compared evaluations of 2000 ex post carbon offset projects against 51 similar field interventions that did not issue certified offsets. Despite the common claim that carbon offsets are economically efficient for reducing emissions, the results suggest that emissions reductions delivered by offset projects are significantly lower than reported – a discrepancy referred to as the 'offset achievement gap'. Only 12% of the total volume of existing credits across the sectors studied represent genuine emissions reductions (referred to as the 'offset achievement ratio'). In absolute terms, approximately 1.1 GT of the total 1.3 GT CO_2 credited across the four sectors reflects emissions reductions that were not actually achieved. Specifically, the study reveals that forestry offset projects achieve only about 25% of their claimed reductions (although this rises to 39.2% for comparable field interventions), while cookstove offset projects only achieved 0.4% of their claimed reductions.

While all wetlands act as long-term carbon sinks, Taillardat et al. (2020) found that only coastal wetlands such as mangroves and saltmarshes exhibited a net cooling effect. Their systematic review compared the net carbon budgets of different wetland types, as quantified in the literature. This comparison was based on the Sustained Global Warming Potential, which

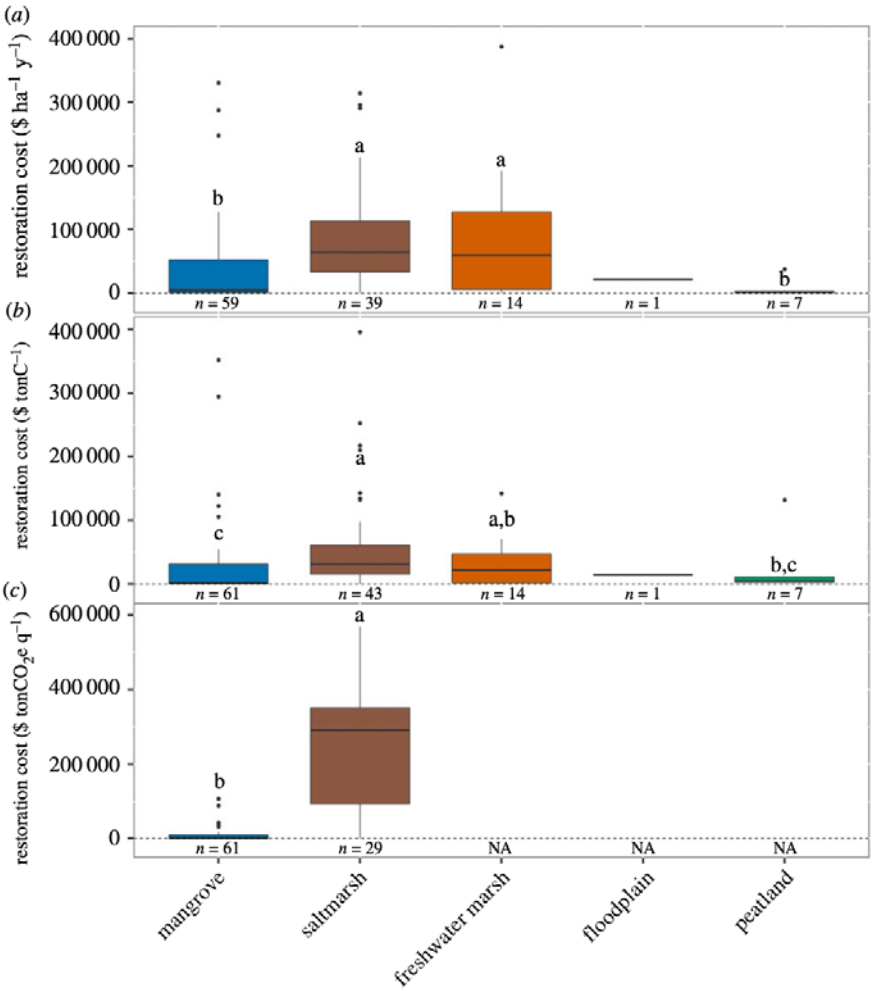
measures how much heat greenhouse gases trap in the atmosphere over a given time period, and the 'switchover time', defined as the point at which a wetland begins to have a net radiative cooling effect. Although inland wetlands (peatlands, floodplains and freshwater marshes) are efficient at sequestering carbon mass over long periods, they also emit significant amounts of methane, a much more potent greenhouse gas than CO_2. Over a 100-year horizon, the warming from methane typically outweighs the cooling from CO_2 sequestration. In contrast, mangroves have a switchover time of 0 years, while saltmarshes' reach this point after 17 years.

There was limited evidence in five of the fifteen intervention types studied in Snilsveit et al.'s (2016) evidence mapping of the effect of land-use change and forest programmes on emissions and human wellbeing. Among the interventions for which evidence was available, modest and generally positive outcomes were found for protected areas (PAs) and community/decentralised forest management (C/DFM). These were associated with improved habitat protection in tropical forest regions and reduced forest conversion in the case of PAs, and with lower deforestation rates and improved measures of forest conditions in the case of C/DFM. By contrast, little to no evidence was found for the effectiveness of other intervention types, including laws and policies related to forests and land, such as civil society legislation, and infrastructure-related interventions. Where evidence does exist, Payment for Ecosystem Services appears to be less effective in improving forest conditions.

Cost-effectiveness

The cost-effectiveness of wetland restoration (Figure 6) shows mangroves to be a cost-effective wetland ecosystem for mitigation (estimated at US$1,800/tC) owing to their high carbon sequestration potential ($-235 gCm^{-2} yr^{-1}$) (Taillardat et al., 2020). Mangrove wetland restoration was found to be more cost-effective than inland wetland restoration (estimated at US$4,200 to US$49,200/tC). These projects might be long-term investments, since they do not yield climate mitigation benefits within 100-year timescales. This suggests that the conservation of existing old inland wetlands should be higher priority than their restoration, at these timescales (Taillardat et al., 2020). We reviewed the underlying studies and found the data being quoted referred to high-income countries, and that care needs to be taken about applying these to an LMIC context. It is important to source more relevant case studies.

Figure 6: Cost of wetland restoration for different biomes



Note: Boxplot of restoration cost per wetland type in (a) US$ ha^{-1} y^{-1}; (b) US$ ton C^{-1}; and (c) US$ ton CO_2eq 100 SGWP^{-1}. Note that for (a), one outlier from the freshwater marsh (1,733,632 US$ ha^{-1} y^{-1}) and two from mangrove (828,033 and 692,814 US$ ha^{-1} y^{-1}) are not presented in this figure. Also note that the lower sample size for (c) is because only sites with a negative SGWP-100y could be considered. Letters indicate significant differences between ecosystems (non-parametric Van der Warden test, $p < 0.05$). Values at the bottom of the lower boxplots indicate the sample size for each wetland type.

Source: Taillardat et al. (2020)

Probst et al. (2023) found that field interventions, conducted by researchers and NGOs, rather than commercial entities selling carbon credits, achieved higher achievement ratios than interventions by commercial offset producers. In absolute terms, the volume of credits without real reductions in the offset market is estimated at ~1.0 $GtCO_2$. For field interventions that did not officially issue offsets, the researchers computed a 'synthetic' offset achievement ratio (i.e., the ratio of achieved emissions reductions if these projects had used assumptions of similar, real-world projects to issue offsets. The synthetic offset achievement ratio is highest for forestry (39.2%) and cookstoves (17.1%) for field interventions, compared to 25% and 0.4% respectively for offset producing interventions. The authors suggest that the costs of implementing the necessary improvements to offset projects (such as strict targeting, local context adaptation, and dynamic monitoring) would probably increase the price of these offsets, rendering the current project-based funding model less effective (Probst et al., 2023).

Other themes

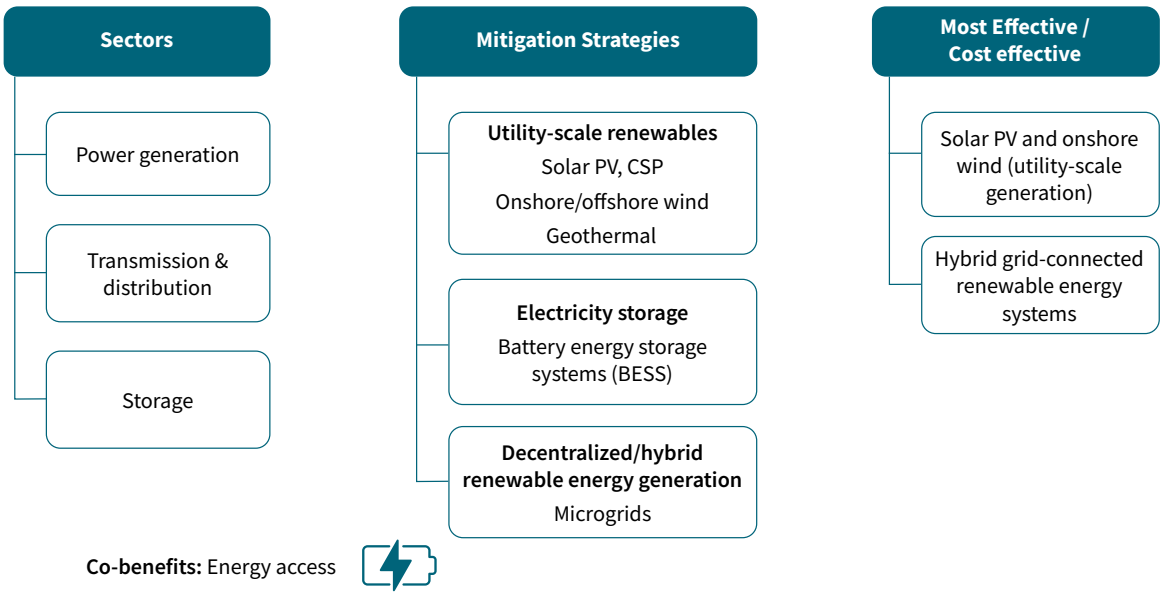
Several studies focused on the cost-effectiveness of natural climate solutions for resilience. The World Bank (2023) found that US$5.53 billion in natural climate solutions projects in their portfolio provided cost-effective alternatives to conventional grey infrastructure. Of the 103 projects with components using nature-based solutions (NbS) for climate resilience identified from 2012 to 2021, 44% were in Africa and 22% in East Asia and the Pacific. While a total aggregate dollar figure is not provided, and the outcomes are focused on resilience, the study identifies specific areas where NbS drive financial savings:

- **Reduced Energy Costs:** The use of tree shading and green roofs is explicitly noted for reducing energy consumption and air conditioning costs.
- **Utility Savings:** Improved watershed management reduces costs for water utilities by decreasing sediment load and erosion, which otherwise require expensive mechanical treatment.
- **Avoided Recovery Costs:** Urban green spaces and nature-based stormwater systems are used to prevent costly recovery and adaptation interventions that follow urban flooding disasters.

Similarly, Vicarelli et al. (2024) found that 71% of studies indicated that NbS have consistently proven to be a cost-effective approach to mitigating hazards, particularly those associated with mangroves (80%), forests (77%), and coastal ecosystems (73%). Their study found that NbS are at least as effective as engineering-based solutions, with 65% of studies reviewed suggesting that NbS are more effective at reducing the intensity and impact of hazards than engineering-based solutions.

We reviewed studies that examined nature-based interventions that reduce or sequester greenhouse gas emissions, primarily in the AFOLU sector. The time horizons of projects play a role in their effectiveness; for example, over shorter timeframes, conservation was found to be more effective than restoration from an emissions perspective, although natural climate solutions are associated with other co-benefits to resilience and biodiversity.

4.5 Renewable energy (RE)



The transition from fossil fuels to renewable energy sources for power generation, accompanied by the electrification of transit and heating, is a central element of many countries' GHG mitigation strategies. In 2024, 452 GW – the highest ever level – of renewable energy capacity was installed (IRENA, 2025). The scope of mitigation opportunities in the energy sector identified in the literature generally covers renewable energy generation and integration, meaning spending on transmission, distribution, and storage. Solar photovoltaics (PV) and onshore wind have been the lowest-cost renewable energy sources over recent years and, in an increasing number of markets, they are cost-competitive with fossil fuels without financial support (ibid). However, financing costs remain a key determinant of renewable project viability and in many LMICs, the costs of capital remain high owing to country risk premiums.

Academic literature on the cost-effectiveness of renewable energy generation in LMICs yielded only ex ante cross-country reviews or single country ex post reviews, with several bibliographic reviews of the state of the literature and evidence gaps. Moreover, systematic reviews generated by our search strategy often lacked a clear mitigation focus but discussed the effectiveness of technologies in terms of other metrics, such as energy access and efficiency. As a result, the retained academic systematic reviews focused on niche solutions such as smart grids and mini grids rather than utility-scale power generation. Given the paucity of peer-reviewed systematic review articles on the cost-effectiveness of large-scale RE power generation, we focused on technical and grey literature from international organisations, particularly the International Renewable Energy Agency (IRENA), which maintains the most comprehensive cost database on renewable energy.[6] Coverage in the grey literature includes global samples, but often specific findings are only disclosed in relation to large middle-income markets such as Brazil, India and China.

Effectiveness

Renewable energy generation technologies are highly effective at reducing emissions, and replacing fossil fuel generation with renewables is already yielding large emissions savings and avoided fossil fuel costs. Overall, renewable electricity generation in 2024 is estimated to have reduced CO_2 emissions by 2.89 billion tonnes in China (21% compared to national emissions), by 372.6 million tonnes in Brazil and by 410.9 million tonnes in India (14% compared to national emissions) compared to a counterfactual scenario in which fossil fuel plants would have generated the same electricity (IRENA, 2025). This has led to avoided fossil fuel costs of US$179.8 billion, US$28.3 billion and US$14.9 billion in the three countries, respectively (ibid).

More specific ex post evaluations of emissions reduction effectiveness were only identified in one review study. In a systematic review and meta-analysis of 30 studies on various microgrid configurations across residential, communal, industrial, commercial, and agricultural applications globally, Wesonga et al. (2025) found that microgrids leveraging renewable energy sources could offer substantial carbon reduction benefits – for every 1% increase in onsite renewable energy production, emissions decrease by approximately 238.1 g CO_2/kWh.[7] Compared to a baseline of conventional grid-based systems, microgrids can achieve up to 80% carbon emissions reduction (ibid). Hybrid grid-connected photovoltaic wind-turbine (G-PV-WT) systems achieve the highest emissions reduction, up to 91% compared to other configurations (ibid).

6 The cost database maintained by IRENA has records for 25,000 projects and 3109 GW of installed capacity (IRENA, 2025). Around 57% of projects are based in China (47%), India (6%) and Brazil (4%) and 30% in 'Rest of the world'. Localised costs are supplied for the largest ten markets for each technology, which generally include China, India and Brazil. Bloomberg New Energy Finance's excellent alternative database is behind a paywall.

7 The sample is global, with most results from Asia (18 papers), Africa (4 papers) and North America (4 papers).

Cost-effectiveness

On a levelised cost of electricity (LCOE) basis, renewables are the most cost-competitive option for new large-scale electricity generation, with 91% of all newly commissioned utility-scale renewable energy projects in 2024 delivering electricity at a lower cost than the cheapest new fossil fuel-fired alternative (IRENA, 2025). Onshore wind and solar PV have the lowest average costs (Table 11). In some regions, geothermal energy can also be a more cost-effective option. Some middle-income economies are now reporting LCOEs for renewable energy technologies that are below the global average (Table 12). The falling capital costs of mature renewable energy technologies such as solar and wind arise from decades of increased cumulative deployment, technological innovation, and competitive supply chains for components (ibid). An additional cost advantage of renewables relative to fossil fuels is that they are not exposed to volatile international fuel markets.[8]

Table 11: LCOE of renewables: global weighted average in 2024 and decline between 2010 and 2024

Technology	LCOE (US$/MWh) in 2024	Decline in cost 2010–2024
Solar PV	43	90%
Geothermal[9]	60	Increase 9%
Onshore wind	34	70%
Offshore wind	79	62%
Concentrated solar power	92	77%
Hydro	57	Increase 30%
Coal power	73	N/A
Combined cycle gas turbine	85	N/A

Source: IRENA (2025)

Table 12: LCOE of selected renewables in key markets in 2024 (US$/MWh)

Technology	China	India	Brazil	Africa	Other Asia
Solar PV	33	38	48	74	70
Onshore wind	29	48	30	51	72
Offshore wind	56	–	–	–	–

Source: IRENA (2025)

8 The levelised cost of electricity (LCOE) is one of the most commonly used metrics for estimating the lifetime cost of a new power generation facility. It measures the lifetime cost per unit of electricity at the generation asset level by dividing total lifecycle costs by total projected output. However, it excludes system-level costs such as (i) backup generation and storage needed to address variable renewable energy (VRE) intermittency, (ii) transmission and distribution infrastructure upgrades, since VRE resources are often far from demand centres, and (iii) grid stability services.

9 In 2024, the LCOE for geothermal power generation ranged from US$33/MWh in Türkiye to US$90/MWh in Indonesia.

Energy storage costs have been falling, and hybrid systems that integrate renewables with battery storage are approaching cost parity with fossil fuel-based generation in advanced markets (IRENA, 2025). However, they still require financial support to be economically viable in LMICs. Electricity storage becomes an increasingly important enabling technology as the share of intermittent sources like wind and solar rises and exceeds the local grid's capacity to evacuate to areas of need or meet prevailing demand. Global average costs of storage for turnkey contracts – that include battery capacity but exclude engineering, procurement and construction (EPC) and grid connection – fell to between US$148/kWh and US$165/kWh, depending on whether the storage systems were four or two hours, a 40% year-on-year decline (ibid). The total installed cost of utility-scale battery energy storage systems (BESS) declined by 93% between 2010 and 2024. Prices in China, the principal user of battery storage in LMICs, are 40% lower than global average prices (ibid).

Utility-scale renewable energy projects in LMICs are capital-intensive and highly sensitive to upfront capital barriers and the local cost of financing. The cost of capital for projects is a major determinant of the total price to purchasers of electricity, and there are material differences in the costs of capital across renewable energy technologies and countries. In an IRENA review of the cost of capital data for onshore wind, offshore wind and solar photovoltaic (PV) projects obtained from an expert survey and interviews covering 45 countries, the average cost of capital for utility-scale solar was 3.9% in China, 6.1% in other Asia-Pacific countries, 8.7% in the Middle East and Africa, 6.6% in Latin America (compared to 4% in Western Europe or 5.4% in North America) (IRENA, 2023). For onshore wind, this was 3% in China, 7.2% in other Asia-Pacific countries, 7.2% in Africa and 6.4% in Latin America (compared to 3.3% in Western Europe and 5.1% in North America). While there are within-region differences in the cost of capital for renewable energy technologies that depend on the developer, off-take arrangements, and other project-specific factors, across-region differences in cost are larger, driven primarily by differences in country risk premiums (ibid).

However, for mature technologies like onshore wind projects, declining costs suggest that concessional financing may no longer be necessary in some emerging markets (CIF, 2023). In 2023, the Climate Investment Fund (CIF), overseen by the World Bank, reviewed the capacity-weighted construction costs of large, utility-scale renewable energy technologies in LMICs through the Clean Technology Fund's (CTF) project portfolio.[10] Within renewable energy generation technologies, the lowest investment cost per MW installed was for onshore wind projects, driven by innovations in wind technology (such as larger wind turbine designs, which produce more electricity), cost reductions in the supply chain, and other advances in the sector (such as increases in project size and lower capital costs, ibid) See Table 13.[11] Wind energy projects were highlighted as no longer featuring in recent CTF project approval requests.

10 The CTF provides concessional financing for the demonstration and deployment of low-carbon projects in LMICs. It collectively added 7.2 GW of installed capacity (CIF, 2023). To date, the CTF portfolio includes 40 LMICs across the Middle East and North Africa, Sub-Saharan Africa, South-East Asia, Latin America and Central Asia.

11 Costs are based on total project financing for construction, including costs unrelated to renewable technology such as technical assistance and capacity building. 'Mixed' refers to projects supporting the integration of different types of renewable energy into the grid.

Table 13: Average total project costs per MW of installed capacity in CTF's portfolio experienced 2017 to 2022

Technology	Average cost per MW (US$ million)
Solar	3.99
Geothermal	3.28
Mixed	2.91
Wind	2.80

Source: CIF (2023)

Beyond centralised power generation, the literature suggests that microgrid interventions leveraging renewable energy sources may be cost-effective solutions for reducing GHG emissions in LMICs in settings where grid extension alone is costly or impractical. Wesonga et al. (2025) conducted a comparative economic analysis to assess the feasibility of the most common microgrid configurations based on metrics such as Net Present Cost (NPC), LCOE and Payback Period (PBP). Grid-connected photovoltaic wind-turbine (G-PV-WT) systems were found to be more cost-effective than other systems, offering the shortest payback periods (median payback period of 2.81 years) and had 50% lower costs than other alternatives considered, such as grid-connected photovoltaic (G-PV), grid-connected wind turbine (G-WT) and their configurations with battery storage (Wesonga et al., 2025). The cost of microgrid systems is mainly influenced by expenses associated with capital costs, replacement costs, and operation and maintenance costs for the technology components such as wind turbines, solar PV panels, and batteries. Integrating battery storage into grid-connected photovoltaic systems enhances system reliability but increases costs up to 21% (ibid).

The study recommended site-specific economic assessments, as the cost-effectiveness of G-PV-WT systems is influenced by the availability of abundant wind and sunlight. In addition to the geographic and climatic conditions, factors that influence the choice of microgrids include: (i) the site-specific energy profile (such as demand patterns, peak demand periods, user behaviour), (ii) technical and operational considerations (industrial microgrids often require hybrid AC/DC architecture and advanced storage systems), (iii) the availability of government incentives (such as feed-in tariffs), and (iv) socio-political context (public awareness and acceptance can influence successful microgrid adoption) (Wesonga et al., 2025).

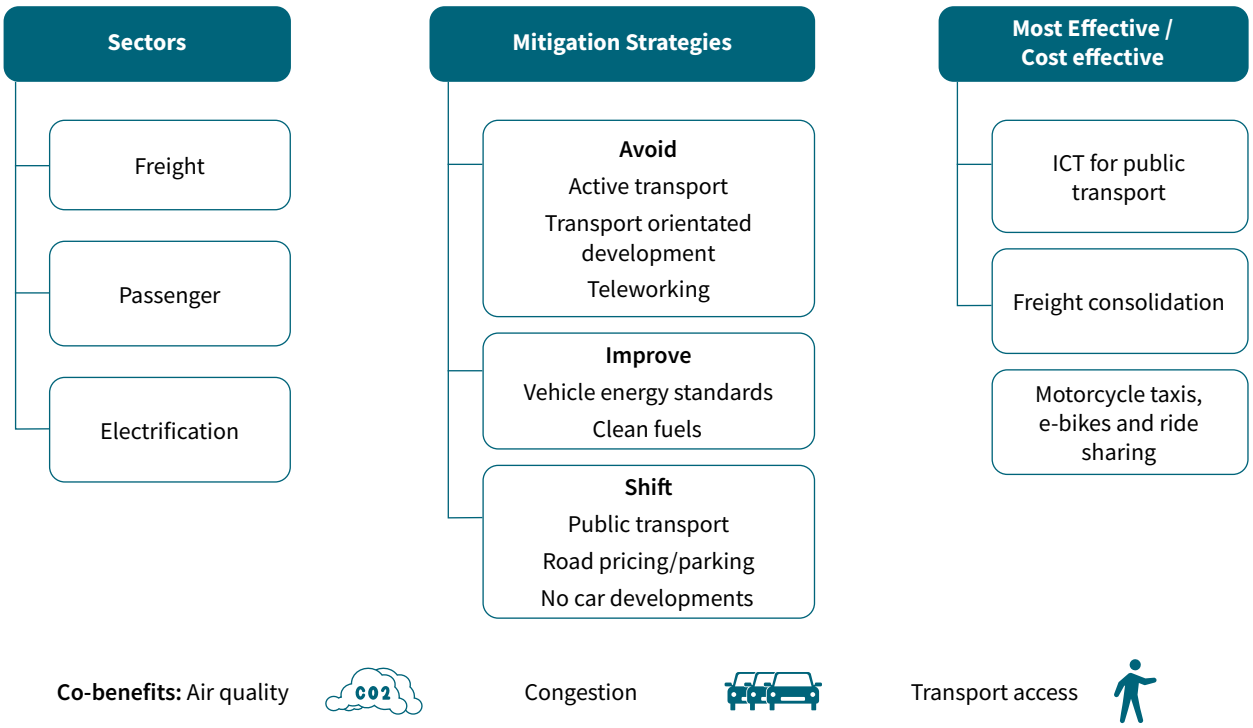
Another systematic review of the economic performance of on-grid and off-grid hybrid renewable energy systems (HRESs) in LMICs, specifically those combining rooftop solar PV, diesel generators (DG), converters and BESS, found several studies showing that hybrid PV/DG systems are economically superior to diesel-only systems (Thango and Obokoh, 2024). Solar PV components in hybrid systems offered substantial long-term savings through reduced operational costs and low maintenance requirements. The review found that HRESs were also effective at managing energy supply during power interruptions, particularly in regions with high solar potential but unreliable grid access (ibid).

Lastly, a systematic review of 17 studies on smart grids, mostly based on modelled findings in HICs owing to their novelty and limited experimental data, concluded that although smart grids are energy efficient and reduce GHG emissions, investments in smart grids may not be economically viable, given that most smart grid systems are still at laboratory or pilot scale

(Moretti et al., 2017). The review reported a wide range of economic costs of smart grid systems, at between 0.03 and 1,143 M€/yr and benefits of between 0.04 and 804 M€/yr. These differences are mainly driven by differences in electricity prices, assumptions about system capacities, and utility operating characteristics (ibid).

Regarding policy mechanisms, evidence on feed-in-tariffs (FiTs) suggests they are an effective tool for supporting private investment in renewables (Bhandary, Gallagher and Zhang, 2021). These tariffs provide low-carbon electricity providers with either a fixed total electricity price per kilowatt-hour or a fixed premium on top of the wholesale electricity rates, over a fixed period. Feed-in-tariffs (FiTs) are good for mobilising resources into renewable energy generation. However, the authors caution that FiTs are not necessarily the most effective intervention and that this finding probably reflects that FiTs have been studied extensively in the literature (Bhandary et al., 2021).

4.6 Transportation



Several reviews use the Avoid–Shift–Improve (ASI) framework for categorising and sequencing suggested interventions (Wimbadi et al., 2021; Jaramillo et al., 2022). This framework stresses the importance of, first, **avoiding** the need for transit co-locating retail, work and accommodation to reduce transit distances (a reference to the so-called 'ten-minute city'), increasing urban density, or concentrating residential blocks around major transport hubs ('transport-oriented development'). Then, focusing on modal **shift** from private, single-occupancy vehicles to public transport, active transport or high occupancy vehicles. Finally, **improve** seeks to reduce the GHG emissions (and health side effects) by switching from high-carbon energy sources to batteries, hydrogen or biofuels.

Except for the IPCC's working group III paper (Jaramillo et al., 2022), the reviews were narrowly focused on a single transport mode (buses, ships) or a specific modal shift (from cars to active transport) to ensure that the number of studies in scope was manageable. Most systematic reviews reviewed between 10 and 20 academic papers. One sought to review over 70 but did so in a cursory manner.

The small number of studies that examined all modes of transport tended to use simulation models to project future transport emissions. These were excluded from the longlist because they did not review ex post articles. Many reviews focused on the bibliographic properties of the literature (countries covered, analytical methodology, modes of transport tackled) rather than their results. These were excluded as they lacked decision-useful information. Several reviews of exclusively HIC case studies were included because some interventions are still uncommon in LMIC countries (such as the switch from vehicles to active transport).

Many of the studies incorporated the effectiveness of interventions in terms of carbon savings, but did not consider the costs, although some also looked at health benefits. Few studies included low- or middle-income countries, and even the global reviews were predominantly focused on advanced economies. There was discussion in some articles about LMIC leapfrogging individual internal combustion engine (ICE) vehicles and moving straight to public transport and electric vehicles. Systematic review authors noted that this required substantial upfront capital spending and was common only in upper-middle income nations like China and the Latin American countries. (Although we note that prices of battery storage have continued to decline, and in some markets electric scooters are common already, without policy support.)

Authors of systematic reviews had difficulty drawing conclusions across the reviewed papers. They noted difficulties in reconciling different fossil fuel prices, carbon intensities of electricity grids (petrol displaced by grid power) and discount rates (for evaluating costs of infrastructure projects), which are outside the control of the promoters of the project. Many systematic reviews of technologies focused on simulated technical performance or life-cycle analysis (LCA), where they could remove the influence of such market-environment differences.

Effectiveness

In a paper on urban experimentation, Wimbadi et al. (2021) reviewed 41 studies covering 64 cities, categorising the experiments using the ASI framework. Several cities sought to avoid emissions using envisioning to adopt city-wide GHG targets (e.g. in Argentina), transit-oriented development, ICT for public transport, and public campaigns to reduce private vehicle usage. Bus rapid transport systems were encouraged in 14 cities in LMICs – China, India, Mexico, Turkey, and Nigeria. This study did not assess the effectiveness or cost-effectiveness in terms of GHG abatement, but simply recommended that cities experiment with public transport and move to low-emission vehicles and bus rapid transport.

Opportunities existed to reduce emissions arising from e-commerce through the consolidation of freight for the last mile, and changes in consumer expectations of same-day delivery (Nogueira et al., 2024). A similar approach was recommended for the shipping of freight, such as ships 'despeeding' (traveling more slowly), localised sourcing, and a relaxation of just-in-time (JIT) replenishment requirements (McKinnon, 2016).

Emissions from freight transport can be reduced by using railways in place of cars and lorries. One review of cases in Brazil, South Korea and China applied a LCA approach to assess emissions (Da Fonseca-Soares et al., 2024). Fuel use during train operation accounted for 92% of life-cycle emissions. Substantial reductions were achieved by substituting diesel with biodiesel in the Brazilian case study, where biofuel production is encouraged to support the local sugar cane sector. The review reports a 26% reduction in GHG emissions from electric trains compared to diesel trains in Belgium. Many LMICs are electrifying their rail track. For example, track in India is now 98% electrified.

There were two studies on the efficacy of modal shift from cars to active transport (Scheepers et al., 2014). This ex post study reviewed 19 European case studies. Interventions in workplaces, city centres, and behavioural change programmes showed positive but statistically insignificant impacts in 16 of the 19 interventions. The more successful interventions required the greatest institutional effort. Creating a car-free city centre in Bologna, Italy, (with many exemptions to enhance political palatability) reduced the entry of passenger cars into the town by 60%, as people switched to bus, cycling and walking. A workplace travel plan at Bristol University that included the provision of cycle storage, subsidised cycle purchase, improved public transport, and restricted car parking reduced car use from 50% to 33% and increased cycling from 7% to 12%, and walking from 19% to 30%. Notably, less invasive measures such as information campaigns and walk-to-work days had little impact.

To apply these findings from HICs to LMIC, we need to understand and remedy the barriers to active transport in middle-income countries. A review by Javaid, Creutzig and Bamberg (2020) analysed a reduction in walking trips in two Indian cities, Delhi and Chennai, which fell from 40% in 2002 to 20% in 2008 at the same time as an increase in the use of cars and two-wheelers. Weak traffic management and lack of public transport has reduced the safety of pedestrians and cyclists. The study advocated switching to motorcycle taxis, e-bikes and ride sharing.

One ex ante study (Longva et al., 2024) examined the life cycle costs of alternative fuels and energy efficiency measures in marine transport, focusing on tankers and cargo ships serving both HICs and LMICs. The assessment was based on information on technical costs and GHG performance from publicly available sources, supplemented by consultations with industry stakeholders and expert knowledge accumulated through more than 100 consultancy projects. The International Maritime Organisation's (IMO's) new regulations require owners to invest in energy efficiency and reduce GHG emissions from ship fleets. The study assessed 50 state-of-the-art options, including eight different fuels and 10 fuel-system configurations. The study estimated emissions reductions of 20–30% by 2030 at a marginal cost of US$50–$100/tCO_2, increasing to 70–80% emissions reductions in 2040 at a marginal cost of 230–240 US$/$tCO_2$, with net-zero emissions by 2050, achievable at around US$300/$tCO_2$. In the near term, emissions reductions can be achieved through operational measures such as reducing vessel speeds, while longer-term reductions depend on transitioning to zero-emission fuels such as e-ammonia and green hydrogen.

This study adopted a mixed ex post/ex ante approach. Interviews with industry experts provided real-life costs of the technologies, while data on the age and structure of the shipping fleet informed the scale and timing of mitigation opportunities. These datasets were used to model the cost-effectiveness of switching to alternative fuels. Though the data was global it was relevant for LMICs since they operate and will refit these vessels as IMO regulations are implemented.

A second review of 103 academic papers and reports on shipping prompted by the IMO's rule change (Dos Santos, Pereira Da Silva and Serrano, 2022) anticipated fuel switching from heavy fuel oil (current use of 72%) to 22 different types of fuel. In total, 88% of the reviewed papers cited liquid natural gas (LNG) as an alternative; biodiesel was mentioned in 14.5% of papers, hydrogen in 16.2%, methanol in 23.8%, and ammonia in 9.8%. LNG reduces emissions by 30% and methanol by 25%. The other option is to use zero fossil-carbon at the point of combustion. Similar changes already implemented in the Mediterranean Sea have increased freight charges by 10%, according to three of the sampled studies.

Cost-effectiveness

Results on the cost-effectiveness of transport measures were rarely examined in the systematic reviews. One study, by Jagietto (2025), assessed the cost-effectiveness of alternative energy sources for buses (Jagiełło, 2025), based on studies published between 2019 and 2024. It found that the upfront capital costs of electric buses are substantially higher than diesel buses, ranging from 120% to 440% higher. However, this difference is partially offset by lower operating costs, with electricity costs averaging around half those of diesel (ranging from 21% to 137%). As a result, the overall lifetime cost of electric buses varies by context, being lower in some cases (for example, 66% lower than diesel in India) and higher in others (up to 172% higher in Uruguay).

Other themes

Several studies highlight improvements in air quality as a key outcome, and in some cases these are quantified in monetary terms. One review, by Bland, Burke and Bertolaccini (2024), examined health outcomes associated with public transport infrastructure investment of more than US$3 million in HICs. It found that, when health impacts are included in projects appraisals, they can account for 77% of total project benefits, compared to around 11% attributed to GHG emissions reductions. These findings are likely to be true in LMICs, too, where poor urban air quality is linked to emissions from internal combustion engine (ICE) vehicles.

Major omissions from the literature reviews

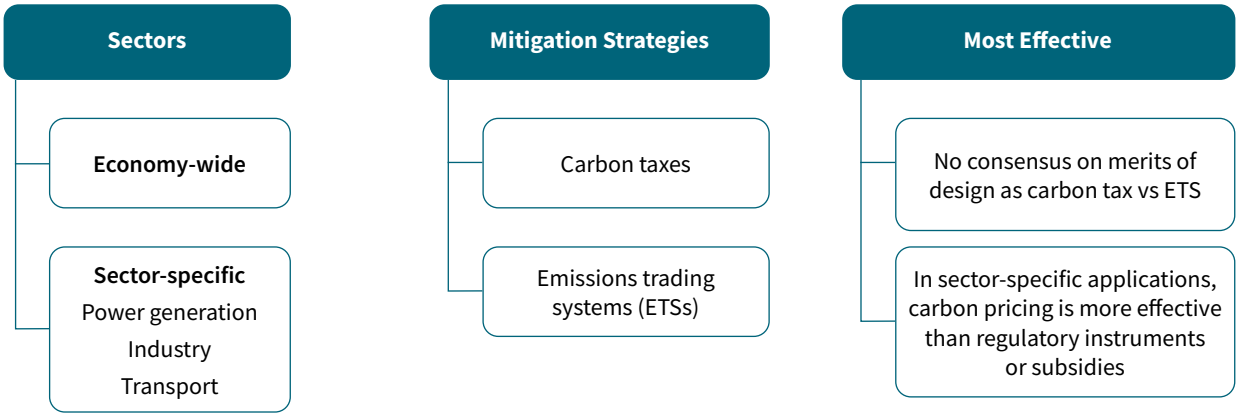
In the longlist of systematic reviews, several articles that did not meet the inclusion criteria nevertheless discussed transport interventions that could be significant. The most prominent idea was the replacement of ICE engine cars with EVs (Gerber Machado et al., 2023). The widespread adoption of EVs over the past decade is still too recent to have been captured by systematic reviews. Investment is needed in reducing the carbon content of electricity grids and in developing the charging infrastructure. In many congested LMICs, micro-mobility and bike sharing for short-distance trips might be a preferable solution over cars but this is an understudied topic. No study sought to understand the cost-effectiveness or carbon savings of

major transport infrastructure projects such as Chinese high-speed networks or the new metro systems across Chinese and Indian cities.

Several reviews assessed the use of hydrogen by road vehicles. One study reviewing 70 papers on the use of hydrogen in transport (Rinawati et al., 2022) focused on an ex ante life-cycle analyses (LCAs), examining a range of emissions arising from the feedstock for hydrogen production and the boundaries and energy input–outputs of the different studies. The paper focused on LCA methodological issues such as system boundaries and which process stages were included, rather than the results themselves.

We identified studies that examined changes in ridership (i.e. the number of people using public transport over a given period) from service improvements, such as providing real-time information about transit times (Brakewood and Watkins, 2019) and reducing crowding on vehicles (Kapatsila and Grisé, 2024). Both interventions led to increased ridership, meaning that more people chose to use public transport. However, neither study quantifies the associated costs or carbon savings. These types of improvements are likely to be low-cost ways to reduce emissions, since very little energy is used to provide real-time information and some of the additional passengers are likely to have shifted from private car use.

4.7 Carbon pricing



There are currently 80 explicit carbon pricing policies – carbon taxes and emissions trading systems (ETSs) – in operation around the world (World Bank, 2025). Conceptually, carbon pricing increases the relative price of carbon-intensive goods and services compared to low-carbon alternatives and creates an incentive for companies to reduce emissions if the carbon price is higher than their marginal abatement costs. However, the academic evidence on their effectiveness is dominated by studies that use economic models to predict the (ex ante) effects of policies, rather than evaluating their observed (ex post) impact. Ex post evaluations are very scarce, even for long-standing policies in HICs (Green, 2021; Döbbeling-Hildebrandt et al., 2024). The literature is also geographically concentrated, primarily focusing on evaluations of policies implemented in North America (British Columbia's carbon tax in Canada, the Regional Greenhouse Gas Initiative in the US), the European emissions trading system (EU ETS), and the regional emissions trading pilots in China.[12]

12 In 2013, eight regional ETS pilots were launched in China, before a nationwide ETS came into operation in 2021.

Ex post reviews of carbon pricing for LMICs outside of China are not available. This is probably because (i) there are no carbon pricing policies in low- or lower-middle-income countries to date and (ii) existing carbon pricing applications in upper-middle income countries are relatively new and adequate data for rigorous evaluations is not yet accessible. The bulk of papers in these countries use ex ante assessments and ad hoc modelling to evaluate the impacts of hypothetical or planned carbon pricing mechanisms, which makes comparisons among countries difficult (Van den Bergh and Drews, 2025). Even when carbon pricing has been implemented in LMICs such as Mexico or Colombia, preparatory studies examining socio-economic impacts were conducted before the policy was fully rolled out, many experimenting with proposed carbon prices that were different from the level at which it was implemented in practice (ibid). Similarly, meta-analyses assessing distributional impacts of carbon pricing policies have typically relied on modelled results (Ohlendorf et al., 2021; Köppl and Schratzenstaller, 2023). Studies whose abstracts indicated that they relied exclusively on ex ante results were excluded from the shortlist.

Effectiveness

The most recent, comprehensive reviews indicate that carbon pricing schemes are effective at reducing carbon emissions, although effects tend to fall within a broad range and vary by implementation context. Döbbeling-Hildebrandt et al.'s (2024) meta-analysis of 80 studies on 21 carbon pricing schemes found that at least 17 of the policies produced emissions reductions of between 5% and 21%. In another meta-analysis based on 81 studies (published 2011–2022), Ahmad et al. (2024) found significant positive effects on emissions reductions from carbon taxes in 82% of the sample, and 88% for ETSs.

While there is debate around the relative merits of the design of a carbon pricing policy as a tax versus a trading scheme, there is no consensus in the evidence to support either view. In LMIC contexts, it is typically argued that carbon taxes are more practical than trading schemes, as they are easier to administer, offering revenue-raising potential and price certainty that can promote investment (Parry, Zhunussova and Black, 2022). In practice, studies of both carbon taxes and ETSs produce varied effects across countries, with differences usually stemming from variations in policy design (such as coverage and permit allocations), different methodologies, and country-level contextual factors such as financial development, tax enforcement, the presence of complementary policies, the elasticity of demand for carbon-intensive products or the availability of alternative energy sources (Ahmad, Li and Wu, 2024). The potential effectiveness of carbon pricing in LMICs is further complicated by the (typical) presence of highly regulated energy markets that aim to keep electricity prices low and prevent costs from being passed on (Van den Bergh and Drews, 2025).

There is some evidence on variation in effectiveness across different sectors. In Ahmad et al.'s (2024) review, carbon pricing mechanisms yielded more substantial emissions reductions in carbon-intensive sectors. In an OECD systematic review of ex post empirical studies on the effectiveness of various climate change mitigation policies on emissions globally (including carbon pricing, regulatory policies and other economic instruments such as subsidies), the authors found that in the power sector, carbon taxes yielded the highest median effects on emissions (~10%) but ETSs were also effective (~5%) (OECD, 2025).[13] In the industry sector, the

13 The OECD review uses a global sample of papers but evaluations specific to carbon taxes and ETSs focus on effects from studies in the EU, UK, US, Canada and China.

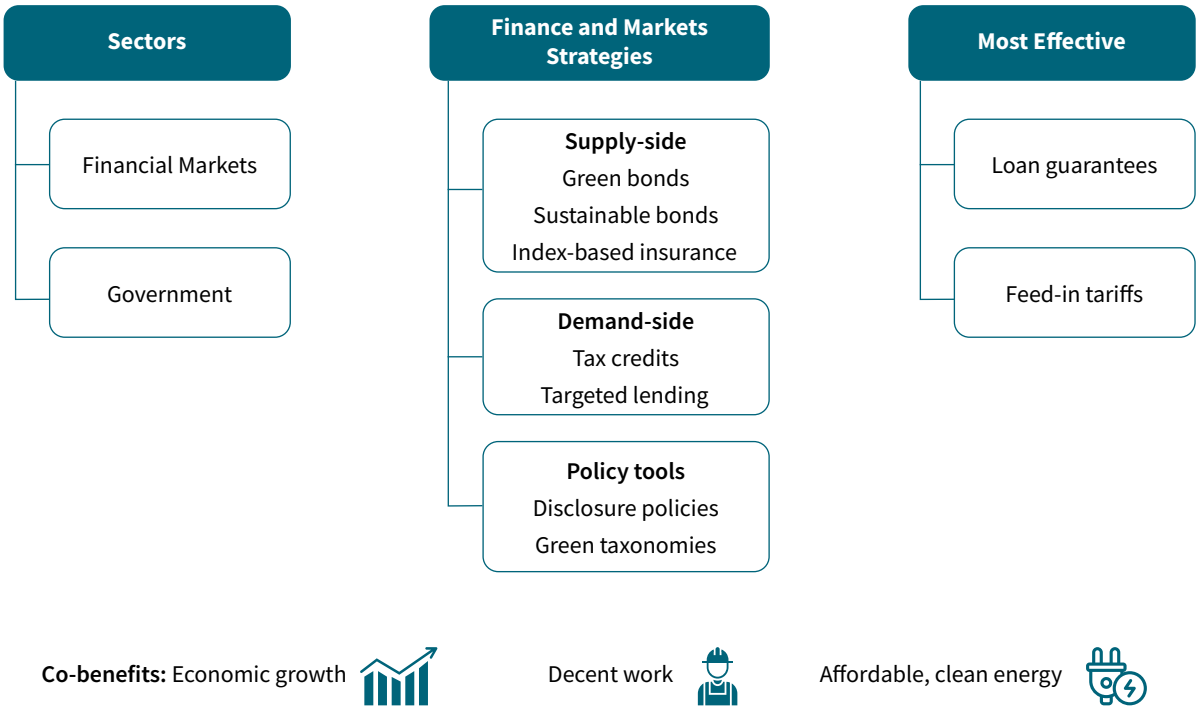
effectiveness of ETSs is well studied, with ETSs generating a median treatment effect of ~8%, although reported estimates varied substantially across studies (ibid). In the transport sector, carbon taxes and ETSs achieved median effectiveness at ~7% and ~5%, respectively, but again with large heterogeneity (ibid).

Cost-effectiveness

A limited number of studies assessed carbon price elasticity, revealing that the extent to which the level of the carbon price affects the effectiveness of the instrument at reducing emissions is still an open question. It is generally acknowledged that so far, implemented carbon prices have been low, and remain below the levels found in the modelled scenarios that achieve mitigation in line with global temperature scenarios (World Bank, 2025). Across all carbon taxes and ETSs implemented as of April 2025, the emissions-weighted average carbon price was US$19 per tCO_2e, up from US$10 per tCO_2e in 2015 (ibid). In Döbbeling-Hildebrandt et al.'s (2024) review, there are fewer than 10 studies that evaluate emissions reductions in schemes with mean carbon prices higher than US$30.

Across countries, heterogeneity analyses conducted by Döbbeling-Hildebrandt et al. (2024) indicate that the effectiveness of emissions reductions resulting from the policies in their sample cannot be well explained by the level of the carbon price, probably because marginal abatement costs and the price incentives created by indirect carbon pricing instruments (such as fuel excise taxes) vary widely across countries. This suggests that even low-carbon prices may still achieve substantial reductions in GHG emissions in contexts where abatement costs are also low. For example, the average treatment effect on emissions reductions in the Chinese ETS pilots was ~13.1%, despite a low average price of US$8 during the study period, compared to ~7.3% in the EU ETS (with an average price of US$20) (Döbbeling-Hildebrandt *et al.*, 2024). Even within the same scheme, such as the EU ETS, differences in permit prices do not seem to explain variations in effectiveness in the power sector, as studies focusing on later years of the scheme (when prices were higher) do not consistently find larger effects than those examining the initial phase (OECD, 2025).

4.8 Finance and markets



The available literature on finance and markets covers a variety of cross-sectoral interventions intended to increase flows of public and private finance to low-emissions opportunities, in line with Article 2.1 (c) of the Paris Agreement. For finance and market interventions, effectiveness is defined as the intervention's capacity to mobilise additional mitigation investment – typically measured through the volume of public and private finance channelled toward sustainable or environmental objectives. Systematic reviews are relatively rare, with most studies analysing interventions in specific markets or databases.

Cost-effectiveness refers to how well the intervention reduces the cost of private sector capital for mitigation investment, rather than the cost per unit of emissions reduced or energy generated, as in other sectors. This approach reflects the indirect nature of finance sector interventions, which influence the real economy by affecting the supply and demand of capital for low-emissions activities rather than directly producing emissions reductions. Where possible, the literature attempts to link these financial flows to real economic impacts and emissions outcomes, although such direct attributions remain challenging. The literature review covered market-based mechanisms such as green bonds, weather-indexed insurance, and tax credits; government-led interventions such as targeted lending, loan guarantees, disclosure policies; as well as institutions such as National Development Banks (NDBs) and national climate funds.[14] The evidence on the effectiveness of these interventions is mixed. While some instruments such as tax credits, loan guarantees, and NDBs are considered effective at mobilising private finance, the evidence is weaker for national climate funds, targeted lending, disclosure, and green bonds (Bhandary, Gallagher and Zhang, 2021).

14 See full list in the accompanying spreadsheet.

Different finance and markets interventions can be combined into policy mixes to achieve stronger emissions reductions (Stechemesser et al., 2024). However, the effectiveness of a single policy is often contingent on the presence of other complementary policies, and such a mix should consider a balance between mobilisation effectiveness, economic efficiency, environmental integrity and equity (Bhandary et al., 2021). The issuance of a green bond, for example, may be viewed as a signal of a company's commitment to environmental sustainability. This 'signalling theory' suggests that companies use green bonds to communicate their commitment to investors, who in turn value companies with strong environmental ratings (Wu, Raghupathi and Raghupathi, 2025). In their study of 2,550 corporate green bonds, Wu et al. (2025) found that green-bond features are associated with enhanced environmental, social and governance (ESG) disclosure scores but not with reductions in CO_2 emissions; in other words, green-bond issuance did not result in decarbonisation. The overall findings suggest that policies need to be tailored to country-specific contexts, in light of regulatory frameworks (Demski et al., 2025) and the time horizons of the evaluations (Wu et al., 2025).

Effectiveness

The systematic reviews mostly examined the impacts of finance and market interventions on the real economy and environmental performance (Table 14) and less commonly evaluated these interventions in terms of their direct link to emissions reductions.

Table 14: List of climate finance policies

Policy	Description
Targeted lending	Requiring banks to lend a certain portion of their credit or deposits towards certain policy priorities, such as agriculture or clean energy
Green bonds (or a green bond policy)	Bonds earmarked for projects with environmental and/or climate benefits
Loan guarantees (or loan guarantee programmes)	Governments commit to cover the borrower's debt obligation if the borrower defaults on climate change projects
Tax credits	Permitting taxpayers to subtract, dollar for dollar, from taxes that they owe in return for new investments in climate-friendly projects
National development banks (NDBs)	Government-backed, sponsored or supported financial institutions that are given a specific public policy mandate to promote low-carbon development in a specific country
National climate funds	Funding vehicles designed by governments to mobilise, access, and channel climate finance
Disclosure (or disclosure policies)	Requiring companies to report climate change information

Source: Bhandary *et al*. (2021)

In their empirical analysis of whether stricter regulatory frameworks encourage green bond issuance, Demski et al. (2025) similarly suggested that green bond financing strategies can act as a signal of firms' broader commitments to greening their operations. The authors found that policies targeting emissions reductions in specific sectors are associated with the largest increase in green bond issuance. Green bond issuance increased in sectors with heavy emissions that have been subject to sectoral mitigation policies. At the firm level, increased green bond issuance has been followed by a significant reduction in emissions, particularly in carbon-intensive sectors (Demski et al., 2025). These results suggest that regulatory stringency generally has a positive and statistically significant correlation with growth in the green bond market, which may be due to the relatively short two-year measurement window used in Demski et al.'s (2025) study. In their analysis, an increase in aggregate policy stringency by one standard deviation is associated with a 2.41% higher annual issuance of green bonds.

Bhandary et al. (2021) reviewed the evidence for nine types of climate finance policies, finding high environmental integrity effectiveness (whether the policy leads to real and verifiable emissions reductions or improved adaptation capacity) for loan guarantees and FiTs, drawing from the International Finance Corporation and Spain, Germany and China, respectively. As some of these countries are not considered LMICs, the relevance of this finding for developing countries is limited.

Cost-effectiveness

Bhandary et al. (2021) evaluated the performance of nine climate finance policies using several criteria, including economic efficiency. The study defined economic efficiency by measuring three specific metrics:

- the net cost of the policy to the government or public (calculated as cost minus benefit);
- the leverage ratio (the use of public finance to mobilise private investments);
- whether the policy genuinely leverages new and additional finance.

Regarding the economic efficiency results, the assessment found that targeted lending, green bonds, and National Development Banks (NDBs) were rated as having high economic efficiency. However, the high rating for the economic efficiency of green bonds and targeted lending is theoretical, based on the assumption that these instruments do not typically impose significant direct costs on government budgets. Policies such as tax credits have a larger evidence base, and have been shown to impose significant direct costs on government budgets. This lack of evidence regarding costs may contribute to their high rating relative to instruments with known high costs. Furthermore, green bonds are described as having the potential to be inexpensive. The authors found no evidence for the economic efficiency of the other types of climate finance policies, including green bonds, priority lending, NDBs, national climate funds, and information disclosure, citing a lack of publicly available data on the administrative costs and benefits of policies.

Bhandary et al. (2021) also measured 'mobilisation effectiveness' by evaluating the volume of private finance mobilised, the duration of that finance (long or short term), and whether the policy successfully reduced the cost of capital. Table 15 shows that loan guarantees and National Development Banks (NDBs) are rated as highly effective, as evidence indicates that both attract substantial private investment and improve investment financing conditions for climate mitigation projects. Feed-in tariffs (FiTs) are discussed separately in Section 4.5 of this report.

Table 15: Comprehensive assessment and rating of climate finance policy in practice

Level of effectiveness	Mobilization effectiveness	Economic efficiency	Environmental integrity	Equality
High	FiT Loan guarentees NCBs Green bonds	Targeted lending Green bonds NDBs	Loan guarentees FiT	
Medium-high	Green bonds		NDBs Tax credits	Weather indexed insurance NDBs (low in China) Tax credits
Medium	Tax credits National climate funds	Loans guarentees Disclosure Policies National climate funds	Targeted lending Green bonds Disclosure Policies National climate funds	FiT National climate funds
Low-medium	Targeted lending Disclosure Policies			Loan guarentees
Low		FiT Tax credits		Green bonds
N/a	Weather indexed insurance	Weather indexed insurance	Weather indexed insurance	Targeted lending Disclosure Policies

Source: Bhandary et al. (2021)
Notes: 'High' means very effective, 'medium' means eeffective, and 'low' means not very effective. Details about the evaluation and country experience are available in Appendix B.

Two studies comment on the existence of a 'greenium' or 'sustainium' – that is, a lower cost of finance for issuers of green or sustainable bonds relative to traditional bonds (Demski et al., 2025; Kumar, 2022). Demski et al. (2025) define the greenium as a price premium that green bonds command over otherwise identical non-green bonds in the primary market. This trading premium is driven by strong investor demand for sustainable instruments, arising from factors such as investor preferences for environmentally responsible firms (the 'preference channel') and the perception that less carbon-intensive firms present a lower probability of default risk (the 'risk channel') (ibid). Because bond prices and yields are inversely related, a higher issuance price implies a lower yield, and therefore a lower cost of borrowing for the issuer. In this sense, the premium presents a financial advantage: issuers can raise capital more cheaply when their green or sustainable bonds are priced above an equivalent plain (or 'vanilla') bond.

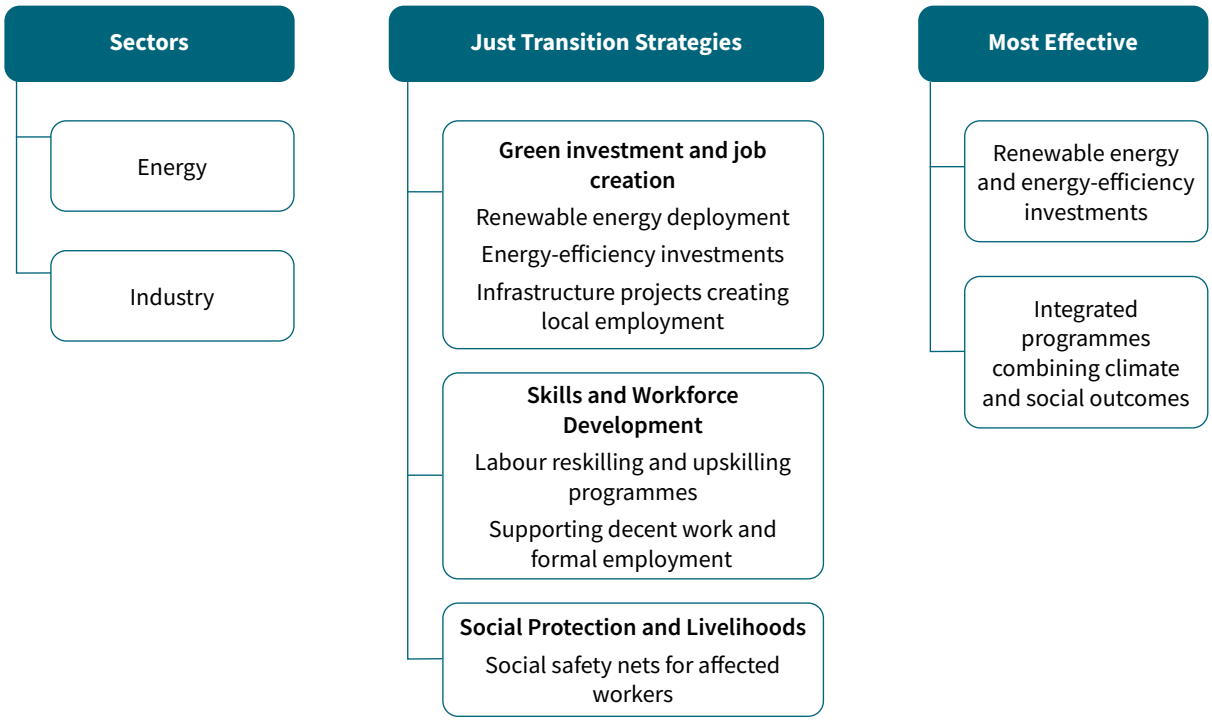
In their literature review, Demski et al. (2025) state that the literature suggests a weak financial advantage to green issuers, and the empirical evidence regarding the size of this premium is mixed. The literature does not indicate whether or not increased use of sustainable debt issuance leads to real emissions reductions by the issuer.

Other themes

The literature is geographically concentrated, with a strong focus on HICs. Among developing countries, there is a scarcity of studies evaluating ex post interventions in LMICs, outside of China and India. The review yielded no results in FCAS countries. Many studies do not have emissions reductions results and focus on the design and enabling conditions for sustainable finance interventions. These include studies on climate-related insurance products aimed at reducing vulnerability to climate impacts rather than mitigating emissions (Lee and Fung, 2023), assessments of overall financing needs for climate action (Ahluwalia and Patel, 2023), analyses of the cost of capital differentials between low-carbon and high-carbon technologies without a measurement of actual deployment or emissions outcomes (Rebelo, 2020), and green bond market development and issuance trends rather than the emissions impacts of bond-financed projects (Hamrani and Hamrani, 2024; Convergence, 2018). Much of the excluded literature comprised bibliometric analyses tracking the growing interest in sustainable finance interventions in the literature.

We identified studies on interventions that increase flows of public and private finance to low-emissions opportunities or reduce the cost of private sector capital for mitigation investment. While most studies focus on HICs, evidence suggests that policy mixes outperform individual interventions. However, signals of environmental considerations (e.g., green bond issuance) do not always result in decarbonisation.

4.9 Just transition



While early conceptualisations of just transitions arose from the US labour movement, broader understandings of just transitions have since emerged, especially in relation to climate change.

The ‘Conclusions’ section of the 2023 International Labour Conference defines a just transition as one that ‘promotes environmentally sustainable economies in a way that is inclusive, by creating decent work opportunities, reducing inequality and by leaving no one behind’. A just transition should therefore ensure that a wide range of stakeholders are involved in designing and delivering climate action, and that any climate plans create decent jobs, provide social protection, and support stakeholders, such as workers and communities, who will be negatively affected by the transition to a low-carbon economy (Jaeger et al., 2021).

There are limited to no ex post systematic reviews on just transition, which could be a result of several factors. The ‘just transition’ is still a relatively new and evolving concept, and many countries have only recently incorporated it into their climate strategies. Consequently, most interventions aimed at promoting just transitions, such as labour reskilling programmes and the promotion of alternative employment, among others, are either still ongoing or too recent to provide data or ex post evaluations of their outcomes. The evidence base is still emerging. The current and emerging literature tends to focus on conceptual frameworks and strategies to implement a just transition, with a few studies documenting lessons from regional transitions, particularly in coal-dependent economies, to highlight the importance of just transitions.

A small number of studies identified in the review examined the effectiveness of interventions related to just transitions, particularly through the lens of employment and social outcomes. These included evaluations of investments in renewable energy and energy efficiency, focusing on their potential to generate decent jobs and contribute to more equitable labour market outcomes. Some studies assessed interventions aimed at advancing just transitions in specific sectors or systems, and others explored the role of green investments in creating better or higher quality jobs. Most of these studies were not ex post, as they reviewed papers that provided forward-looking early estimates and evidence. Nevertheless, these studies may provide partial insights into how certain mitigation actions could support socially inclusive outcomes. The studies were global; however, one review focused on Argentina, Brazil, China, India, Turkey, Japan, and eight European countries, whereas another focused on non-Annex I countries, including 45 developing countries.

Effectiveness

There was consensus among the reviews that green investments have led to positive net job creation and the creation of better-quality jobs. Hanna, Heptonstall and Gross (2024) and Jaeger et al. (2021) did not meet the ex post criteria, as they were systematic reviews that primarily synthesised ex ante modelling studies rather than actual observed outcomes. However, they are included here because they offer useful context on expected job impacts. One study reviewed recent studies that estimated the net employment effects of decarbonisation in the energy sector at a national scale, finding that there is likely to be positive net job creation from replacing fossil fuels with renewables and improving energy efficiency (Hanna, Heptonstall and Gross, 2024).

Among the studies consulted in the systematic review, several identified a risk of job destruction. For example, it was found that in Argentina, job creation in energy, construction, and manufacturing could be offset by job destruction in other economic sectors. In India, it was found that net job destruction is projected in states that have considerable coal mining activity. However, based on the data, this study highlights that the construction and installation

of solar PV, biomass, and small hydro create the most jobs across different energy-generation technologies, creating between 15,000 and 18,000 job-years per GW installed (Hanna et al. 2024).

Similarly, Jaeger et al. (2021) found that renewable energy and energy-efficiency interventions could create more near-term jobs than fossil fuel investments. These authors highlight that investments in efficiency might create the most jobs. However, they also note that in developing countries, while these jobs provide opportunities for people to get out of poverty, many of them are temporary and informal and therefore do not provide long-term security. In the distributed renewable energy sector in India, Nigeria and Kenya, 60 to 70% of jobs are informal (Jaeger et al., 2021). While formal jobs in the distributed renewable energy sector last for three years on average, jobs in the informal sector last for one year or less, leading to job insecurity. The short-term nature of the jobs also means that employees may not receive benefits or access to social protection. Many new green jobs in developing countries do not have high wages, especially if they are informal, as it was noted that informal workers earn around one-tenth as much as formal workers.

The Green Climate Fund (2024) conducted a realist review of just transition interventions currently taking place in developing countries, with the realist approach focusing on the mechanisms, contextual enablers and barriers to successful just transition. While the study did not strictly meet the ex post evaluation criteria, it was included owing to its useful synthesis of evidence from implemented interventions with observable outcomes. This study focused specifically on a wide range of interventions (Table 16) that could contribute to a just transition and their effect on relevant outcomes.

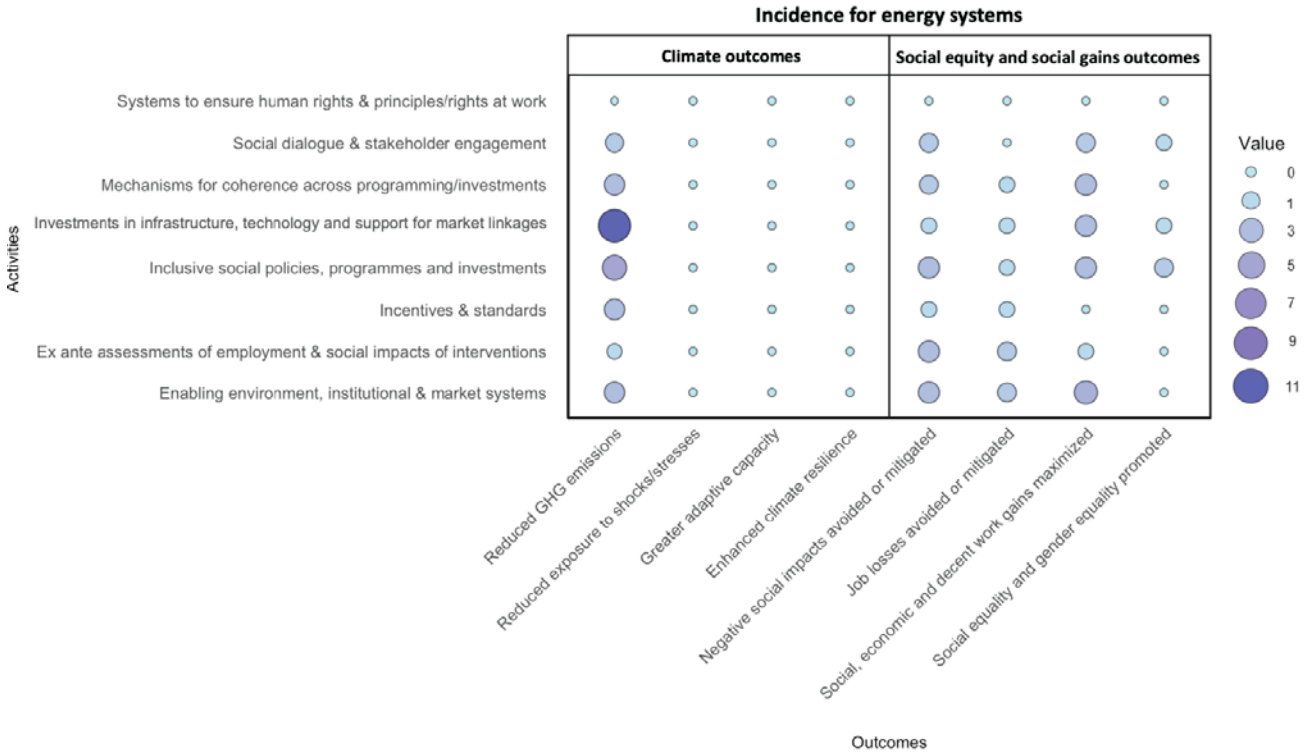
Table 16: Intervention types identified within each sector (Green Climate Fund, 2024)

	Energy	Agriculture/ Food	Infastructure	Ecosystem services	Cross-sector
Climate-smart agriculture	–	7	–	–	3
Community rural/ agricultural development	–	5	–	–	2
Employment restructuring in the coal industry	2	–	–	–	–
Energy demand-side measures	3	–	–	–	–
Fossil fuel subsidy reform	6	–	–	–	–
Green energy transmission corridor development	3	–	–	–	–
JETP – International financing for just energy transition	2	–	–	–	1

	Energy	Agriculture/ Food	Infastructure	Ecosystem services	Cross-sector
Land conservation and protection and/or reforestation	–	–	–	10	4
Marine/coastal conservation	–	–	–	2	–
Moratorium on oil activities on protected land	1	–	–	–	1
National green/ economic development or green jobs plan	1	–	–	–	7
Natural resource/water management	–	1	–	1	3
Platform for private sector involvement in renewable energy projects	1	–	–	–	–
Large-scale renewable energy intervention with social equity components	14	–	1	–	–
Skills and knowledge development in low-carbon technology	2	2	–	–	1
Small-scale and/ or community-run renewable energy development	6	–	–	–	2
Tariff structures for renewable energy	3	–	–	–	–
Waste-to-energy	1	–	1	–	–

Most interventions were found in the energy sector and focused on infrastructure investment. Reduced GHG emissions was the most reported outcome. Outcomes were often linked to investment in technology, infrastructure and market development (see Figure 7).

Figure 7: Activities mapped against outcomes in the energy sector (Green Climate Fund, 2024)



Although energy interventions reviewed in the Green Climate Fund study tended to prioritise climate goals, some also delivered social equity benefits. Social outcomes that had the highest incidence across energy sector interventions included 'prevented or reduced' negative social impacts within social groups and across societies and maximised social, economic and employment gains in regions or countries. These outcomes were linked to activities such as investments in infrastructure and technology, support for market linkages, the creation of an enabling environment, institutional and market systems, social dialogue, stakeholder engagement, and inclusive social policies, programmes and investments. These results highlight the importance of designing strategies that intentionally address equity alongside mitigation goals. For example, the 'Pollinate' intervention in Bangalore combines solar deployment with community training, which not only reduces emissions but also develops local skills and creates a local market.

In contrast, interventions in the agriculture and ecosystems sectors more frequently emphasise social equity and livelihood improvements. Overall, while evidence remains limited, the review shows that well-designed interventions in non-Annex I countries can align climate goals with social equity, especially when supported by strong governance, finance, and stakeholder engagement. In the energy sector, this includes combining emissions-reduction investments (including investments in infrastructure, technology, and support for market linkages) with measures such as social dialogue and broad stakeholder engagement across systems. Scaling just transition efforts will require adapting to local contexts and addressing both climate and development needs.

Cost-effectiveness

Evidence on the cost-effectiveness of just transition measures is limited to insights that analyse how many jobs can be created per dollar invested in green investments. Hanna, Heptonstall and Gross (2024) found that gross jobs per US$ million invested were highest on average for wind power and building energy efficiency interventions. This was based on a comparison of a range of recent job creation estimates from 14 studies across Europe, Croatia, Germany, Greece, Spain, UK, US and India. Jaeger et al. (2021) similarly found that investing US$1 million in building and industrial efficiency can create 2.8 and 1.8 times as many jobs, respectively, as investing the same amount in fossil fuels. This was followed by investments in geothermal energy, solar PV, wind and hydropower, which can create between 1.2 to 1.7 times as many jobs. Other clean energy investments, such as upgrades to existing grids, and other green investments related to public and non-motorised transport infrastructure, as well as vehicles and nature, also create more jobs than fossil fuel investments. These findings are based on data from studies across Europe, South Korea, Brazil, South Africa, Indonesia, China, the United States, Colombia and the Middle East/North Africa and include a mix of direct and indirect jobs.

Other themes

Hanna, Heptonstall and Gross (2024) highlighted the lack of metrics and data on job quality, skills, and the geographic distribution of employment impacts in decarbonising energy systems. Jaeger et al. (2021) also highlight that much of the literature focuses on high-income countries, particularly the United States. This is a finding throughout the literature; most reviews of just transition interventions focus on countries in the Global North. However, with the launch of the Just Energy Transition Partnership (JETP) in South Africa in 2021, studies are beginning to emerge that explore just transitions in the Global South. It remains too early to assess evidence on the effectiveness of these recently implemented just transition measures.

Photo credit: Patrick Hendry on Unsplash

5 Conclusion

Insights from the rapid umbrella review as a tool

We found 63 studies on the nine themes in the academic databases and grey literature that met the project's goals. Given the lack of overlap in the article lists from the different search engines, there are probably more systematic reviews that our searches did not uncover.

There were many sub-headings within our nine themes for which we found no decision-useful systematic reviews. For instance, we found no review of mitigation options for long distance passenger transport, no studies on the cost-effectiveness of changing diets, and no assessment of the efficacy of carbon or transport fuel taxes, to name just three gaps. We found only one result relevant to FCAS. Very few studies discussed other development outcomes such as climate resilience and incomes.

In practice, there was virtually no discussion of environmental or social issues other than climate mitigation. The single non-GHG issue that quite a few studies included, often in passing, was health impacts.

We encountered several challenges:

- To keep the task manageable, many reviews define their scope narrowly, leaving many measures unanalysed.
- Broader reviews, such as across the agriculture sector, often report only on bibliographic details gleaned from the metadata without analysing the case studies' findings, and therefore reach no decision-useful conclusions for our inquiry.
- Typically, ex post reviews did not draw comparisons between case studies, since differences in the policy and market context confounded comparison.
- Researchers could not locate data suitable for undertaking an ex post evaluation of some projects/policy interventions.

Identifying case studies in LMICs is a further challenge, as there is less tradition of evaluating projects or government policy, and few public bodies exist to fund and conduct large field trials. Indeed, a cost-effectiveness study purporting to focus on LMICs was unable to find air quality and health data from low-income countries and middle-income countries and instead relied on Public Health England and WHO data.

The idea that results from ex post studies are more valid than ex ante is an over-simplification. Conceptually, ex post results should be more useful than ex ante studies to decision makers, as they use observed performance rather than assumed 'idealised' performance of mitigation measures. Ex post case studies are not experiments undertaken in laboratory conditions, but evaluations of technologies and policies in the field. Each case study therefore takes place in a different socio-political context and faces different technology costs, fuel costs, grid carbon intensities, interest rates, and policy environments, which made it hard to disentangle the focus of the literature reviews – differences in carbon mitigation effectiveness and cost-effectiveness – from the case study's political and market environment. Also, results from ex post evaluations can be unduly pessimistic if regulators', suppliers', and professional advisors' unfamiliarity render the observed costs of the novel technology unduly high. However, such teething costs should reduce as technologies mature.

Cost-effective climate mitigation measures

All the themes examined in this report present 'no regrets' mitigation opportunities. These typically rely on behaviour change through information or education, energy efficiency and fuel replacement measures, or non-contentious regulatory reforms. Examples include changing diets to avoid meat and dairy in agriculture, replacing old energy-inefficient capital equipment with more efficient modern equipment (e.g., replacing blast furnaces with electric arc furnaces), using refuse-derived fuels in cement kilns in industrial energy use, mandating energy efficiency labelling on consumer electrical appliances, and providing public-transport passengers with real-time information about schedules. The evidence suggests these provide marginal but useful improvements in emissions.

Some GHG mitigation measures are low cost and provide valuable co-benefits. Segregated solid waste collection and treatment reduces landfill methane emissions, enhances recovery of valuable secondary raw materials like scrap steel, plastic pellets, and compost, and reduces nuisance and litter. Switching fuels in transport vehicles from petrol and marine diesel to compressed natural gas (CNG) in the short term, and electricity/hydrogen in the long term, can be low cost, and can provide significant health benefits from better air quality. Switching from fossil-fuel electricity generation to renewables is already cost-effective in many countries, but might require substantial investment in transmission and distribution, or storage. The just transition literature gives some ideas on the retraining and redeployment of workers whose livelihoods are dependent on fossil fuel production, but there are still too few ex post evaluations of their success.

There are also many longer-term climate mitigation technologies that need upfront investment, but with payback periods that may extend over decades. Typically, these appear in the literature as ideas, but are still too recent or have too few real-world examples to be the subject of ex post evaluations. This is especially true of urban development changes such as the densification of cities and transport-oriented development, which co-locates homes and commercial and retail space. It is also true of the creation and electrification of mass-transport systems in cities, such as bus rapid transit (BRTs), metro lines, and intercity train services. Other longer-term solutions include alternate renewable electricity systems like geothermal, solar thermal, and green hydrogen/ammonia-based shipping.

There were also some topics for which we found no ex post evidence of effectiveness. Several of these are cited as mitigation solutions, including CCS, green hydrogen and nuclear. Papers citing these technologies rely on ex ante or modelling.

Recommendations for further work

In future research of this kind, rather than conducting an open-ended search for ex post studies that report on cost-effectiveness, an alternative approach might be to:

- undertake a more targeted search for a handful of major GHG sources that need transformation;
- locate research (not necessarily systematic reviews and not necessarily by academics) that identifies a broad technical solution set. These might include studies on alternatives for cement, low-carbon steel, cooling homes and offices, low-carbon long distance travel, and segregated solid waste collection and treatment.
- analyse the cost and GHG mitigation from deploying these solutions using stylised assumptions about local market prices and support policies for different countries to provide localised advice on applicability.

We made some use of AI to identify studies, especially in the grey literature. These produced a small number of well-targeted articles. We think it could be useful to make greater use of AI to identify case studies (not necessarily reviews) and read these directly, rather than focusing only on systematic reviews, which often did not deliver as much as we anticipated from the title or abstract.

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Annexures

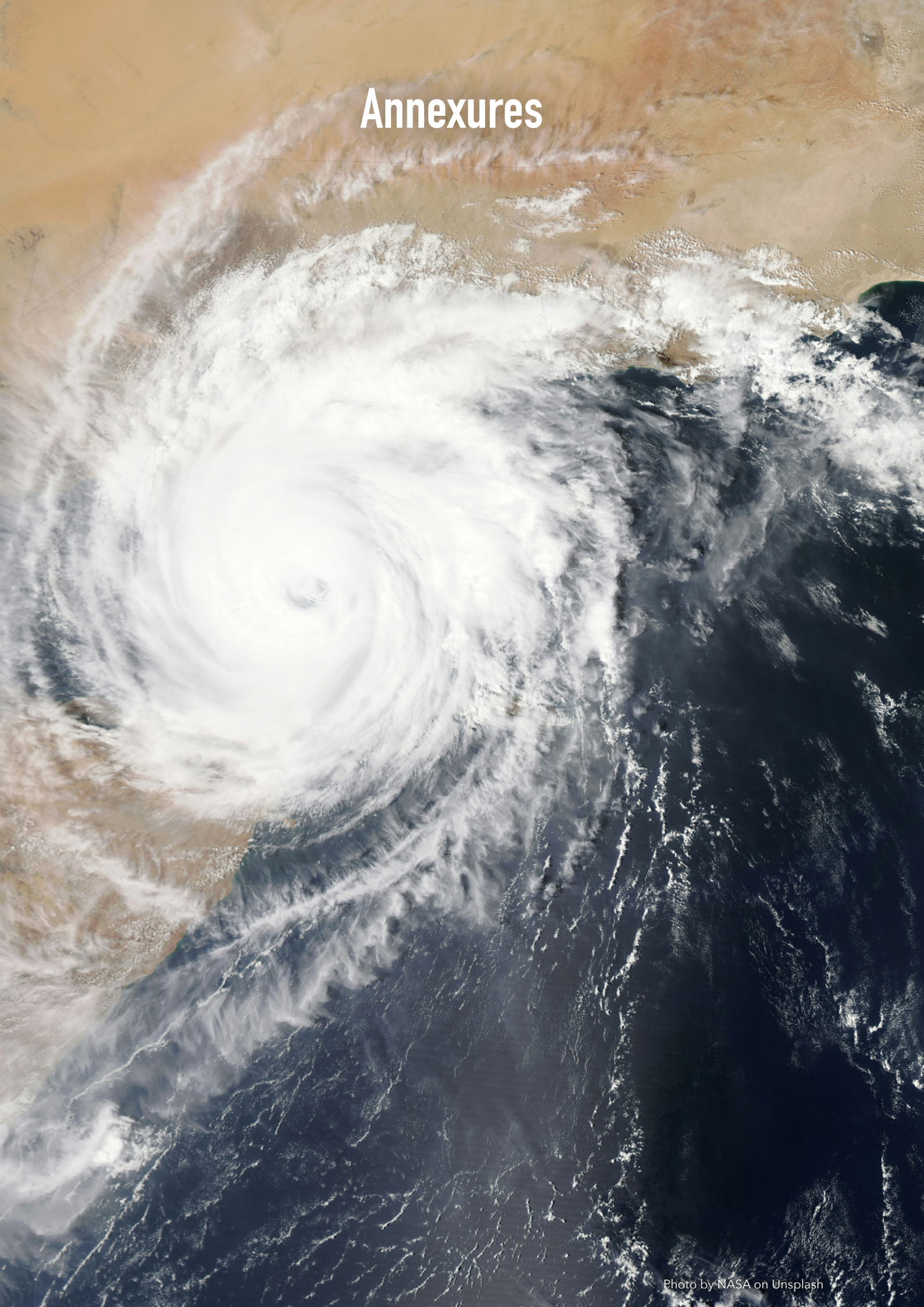

Photo by NASA on Unsplash

Annex 1 Websites used for grey literature searches

- African Development Bank
- Asian Development Bank
- Asian Infrastructure Investment Bank
- British International Investment
- Climate and Development Knowledge Network
- European Bank for Reconstruction and Development
- FMO: Dutch Entrepreneurial Development Bank
- Foreign Commonwealth Development Office Research Outputs
- Green Climate Fund
- IDEAS Research Papers in Economics (RePEc)
- Inter-American Development Bank
- International Initiative for Impact Evaluation i.e. the 3ie Development Evidence Portal
- International Institute for Sustainable Development
- International Renewable Energy Agency (IRENA)
- KfW Development Bank
- Organisation for Economic Co-operation and Development (OECD)
- Swedish International Development Agency Publications
- United Nations Development Program
- United Nations Environment Program
- Wiki.com
- World Bank – Open Knowledge Repository

Annex 2 AI search prompts for (sector)

'I need you to conduct a comprehensive search to identify academic papers for a systematic literature review on mitigation investment opportunities in low- and middle-income countries (LMICs), specifically focusing on *(sector).*

Search Objective: Find systematic reviews or meta-analysis that evaluate carbon mitigation from (*sector)* focused on GHG emission reduction and/or cost-effectiveness. Find studies that focus on countries in the global south, low- and middle-income countries particularly interventions encouraging the *(tailored to sector)*

Key Search Terms to Use:

- Primary: [sector specific words], 'systematic reviews', 'meta-analysis'
- Secondary: 'mitigation', 'GHG emissions', 'carbon reduction', 'cost-effectiveness'
- Geographic: 'low-income countries', 'middle-income countries', 'LMICs', 'developing countries', 'Global South'
- Policy/Intervention: 'market reform', 'renewable energy', 'carbon pricing', 'decarbonisation'

Search Parameters:

- **Date Range:** 2015 to present
- **Study Types:** Prioritise systematic reviews, rapid reviews, realist reviews, and meta-analyses
- **Evidence Type:** Focus on ex post evaluations (actual results, not theoretical models or projections)
- **Geographic Focus:** Studies conducted in or including LMICs

Literature Sources to Search:

- Academic journals like (*sector-specific journals)*
- Sector-specific journals and reports
- Climate policy databases and repositories
- Regional development bank publications

For Each Source Found, Please Provide:

- full citation details (authors, article title, publication, volume, number, year)
- abstract or executive summary
- key findings related to GHG emissions or cost-effectiveness
- geographic coverage (which LMICs/regions)
- type of intervention studied
- whether it provides ex post evidence
- study methodology (systematic review, meta-analysis, etc.)
- direct link/DOI if available

Prioritise Sources that:

- include quantitative results on emissions reduction
- provide cost-effectiveness analysis
- cover multiple LMIC contexts
- are recent (2020–2025) systematic reviews.'

Annex 3 Search strategies for academic databases that diverged from the protocol given in Annex 2

The annex shows the sector-specific search strategies we used to sort through academic databases.

Renewable energy (RE)

EBSCO

Search strings used:

1. TI 'systematic review' AND TX ('renewable energy' OR 'solar' OR 'wind') AND TX ('energy access' OR 'electricity access') AND TX ('developing countries' OR 'LMICs') AND TX ('cost' OR 'economic') AND TX 'ex post'
2. TI ('Systematic review' OR 'meta-analysis') OR TX ('Systematic review' OR 'meta-analysis') AND TX ('renewable energy' OR 'energy access') AND TX ('market reform' OR 'energy pricing' OR 'electricity pricing') AND TX ('mitigation' OR 'emission reduction') AND TX ('developing countries' OR 'LMICs' OR 'low income' OR 'middle income') AND TX 'ex post'
3. TI ('Systematic review' OR 'meta-analysis') AND TX ('renewable energy' OR 'mini-grid' OR 'off-grid' OR 'distributed energy') AND TX ('energy access' OR 'electricity access') AND TX ('cost effectiveness' OR 'economic evaluation') AND TX ('developing countries' OR 'low income' OR 'middle income' OR 'LMIC') AND TX 'ex post'
4. TX (('Systematic Review' OR 'Meta Analysis') AND (carbon* OR Mitigation OR GHG)) AND TX (('Abatement cost' OR 'Economic analysis' OR 'cost per ton')) AND TI ('renewable energy' OR 'energy access' OR 'clean energy')
5. TX (('Systematic Review' OR 'Meta Analysis') AND (carbon* OR Mitigation OR GHG)) AND TX (('Abatement cost' OR 'Economic analysis' OR 'cost per ton')) AND TI ('renewable energy' OR 'energy access' OR 'clean energy') AND TX('low income' OR 'middle income' OR 'developing countr*' OR 'LMIC')
6. TX (('Systematic Review' OR 'Meta Analysis') AND (carbon* OR itigation OR GHG)) AND TX (('Abatement cost' OR 'Economic analysis' OR 'cost per ton')) AND TI ('energy access' AND ('renewable' OR 'solar' or 'wind' OR 'geothermal' OR 'hydro'))
7. TX (('Systematic Review' OR 'Meta Analysis') AND (carbon* OR Mitigation OR GHG)) AND TX (('Abatement cost' OR 'Economic analysis' OR 'cost per ton')) AND TX ('energy price' OR 'market reform' AND ('renewable energy' OR 'clean energy'))

Google Scholar

Search strings used:

1. (‘Systematic review’ OR ‘meta-analysis’) AND (‘renewable energy’ OR ‘energy access’) AND (‘market reform’ OR ‘energy pricing’) AND (‘mitigation’ OR ‘emission reduction’) AND (‘low income’ OR ‘developing countries’) AND ‘ex post’
2. (‘Systematic review’ OR ‘meta analysis’) AND (‘renewable energy’ OR ‘mini-grid’ OR ‘off-grid’) AND (‘energy access’ OR ‘electricity access’) AND (‘cost effectiveness’ OR ‘economic evaluation’) AND (‘developing countries’ OR ‘LMICs’) AND ‘ex post’
3. (‘Systematic review’ OR ‘meta-analysis’) AND (‘energy market reform’ OR ‘renewable energy auctions’ OR ‘electricity market’) AND (‘fossil fuel subsidy’ OR ‘energy pricing’) AND (‘emission reduction’ OR ‘mitigation’) AND (‘global south’ OR ‘low income’) AND ‘ex post’
4. (‘Systematic review’ OR ‘meta analysis’) AND (‘energy storage’ OR ‘grid modernisation’ OR ‘power grid’) AND (‘renewable energy integration’ OR ‘clean energy’) AND (‘cost benefit’ OR ‘economic analysis’) AND (‘developing countries’ OR ‘middle income’) AND ‘ex post’
5. (‘Systematic review’ OR ‘meta-analysis’) AND (‘Solar’ OR ‘wind’ OR ‘hydroelectric’ OR ‘geothermal’ OR ‘renewable electricity’) AND (‘energy policy’ OR ‘market design’) AND (‘emission reduction’ OR ‘carbon mitigation’) AND (‘developing world’ OR ‘emerging economies’) AND (‘evaluation’ OR ‘ex post’)
6. (‘Systematic review’ OR ‘meta analysis’ OR ‘meta-analysis’) AND (‘cost effectiveness’ OR ‘abatement cost’ OR ‘economic analysis’) AND (‘emissions reduction’ OR ‘GHG emission’ OR ‘low carbon’ OR ‘mitigation’) AND (‘global south’ OR ‘low income’ OR ‘middle income’ OR ‘developing’) AND (‘renewable energy’ AND (‘energy access’ OR ‘market reform’ OR ‘energy pricing’)
7. (‘Systematic review’ OR ‘meta-analysis’) AND (‘mitigation’ OR ‘emission reduction’) AND (‘low income’ OR ‘developing countries’) AND (‘renewable’ OR ‘biomass’ OR ‘clean energy’ OR ‘wind’ OR ‘solar’ OR ‘geothermal’) AND ‘ex post’
8. (‘Systematic review’ OR ‘meta-analysis’) AND (‘mitigation’ OR ‘emission reduction’) AND (‘low income’ OR ‘developing countries’) AND (‘market’ AND (‘electrification’ OR ‘feed-in tariff*’ OR ‘energy access’))
9. (‘Systematic review’ OR ‘meta-analysis’) AND (‘mitigation’ OR ‘emission reduction’) AND (‘low income’ OR ‘developing countries’) AND (‘photovoltaic’ OR ‘decentralised’ OR ‘off-grid’)
10. (‘Systematic review’ OR ‘meta analysis’ OR ‘meta-analysis’) AND (‘return on investment’ OR ‘payback period’) AND (‘emissions reduction’ OR ‘GHG emission’ OR ‘low carbon’ OR ‘mitigation’) AND (‘global south’ OR ‘low income’ OR ‘middle income’ OR ‘developing’) AND (‘renewable energy’ AND (‘energy access’ OR ‘market reform’ OR ‘energy pricing’)
11. (‘Systematic review’ OR ‘meta-analysis’) AND (‘biomass’ OR ‘bioenergy’ OR (‘tidal’ OR ‘wave’ AND ‘energy’)) AND (‘market reform’ OR ‘energy pricing’) AND (‘mitigation’ OR ‘emission reduction’) AND (‘low income’ OR ‘developing countries’) AND ‘ex post’
12. (‘Systematic review’ OR ‘meta analysis’) AND (‘grid’ AND (‘photovoltaic’ OR ‘decentralised’ OR ‘off-grid’)) AND (‘renewable energy integration’ OR ‘clean energy’) AND (‘cost benefit’ OR ‘economic analysis’) AND (‘developing countries’ OR ‘middle income’) AND ‘ex post’
13. (‘Systematic review’ OR ‘meta-analysis’)) AND (‘market reform’ OR ‘energy pricing’) AND (‘market design’ OR ‘access’ AND (‘electrification’ OR ‘feed-in tariff’ OR ‘feed in tariff’)) AND (‘mitigation’ OR ‘emission reduction’) AND (‘low income’ OR ‘developing countries’) AND ‘ex post’

Filters:

- Date range 2015–2025

Web of Science

Search strings used:

1. ('Systematic review' OR 'meta-analysis') AND ('renewable energy' OR 'energy access') AND ('market reform' OR 'energy pricing') AND ('mitigation' OR 'emission reduction') AND ('low income' OR 'developing countries') AND 'ex post'
2. ('Systematic review' OR 'meta-analysis') AND ('mitigation' OR 'emission reduction') AND ('low income' OR 'developing countries') AND ('renewable' OR 'biomass' OR 'clean energy' OR 'wind' OR 'solar' OR 'geothermal') AND 'ex post'
3. ('Systematic review' OR 'meta analysis' OR 'meta-analysis') AND ('cost' OR 'economic analysis') AND ('mitigation' OR 'GHG emissions' OR 'emissions reduction') AND 'renewable energy'
4. ('Systematic review' OR 'meta-analysis') AND ('mitigation' OR emission*) AND ('low income' OR 'developing countries') AND ('renewable' OR 'biomass' OR 'clean energy' OR 'wind' OR 'solar' OR 'geothermal' OR 'access' OR 'electrification')
5. ('Systematic review' OR 'meta analysis' OR 'meta-analysis') AND ('cost' OR 'economic analysis') AND ('mitigation' OR 'GHG emissions' OR 'emissions reduction') AND ('renewable' AND 'technology')

Scopus

Search strings used:

1. ('Systematic review' OR 'meta analysis' OR 'meta-analysis' OR 'ex post') AND ('cost effective' OR 'abatement cost' OR 'economic analysis') AND ('clean energy' OR 'bioenergy' OR 'renewable energy' AND ('mitigation'))
2. ('Systematic review' OR 'meta analysis' OR 'meta-analysis' OR 'ex post') AND ('cost effective' OR 'abatement cost' OR 'economic analysis') AND ('renewable energy' AND ('energy access' OR 'market reform' OR 'energy pricing')
3. ('Systematic review' OR 'meta analysis' OR 'meta-analysis' OR 'ex post') AND ('cost effective' OR 'abatement cost' OR 'economic analysis') AND ('renewable energy' AND ('feed-in tariff' OR 'feed in tariff' OR 'access' OR 'grid' OR 'storage')
4. ('Systematic review' OR 'meta analysis' OR 'meta-analysis' OR 'ex post') AND ('cost effective' OR 'abatement cost' OR 'economic analysis') AND (('Solar' OR 'wind' OR 'hydroelectric' OR 'geothermal' OR 'renewable*') AND ('energy policy' OR 'market design' OR 'pricing')

Searching by key journals through EBSCO

Search strings used:

- AB ('mitigation' OR 'prevention' OR 'reduction') AND SO 'XXX' AND AB ('review' OR 'meta-analysis' OR 'systematic') AND renewable energy
- AB ('mitigation' OR 'prevention' OR 'reduction') AND SO 'XXX' AND AB ('review' OR 'meta-analysis' OR 'systematic') AND AB ('developing' OR 'middle income' OR 'low income') AND renewable energy

Check the following journals (*XXX):*

- Nature Energy
- Renewable and Sustainable Energy Reviews
- Energy Policy
- Energy Economics
- The Energy Journal

Carbon pricing

The theme-specific search terms applied (italicised below) were 'carbon pricing', 'carbon tax' and 'emissions trading'.

Google Scholar
Search strings used:
1. ('literature review' OR 'systematic review' OR 'meta analysis') AND ('abatement cost' OR 'economic analysis') AND ('GHG emission' OR 'low carbon' OR 'mitigation') AND ('*theme search term')*
2. ('literature review' OR 'systematic review' OR 'meta analysis') AND ('abatement cost' OR 'economic analysis') AND ('GHG emission' OR 'low carbon' OR 'mitigation') AND *('theme search term')* AND ('global south' OR 'low income' OR 'middle income')

Web of Science
Search strings used:
1. ('literature review' OR 'systematic review' OR 'meta analysis') AND ('GHG emission' OR 'low carbon' OR 'mitigation') AND ('*theme search term')*
2. *(*'literature review' OR 'systematic review' OR 'meta analysis') AND 'effectiveness' AND ('GHG emission' OR 'low carbon' OR 'mitigation' OR 'price' OR 'cost') AND *('theme search term')*
3. ('literature review' OR 'systematic review' OR 'meta analysis') AND ('GHG emission' OR 'low carbon' OR 'mitigation' OR 'price' OR 'cost') AND *('theme search term')*

Scopus
1. ('literature review' OR 'systematic review' OR 'meta analysis') AND ('GHG emission' OR 'low carbon' OR 'mitigation') AND ('carbon pricing' OR 'carbon tax' OR 'emissions trading')
2. ('literature review' OR 'systematic review' OR 'meta analysis') AND ('effectiveness') AND ('GHG emission' OR 'low carbon' OR 'mitigation' OR 'price' OR 'cost') AND ('carbon pricing' OR 'carbon tax' OR 'emissions trading')
3. ('literature review' OR 'systematic review' OR 'meta analysis') AND ('GHG emission' OR 'low carbon' OR 'mitigation' OR 'price' OR 'cost') AND ('carbon pricing' OR 'carbon tax' OR 'emissions trading')

Searching by key journals through EBSCO
Search string used:
- AB ('mitigation OR 'prevention' OR 'reduction') AND SO '*XXX'* AND AB ('review' OR 'meta-analysis' OR 'systematic') AND carbon pricing

Checked the following journals (*XXX):*
- Journal of Environmental Economics and Management (JEEM)
- Environmental and Resource Economics (ERE)
- Review of Environmental Economics and Policy (REEP)
- Energy Economics
- The Energy Journal
- Climate Policy
- Nature Climate Change
- Journal of Cleaner Production
- Nature Communications

Natural climate solutions

EBSCO

Search strings used:

1. TI (‘Systematic review’ OR ‘meta-analysis’) AND TX (‘ecosystems’ OR ‘land stewardship’ OR ‘natural climate solutions’) AND TX(‘carbon storage’ OR ‘emission reduction’) AND TX (‘Global South’ OR ‘developing countries’) AND TX ‘ex post’
2. TI (‘natural climate solution’ OR ‘nature-based solution’) AND TX (‘ecosystem services’ OR ‘natural capital’ OR ‘green infrastructure’) AND TX (‘climate mitigation’ OR ‘carbon benefits’) AND TX (‘low income’ OR ‘developing countries’) AND ‘ex post’
3. TX (‘ecosystem services’ OR ‘natural capital’ OR ‘natural climate solution’ OR ‘nature-based solution’) AND TX (‘climate mitigation’ OR ‘carbon benefits’) AND TX (‘low income’ OR ‘developing countries’) AND ‘ex post’
4. AB (‘cost’) AND TX (‘ecosystem services’ OR ‘natural capital’ OR ‘natural climate solution’ OR ‘nature-based solution’) AND TX (‘mitigation’ OR ‘emission reduction’) AND TX (‘low income’ OR ‘developing countries’) AND ‘ex post’
5. TX (‘ecosystem services’ OR ‘natural capital’ OR ‘natural climate solution’ OR ‘nature-based solution’) AND TX (‘mitigation’ OR ‘emission reduction’) AND TX (‘low income’ OR ‘developing countries’) AND ‘ex post’

Filters:

- Peer-reviewed literature
- Date range 2015–2025

Google Scholar

Search strings used:

1. (‘Systematic review’ OR ‘meta-analysis’) AND (‘natural climate solutions’ OR ‘nature-based solutions’ OR ‘ecosystem restoration’) AND (‘carbon sequestration’ OR ‘carbon storage’ OR ‘mitigation’) AND (‘climate finance’ OR ‘market reform’ OR ‘payment ecosystem services’) AND (‘low income’ OR ‘developing countries’) AND ‘ex post’
2. (‘Systematic review’ OR ‘meta-analysis’) AND (‘reforestation’ OR ‘afforestation’ OR ‘forest conservation’ OR ‘avoided deforestation’) AND (‘carbon credits’ OR ‘REDD+’ OR ‘forest finance’) AND (‘emission reduction’ OR ‘carbon storage’) AND (‘low income’ OR ‘developing countries’) AND ‘ex post’
3. (‘Systematic review’ OR ‘meta-analysis’) AND (‘mangrove restoration’ OR ‘seagrass’ OR ‘blue carbon’ OR ‘Blue ecosystems’) AND (‘blue finance’ OR ‘ocean finance’ OR ‘marine conservation’) AND (‘carbon sequestration’ OR ‘mitigation’) AND (‘low income’ OR ‘developing countries’) AND ‘ex post’
4. (‘Systematic review’ OR ‘meta-analysis’) AND (‘regenerative agriculture’ OR ‘agroforestry’ OR ‘grassland management’ OR ‘soil carbon’) AND (‘conservation finance’ OR ‘sustainable agriculture’ OR ‘carbon farming’) AND (‘emission reduction’ OR ‘carbon storage’) AND (‘low income’ OR ‘developing countries’) AND ‘ex post’
5. (‘Systematic review’ OR ‘meta-analysis’) AND (‘conservation finance’ OR ‘biodiversity credits’ OR ‘green bonds’ OR ‘impact investing’) AND (‘ecosystem restoration’ OR ‘habitat conservation’) AND (‘carbon offset’ OR ‘mitigation’) AND (‘low income’ OR ‘developing countries’) AND ‘ex post’

6. (‘Systematic review’ OR ‘meta-analysis’) AND (‘community-based management’ OR ‘indigenous land management’ OR ‘participatory conservation’) AND (‘natural resource management’ OR ‘ecosystem services’) AND (‘carbon sequestration’ OR ‘emission reduction’) AND (‘low income’ OR ‘developing countries’) AND ‘ex post’
7. (‘Systematic review’ OR ‘meta-analysis’) AND (‘ecosystem services’ OR ‘natural capital’ OR ‘green infrastructure’) AND (‘environmental finance’ OR ‘sustainability bonds’) AND (‘climate mitigation’ OR ‘carbon benefits’) AND (‘low income’ OR ‘developing countries’) AND ‘ex post’
8. (‘Systematic review’ OR ‘meta-analysis’) AND (‘protect’ OR ‘manage’ OR ‘restore’) AND (‘ecosystems’ OR ‘land stewardship’ OR ‘natural climate solutions’) AND (‘carbon storage’ OR ‘emission reduction’) AND (‘tropical’ OR ‘developing countries’) AND ‘ex post’

Filters:
Date range 2015–2025

Web of Science
Search strings used:
1. (‘Systematic review’ OR ‘meta analysis’ OR ‘meta-analysis’ OR ‘ex post’) AND (‘cost effective’ OR ‘abatement cost’ OR ‘economic analysis’) AND (‘natural climate solution’ OR ‘nature-based solution’ or ‘‘ecosystem restoration’ AND (‘mitigation’)
2. (‘Systematic review’ OR ‘meta analysis’ OR ‘meta-analysis’ OR ‘ex post’) AND (‘cost effective’ OR ‘abatement cost’ OR ‘economic analysis’) AND (‘natural climate solution’ OR ‘nature-based solution’ or ‘‘ecosystem restoration’)
3. (‘Systematic review’ OR ‘meta analysis’ OR ‘meta-analysis’ OR ‘ex post’) AND (‘cost effective’ OR ‘abatement cost’ OR ‘economic analysis’) AND (‘reforestation’ OR ‘afforestation’ OR ‘forest conservation’ OR ‘avoided deforestation’)
4. (‘Systematic review’ OR ‘meta analysis’ OR ‘meta-analysis’ OR ‘ex post’) AND (‘cost effective’ OR ‘abatement cost’ OR ‘economic analysis’) AND (‘regenerative agriculture’ OR ‘agroforestry’ OR ‘grassland management’ OR ‘soil carbon’) AND (‘emission reduction’ OR ‘carbon storage’ OR ‘mitigation’)

Scopus
Search strings used:
1. (‘Systematic review’ OR ‘meta analysis’ OR ‘meta-analysis’ OR ‘ex post’) AND (‘cost effective’ OR ‘abatement cost’ OR ‘economic analysis’) AND (‘natural climate solution’ OR ‘nature-based solution’ or ‘‘ecosystem restoration’ AND (‘mitigation’))
2. (‘Systematic review’ OR ‘meta analysis’ OR ‘meta-analysis’ OR ‘ex post’) AND (‘cost effective’ OR ‘abatement cost’ OR ‘economic analysis’) AND (‘natural climate solution’ OR ‘nature-based solution’ or ‘‘ecosystem restoration’)
3. (‘Systematic review’ OR ‘meta analysis’ OR ‘meta-analysis’ OR ‘ex post’) AND (‘cost effective’ OR ‘abatement cost’ OR ‘economic analysis’) AND (‘reforestation’ OR ‘afforestation’ OR ‘forest conservation’ OR ‘avoided deforestation’)
4. (‘Systematic review’ OR ‘meta analysis’ OR ‘meta-analysis’ OR ‘ex post’) AND (‘cost effective’ OR ‘abatement cost’ OR ‘economic analysis’) AND (‘regenerative agriculture’ OR ‘agroforestry’ OR ‘grassland management’ OR ‘soil carbon’) AND (‘emission reduction’ OR ‘carbon storage’ OR ‘mitigation’)

Searching by key journals through EBSCO
Search string used:
(SO (*XXX*) AND (AB (Review OR Meta-analysis OR Systematic)) AND Just Transition) or (AB (mitigation OR prevention OR reduction) AND (climate OR GHG OR carbon) AND SO 'natural climate solutions reviews'

Filters:
Date range 2015–2025

Checked the following journals (*XXX):*

- Nature Climate Change
- Global Change Biology
- Climate Policy
- Environmental Research Letters
- Conservation Biology
- Ecological Applications
- Journal of Applied Ecology
- Restoration Ecology
- Forest Ecology and Management
- Global Environmental Change
- Land Use Policy
- Nature Sustainability
- Science of The Total Environment

Agriculture

Search strings were created to search for both (i) mitigation interventions specific to the agriculture sector and (ii) food supply chains, or interventions beyond the farm.

EBSCO
Search strings used:

1. AB (literature review or review of the literature or systematic review or meta-analysis or meta) AND AB (GHG emissions or greenhouse gas emissions or mitigation) AND AB (cost or effectiveness) AND AB (agric* or farm* or forest*)
2. TI (mitigation or abatement or emission) AND AB supply chain AND AB (food or agric*) AND AB (systematic or 'meta analysis')
3. AB ('Systematic review' OR 'meta analysis' OR evaluation) AND AB ('GHG emissions' OR 'greenhouse gas emissions' OR mitigation) AND AB 'food processing'
4. AB ('Systematic review' OR 'meta analysis' OR evaluation) AND AB ('GHG emissions' OR 'greenhouse gas emissions' OR mitigation) AND AB 'food packaging'
5. AB ('Systematic review' OR 'meta analysis' OR evaluation) AND AB ('GHG emissions' OR 'greenhouse gas emissions' OR mitigation) AND AB ('food retail*'
6. AB ('Systematic review' OR 'meta analysis' OR evaluation) AND AB ('GHG emissions' OR 'greenhouse gas emissions' OR mitigation) AND AB ('food industry')
7. AB ('Systematic review' OR 'meta analysis' OR evaluation) AND AB ('GHG emissions' OR 'greenhouse gas emissions' OR mitigation) AND AB ('food waste')

Filters:

- Peer-reviewed literature
- Date range 2015–2025

Google Scholar

Search strings used:

1. ('Systematic review' OR 'meta analysis') AND ('GHG emissions' OR 'greenhouse gas emissions') AND mitigation AND ('abatement cost' OR 'economic analysis') AND agric*
2. ('Systematic review' OR 'meta analysis') AND ('GHG emissions' OR 'greenhouse gas emissions') AND mitigation AND ('abatement cost') AND agric*
3. 'systematic review' OR 'meta analysis') AND in title: ('GHG emissions' OR 'greenhouse gas emissions' AND agric* in text: (systematic review OR meta)
4. ('Systematic review' OR 'meta analysis') AND ('GHG emissions' OR 'greenhouse gas emissions') AND mitigation AND ('abatement cost' OR 'economic analysis') AND 'food processing'
5. ('Systematic review' OR 'meta analysis') AND ('GHG emissions' OR 'greenhouse gas emissions') AND mitigation AND ('abatement cost' OR 'economic analysis') AND 'food packaging'
6. ('Systematic review' OR 'meta analysis') AND ('GHG emissions' OR 'greenhouse gas emissions') AND mitigation AND ('abatement cost' OR 'economic analysis') AND 'food retail*'

Filters:

- Date range 2015–2025

The publications of two of the identified experts in this field – Pete Smith and Frank Tubiello – were also separately screened.

Web of Science

Search strings used:

1. ('Systematic review' OR 'meta analysis') AND ('GHG emissions' OR 'low carbon' OR 'mitigation') AND 'agriculture' AND ('abatement cost' OR 'cost effective' OR 'economic analysis') AND ('global south' OR 'low income' OR 'middle income' OR 'developing')
2. ('Systematic review' OR 'meta analysis') AND ('GHG emissions' OR 'mitigation') AND 'agriculture' AND ('cost' OR 'economic analysis') AND ('global south' OR 'low income' OR 'middle income' OR 'developing')
3. ('Systematic review' OR 'meta analysis') AND ('GHG emissions' OR 'mitigation' OR 'emissions reduction') AND agricultur* AND ('cost' OR 'economic analysis' OR 'cost effective')
4. ('Systematic review' OR 'meta analysis') AND ('GHG emissions' OR 'mitigation' OR 'emissions reduction') AND nutrient management AND ('cost' OR 'economic analysis' OR 'cost effective')

Scopus

Search strings used:

1. ('Systematic review' OR 'meta analysis') AND ('GHG emissions' OR 'mitigation' OR 'emissions reduction' OR 'greenhouse gas emissions') AND agricultur* AND ('cost' OR 'economic analysis' OR 'cost effective') AND ('global south' OR 'low income' OR 'middle income' OR 'developing')
2. ('Systematic review' OR 'meta analysis') AND ('GHG emissions' OR 'mitigation' OR 'emissions reduction' OR 'greenhouse gas emissions') AND agricultur* AND ('cost' OR 'economic analysis' OR 'cost effective')

Searching by key journals through EBSCO

Search string used:

- AB (mitigation or reduction or abatement) AND AB (emissions or greenhouse) AND SO *XXX* AND AB (review or review of literature or literature review or meta-analysis or systematic review)

Filters:

- Date range 2015–2025

Checked the following journals (*XXX)*:

- Agricultural and Resource Economics Review
- Agriculture, Ecosystems & Environment
- American Journal of Agricultural Economics
- Annual Review of Resource Economics
- Australian Journal of Agricultural and Resource Economics
- Carbon management
- Climate Change Economics
- Climate Policy
- Ecological Economics
- Economics of Disasters and Climate Change
- Economics of Energy and Environmental Policy
- Environment and Development Economics
- Environmental and Resource Economics
- Environmental Economics
- Environmental Management
- Environmental Research Letters
- Environmental Science and Policy
- Global Change Biology
- International Journal of Ecology & Development
- Journal of Agricultural and Applied Economics
- Journal of Agricultural and Resource Economics
- Journal of Development Economics
- Journal of Environmental Economics and Management
- Journal of Environmental Economics and Policy
- Journal of Environmental Management
- Journal of Environmental Planning and Management
- Journal of the Association of Environmental and Resource Economics
- Land Economics
- Nature
- Nature climate change
- Nature Communications
- Nature Food
- Nature sustainability
- PloS one
- Review of Environmental Economics and Policy
- Sustainability

Finance and markets

EBSCO

Search strings used:

1. TX ((‘Systematic Review’ OR ‘Meta Analysis’) AND (carbon* OR Mitigation OR GHG)) AND TX ((‘Abatement cost’ OR ‘Economic analysis’ OR ‘cost per ton’)) AND TI (‘blended finance’ OR ‘climate finance’ OR ‘carbon credits’ OR ‘carbon finance’ AND ‘blue’ OR ‘green’)
2. TX ((‘Systematic Review’ OR ‘Meta Analysis’ OR ‘ex post’) AND (carbon* OR Mitigation OR GHG)) AND TX ((‘Abatement cost’ OR ‘Economic analysis’ OR ‘cost per ton’)) AND TI (‘blended finance’ OR ‘climate finance’ OR carbon* AND blue OR green)
3. TX ((‘Systematic Review’ OR ‘Meta Analysis’ OR ‘ex post’) AND (carbon* OR Mitigation OR GHG)) AND TX ((‘Abatement cost’ OR ‘Economic analysis’ OR ‘cost per ton’)) AND TI (‘blended finance’ OR ‘climate finance’ OR carbon*) AND AB (blue OR green OR nature OR ocean OR coastal OR ecosystem AND ‘finance’)
4. TX ((‘Systematic Review’ OR ‘Meta Analysis’ OR ‘ex post’) AND (carbon* OR Mitigation OR GHG)) AND TX ((‘Abatement cost’ OR ‘Economic analysis’ OR ‘cost per ton’)) AND TX (‘blended finance’ OR ‘climate finance’ OR carbon*) AND TI ((blue OR green OR nature OR ocean OR coastal OR ecosystem AND ‘finance’) AND (‘blue bond*’ OR ‘green bond*’ OR ‘blue finance’ OR ‘green finance’ OR ‘nature finance’ OR ‘ocean finance’)) AND TX (‘mobilisation’ OR ‘mobilization’)
5. TX ((‘Systematic Review’ OR ‘Meta Analysis’ OR ‘ex post’) AND (carbon* OR Mitigation OR GHG)) AND TX ((‘Abatement cost’ OR ‘Economic analysis’ OR ‘cost per ton’)) AND TX (‘blended finance’ OR ‘climate finance’ OR ‘blue finance’ OR ‘green finance’ OR ‘nature finance’ OR ‘ocean finance’) AND TI (blue OR green OR nature OR ocean OR coastal OR ecosystem AND ‘finance’) AND TX (‘blue bond*’ OR ‘green bond*’ OR ‘mobilisation’ OR ‘mobilization‘)
6. TX ((‘Systematic Review’ OR ‘Meta Analysis’ OR ‘ex post’) AND (carbon* OR Mitigation OR GHG)) AND TX ((‘Abatement cost’ OR ‘Economic analysis’ OR ‘cost effective’)) AND TI (‘blended finance’ OR ‘climate finance’ OR ‘blue finance’ OR ‘green finance’ OR ‘nature finance’ OR ‘ocean finance’) AND TX (blue OR green OR nature OR ocean OR coastal OR ecosystem AND ‘finance’) AND TX (‘blue bond*’ OR ‘green bond*’ OR ‘mobilisation’ OR ‘mobilization’)

Filters:

- Peer-reviewed literature
- Date range 2015–2025

Google Scholar

Search strings used:

1. (‘Systematic review’ OR ‘meta analysis’) AND (‘blended finance’ OR ‘climate finance’) AND (‘private finance leverage’ OR ‘carbon credits’) AND (‘mitigation’ OR ‘GHG emissions’) AND (‘global south’ OR ‘low income’ OR ‘middle income’)
2. (‘Systematic review’ OR ‘meta analysis’) AND (‘blended finance’ OR ‘climate finance’) AND (‘private finance’ OR ‘leverage’ OR ‘carbon credits’) AND (‘mitigation’ OR ‘GHG emissions’) AND (‘global south’ OR ‘low income’ OR ‘middle income’)
3. (‘Systematic review’ OR ‘meta analysis’) AND (‘blended finance’ OR ‘climate finance’) AND (‘private finance’ OR ‘leverage’ OR ‘carbon credits’) AND (‘mitigation’ OR ‘GHG emissions’) AND (‘global south’ OR ‘low income’ OR ‘middle income’) AND (‘global south’ OR ‘low income’ OR middle income’) AND ‘ex post’

4. (‘Systematic review’ OR ‘meta analysis’ OR ‘ex post’ OR ‘economic analysis’) AND (‘blended finance’ OR ‘climate finance’) AND (‘private finance’ OR ‘leverage’ OR ‘carbon credits’ OR ‘mobilis*’ OR ‘mobilis*’) AND (‘mitigation’ OR ‘abatement’ OR ‘emissions’) AND (‘global south’ OR ‘low income’ OR ‘middle income’) AND (green OR blue)
5. (‘Systematic review’ OR ‘meta analysis’ OR ‘economic analysis’) AND (‘blended finance’ OR ‘climate finance’) AND (‘private finance’ OR ‘leverage’ OR ‘carbon credits’) AND (‘mitigation’ OR ‘abatement’ OR ‘emissions’) AND (‘global south’ OR ‘low income’ OR ‘middle income’) AND (green OR blue) AND ‘ex post’
6. (‘Systematic review’ OR ‘meta analysis’ OR ‘economic analysis’) AND (‘blended finance’ OR ‘climate finance’) AND (‘private finance’ OR ‘leverage’ OR ‘carbon credits’) AND (‘mitigation’ OR ‘abatement’ OR ‘emissions’) AND (‘global south’ OR ‘low income’ OR ‘middle income’) AND (‘nature’ OR ‘blue economy’ OR ‘ocean’) AND ‘ex post’
7. (‘Systematic review’ OR ‘meta analysis’ OR ‘economic analysis’) AND (‘blended finance’ OR ‘climate finance’) AND (‘private finance’ OR ‘leverage’ OR ‘carbon credits’) AND (‘mitigation’ OR ‘abatement’ OR ‘emissions’) AND (‘global south’ OR ‘low income’ OR ‘middle income’) AND (‘nature’ OR ‘blue economy’ OR ‘ocean’ OR ‘marine’ OR ‘coastal’ OR ‘ecosystem’) AND ‘ex post’
8. (‘Systematic review’ OR ‘meta analysis’ OR ‘economic analysis’) AND (‘blended finance’ OR ‘climate finance’ OR ‘private finance’ OR ‘leverage’ OR ‘carbon credits’) AND (‘mitigation’ OR ‘abatement’ OR ‘emissions’) AND (‘global south’ OR ‘low income’ OR ‘middle income’) AND (‘nature finance’ OR ‘blue economy’ OR ‘ocean finance’ OR ‘marine finance’ OR ‘coastal’ OR ‘ecosystem’) AND ‘ex post’
9. (‘Systematic review’ OR ‘meta analysis’ OR ‘meta-analysis’) AND (‘cost-effectiveness’ OR ‘abatement cost’ OR ‘economic analysis’) AND (‘emissions reduction’ OR ‘GHG emission’ OR ‘low-carbon’ OR ‘mitigation’) AND (‘nature finance’ OR ‘blue economy’ OR ‘ocean finance’ OR ‘marine finance’ OR ‘coastal’ OR ‘ecosystem’)
10. (‘Systematic review’ OR ‘meta analysis’ OR ‘meta-analysis’) AND (‘cost-effectiveness’ OR ‘abatement cost’ OR ‘economic analysis’) AND (‘emissions reduction’ OR ‘GHG emission’ OR ‘low-carbon’ OR ‘mitigation’) AND (‘nature finance’ OR ‘blue economy’ OR ‘ocean finance’ OR ‘marine finance’ OR ‘coastal’ OR ‘ecosystem’) AND (‘global south’ OR ‘low income’ OR ‘middle income’)
11. (‘Systematic review’ OR ‘meta analysis’ OR ‘meta-analysis’) AND (‘cost-effectiveness’ OR ‘abatement cost’ OR ‘economic analysis’) AND (‘emissions reduction’ OR ‘GHG emission’ OR ‘low-carbon’ OR ‘mitigation’) AND (‘global south’ OR ‘low income’ OR ‘middle income’ OR ‘developing’) AND (‘blue bond*’ OR ‘green bond*’ OR ‘blue finance’ OR ‘green finance’ OR ‘nature finance’ OR ‘ocean finance’) AND (‘mobilisation’ OR ‘mobilization’)
12. (‘Systematic review’ OR ‘meta analysis’ OR ‘meta-analysis’) AND (‘cost effective’ OR ‘abatement cost’ OR ‘economic analysis’) AND (‘emissions reduction’ OR ‘GHG emission’ OR ‘low-carbon’ OR ‘mitigation’) AND (‘global south’ OR ‘low income’ OR ‘middle income’ OR ‘developing’) AND (‘blue bond*’ OR ‘green bond*’ OR ‘blue finance’ OR ‘green finance’ OR ‘nature finance’ OR ‘ocean finance’) AND (‘mobilisation’ OR ‘mobilization’)

Filters:

- Date range 2015–2025

Web of Science

Search strings used:

- (‘Systematic review’ OR ‘meta analysis’ OR ‘meta-analysis’) AND (‘cost-effectiveness’ OR ‘abatement cost’ OR ‘economic analysis’) AND (‘emissions reduction’ OR ‘GHG emission’ OR ‘low-carbon’ OR ‘mitigation’) AND (‘nature finance’ OR ‘blue economy’ OR ‘ocean finance’ OR ‘marine finance’ OR ‘coastal’ OR ‘ecosystem’)

Scopus

Search strings used:

- (‘Systematic review’ OR ‘meta analysis’ OR ‘meta-analysis’) AND (‘cost-effectiveness’ OR ‘abatemeIn an academic study is the (‘emissions reduction’ OR ‘GHG emission’ OR ‘low-carbon’ OR ‘mitigation’) AND (‘nature finance’ OR ‘blue economy’ OR ‘ocean finance’ OR ‘marine finance’ OR ‘coastal’ OR ‘ecosystem’)

Annex 5 Details of the quality assessment

Top-level criterion	Explanation	Aspects of criterion
1. Cogency	The report presents a **convincing causal argument** about the effectiveness of climate change mitigation interventions.	***Theoretically grounded:*** *The empirical relationship being examined is justified theoretically; for example, there may be a theory section, a theory of change, a programme theory, or a review of theoretical literature. The theory connects inputs to outcomes; theoretical grounding literature is identified; underpinning assumptions of the theory are discussed. Failing these, is there clarity in research questions and confidence that they have been answered sufficiently?*
		Causal: *The causal argument being made is clearly connected to the type of evidence and the theory presented. For example, conclusions link findings back to theoretical grounding; evidence collected is relevant to testing the theory presented; the study supports the link to theory through consultation with experts in the field.*
2. Transparency	The abstract or a quick full-text scan clearly **reveals the methodology** used to collect and analyse the data	***Data collection approach and/or sources:*** *Has grey literature been searched alongside academic databases? Have studies been screened by at least two independent reviewers?*
		Pre-specified eligibility criteria in place? *For example, PICOS specifying types of studies, participants/settings/population, interventions, comparators and outcomes?*
		*Data **analysis methodology**. For example, was an appropriate quality appraisal or risk of bias tool used to assess the quality of the included studies? Have descriptive summary tables been included to report on the key characteristics (in relation to PICOS) and results of the included studies?*

Top-level criterion	Explanation	Aspects of criterion	
3. Credibility	The **data collection** method generates **credible data**. The **methodology** to collect results is not only transparent but **also credible**, thanks to a clear logic of inference (e.g. threats to internal validity are appropriately addressed). In the social research context, this relates to the synthesis approach taken.	***Synthesis/Presentation of results***	***Transferability:*** *Can findings be generalised based on sufficient thick description to enable case-to-case transfer. This means: Can the findings be transferred to other geographical contexts, populations and/or other interventions? Were the findings of the relevant studies presented in such a way that the primary review question is addressed? In global studies, at least 50% of included studies need to have focused on LMICs.*
			Dependability: *The research process is logical, traceable, and clearly documented. Does the review integrate the findings from quantitative and qualitative evidence? Do these integrated findings inform conclusions and implications? If only quantitative or qualitative synthesis tools are used, have these been documented clearly and applied logically?*
			Confirmability: *There is a clear demonstration of how conclusions and interpretations were reached. For example, did the review examine the extent to which specific factors might explain differences in the results of the included studies? How much confidence do you have in the methods used to analyse the findings relative to the primary question addressed in the review?*

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