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Rapid evidence profile: Decarbonization technologies

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- Rapid evidence profile developed in 10 business days (Appendix 1)
- Global evidence: Evidence synthesis based on relevance and recency of search
- Other types of evidence: Non-systematic reviews and single studies describing equity and governance considerations

Contextualization

Contextualization

- The context of decarbonization is rooted in the urgent need to mitigate climate change and transition toward sustainable development. The United Nations Framework Convention on Climate Change (UNFCCC) has published, as an outcome of the Conference of the Parties in 2023, an agreement to transition away from fossil fuels.
- Low-emission technologies are becoming increasingly affordable, with viable options available across energy, transport, buildings, and industry sectors. This makes the transition to a low-carbon economy both achievable and cost-effective.
- The Intergovernmental Panel on Climate Change (IPCC) identifies five illustrative mitigation pathways (IMPs), such as reliance on renewables (IMP-Ren) and carbon dioxide removal (IMP-Neg), which provide diverse strategies for countries to tailor their decarbonization efforts.
- Several organizations have contributed to showcasing the potential of decarbonization technologies. The Integrated Assessment Modeling Consortium (IAMC), for instance, has consolidated a database of models, tools and scenarios regarding decarbonization technologies' use. Additionally, the AR6 Scenarios Database, hosted by the International Institute for Applied Systems Analysis (IIASA, compiles and assesses quantitative, model-based scenarios related to climate change mitigation.
- Nevertheless, technologies are but one of many components (including regulation, stakeholder coordination, financing, planning, communication) that, together, enable a collective group of actors to decarbonize some realm of economic activity.
- In this rapid evidence profile, we provide a brief overview of evidence synthesis related to decarbonization technologies, its opportunities and risks, as well as equity and governance considerations.

Questions

1) How does the scientific literature define decarbonization and what technologies are encompassed in this definition?

2) What are the main risks – including equity considerations – and opportunities related to decarbonization and its associated technologies?

3) What are countries' experiences with the governance of decarbonization technologies?

High-level summary of key findings

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- Overall, we found low-quality evidence syntheses describing risks and opportunities and very little empirical evidence dedicated to equity and governance of decarbonization technologies.

- Despite the relevance of the topic to multiple countries and the crescent number of publications, none of the syntheses was a living evidence synthesis.

- For the first question, most documents didn't provide an explicit definition of decarbonization. Instead, the concept was tacitly linked to sustained emissions reductions, net zero greenhouse gas, carbon neutrality, negative emissions, low or zero-carbon transition, carbon dioxide removal technologies, transition to cleantech or renewable energy sources [1].

- While the literature indicates a consensus on a "thin" definition of decarbonization - any set of measures aimed at decreasing CO^2-equivalent emissions in a realm of economic activity - there is substantial contextual variability in the extent and type of emission reductions, as well as in the scope of the measures counted as "decarbonizing".

- The documents that provided a definition ranged from a more matter-of-fact approach, where decarbonization means "reduction of carbon dioxide emissions and other greenhouse gas (GHG) emissions from activities processes" [2] to recognizing it as a multifaceted concept [1] that involves the scale of emissions, the scope of subsectors and types of emissions included, the stakeholders that are accountable in this process, and the strategies and mechanisms applied to achieve this goal [3].

- The most mentioned decarbonization technologies are Alternative & Renewable Energy (n = 35), Energy Storage & Efficiency (n = 29), Carbon Capture, Utilization and Storage (n = 22), and Smart Technologies and Artificial Intelligence (n = 21). With respect to economic sectors industry (n = 17), waste and water (n = 10), construction (n = 6), and transportation (n = 5) were the most frequently mentioned. Nevertheless, because of the chosen search terms, it is possible that materials or process-related decarbonization were less represented in our results.

- For the second question, low-quality evidence syntheses point to potential opportunities and risks of decarbonization technologies. They show strong potential in emission-intensive sectors, such as manufacturing, energy, transportation, agriculture, and construction. These technologies can address environmental challenges while also creating economic benefits, including job creation, energy security, and resource efficiency.

- Economic viability is presented as the main barrier, as high upfront costs, energy-intensive processes, reliance on critical raw materials and uncertain returns on investment hinder widespread adoption. Infrastructure challenges, such as the extensive CO_2 transport networks needed for carbon capture and storage, and aging energy systems that are more prone to blackouts and may not be able to handle increased loads from the electrification or distributed generation, further complicate implementation.

- Public acceptance is often limited due to concerns about safety, environmental impacts, and health hazards.

- Balancing these opportunities and risks requires robust policy support, innovative financing mechanisms, and collaborative efforts among stakeholders to ensure a just and effective transition to a low-carbon future.

- Regarding equity considerations, low-quality evidence syntheses, reviews and single studies emphasize that decarbonization demands structural reforms, funding, and compliance, which can add pressure on emerging economies [4]. The distribution of benefits and risks is described to favor wealthier communities. Social and ecological concerns, such as land use conflicts, biodiversity loss, and competition for resources are highlighted.

- Finally, regarding the third question on governance, it is noted that governance for decarbonization requires coordinated policies, regulatory mechanisms, and multi-level collaboration, but the regulatory framework remains underdeveloped.

Framework to organize what we looked for

Framework to organize what we looked for

- **Technologies**

    - Renewable Energy (i.e. Photovoltaic (PV) systems, wind energy, nuclear power, energy storage, green electricity)
    - Smart technologies and AI (i.e. smart grids, machine learning)
    - Alternative Fuels (i.e. green hydrogen, biomass, alternative marine fuels, LNG, ammonia, biofuels, methanol)
    - Carbon Capture, Utilization, and Storage (CCUS), i.e. - direct air capture, bio-based carbon sequestration, CO2 mineralization and storage in industrial byproducts.
    - Energy and Resource Efficiency (i.e. waste heat recovery, process optimization, material efficiency/alternative raw materials)
    - Sustainable Construction and Materials (i.e. carbon-neutral building technologies, alternative cement and concrete technologies, industrialized construction, green roofs)
    - Climate-smart agriculture (i.e. reforestation, soil carbon management, agroforestry)

- **Sectors [5]**

    - Energy systems
    - Industry
    - Cities, Settlements and Infrastructure
    - Land, Ocean, Food, and Water
    - Health and nutrition

- **Risks and barriers to decarbonization technologies use [6]**

    - Business and market barriers
    - Construction, technical and operational barriers
    - Environmental sustainability barriers
    - Financial barriers
    - Legal and ownership barriers
    - Policy and regulation barriers

○ Government, political institutions, and societal barriers

- **Governance**

○ Commitments and policy mechanisms

- **Equity**

○ Concerns about inequities
○ Mechanisms to foster equitable technology availability/use

What we found

We identified 205 evidence documents related to the three questions above. However, given the time available for the review, we only conducted data extraction for 106 of these documents, which we identified as being the most directly relevant to the questions [1-4;6-107]. These highly relevant evidence documents include:
• 75 evidence syntheses
• 31 non-systematic reviews and single studies

Additionally, we reviewed 03 grey literature documents recommended by an expert (JM) to organize the framework and contextualization

Coverage by and gaps in existing evidence syntheses

While we identified a significant number of evidence synthesis published between 2020 and 2025, all of them were classified as critically low or low quality (Appendix 2). None of them were living evidence synthesis. Most systematic reviews didn't detail their methods section, so their findings should be interpreted with caution as they do not include assessments of quality or risk of bias for the included literature.

For the topics of equity and governance, further details were found in non-systematic reviews and single studies (Appendix 3). Frameworks for equity appraisal in decarbonization efforts and case studies of countries supported the findings, but an assessment of quality wasn't conducted.

Some reviews included bibliometric analysis [1,7,42,80], showcasing the growth in primary publications about decarbonization technologies in the past 10 years, especially after the signing of the Paris Agreement. Nevertheless, there is a gap related to high-quality evidence synthesis to inform effective decision-making, both in terms of the effectiveness of the technologies and other implementation considerations.

The PRISMA Flowchart is available in Appendix 4.

Key findings from included evidence documents

Definition of decarbonization

Decarbonization definitions are plural, which constitutes a challenge when exploring literature on the topic. Most documents refer to synonyms such as sustained emissions reductions, net zero greenhouse gas, carbon neutrality, negative emissions, low or zero-carbon transition, carbon dioxide removal technologies, transition to clean tech or renewable energy sources.
While the literature indicates a consensus on a "thin" definition of decarbonization - any set of measures aimed at decreasing CO^2-equivalent emissions in a realm of economic activity - there is substantial contextual variability in the extent and type of emission reductions, as well as in the scope of the measures counted as "decarbonizing".

The few documents that provided a definition ranged from a more matter-of-fact approach, where decarbonization means "reduction of carbon dioxide emissions and other greenhouse gas (GHG) emissions from activities processes" [2] to recognizing it as a multifaceted concept involving problems and solutions, both biophysical and technological [1]. Decarbonization also refers to a combined framework considering the scale of emissions, the scope of subsectors and types of emissions included, the stakeholders that are accountable in this process, and the strategies and mechanisms applied to achieve this goal [3].

The most mentioned decarbonization technologies are Alternative & Renewable Energy (n = 35), Energy Storage & Efficiency (n = 29), Carbon Capture, Utilization and Storage (n = 22), and Smart Technologies and Artificial Intelligence (n = 21). Some sectors also were highlighted, such as industry (n = 17), waste and water (n = 10), building (n = 6), transportation (n = 5). Nevertheless, because of the chosen search terms, it is possible that materials or process-related decarbonization were less represented in our results.

Risks and opportunities

Risks and opportunities (Table 01) were addressed by 75 critically low- or low-quality evidence synthesis. Decarbonization technologies offer significant opportunities to mitigate climate change by reducing greenhouse gas emissions across various sectors, and strong potential in emission intensive sectors [8], such as manufacturing, energy, transportation, agriculture, and construction (METAC). Renewable energy sources like solar, wind, and nuclear power provide alternatives to fossil fuels, as do alternative fuels such as green hydrogen, biofuels, and ammonia, which present pathways for decarbonizing transportation and industrial processes. Green hydrogen, in particular, has received much attention due to its abundance in the atmosphere and as an energy dense fuel capable of not just meeting industrial energy requirements, but also providing long-duration energy storage [7]. In this sense, energy storage systems and smart grids enhance efficiency and grid stability of operations.

Carbon capture, utilization, and storage (CCUS) technologies are among the most promising measures in "hard to decarbonize sectors" with a potential of 48-60% reduction of CO2 emissions in cement industry [9] and in the construction sector more generally [10]. Further literature suggested by experts on CCUS is available on Appendix 5. Additionally, climate-smart agriculture and negative emissions technologies, such as reforestation and bioenergy with carbon capture, offer opportunities for carbon sequestration and ecosystem restoration [11]. Decarbonization technologies not only address environmental challenges but also create economic benefits, including job creation, energy security, and resource efficiency, while supporting the transition to a circular economy [12,13].

However, the deployment of decarbonization technologies is not without risks. Economic viability remains a major barrier [14], as high upfront costs, energy-intensive processes, and uncertain returns on investment hinder widespread adoption [2]. Infrastructure challenges, such as the need for extensive CO_2 transport networks and aging energy systems, further complicate implementation. The transition to renewable energy can present challenges like grid instability, as seen in recent blackouts due to shortages in supply of renewable energy [15]. Public acceptance is often limited due to concerns about safety, environmental impacts, and health hazards, while regulatory frameworks remain underdeveloped [16]. Technological uncertainties, including scalability, long-term performance and data security, and reliance on critical raw materials, pose additional risks [103]. Social and ecological concerns, such as land use conflicts, biodiversity loss, and competition for resources, also need to be addressed. Balancing these opportunities and risks requires robust policy support, innovative financing mechanisms, and collaborative efforts among stakeholders to ensure a just and effective transition to a low-carbon future.

Table 01: Risks and opportunities of decarbonization technologies

Technology	Opportunities	Risks
Photovoltaic (PV) Systems [12, 14, 17, 18]	PV-based heating systems, such as solar-assisted heat pumps and thermal storage, enhance efficiency and reduce emissions. Energy storage solutions like heat storage tanks and batteries further improve system performance.	PV-based heating systems are dependent on regional solar radiation, making them less stable than fossil fuel-based systems. Energy storage facilities are necessary to enhance stability, but this adds complexity and cost. Additionally, large-scale PV installations can lead to land use conflicts, habitat disruption, and water resource strain during manufacturing and recycling.
Wind Energy [15, 19, 20]	Offshore wind power is a mature technology with high potential for clean energy production, significantly reducing port carbon emissions. Building-integrated wind turbines, especially vertical axis wind turbines (VAWTs), are suitable for urban areas, reducing transportation losses and generating economic benefits.	Offshore wind projects face ecological risks, such as impacts on marine life due to noise and electromagnetic fields. Onshore wind projects often encounter social resistance due to the "Not In My Backyard" (NIMBY) effect, delaying implementation.
Nuclear Power [21]	Provides reliable power supply, ensuring electricity adequacy during periods of low renewable energy output or extreme disasters.	Risks include nuclear safety concerns, potential for serious accidents under natural disasters, and high upfront investment costs. Public acceptance is also a challenge due to fears of radiation leaks.

Smart Grids [22]	Enables dynamic energy pricing, demand response, and integration of renewable energy sources, enhancing grid resilience and efficiency.	Cybersecurity risks are significant due to increased IoT devices and bidirectional power flows, which can lead to cascading failures if attacked. Grid instability is another risk, as seen in California and the UK, where high renewable penetration led to blackouts.
Energy Storage [23]	Technologies like hybrid energy storage systems (HESS) and vehicle-to-grid (V2G) systems optimize power flow and improve microgrid efficiency, supporting renewable energy integration.	High initial costs, technical complexity, and space requirements for systems like thermal energy storage (TES) and hybrid energy storage systems (HESS) pose challenges. Maintenance and environmental risks, such as groundwater contamination, are also concerns.
Carbon Capture, Utilization and Storage – CCUS [9, 13, 14, 16, 17, 24, 25, 27, 43, 45]	One of the primary options with clear benefits to energy and carbon savings, cost savings, and other environmental co-benefits. Highest decarbonization potential in hard to decarbonize sectors.	The primary concern is the potential for CO2 leakage from underground storage sites, posing significant environmental and health risks. There is also a need for structural cement changes that can be costly. There are currently incipient pipelines for transportation.
Hydrogen [7, 14, 26, 28]	Offers long-duration energy storage. Green hydrogen can replace fossil fuel-derived hydrogen in industrial processes, transportation, and heating. Green hydrogen is expected to dominate the market alongside ammonia by 2035.	High production costs, storage challenges due to low volumetric energy density, and flammability risks hinder widespread adoption. Infrastructure for hydrogen transport and distribution is also underdeveloped.
Biofuels [25, 26, 28, 29]	Derived from renewable sources, biofuels are biodegradable, non-toxic, and compatible with existing systems. They reduce emissions when blended with fossil fuels and are practical	Environmental risks include deforestation, habitat destruction, and competition with food production. Socioeconomic risks involve price impacts on food commodities and displacement of marginalized communities.

	for local and international shipping.	
Ammonia [28]	It can be used as a fuel in engines and fuel cells, enabling long sea voyages with minimal cargo loss. Green ammonia is promising but requires further development for commercial use in shipping.	Health hazards from inhalation, high toxicity, and infrastructure challenges (e.g., larger storage tanks) limit its adoption. Ammonia production must increase significantly to meet energy demands, raising scalability concerns
Liquefied Natural Gas [20, 30, 31, 32]	Reduces CO_2 emissions by approximately 25% compared to heavy fuel oil and is increasingly adopted in vessels and port equipment.	Requires cryogenic storage and additional systems, increasing costs and space requirements. Methane leakage is a safety and environmental concern, and the lack of a secondary market for LNG-using ships is a barrier.
Methanol [20, 28]	Can be produced from natural gas, coal, waste, and CO_2. It offers low emissions and is easy to store, making it a promising fuel for ships.	Corrosive nature, low energy density, and safety risks (e.g., low flash point) limit its use in diesel engines. High demand for methanol could also strain biomass production.
Bio-based Carbon Sequestration [14]	Bio-based carbon sequestration methods, such as BECCS and biochar, utilize biomass to capture and store CO_2, contributing to climate change mitigation.	Faces risks including land use conflicts, food security threats, ecological impacts, high water and energy consumption.
CO_2 Mineralization [33]	Offers permanent carbon storage by locking CO_2 into stable carbonates, which can be used in construction materials, reducing the demand for cement and other carbon-intensive materials. It has economic potential through integration with technologies like enhanced metal recovery.	Main challenges derive from high capital costs, and obstacles to scalability due to slow reaction rates and specific geological requirements.

CO_2-Enhanced Geothermal Systems - CO_2-EGS [34]	Combines carbon storage with geothermal energy production, enhancing heat extraction, enabling CO_2 sequestration, and reducing water consumption.	Risks include leakage, similar to other CO_2 sequestration technologies, and upfront costs, which pose a barrier to further implementation.
Waste Heat Recovery [14, 17, 35]	Technologies like coke dry quenching (CDQ) and waste heat recovery for sintering ring coolers repurpose waste heat for power generation or material preheating, reducing the need for primary energy sources and lowering operational costs. This can lead to substantial energy savings, such as up to 20% in steel production and 75% in certain manufacturing processes.	Requires substantial upfront costs, which can be a barrier for some businesses. Specific industrial processes require specific expertise and add complexity to optimal implementation and maintenance, adding operational costs
Process Optimization Techniques [35]	Techniques like thick layer sintering and intelligent system scheduling optimize energy use and reduce emissions in industrial processes.	High exit charges for installing co-generation units and declining availability of waste materials for heating pose challenges. Process optimization technologies may also face resistance due to high upfront costs.
Material Efficiency [9]	Using alternative raw materials like fly ash, blast furnace slag, and recycled aggregates reduces the carbon footprint of construction materials.	Variability in recycled materials can impact performance, requiring further testing and optimization. Infrastructure for collecting and processing recycled materials is often lacking.
Carbon-Neutral Building Technologies [36, 41]	Integrating renewable energy sources and system improvements with carbon-neutral building technologies (CNBTs) can effectively reduce payback periods and achieve carbon neutrality.	High initial investment costs and long payback periods deter adoption. Additionally, rebound effects may negate efficiency gains if companies increase output to maintain profitability.

Alternative Cement and Concrete Technologies [37]	Using supplementary cementitious materials (SCMs) like fly ash and blast furnace slag reduces clinker content and CO_2 emissions. Carbon-cured concrete and biochar-based concrete offer carbon sequestration benefits.	High upfront costs, supply chain variability, and regional regulations hinder the adoption of industrialized construction (IC) practices. Transportation of prefabricated modules can also increase emissions.
Reforestation [11]	Reforesting at a certain rate can significantly enhance carbon sequestration and biodiversity.	Soil organic carbon sequestration rates vary significantly, and conversion from arable land to forestry can lead to carbon losses in highly organic soils. Biodiversity impacts are also a concern, particularly for vertebrates at higher trophic levels.
Soil Carbon Management [38]	Techniques like agroforestry and the use of high-yielding crop varieties reduce greenhouse gas emissions and improve soil health.	Water use efficiency varies between crops, and rising global temperatures may strain water resources. Limited coherent policies in Africa further hinder the adoption of climate-smart practices.
Agroforestry [11, 38]	Combines agriculture with tree planting, enhancing carbon sequestration and providing additional income streams for farmers.	Competition for land and resources with food production systems can lead to socioeconomic challenges, such as price impacts on food commodities and displacement of marginalized communities.
Carbon Sinks [14, 39]	Forests, oceans, and soil sequestration act as natural carbon sinks, capturing and storing CO_2 from the atmosphere.	Natural carbon sinks like forests and oceans face risks from deforestation, land use change, and ecosystem disruption. Secondary hazards, such as impacts on biodiversity and land use patterns, are also concerns.
Bioenergy with Carbon Capture and Storage - BECCS	Combines bioenergy production with carbon capture, offering a pathway to negative emissions.	High costs, energy intensity, and scalability challenges limit the feasibility of BECCS. Public acceptance is also low due to

		concerns about land use and food security.
Algal-Bacterial Systems [40]	Enhance wastewater treatment while capturing CO_2 and producing biomass for biofuels or fertilizers.	Microbial stability, light limitations, and large-scale implementation challenges hinder the effectiveness of these systems for CO_2 capture and wastewater treatment.
Green roofs [44]	Energy saving benefits for houses and buildings; decreasing roof surface temperatures. Opportunities to explore the potential of green roofs to help capture and storage CO2.	Most research on green roofs, especially intensive ones, is based on simulations and small-scale experiments,

Equity considerations

There are several equity considerations related to decarbonization technologies. We identified single studies describing specific contexts, as well as global considerations in non-systematic and systematic reviews. Nevertheless, these studies had either low methodological quality or were not assessed for quality, so these findings should be interpreted with caution. Equity and sustainability are positioned as central in the transition to a low-carbon economy, aiming for fairness in distributing the burdens and benefits of sustainable options across social groups [46, 47], especially in liberalized market structures that favor private interests [48], especially indigenous communities [49]. Some studies also reinforce the matter of intergenerational justice in the sense of not accurately managing the risks imposed on current or future generations [50].

Equity challenges in energy transitions and climate policies manifest in various ways across different contexts. Access to energy innovations and citizen participation in this topic is often skewed toward high-income, highly educated individuals, necessitating government interventions to promote inclusivity, particularly in poorer communities, low-income households and smaller farmers [51, 52, 53, 54].

For many decarbonization technologies, such as Carbon Capture, Utilization, and Sequestration and hydropower development, facilities are often installed in low-income communities or indigenous territories, creating land conflicts and requiring resettlement and displacement measures [55] and exposing them to health and environmental hazards [56]. The exploitation of natural resources can also aggravate water scarcity [57], reliance on critical minerals from developing countries [58] and deforestation [59], especially in the Global South [60]. Electric vehicle adoption also follows socio-economic lines, with wealthier groups benefiting while low-income individuals in peripheral areas lack access to charging infrastructure [61]. Another major concern is the fact that many decarbonization technologies depend on crops, creating a food vs. fuel dilemma that can expose the population to food insecurity or scarcity [59, 62].

Evaluating equity and justice in decarbonization is a context-dependent process [63]. Some studies propose climate justice frameworks, either incorporating distributive, procedural, and intergenerational equity [64] or energy poverty alleviation [65]. Some countries have adopted composite indices such as CalEnviroScreen [66] or Social Life Cycle Assessments (SLCA), considering not only environmental and economic sustainability of decarbonization, but also workers' employment and working conditions, health and safety, social and gender equity, community engagement, and food security [62].

Finally, public participation is highlighted as a key factor in just transitions, with renewable energy projects facing resistance due to procedural injustices and inadequate community engagement [52, 67]. Stakeholder engagement can benefit from structured approaches to include diverse voices and balance power [68]. To this end, combining climate change awareness with evidence of CCS implementation, its benefits and risks, appears to be a driver of public support [69, 70].

Governance experiences

Governance experiences towards decarbonization technologies were less explored in the literature. We identified single studies describing case studies, as well as non-systematic reviews of national policies. These studies were not assessed for quality, which inspires caution when interpreting findings. The literature reinforces that governance for decarbonization requires coordinated policy frameworks, regulatory mechanisms, and multi-level collaboration [71]. Kenya, for instance, has developed a collaborative approach involving multisectoral engagements of both the government, multilateral organizations, NGOs, and local communities. Through an integrated top-down (government) and bottom-up (local community) method, the country seeks to promote economic, socio-cultural, and environmental sustainability, as well as greater participation of women and youth [72]

Desirable policy instrument mixes should be tailored to the characteristics of targeted agents and technologies [73]. Countries and regions have adopted various approaches (Table 02), from setting stringent emission reduction targets to implementing financial incentives and technological advancements. Most of those are described in plans or strategies but still lack regulatory strength and institutional coordination [71, 74]. The European Union, for instance, has integrated circular economy principles into its regulatory framework, promoting sustainable production and consumption practices [75]. France has implemented policies to enhance renewable energy adoption while phasing out nuclear power [58], while Germany has established a "coal commission" to eliminate coal-fired power generation [76]. The United Kingdom has pursued strategies such as the Road to Zero [76], targeting an all-electric transport system, while China has progressively integrated Carbon Capture, Utilization, and Storage (CCUS) technologies into its five-year development plans [77].

Table 02: Countries' Experiences in Governance for Decarbonization

Country/Region	Governance Approach
Bangladesh [71]	• Has employed an "Avoid–Shift–Improve" framework, alongside the development of mass rapid transit (MRT), bus rapid transit (BRT) and energy efficient rail locomotives
China [77]	• 2006-2010 - 11th Five-Year Plan called for clean and green development. • 2011-2015 - 12th Five-Year Plan highlighted the importance of CCUS as one of three key approaches to clean coal development. • 2016-2020 - CCUS became more widely covered by various policies formulated under the 13th Five-Year Plan and the "National Key Energy-saving and Low-carbon Technology Promotion Catalogue". Formulation of a "Guidance on Building a Green Financial System". • 2021-2025 - 14th Five-Year Plan includes goals for carbon neutrality in 2060 and the construction of major CCUS demonstration projects.
European Union [75]	• The EU has developed a series of regulations for the implementation and strengthening of the circular economy. The 2008 Directive harmonized previous legislation, and the 2015 Action Plan established 54 specific measures interconnecting the circular economy and the objectives of the energy transition. • Circular Economy Action Plan (2021): includes the implementation of new recycling laws, with more stringent measures and the definition of binding targets toward the reduction in the ecological footprint, the commitment to a carbon-neutral economy, the minimization of the negative impact of the use of chemicals and hazardous substances in the supply chain. • September 2023 - European Parliament on Directive (EU) 2024/825 on consumer empowerment for the green transition.
France [58, 76]	• France has adopted new energy efficiency regulation, sustainable development tax credit, zero percent ecological loan, renovation of government buildings, and social housing renovation for the residential and service sectors. • France's Multi-Year Energy Program aims to increase renewable electricity production.

	• Power to hydrogen (P2H2) is among France's tools to support this transition to renewable energies.
Germany [52, 76]	• Has established the Energiewende (Renewable Energy Act), including Feed-in Tariff, overarching legislation to increase in national share of renewables • Has published a German Climate Act and a Climate Action 2050
Kenya [72]	• Kenya has enacted several climate-specific policies including National Climate Change Strategy (2010), Climate Change Act (2016), Climate Finance Policy (2018), National Climate Change Action Plan 2018-2022 (which is a 5-year rolling plan), and National Adaptation Plan (2015-2030) which guides the climate actions of the National and County governments and other stakeholders. The country's National Blue Economy Strategy 2023-2027 was formulated and aligned to the BE Strategies of the African Union (AU) and Intergovernmental Authority on Development (IGAD)
Japan [76]	• In addition to promoting renewable generation, has developed a new high-efficiency framework to ensure the phase-out of inefficient coal-fired power plants by 2030 as part of the energy strategy
Philippines [71]	• The National Climate Change Action Plan (2011–2028 promotes the adoption of environmentally sustainable transport, fuel conservation measures, public transport planning, integrated land-use, and transport planning.
South Africa [52]	• Has established the Independent Power Producers Procurement Programme to secure electrical energy from the private sector for renewable and non-renewable energy sources. With regard to renewables, the program is designed to reduce the country's reliance on fossil fuels, stimulate an indigenous renewable energy industry and contribute to socio-economic development and environmentally sustainable growth.
Spain [75]	• Pact for a Circular Economy in 2017 began the transformation of the linear model into a circular one. • The approval of the Spanish Strategy for a Circular Economy in 2020 represents the adoption of the EU approach in this matter.

United Kingdom [52, 76]	• The Road to Zero Strategy (2018) pushes the transport sector to explore policies on achieving an all-electric transportation system, including public consultations about prohibiting new petrol and diesel automobiles. • Warm Front Home Energy Efficiency Program: Subsidy (energy efficiency retrofits) to households
United States [52, 54, 76, 78]	• Federal and state-level renewable initiatives. In the absence of a comprehensive national policy framework to address the implications of coal transition, some Western states have implemented legislation to address the effects of the decline of the coal industry. • At the federal level, the U.S. Weatherization Assistance Program is a direct procurement for energy retrofit measures in households. • The regulation of agricultural biotechnology is overseen by the Coordinated Framework which consists of the Environmental Protection Agency (EPA), Food and Drug Administration (FDA), and the United States Department of Agriculture (USDA). • The Justice40 Initiative aimed to address environmental justice through making sure that 40% of the overall benefits of certain federal investments flow to disadvantaged communities that are marginalized, underserved, and overburdened by pollution. • At state-level, one example is California (US) that has developed policies like the Self-Generation Incentive Program (SGIP) to promote residents to generate and store their own energy and the California Global Warming Solutions Act, the Renewable Portfolio Standard, and the Low Carbon Fuel Standard are addressing these challenges.

Effective governance frameworks are characterized by comprehensive policy planning, stakeholder engagement, capacity building and financial incentives that drive innovation and adaptation. A key challenge in governance for decarbonization is the integration of cross-sectoral strategies and international cooperation to address policy gaps and financial barriers [57]. Finally, Global South countries face particular hurdles in aligning climate goals with economic development needs [4], often facing uncertainty regarding whether the decarbonization efforts will affect positively or negatively the GDP, or promote job creation or displacement [79].

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Appendix 1 - Methodological details

Identifying research evidence
For this REP, initially we searched Social Systems Evidence and Web of Science for:
1) evidence syntheses
2) protocols for evidence syntheses that are underway.
3) single studies for specific gaps.

We first searched Social Systems Evidence using an open text search for “decarbonization” OR “decarbonisation” OR “decarbonization technology” OR “decarbonisation technology” OR “carbon capture” OR “carbon neutrality” OR “smart grids”. When this search resulted in 02 studies, we ran a second search “decarbonization” OR “decarbonisation", finding 13 potentially relevant studies.

We also searched Web of Science using: TS=((“decarbonization” OR “decarbonisation” OR “decarbonization technology” OR “decarbonisation technology” OR “carbon capture” OR “carbon neutrality” OR “smart grids”)). We applied filters on Year: 2020 to 2025 and Type of studies: Review Studies to limit the results, due to the timeline of this profile, finding 3,946 potentially relevant studies.

No hand searches or keyword searches to identify other potentially relevant documents were conducted. An expert, JM, was consulted and recommended 4 single studies to organize the framework. Single-person screening was performed using Rayyan. A final inclusion assessment was performed by the lead author of the rapid evidence profile, with disagreements resolved by input of a third reviewer on the team.

The team used a dedicated virtual channel to discuss and iteratively refine inclusion/exclusion criteria throughout the process, providing a running list of considerations that all members could consult during the first stages of assessment.

We labeled all single studies focused on equity and governance to include them, as these topics constituted a gap in the evidence synthesis included. We did not exclude documents based on the language of a document.

Assessing relevance and quality of evidence

We assessed the relevance of each included evidence document as being of high, moderate, or low relevance to the questions. Studies were considered of High relevance if they provided detailed information on one or more of the prioritized questions. For quality of evidence, methodological quality of single studies was not appraised due to their heterogeneity.

Two reviewers independently appraised the methodological quality of evidence syntheses that were deemed to be highly relevant using the AMSTAR-2 tool. Disagreements were resolved by consensus with a third reviewer if needed. AMSTAR-2 rates overall methodological quality of syntheses based on critical and non-critical weaknesses:

High - Zero or one non-critical weakness: The systematic review provides an accurate and comprehensive summary of the results of the available studies that address the question of interest

Moderate - More than one non-critical weakness*: The systematic review has more than one weakness, but no critical flaws. It may provide an accurate summary of the results of the available studies that were included in the review.

Low - One critical flaw with or without non-critical weaknesses: The review has a critical flaw and may not provide an accurate and comprehensive summary of the available studies that address the question of interest.

Critically low - More than one critical flaw with or without non-critical weaknesses: The review has more than one critical flaw and should not be relied on to provide an accurate and comprehensive summary of the available studies.

*Note: Multiple non-critical weaknesses may diminish confidence in the review and it may be appropriate to move the overall appraisal down from moderate to low confidence.

A High classification in AMSTAR-2 signals that readers of the evidence synthesis can have a high level of confidence in its findings. A Low or Critically low classification, on the other hand, does not mean that the evidence synthesis should be discarded, merely that less confidence can be placed in its findings and that it needs to be examined closely to identify its limitations. (Lewin S, Oxman AD, Lavis JN, Fretheim A. SUPPORT Tools for evidence-informed health Policymaking (STP): 8. Deciding how much confidence to place in a systematic review. Health Research Policy and Systems 2009; 7 (Suppl1): S8.)

Preparing the profile

Each document included was cited in the reference list at the end of the REP. For all evidence syntheses included, we prepared a small number of bullet points that provide a summary of the key findings (Extraction sheet #1), which are used to summarize key messages in the text. The same was done to all single studies focused on Equity and Governance (Extraction sheet #2). We drafted a summary that highlights the key findings from all highly relevant documents (alongside their date of last search and methodological quality). Upon completion, the REP was sent to two subject-matter experts (BM, MSM) for their review.

Finally, the demand-side colleagues also reviewed the first draft of the REP and suggested additional literature focused on the priority-topic of Carbon Capture, Utilization, and Storage (CCUS), which was added to Appendix 5.

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