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FROM RENEWABLE-ENERGY DEPLOYMENT TO SDG OUTCOMES: A GLOBAL, LIFE-CYCLE- AND EVIDENCE-SENSITIVE INTEGRATIVE FRAMEWORK OF SYNERGIES AND TRADE-OFFS

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Abstract

Renewable energy is central to climate mitigation and to SDG 7, yet its wider contribution to the Sustainable Development Goals (SDGs) is not automatic. Existing studies identify potential synergies with health, employment, infrastructure, poverty reduction, and climate action, alongside trade-offs involving land, water, food systems, biodiversity, materials, waste, and the distribution of costs and benefits. Because recent global syntheses have already mapped renewable-energy contributions across all 17 SDGs, a further general mapping would offer limited novelty. This paper therefore develops a complementary conceptual framework through an integrative synthesis of research on SDG interactions, renewable-energy life cycles, technology-specific effects, energy access, environmental justice, and impact evaluation. The framework links context and governance to deployment attributes, life-cycle activities, mediating mechanisms, target-level SDG outcomes, distributional outcomes, and feedback over time, and it introduces a five-level evidence ladder that distinguishes stated alignment and potential interactions from outputs, observed outcomes, and attributable impacts. The synthesis indicates that service quality and actual use condition the development effects of access, that technology and supply-chain choices shape environmental burdens, and that participation and distributional arrangements determine who benefits and who bears costs. Six testable propositions, an operational indicator scheme, and a research agenda are proposed. The paper is a transparent conceptual synthesis based on a discovery-led literature search rather than an exhaustive systematic review, and it does not claim that any single renewable technology uniformly advances the SDGs.

Keywords: Renewable Energy, Sustainable Development Goals, SDG Interactions, Energy Transition, Life-Cycle Assessment, Energy Justice, Synergies and Trade-Offs, Integrative Review, Conceptual Framework

1. Introduction

The Sustainable Development Goals (SDGs) frame development as a system of interconnected objectives rather than as a list of separate sectoral targets. Under this framing, energy decisions matter well beyond the energy sector: they shape social, economic, and environmental outcomes simultaneously (McCollum et al., 2018; Nilsson et al., 2018). Energy is addressed directly by SDG 7, yet choices about energy systems also bear on targets for health, education, water, food, employment, industry, inequality, ecosystems, and institutions (Fuso Nerini et al., 2017; McCollum et al., 2018). Renewable-energy expansion is therefore

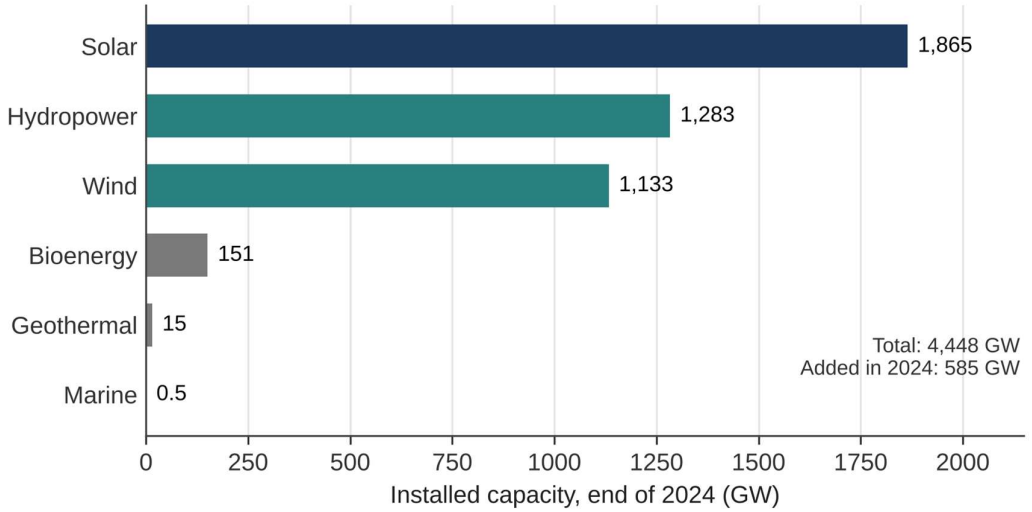
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both a strategy for the energy transition and a collection of place-specific interventions whose wider effects require careful assessment (Hernandez et al., 2020; Adnan Afzal et al., 2026).

The scale of that expansion makes the question urgent. Global renewable power capacity reached 4,448 GW at the end of 2024 after a record 585 GW was added in a single year, with solar photovoltaics accounting for most of the growth (International Renewable Energy Agency [IRENA], 2025; see Figure 1). At the same time, progress toward universal access remains uneven: 666 million people still lacked electricity in 2023, and about 85% of them lived in Sub-Saharan Africa (International Energy Agency [IEA] et al., 2025; see Figure 2). Rapid deployment and persistent deprivation can therefore coexist, which underlines that installed capacity alone does not reveal who benefits from the transition.

Figure 1

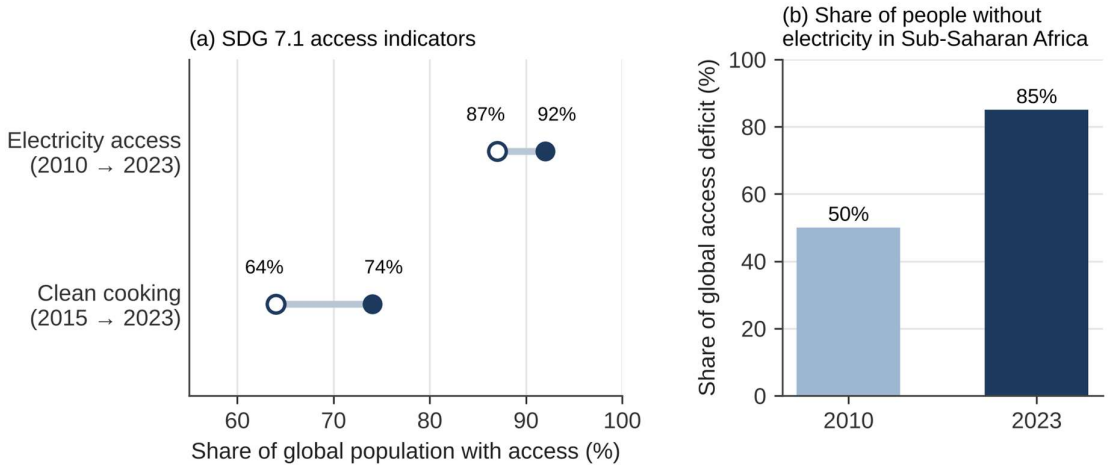
Global Installed Renewable Power Capacity by Technology, End of 2024



Note. Hydropower excludes 142 GW of pure pumped storage. Data from *Renewable Capacity Statistics 2025*, by International Renewable Energy Agency, 2025. Figure image as supplied in the source file.

Figure 2

Progress and Persistent Gaps in SDG 7.1 Access Indicators



Note. Panel (a) shows the global share of the population with access to electricity (2010 and 2023) and to clean cooking fuels and technologies (2015 and 2023). Panel (b) shows the proportion of the global population without electricity that lives in Sub-Saharan Africa; 666 million people lacked access in 2023.

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Data from *Tracking SDG 7: The Energy Progress Report 2025*, by International Energy Agency et al., 2025. Figure image as supplied in the source file.

Renewable technologies can reduce reliance on fossil-fuel generation and the greenhouse-gas and air-pollution burdens associated with it. A climate benefit, however, does not by itself establish that a project is sustainable in other respects (Luderer et al., 2019; Kamran & Afzal, 2025). Renewable-energy systems require materials, land, infrastructure, labor, water, storage, and end-of-life management, and their impacts may arise at stages and in locations far removed from the generating site (Klemm et al., 2022). System boundaries matter because supply-chain burdens can be shifted to communities or countries that receive few of the principal energy or climate benefits (Ahlbäck et al., 2026; Long et al., 2026).

The literature has already established that energy–SDG interactions may be positive, negative, or context-dependent, and that assessments should not assume a single direction for all technologies or settings (Fuso Nerini et al., 2017; McCollum et al., 2018; Nilsson et al., 2018). Tian et al. (2024) mapped six renewable-energy technologies across seven production-process aspects and identified potential enabling and inhibiting relationships at the level of SDG targets. Klemm et al. (2022) traced technology components and services through industries to SDG indicators, showing that the pattern of potential linkages depends on supply-chain boundaries and on whether manufacturing occurs locally or abroad. Given these contributions, a further map of renewable technologies against the 17 goals would add little.

The closest recent review, by Almulhim and Abubakar (2026), searched Scopus and Web of Science for English-language studies published between 2015 and 2025, synthesized 57 studies, and classified all 17 SDGs into direct, indirect, and broader-development linkages. It also examined policy, technology, environmental, and energy-use themes, together with barriers and

Table 1

Comparison of Selected Prior Syntheses With the Present Framework

Study	Scope and unit of analysis	Principal contribution	Limitation addressed here
Fuso Nerini et al. (2017)	Energy (SDG 7) against all 169 SDG targets	Expert-based mapping of synergies and trade-offs	Magnitude and realized effects not estimated
McCollum et al. (2018)	Energy-related target interactions	Interaction typology with evidence, agreement, and confidence ratings	Not technology- or life-cycle-specific
Nilsson et al. (2018)	Interactions across all SDGs	Seven-point interaction scale; lessons for mapping	Generic; not focused on energy projects
Klemm et al. (2022, 2024)	Technology value chains linked to SDG indicators	Linkage-density method; protocol for defining boundaries	Linkage counts, not effect sizes; limited justice dimension
Tian et al. (2024)	Six technologies × seven production-process aspects	Target-level enabling and inhibiting relationships	Potential relationships only; some upstream emissions excluded
Yavuz et al. (2025)	47 off-grid impact evaluations in low- and middle-income countries	Pooled estimates for access, climate, and socioeconomic outcomes	Off-grid only; many null or high-risk-of-bias estimates
Almulhim & Abubakar (2026)	57 studies across all 17 SDGs	Direct, indirect, and broader-development tiers; barriers and policies	Tiers do not trace mechanisms or evidence strength
Present framework	Deployment pathways; global conceptual scope	Integrates life cycle, context, justice, and an evidence ladder	Requires empirical validation

Note. Entries summarize each source's stated scope and are not exhaustive.

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A central problem in this field is that potential alignment, project delivery, observed outcomes, and causal impact are often treated as equivalent forms of evidence (Klemm et al., 2022; Tian et al., 2024; Yavuz et al., 2025). A target-level map can identify plausible relationships, but it cannot establish their magnitude, their direction in every context, or their realized effect (Nilsson et al., 2018). A project that expands basic electricity access does not necessarily improve household income, school attendance, affordability, or health within the same period (Aklin et al., 2017; Yavuz et al., 2025). Likewise, renewable generation may be associated with lower emissions and greater economic activity without any evidence that the gains are equitably distributed or that household electricity prices fall (Silva et al., 2026).

This paper addresses the following research question: How can renewable-energy deployment be conceptualized as a set of conditional, life-cycle-based pathways that generate potential synergies and trade-offs across SDG targets, and how should the strength of evidence for those pathways be represented? To answer it, the paper develops a global-scope conceptual framework grounded in an integrative synthesis of research on SDG interactions, renewable-energy technologies and supply chains, energy-access interventions, justice, and impact assessment (Whittemore & Knafl, 2005). The framework treats context and governance as conditions that shape how deployment is converted into energy services, local economic effects, environmental impacts, and distributional outcomes (Batra et al., 2025; Long et al., 2026; McCollum et al., 2018).

The contribution is deliberately bounded. The paper does not estimate a pooled causal effect of renewable energy, rank technologies by a single sustainability score, or claim that the framework has been empirically validated. It offers an integrative model for organizing evidence and generating testable propositions while distinguishing potential SDG linkages from observed and attributable outcomes (Makešová & Valentová, 2021; Whittemore & Knafl, 2005).

2. Method

2.1 Review Design

An integrative review is appropriate when a research question requires synthesis across empirical, theoretical, and methodological literatures rather than aggregation of a single, uniform intervention or outcome (Torraco, 2005; Whittemore & Knafl, 2005). Its rigor depends on a clear purpose, transparent searching and selection, appropriate appraisal of diverse evidence, systematic analysis, and a synthesis whose reasoning can be traced (Snyder, 2019). This design suits the present question because the relevant literature spans target-interaction frameworks, technology and life-cycle assessments, qualitative justice studies, observational analyses, causal evaluations, and systematic reviews (Klemm et al., 2022; Long et al., 2026; McCollum et al., 2018; Yavuz et al., 2025).

The review is global in conceptual scope, but this does not imply that the evidence base is geographically balanced or that every result generalizes worldwide (Hernandez et al., 2020; Robledo-Abad et al., 2017; Yavuz et al., 2025). The framework is designed to make regional and local context explicit, and the synthesis reports where evidence is concentrated in particular technologies, countries, or study types.

2.2 Literature Identification and Evidence Sources

An academic discovery search completed on July 24, 2026, identified 239 candidate records relevant to renewable energy, SDG synergies and trade-offs, contextual conditions, measurement, and conceptual frameworks. The search was used to assemble a pool of relevant scholarship and to prioritize central sources; it was not a conventional database export with a fixed query string and a record-level deduplication log. The figure of 239 is therefore a discovery-pool count, not the number of studies formally screened or included (Snyder, 2019; Whittemore & Knafl, 2005).

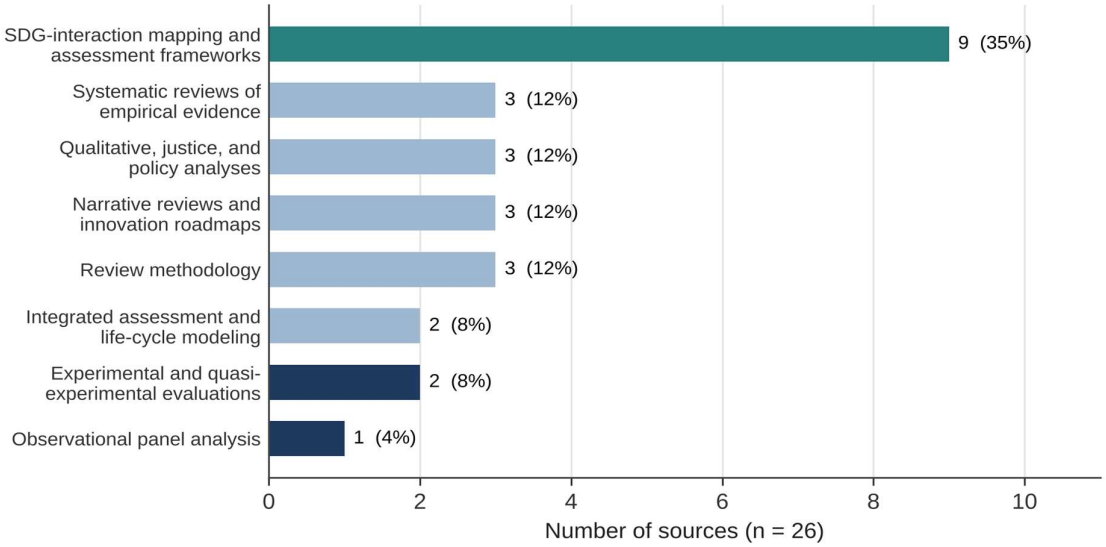
The synthesis gives closest attention to full-text studies that directly inform the framework, including global SDG-interaction assessments, technology and life-cycle mapping, off-grid impact evaluations, analyses of bioenergy and resource trade-offs, justice studies, and recent conceptual reviews. Abstracts and metadata were used to identify further relevant work where full text was unavailable, and claims drawn from such records are kept at the level the available information supports (Gupta, 2019; Levenda et al., 2021). Figure 3 summarizes the 26 scholarly sources cited in the synthesis by study design, excluding the two

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statistical reports used for context. It shows that mapping and assessment frameworks dominate the base, whereas experimental, quasi-experimental, and observational studies together account for fewer than one in eight sources.

Figure 3

Composition of the Synthesized Evidence Base by Study Design



Note. *n* = 26 scholarly sources cited in this synthesis; the two statistical reports used for context (IEA et al., 2025; IRENA, 2025) are excluded. Each source was assigned to its primary design by the author. Dark bars denote designs that estimate observed or attributable outcomes. Percentages are rounded. Figure image as supplied in the source file.

Because the synthesis was discovery-led, the paper does not present a PRISMA flow diagram, a formal count of included primary studies, or a claim that all 239 candidate records were screened. A version claiming systematic or exhaustive coverage would require reproducible database-specific searches, duplicate removal, title-and-abstract screening, documented full-text eligibility decisions, and a formal quality-appraisal process (Snyder, 2019). This distinction matters because the closest existing review reports a formal PRISMA process and 57 included studies (Almulhim & Abubakar, 2026).

2.3 Analytical Procedure

The synthesis was organized around five linked questions: (a) which renewable-energy intervention or technology is considered; (b) which life-cycle stages and system boundaries are included; (c) which mechanisms connect the intervention to SDG-relevant outcomes; (d) which contextual conditions shape the pathway; and (e) what type of evidence supports the stated relationship (Klemm et al., 2022, 2024; Tian et al., 2024; Yavuz et al., 2025). The framework was developed iteratively by comparing recurring mechanisms and boundary conditions across studies and grouping them into deployment attributes, life-cycle activities, mediating pathways, SDG outcomes, contextual moderators, and feedbacks (Torraco, 2005; Whittemore & Knafl, 2005). Where studies used different indicators or methods, results were synthesized narratively rather than combined into a numerical estimate. Counts of mapped linkages, or the frequency with which a goal appears in a review, were not interpreted as measures of impact strength (Almulhim & Abubakar, 2026; Klemm et al., 2022).

2.4 Evidence Categories and Interpretive Rules

Four evidence categories guide the synthesis (Table 2). A potential linkage is a theoretical, expert-assessed, or literature-mapped connection between renewable-energy activity and an SDG target (Nilsson et al., 2018; Tian et al., 2024). A project output is a delivered asset or service, such as installed capacity, electricity connections, or hours of service (Yavuz et al., 2025). An observed outcome is a measured change

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in energy use, emissions, welfare, employment, health, or another indicator (Aklin et al., 2017; Silva et al., 2026). An attributable impact requires a credible design or argument linking that measured change to the intervention rather than to concurrent factors (Aklin et al., 2017; Yavuz et al., 2025).

Table 2

Evidence Categories and Interpretive Rules Used in the Synthesis

Category	Definition	Typical sources	Supported claim	Unsupported claim
Potential linkage	Theoretical, assessed, or literature-mapped connection to an SDG target	SDG-interaction maps; assessments	Activity or expert assessment indicates X may affect target Y	X caused change in Y
Project output	Delivered asset or service	Monitoring data; project reports	X was delivered at stated scale	X changed SDG-relevant outcomes
Observed outcome	Measured change in an SDG-relevant indicator	Surveys; panel data; life-cycle inventories	Indicator changed alongside X	Changed X caused change in Y for population P
Attributable impact	Measured change credibly linked to the intervention	Randomized and quasi-experimental evaluations	X caused change in Y for population P	Generalization beyond the studied setting

Note. Categories adapted from Aklin et al. (2017), Nilsson et al. (2018), Tian et al. (2024), and Yavuz et al. (2025).

This hierarchy does not imply that only randomized experiments are useful. Qualitative, systems-modeling, life-cycle, and policy analyses answer different questions and can reveal mechanisms or risks that an impact evaluation may not capture (Long et al., 2026; Luderer et al., 2019; McCollum et al., 2018). It does require that conclusions match the evidence type, so that an SDG mapping is not presented as proof of progress and a modeled scenario is not presented as an observed outcome (Ahlbäck et al., 2026; Tian et al., 2024).

3. Conceptual Foundations

3.1 SDG Interactions Are Target-Level and Context-Dependent

The SDG-interaction literature offers a vocabulary for distinguishing positive from negative relationships between targets. Nilsson et al. (2018) proposed a seven-point scale that runs from indivisible and reinforcing interactions, through enabling and consistent relationships, to constraining, counteracting, and cancelling interactions (Table 3). The scale describes the nature of an interaction, not its empirical size, and a relationship may be directional rather than symmetric.

Table 3

Seven-Point Scale of SDG Interactions With Illustrative Renewable-Energy Examples

Score	Interaction	Meaning	Illustrative renewable-energy example
+3	Indivisible	Progress on one target is inextricably linked to another	Clean cooking access (7.1) and reduced household air-pollution mortality (3.9)
+2	Reinforcing	One target directly aids achievement of another	Reliable off-grid power for clinics (7.1) and health-service delivery (3.8)
+1	Enabling	One target creates conditions that further another	Solar irrigation (7.2) and agricultural productivity (2.3)
0	Consistent	No significant positive or negative interaction	Rooftop solar on existing buildings and terrestrial habitat (15.5)
−1	Constraining	One target limits options for another	Utility-scale solar siting and land for food production (2.4)
−2	Counteracting	One target clashes with another	Unregulated solar pumping and sustainable groundwater withdrawal (6.4)
−3	Cancelling	One target makes another impossible	Bioenergy expansion converting primary forest and halting deforestation (15.2)

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Note. Scale adapted from Nilsson et al. (2018). Examples are illustrative; the score of any real interaction depends on context, design, and time horizon. Numbers in parentheses are SDG targets.

Energy-focused assessments show that the same intervention can support one target while constraining another, and that broad goal labels can mask differences among targets (Fuso Nerini et al., 2017; McCollum et al., 2018). McCollum et al. (2018) assessed energy-related interactions together with the strength of evidence, the degree of agreement, and confidence, and identified time, geography, governance, technology, and directionality as key contextual dependencies. Nilsson et al. (2018) likewise emphasized that resource endowments, policy design, time horizon, and governance can alter the strength or direction of an interaction. The present framework therefore treats SDG targets, where available, as the preferred unit of analysis and records the direction of each effect rather than assigning a single positive or negative score to renewable energy as a whole. It also separates the conceptual classification of an interaction from estimates of its magnitude or certainty.

3.2 Renewable Energy as a Life-Cycle and System Intervention

Renewable-energy technologies differ in material requirements, land and water needs, operating characteristics, storage and grid-integration demands, and end-of-life challenges (Klemm et al., 2022; Luderer et al., 2019; Zandi et al., 2026). A project boundary limited to electricity generation can omit upstream extraction, manufacturing, construction, transmission, storage, and waste-management effects that occur elsewhere or later. Tian et al. (2024) organized renewable-energy production into source selection, operational requirements, conversion, reuse, waste production, storage, and transmission and distribution, while noting that their assessment excluded some upstream indirect emissions.

Klemm et al. (2022) showed how technology components and deployment services can be linked through industries to SDG indicators, and how assumptions about local manufacturing alter the mix of potential co-benefits and trade-offs. Their linkage-density method measures the prevalence of documented possible connections, not the magnitude of realized effects. A subsequent protocol requires analysts to define the technology, life-cycle representation, geography, time frame, scenario, linkage concept, and indicator before summarizing potential SDG relationships (Klemm et al., 2024). A life-cycle lens thus prevents a narrow focus on the operational carbon intensity of electricity from obscuring questions of material supply, biodiversity, land use, labor, and disposal (Long et al., 2026; Sovacool, 2021). A global framework must allow impacts to occur both where technologies are deployed and where materials are extracted, components manufactured, and waste processed (Ahlbäck et al., 2026).

3.3 Energy Services and Ultimate Development Outcomes

Renewable-energy deployment affects people through the energy services it provides rather than through installed equipment alone (Makešová & Valentová, 2021; Yavuz et al., 2025). Relevant service attributes include access, affordability, reliability, adequacy, quality, timing, and the possibility of using electricity for household or productive purposes. These proximal changes may mediate effects on health, education, work, income, gender equality, and household welfare, but downstream effects depend on service quality, actual use, economic opportunity, and implementation (Aklin et al., 2017).

The distinction between implementation effects and ultimate impacts is central to research on multiple impacts (Makešová & Valentová, 2021). A project may produce immediate technical effects, such as electricity generation or reduced use of a fossil source, while broader outcomes such as employment, poverty reduction, or public health are shaped by additional policies and social conditions. Attribution becomes more difficult as the outcome of interest moves further from the project and is affected by more external drivers. The framework therefore represents a causal chain rather than a single arrow from “renewable energy” to “all SDGs,” and it allows for feedback because changes in services, employment, resource use, local acceptance, and policy can influence subsequent project design (Hernandez et al., 2020; Nilsson et al., 2018).

3.4 Justice, Participation, and Distribution

Aggregate benefits do not reveal how gains and costs are distributed among households, workers, communities, regions, or generations (Silva et al., 2026; Sovacool, 2021). Energy-justice research distinguishes distributional justice, procedural justice, and the recognition of groups, rights, identities, and

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knowledge systems (Batra et al., 2025; Long et al., 2026). These dimensions matter for renewable-energy planning because a project can lower emissions while concentrating land, water, labor, or ecological burdens on groups with little influence over decisions. A global systematic review of the environmental-justice implications of renewable technologies reached a similar conclusion, documenting distributional and procedural concerns across multiple technologies and regions (Levenda et al., 2021).

Long et al. (2026) described how renewable-energy transitions can involve impacts, contestation, and Indigenous-led collective action, and emphasized that communities are not merely passive recipients of project effects. Batra et al.'s (2025) analysis of Indian state solar policies found that policies more often addressed access, employment, and skills than structural inclusion and the recognition of marginalized groups. Together, these studies support treating participation and distribution as mechanisms within the framework rather than as optional co-benefits considered after technical choices have been made.

4. Integrative Synthesis of Renewable-Energy and SDG Pathways

4.1 Energy Access, Service Quality, and Human Development

Renewable electricity can expand access in both grid-connected and off-grid settings, but access is only the first step in a potential pathway to wider development outcomes (Almulhim & Abubakar, 2026; Yavuz et al., 2025). A systematic review of 47 impact evaluations of off-grid electrification in low- and middle-income countries found a significant pooled reduction in kerosene consumption and small or positive effects on several access and technology-use measures, whereas many socioeconomic and health outcomes were statistically uncertain or null (Yavuz et al., 2025). The review reported no significant pooled effects for outcomes including affordability, reliability, school attendance, test scores, and respiratory illness, and it rated many impact estimates as having a high risk of bias (Table 4).

Table 4

Selected Impact Evidence on Renewable-Energy Access and Use

Study and design	Setting	Effects detected	Effects not detected or uncertain	Interpretive caution
Aklin et al. (2017); randomized experiment	Rural India	Higher electricity access; lower private-market kerosene spending	Savings, ownership, women's work time, study time	Low adoption; modest service level; short follow-up
Yavuz et al. (2025); systematic review of 47 impact evaluations	Low- and middle-income countries	Reduced kerosene use; small or positive effects on several access and use measures	Affordability, reliability, attendance, test scores, respiratory illness	Many estimates at high risk of bias; heterogeneous outcomes
Gupta (2019); difference-in-differences, farmers	Rajasthan, India	Estimated shifts in energy cropping, security, and profits	Net water-resource effect depends on groundwater governance	Single region; context-specific water regime

Note. Effects are reported as described by the original authors; no effect sizes are recomputed.

A randomized field experiment of a basic solar service in rural India increased electricity access and reduced private-market kerosene spending but did not detect significant effects on savings, household business ownership, women's working time, or time spent studying during the study period (Aklin et al., 2017). The authors attributed these limits partly to low adoption and the modest level of service, and they did not conclude that larger or more reliable systems would fail to yield broader benefits. Taken together, these studies indicate that access should not be treated as interchangeable with service adequacy or with downstream SDG progress.

A framework should therefore distinguish technology provision from household connection, adoption, consistent use, service quality, fuel substitution, and final outcomes. It should also specify whether outcomes concern household services, social infrastructure such as clinics and schools, or productive uses such as

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irrigation and enterprise (Almulhim & Abubakar, 2026; Yavuz et al., 2025). The evidence does not support a universal assumption that a renewable-energy connection automatically improves health, education, income, or gender equality.

4.2 Climate, Air Quality, and Health

Renewable generation contributes to climate mitigation when it displaces higher-emitting generation, but the size of the benefit depends on the counterfactual energy source, system integration, and the life-cycle boundary (Iacobuta et al., 2021; Luderer et al., 2019). Integrated assessment and life-cycle modeling of alternative power-sector pathways found that decarbonization can reduce several air-pollution and health burdens while altering pressures on minerals, land, water, and other resources according to the technology mix (Luderer et al., 2019). In that analysis, a pathway with greater wind and solar deployment reduced some fossil-related health burdens but increased mineral-resource requirements relative to other modeled pathways.

Evidence on renewable energy and health is not uniform across technologies or stages, and potential harms may arise through conversion processes, operational requirements, pollution, or siting (Tian et al., 2024). Climate-focused assessments can therefore be incomplete if they count avoided emissions but exclude upstream supply chains or local environmental effects. A sound synthesis must identify the counterfactual and the system boundary before describing an emissions or health outcome as a benefit of renewable energy (Klemun et al., 2024; Luderer et al., 2019).

4.3 Jobs, Innovation, and Productive Value Chains

Renewable-energy deployment can support employment and industry through project development, installation, operation, manufacturing, and related services, but these effects depend on the technology and on where economic activity is located (Hernandez et al., 2020; Klemm et al., 2022). Klemm et al.'s (2022) value-chain analysis found that deployment and service industries tend to contribute more potential co-benefit linkages, whereas manufacturing can generate both benefits and trade-offs. The distinction between imported components and domestic manufacturing also changes which industries are counted in the local SDG pathway.

A panel analysis of European Union and United Kingdom data for 2007–2022 found associations between renewable generation and lower greenhouse-gas emissions, higher GDP per capita, and employment for some technology groups. It did not, however, find significant evidence that renewable generation by itself reduces income inequality or consistently lowers household electricity prices (Silva et al., 2026). Because the analysis is observational and acknowledges possible endogeneity, its results are best read as conditional associations rather than definitive causal effects. These findings reinforce the difference between aggregate economic gains and distributional outcomes (Batra et al., 2025).

An innovation-systems roadmap for solar and wind energy links research, siting, public acceptance, wildlife interactions, and end-of-life management to SDG themes, and it emphasizes coordination among actors and iterative monitoring (Hernandez et al., 2020). Its workshop-derived priorities reflected mainly U.S. participants and the state of the field in 2019, so they should inform rather than dictate the design of a global framework. Local content, skills, ownership, and participation shape whether employment and innovation benefits accrue to host communities or remain elsewhere in the value chain (Klemm et al., 2022; Long et al., 2026).

4.4 Land, Water, Food, Biodiversity, and Materials

Renewable-energy trade-offs are often technology-specific and may be concentrated in land- or resource-intensive production pathways (Table 5). Large-scale bioenergy modeling shows that dedicated energy crops can create competition for land and water and affect food prices, forests, nitrogen losses, and land-use emissions, with the severity of these effects depending on food demand and on complementary land and water policies (Humpenöder et al., 2018). A systematic review of bioenergy research likewise found that evidence is unevenly distributed across regions and impact categories, and that environmental and social outcomes are less consistently positive than economic or technological ones (Robledo-Abad et al., 2017). These findings should not be generalized to solar, wind, or all renewables, but they show why technology-specific evaluation is necessary.

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Table 5

Technology-Specific Resource Synergies and Trade-Offs

Technology configuration or source	Potential synergies	Potential trade-offs	Conditioning factors	Evidence type and source
Dedicated bioenergy crops	Low-carbon energy; rural income	Land and water competition; prices; forest loss; nitrogen losses; land-use emissions	Food demand; land and water policy	Global modeling (Humpenöder et al., 2018); systematic review (Robledo-Abad et al., 2017)
Solar water pumps	Diesel displacement; irrigation; farm income	Increased groundwater extraction	Groundwater governance; tariffs; cropping	Quasi-experimental (Gupta, 2019)
Agrivoltaics	Joint food-energy production; habitat provision	Yield reductions for some crops; system costs	Design; species; climate; management	Review, partly model-based (Walston et al., 2022)
Large-scale wind and solar	Lower fossil-related air-pollution and health burdens	Higher resource requirements	Technology recycling; sourcing	Integrated assessment and LCA (Luderer et al., 2019)
Imported components and critical minerals	Domestic decarbonization benefits	Transboundary mining and manufacturing risks	Supply-chain governance	Qualitative expert assessment (Ahlbäck et al., 2026)

Note. LCA = life-cycle assessment. Findings are technology- and context-specific and should not be generalized across renewable technologies.

Solar water pumps illustrate a related energy–water–food nexus. A difference-in-differences study of 414 farmers in Rajasthan, India, estimated changes in groundwater use, energy sources, cropping patterns, food security, and profits, indicating that energy substitution may carry both agricultural benefits and water-resource consequences (Gupta, 2019). The magnitude and direction of these effects depend on local cropping systems, groundwater governance, and the energy and water systems being displaced.

Agrivoltaics provides a further example of context-sensitive co-location rather than a universal land-sparing solution. Walston et al. (2022) identified potential joint production of electricity with crops, livestock, or habitat, while noting that crop responses, system costs, biodiversity outcomes, and land-use benefits vary with design, species, climate, and management. Evidence for several ecological and regulating services at agrivoltaic sites remains limited or model-based, so such benefits should be presented as conditional rather than established.

Supply-chain and end-of-life analysis extends the scope beyond the project site. A prospective assessment of Sweden's pathway to net-zero emissions identified potential domestic benefits alongside international spillover risks associated with critical-mineral mining, although it relied on qualitative expert and literature-informed judgment rather than observed outcomes (Ahlbäck et al., 2026). Life-cycle modeling similarly shows that decarbonization pathways can reduce fossil-related impacts while increasing mineral demand or other technology-specific burdens (Luderer et al., 2019).

4.5 Justice, Participation, and Cross-Border Spillovers

The impacts of renewable projects fall on different people and places, and a national or global net benefit can conceal locally concentrated harm (Long et al., 2026; Sovacool, 2021). A review of low-carbon transitions identified processes of enclosure, exclusion, encroachment, and entrenchment in case studies involving land, ecological change, participation, labor, and benefit distribution (Sovacool, 2021). Because

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that corpus was an expert-guided selection rather than a representative sample, its reported frequencies describe the literature and should not be read as incidence rates.

The experiences of Indigenous peoples illustrate why recognition and consent matter alongside distribution. Long et al. (2026) described renewable-energy impacts, contestation, and Indigenous community energy, while noting geographical gaps in the underlying scholarship. Indian state solar policies similarly address access and employment more often than targeted inclusion or recognition of structural inequalities (Batra et al., 2025). A global framework should therefore record who participates, who holds decision-making authority, who receives benefits, and who bears land, water, labor, and ecological burdens.

Cross-border effects are especially important when equipment and minerals are produced in one location and electricity is consumed in another (Ahlbäck et al., 2026; Klemm et al., 2022). A deployment pathway may appear beneficial within the territory where generation occurs while relying on extraction or manufacturing practices that create risks elsewhere (Sovacool, 2021). SDG assessments should therefore distinguish domestic effects from transboundary spillovers and state the supply-chain boundary used.

4.6 Interactions Among Pathways

The pathways described above are not independent channels. Renewable-energy interventions can create linked effects across energy, water, land, food, health, and livelihoods (McCollum et al., 2018; Nilsson et al., 2018). Solar-powered irrigation, for example, may reduce diesel use and support agricultural production while increasing groundwater extraction where pumping is not governed by water availability (Gupta, 2019). Bioenergy expansion can support low-carbon energy while increasing land competition, food prices, water withdrawals, or land-use emissions under some demand and policy conditions (Humpenöder et al., 2018). Such examples show why a framework must identify interacting mechanisms rather than count each SDG linkage as a separate benefit or cost.

Interactions may also be sequential. A siting decision affects land and participation; construction affects jobs and material demand; operation changes energy services and emissions; and decommissioning affects waste and future land use (Hernandez et al., 2020; Tian et al., 2024). Because the timing and scale of one pathway can condition another, an immediate employment gain may coexist with delayed ecological costs or with future recycling benefits (Luderer et al., 2019). A global synthesis should therefore record whether reported effects occur together, in sequence, or at different spatial scales (Klemm et al., 2024).

4.7 What Current Evidence Can and Cannot Establish

The reviewed literature contains several forms of evidence that cannot be collapsed into a single score (Klemm et al., 2022; McCollum et al., 2018). Target-level maps identify plausible interactions and organize knowledge but do not estimate effect sizes (Fuso Nerini et al., 2017; Tian et al., 2024). Linkage-density approaches measure the share of documented potential connections under specified assumptions, not the net welfare or environmental effect of a technology (Klemm et al., 2022). Systems and life-cycle models compare internally consistent scenarios, but their results depend on model boundaries and assumptions (Humpenöder et al., 2018; Luderer et al., 2019). Impact evaluations estimate intervention effects for particular populations and programs but may not generalize across technologies or countries (Aklin et al., 2017; Yavuz et al., 2025). Observational panel analyses capture associations across larger samples but may leave endogeneity and distributional heterogeneity unresolved (Silva et al., 2026). Qualitative and justice-oriented studies reveal mechanisms, institutional power, recognition, and lived experience that standardized indicators may miss, although they do not by themselves estimate average causal effects (Batra et al., 2025; Long et al., 2026).

The principal gap, therefore, is not a shortage of SDG maps. It is the absence of a common structure connecting mapped interactions to mechanisms, context, distribution, life-cycle boundaries, and evidence strength. The framework proposed in the next section addresses this need while preserving the distinct role of each evidence design.

5. Proposed Conceptual Framework

5.1 Framework Architecture

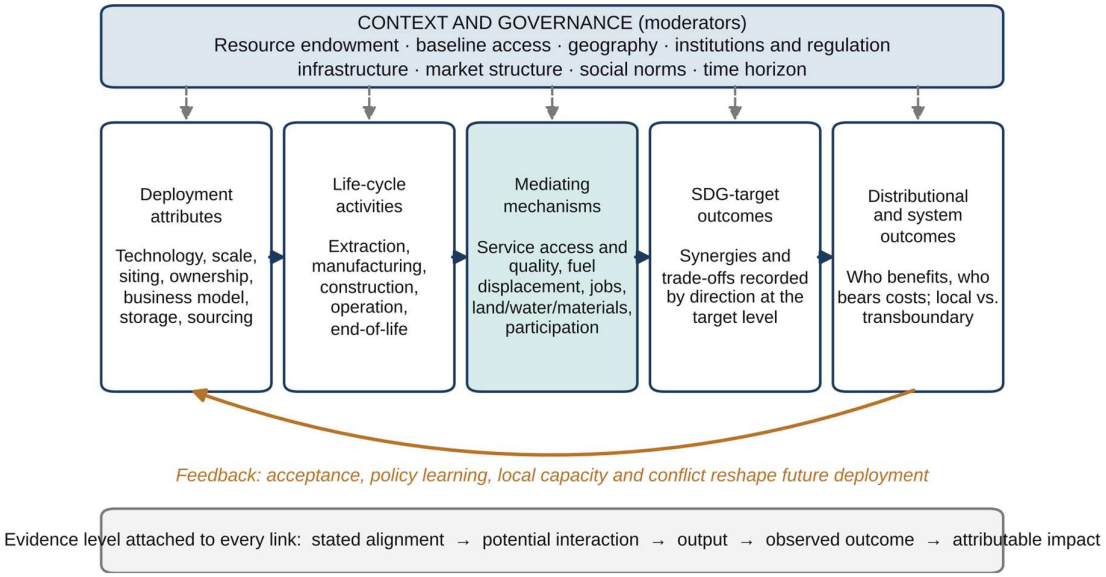
The framework represents renewable-energy development as a multilevel sequence in which context shapes deployment, deployment activities activate mechanisms, mechanisms affect SDG-target outcomes,

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and observed outcomes feed back into future decisions (Hernandez et al., 2020; Klemm et al., 2024; McCollum et al., 2018). The sequence is conditional and potentially bidirectional rather than a universal linear effect (Makešová & Valentová, 2021; Nilsson et al., 2018). Figure 4 depicts the full architecture.

Figure 4

Integrative Framework Linking Renewable-Energy Deployment to SDG Outcomes



Note. Solid arrows show the hypothesized sequence from deployment to outcomes; dashed arrows show moderation by context and governance; the curved arrow denotes feedback to future deployment. Every link is labeled with the level of evidence that supports it (see Figure 6). Framework synthesized by the author from Klemm et al. (2022, 2024), McCollum et al. (2018), Nilsson et al. (2018), Tian et al. (2024), and Yavuz et al. (2025). Figure image as supplied in the source file.

Context includes resource endowment, baseline energy access, geography, institutional quality, regulation, infrastructure, social norms, market structure, and time horizon (McCollum et al., 2018; Nilsson et al., 2018). Deployment attributes include technology, scale, siting, ownership, business model, grid connection, storage, and supply-chain sourcing (Klemm et al., 2022, 2024). Life-cycle activities include extraction, manufacturing, construction, operation, maintenance, transmission, storage, and end-of-life management (Luderer et al., 2019; Tian et al., 2024). Mediating mechanisms include changes in service access and quality, fossil-fuel displacement, local employment and supplier activity, land and water use, material demand, waste, and participation in project decisions (Batra et al., 2025; Yavuz et al., 2025). These mechanisms may support or constrain different SDG targets, and their effects may differ for households, workers, Indigenous communities, host regions, and people located along supply chains (Long et al., 2026; Sovacool, 2021).

5.2 Framework Layers and Analytical Questions

Table 6 sets out the five analytical layers of the framework, their core dimensions, and the question each layer asks. The architecture combines the target-level interaction lens with technology-specific life-cycle analysis and explicit outcome pathways (Klemm et al., 2022; Nilsson et al., 2018; Tian et al., 2024). It differs from classifying SDGs into broad relevance tiers because it asks how project attributes and context activate particular mechanisms and what evidence supports each link (Almulhim & Abubakar, 2026; Makešová & Valentová, 2021).

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Table 6

Framework Layers, Core Dimensions, and Analytical Questions

Layer	Core dimensions	Analytical question
Context	Geography, baseline access, governance, time horizon, resource endowment	Under what conditions does the pathway operate?
Deployment	Technology, scale, site, ownership, business model	What is deployed, where, and by whom?
Life cycle	Materials, manufacturing, operation, storage, end of life	Which activities create benefits or burdens, and where?
Mechanisms	Energy service, fuel displacement, jobs, land/water/materials, participation	Through what intermediate process does change occur?
Outcomes evidence	SDG target, distribution, evidence uncertainty	What changed, for whom, and how strongly can it be attributed?

Note. Layers correspond to the boxes in Figure 4.

5.3 Pathways and Associated SDG Domains

The framework does not assign a fixed SDG score to each technology, because the direction and magnitude of effects depend on project design, system boundary, and context (McCollum et al., 2018; Tian et al., 2024). Instead, it organizes pathways that can be tested within a specified project or policy setting (Klemm et al., 2024). Table 7 summarizes five pathways, the SDG domains each commonly implicates, and the conditions under which a potential synergy may become a trade-off; Figure 5 displays the same pathways as a matrix across the 17 goals.

Table 7

Renewable-Energy Pathways, Associated SDG Domains, and Conditions

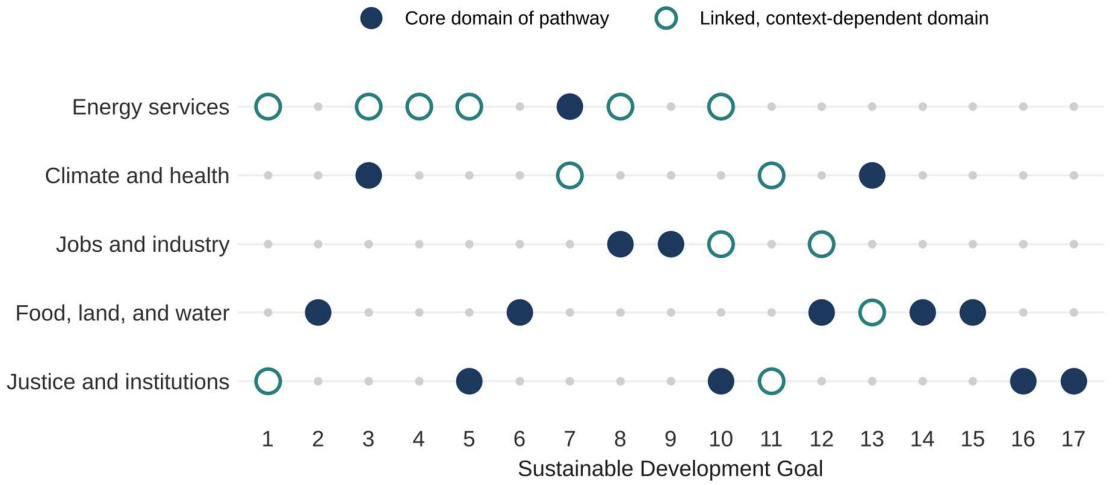
Pathway	SDG domains	Potential synergy	Possible trade-off or condition
Energy services	SDG 7; links to 1, 3, 4, 5, 8, 10	Improved access; fossil-fuel substitution	Access may be inadequate, unaffordable, unreliable, or unequally distributed (Aklin et al., 2017; Yavuz et al., 2025)
Climate and health	SDGs 3, 13	Lower fossil-related emissions and pollution	Benefits depend on the displaced source and life-cycle boundary (Iacobuta et al., 2021; Luderer et al., 2019)
Jobs and industry	SDGs 8, 9	Local installation, services, manufacturing, innovation	Jobs may be temporary, geographically concentrated, or not locally captured (Klemm et al., 2022; Silva et al., 2026)
Food, land, and water	SDGs 2, 6, 12, 14, 15	Productive use; land sharing; resource efficiency	Bioenergy, irrigation, siting, or materials may intensify resource competition (Gupta, 2019; Humpenöder et al., 2018; Walston et al., 2022)
Justice and institutions	SDGs 5, 10, 16, 17	Participation; recognition; local ownership; partnerships	Exclusion, displacement, weak consent, or unequal benefit sharing (Batra et al., 2025; Long et al., 2026; Sovacool, 2021)

Note. The table identifies domains discussed in the literature; it is not a comprehensive target-level mapping or evidence that each pathway operates in every setting.

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Figure 5

Pathway-by-SDG Matrix of Potential Synergies and Trade-Offs



Note. Filled circles indicate the core SDG domains of each pathway; open circles indicate linked domains whose involvement depends on context and design. Markers denote where potential synergies and trade-offs arise, not their magnitude or direction. Coded by the author from the sources summarized in Table 7. Figure image as supplied in the source file.

Table 7 and Figure 5 represent domains identified in the literature; they are neither a comprehensive mapping of every target nor a claim that every pathway is empirically established. Their purpose is to ensure that a project assessment examines both direction and conditionality rather than assuming a net positive effect from a renewable label alone (Nilsson et al., 2018; Tian et al., 2024).

5.4 Context as Moderator and Mechanism

Geography and resource endowment determine which technologies are feasible, which environmental systems are exposed, and whether local suppliers and skills exist (Klemm et al., 2022; McCollum et al., 2018). Governance and policy design influence permitting, benefit sharing, affordability, labor standards, land access, environmental safeguards, and the distribution of transition costs (Batra et al., 2025; Long et al., 2026). Time horizon matters because capital costs, construction impacts, operating benefits, and decommissioning burdens emerge at different stages (Hernandez et al., 2020).

Within this structure, service quality and affordability act as mediators between technology provision and household outcomes (Aklin et al., 2017; Yavuz et al., 2025). Participation, recognition, and ownership shape both project legitimacy and the distribution of local benefits (Batra et al., 2025; Long et al., 2026). Supply-chain sourcing and end-of-life arrangements determine whether local economic gains are accompanied by overseas or future environmental burdens (Ahlbäck et al., 2026; Luderer et al., 2019). Context should therefore not be treated merely as a control variable added after a model is specified; it can reverse the direction of a relationship, change which targets are affected, or create feedback between project outcomes and future deployment (Nilsson et al., 2018).

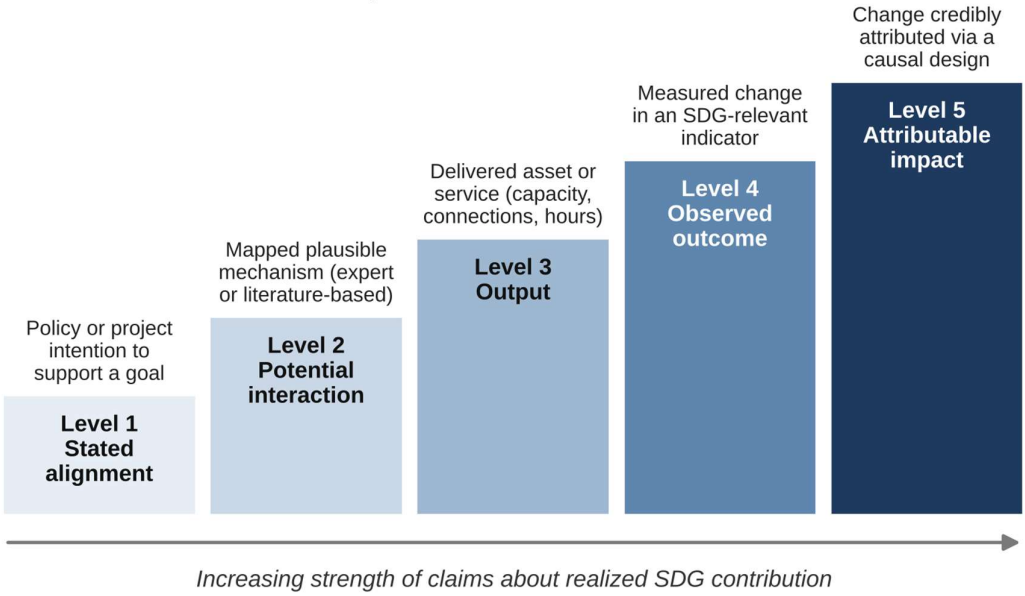
5.5 The Evidence and Outcome Ladder

The framework uses a five-level evidence ladder to prevent potential alignments from being reported as demonstrated SDG progress (Figure 6). At the first level, a stated alignment records a policy or project intention to support a goal. At the second, a potential interaction maps a plausible mechanism, usually through expert assessment or literature synthesis (Fuso Nerini et al., 2017; Tian et al., 2024). At the third, an output documents a delivered activity or service, such as capacity or a connection. At the fourth, an observed outcome measures change in a relevant indicator (Silva et al., 2026). At the fifth, an attributable impact uses a credible comparison or causal design to estimate the change due to the intervention (Aklin et al., 2017; Yavuz et al., 2025).

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Figure 6

Five-Level Evidence and Outcome Ladder for SDG Claims



Note. Higher levels are not universally superior; each answers a different question. The ladder governs the strength of claim that may be made about realized SDG contribution, not the value of the research design. Developed by the author from the evidence categories in Table 2. Figure image as supplied in the source file.

A project may have strong evidence of an output but weak evidence of downstream health, educational, or distributional effects (Yavuz et al., 2025). A model may estimate system-wide co-benefits and trade-offs under a scenario without observing any real-world outcome (Humpenöder et al., 2018; Luderer et al., 2019). A target map may identify a potential relationship without estimating its magnitude or confidence (Klemm et al., 2022). Reports should therefore label the evidence level, study design, population, system boundary, time horizon, and uncertainty attached to each SDG claim (Klemm et al., 2024; McCollum et al., 2018).

5.6 Operationalization for Empirical Studies

The framework can guide empirical work without imposing a single universal indicator set (Table 8). Researchers should define the intervention at a comparable level, such as installed capacity, generation, technology adoption, project commissioning, or a policy-induced change, and should state the relevant counterfactual (Aklin et al., 2017). A capacity measure alone is inadequate when the research question concerns household services, because capacity does not establish connection, affordability, reliability, or use (Yavuz et al., 2025).

Table 8

Operationalizing the Framework: Constructs and Example Indicators

Construct	Role	Example indicators	Measurement caution
Intervention	Treatment	Installed capacity; generation; adoption; commissioning; policy change	State the counterfactual; capacity is not service
Service quality	Mediator	Daily service hours; interruptions; voltage; expenditure share	Measure separately; avoid composite access indices
Fuel substitution	Mediator	Kerosene, diesel, and traditional biomass use	Verify the displaced energy source

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Local economic activity	Mediator	Local employment; supplier contracts; productive uses	Separate temporary construction jobs from lasting jobs
Resource use	Mediator	Land conversion; water withdrawals; material demand	Specify the life-cycle boundary
Participation	Mediator or moderator	Decision authority; ownership shares; consent processes	Formal consultation is not influence
SDG outcomes	Outcome	Target-linked indicators with baseline, unit, population, and period	Disaggregate by income, gender, Indigenous identity, and location
Context	Moderator	Baseline electrification; grid strength; governance; land tenure; subsidy design	Pre-specify; avoid post hoc subgroup analysis

Note. Indicators are examples, not a mandatory set; selection should follow the mechanism specified for the SDG target under study.

Mediators should be measured as separate constructs rather than merged into an undifferentiated "energy access" index. Examples include connection and adoption, daily hours of service, interruptions, voltage or service quality, household energy expenditure, fuel substitution, productive use, local employment, land conversion, water withdrawals, and community participation (Aklin et al., 2017; Gupta, 2019; Yavuz et al., 2025). The choice of mediator should follow the causal mechanism specified for the target under study (Klemun et al., 2024). Outcome measures should be mapped to the most relevant SDG target and reported with their baseline, unit, population, and time period. Where global indicators do not capture local concerns such as energy sovereignty, recognition, or culturally significant land, project-level indicators may be needed alongside official measures (Long et al., 2026). Disaggregation by income, gender, Indigenous identity, occupation, location, or other locally relevant characteristics can reveal distributional patterns hidden by averages (Batra et al., 2025; Silva et al., 2026).

Moderators should be specified before effects are estimated, because post hoc subgroup analysis can yield unstable interpretations when study counts are small (Yavuz et al., 2025). Candidate moderators include baseline electrification, resource availability, grid strength, governance and enforcement, ownership arrangements, local manufacturing, subsidy design, land tenure, and time horizon. Researchers should also distinguish variables that modify a treatment effect from variables that lie on the causal pathway, since controlling for a mediator may remove part of the effect a study intends to estimate (Makešová & Valentová, 2021).

Evidence appraisal should match the research design (McCollum et al., 2018; Whittemore & Knafl, 2005). Randomized and quasi-experimental designs can estimate selected intervention effects when their assumptions are credible, but they may not capture long-term, cross-border, or ecosystem impacts. Life-cycle assessment estimates burdens within a defined boundary, and scenario models compare alternative futures under explicit assumptions (Humpenöder et al., 2018; Luderer et al., 2019). Qualitative and participatory research can identify recognition, power, local meaning, and implementation mechanisms invisible to standardized indicators (Batra et al., 2025; Long et al., 2026). Combining these designs strengthens causal interpretation without implying that any single method captures the whole of an SDG contribution.

Feedbacks and Cross-Scale Effects

Renewable projects can influence future deployment through public acceptance, policy learning, local economic capacity, infrastructure investment, and institutional trust (Hernandez et al., 2020). Feedback is reinforcing when reliable service supports productive activity and local support, and constraining when burdens and exclusion weaken acceptance or intensify conflict (Long et al., 2026). Cross-scale effects arise when local siting decisions interact with national electricity systems, global climate outcomes, and transnational supply chains (Ahlbäck et al., 2026; Luderer et al., 2019). The framework therefore records at least three spatial scales: the project or community; the national energy and policy system; and the

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transnational supply chain and climate system. It also recognizes temporal asymmetry, since construction and material sourcing precede the benefits of operation, while waste and ecological effects may persist beyond the life of the asset.

6. Propositions for Future Empirical Testing

The following propositions translate the framework into researchable relationships. They are not findings established by this synthesis but hypotheses for empirical testing (Nilsson et al., 2018; Whittemore & Knafl, 2005). Table 9 pairs each proposition with suitable research designs and indicative measures.

6.1 Proposition 1: Life-Cycle Specificity

The relationship between renewable-energy deployment and SDG outcomes varies by technology and life-cycle stage; assessments that aggregate technologies or focus only on operation will therefore omit relevant trade-offs and co-benefits (Klemun et al., 2022; Luderer et al., 2019; Tian et al., 2024).

6.2 Proposition 2: Service Quality Mediates Development Outcomes

The association between renewable-energy access and wider household development outcomes is mediated by service reliability, affordability, adequacy, actual use, and productive opportunity (Aklin et al., 2017; Yavuz et al., 2025). Evaluations should test these mechanisms rather than infer education, income, health, or gender effects from installation or connection counts.

6.3 Proposition 3: Context Can Alter the Direction of SDG Interactions

Resource conditions, governance, baseline infrastructure, and time horizon moderate the direction and strength of renewable-energy interactions with SDG targets (McCollum et al., 2018; Nilsson et al., 2018). Comparable technologies may therefore produce different outcomes across settings, and global syntheses should preserve rather than average away such differences (Robledo-Abad et al., 2017).

6.4 Proposition 4: Distributional Arrangements Shape Justice Outcomes

The distribution of ownership, participation, compensation, and local economic opportunity mediates who benefits from deployment and who bears its costs (Batra et al., 2025; Long et al., 2026; Sovacool, 2021). Projects designed with meaningful influence by affected communities may yield different distributional outcomes from those designed without it.

6.5 Proposition 5: Supply-Chain Boundaries Affect Apparent Sustainability

The geographical boundary of an assessment moderates the measured balance of synergies and trade-offs, because extraction, manufacturing, use, and disposal may occur in different jurisdictions (Ahlbäck et al., 2026; Klemm et al., 2022). Studies should report domestic effects separately from international spillovers.

6.6 Proposition 6: Evidence Strength Constraints the Scope of SDG Claims

The strength of claims about SDG contributions should rise with the quality, relevance, and convergence of evidence, and uncertainty should remain explicit where findings rely on mapping, modeling, small samples, or impact estimates at high risk of bias (McCollum et al., 2018; Yavuz et al., 2025).

Table 9

Propositions, Suitable Research Designs, and Indicative Measures

Proposition	Core claim	Suitable designs	Indicative measures
P1. Technology specificity	SDG effects vary by technology and life-cycle stage	Comparative supply-chain analysis; LCA	Stage-specific emissions, materials, land, labor
P2. Service quality mediates outcomes	Reliability, affordability, and use mediate development effects	RCTs and quasi-experiments with mediation analysis	Use, income, schooling
P3. Context alters direction	Context moderates the sign and strength of interactions	Multi-site comparative studies; pre-specified moderators	Interaction scores by setting; effect heterogeneity
P4. Distribution shapes justice	Ownership and participation determine	Mixed methods; participatory and comparative case studies	Benefit shares; decision authority; burden incidence

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Proposition	Core claim	Suitable designs	Indicative measures
	who gains and who bears costs		
P5. Boundaries shape apparent sustainability	Assessment boundary changes the synergy–trade-off balance	Multi-regional input–output and LCA with boundary scenarios	Domestic vs. transboundary impacts
P6. Evidence constrains claims	Claim strength should track evidence quality and convergence	Structured evidence appraisal; triangulation	Evidence level and convergence

Note. LCA = life-cycle assessment; RCT = randomized controlled trial. Propositions are hypotheses for testing, not findings of this synthesis.

7. Discussion

7.1 Contribution Beyond Existing SDG Maps

The framework responds to a literature that already contains broad renewable-energy-to-SDG reviews, target-level interaction maps, technology-by-life-cycle assessments, and project-level screening protocols (Almulhim & Abubakar, 2026; Fuso Nerini et al., 2017; Klemm et al., 2022, 2024; Tian et al., 2024). It does not claim any of these dimensions as new in isolation. Its contribution is to connect them in a single evidence-sensitive pathway running from context and deployment choice through life-cycle activity, mediating mechanism, and target-level outcome to distribution and feedback. This integration makes it possible to distinguish a plausible SDG linkage from a measured outcome, to locate where evidence is missing along the causal chain, and to place distributional justice and cross-border spillovers within the same model as technological and environmental effects (Ahlbäck et al., 2026; Long et al., 2026; Sovacool, 2021).

The framework is deliberately not a single numerical sustainability score. A composite score can obscure whether a relationship is potential or measured, whether it benefits one group while harming another, and whether it is local or transboundary (Klemm et al., 2022; Long et al., 2026). Where assessments do use interaction scores or linkage densities, they should report their definitions and avoid interpreting counts as effect magnitudes. The pattern in Figure 3 reinforces this point: an evidence base dominated by mapping exercises can describe the shape of potential interactions far better than it can confirm their realized size.

7.2 Theoretical Implications

The framework extends SDG-interaction theory by placing technology and project attributes between broad energy goals and target-level effects (Klemm et al., 2022; Nilsson et al., 2018). This makes the unit of analysis more concrete: instead of asking whether renewable energy as a category supports a goal, it asks which technology, at what scale, through which activity, and under what conditions affects which target (Klemm et al., 2024; Tian et al., 2024). It also links energy-transition research to theories of multiple impacts and energy justice. The multiple-impacts perspective separates implementation effects from ultimate societal outcomes, while justice analysis asks how benefits and burdens are distributed and recognized (Makešová & Valentová, 2021; Sovacool, 2021). Integrating these perspectives explains why aggregate emissions reductions or employment growth cannot stand in for equitable or comprehensive SDG achievement (Silva et al., 2026). Finally, the framework treats evidence type as part of theory-building rather than as a closing methodological note: a conceptual linkage, a model result, an observed association, and an attributable impact provide different kinds of knowledge, and combining them indiscriminately can produce conclusions stronger than the evidence warrants (McCollum et al., 2018).

7.3 Policy and Project Implications

Policymakers should assess renewable-energy pathways at the technology and project level, paying explicit attention to life-cycle boundaries, supply-chain sourcing, local resource conditions, and the distribution of costs and benefits (Ahlbäck et al., 2026; Klemm et al., 2024). Planning should consider service quality and affordability alongside installed capacity, because household outcomes depend on the electricity actually received and used (Aklin et al., 2017; Yavuz et al., 2025). The concentration of the remaining access

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deficit in Sub-Saharan Africa (Figure 2) suggests that service-quality and affordability criteria are especially important where new connections are now being targeted (IEA et al., 2025).

Developers and regulators should identify affected communities early and specify how participation, recognition, compensation, and benefit sharing will be built into decisions (Batra et al., 2025; Long et al., 2026). Siting decisions should consider land, water, biodiversity, food production, and cultural values, and should assess whether cumulative pressures from multiple projects exceed local ecological or social limits (Humpenöder et al., 2018; Walston et al., 2022). Monitoring frameworks should report output, outcome, and impact indicators separately; disclose the evidence design behind each public SDG claim; include both positive and negative effects; and disaggregate results by relevant groups or locations wherever data permit (McCollum et al., 2018; Yavuz et al., 2025).

7.4 Research Agenda

Seven priorities follow from the synthesis. First, empirical work should test the mediating sequence from deployment to service quality and then to wider social, economic, and environmental outcomes. Studies should specify baseline conditions, counterfactual energy sources, adoption and use, reliability, affordability, and time horizon; distinguish intention-to-treat effects from effects among actual adopters; and allow longer follow-up where outcomes such as enterprise development or educational attainment take time to materialize (Aklin et al., 2017; Yavuz et al., 2025).

Second, research should compare pathways rather than technologies in the abstract. Useful contrasts include grid-connected versus off-grid systems, imported versus locally manufactured components, centralized versus community ownership, and projects with or without storage or productive-use support (Hernandez et al., 2020; Klemm et al., 2022). Each comparison should state whether it aims to estimate a local treatment effect, profile a supply chain, map plausible interactions, or compare future scenarios (Klemm et al., 2024; Luderer et al., 2019).

Third, the evidence base should become more geographically and technologically balanced. Off-grid impact evaluations are concentrated in Sub-Saharan Africa and South Asia, and the justice literature has gaps across regions and technologies (Long et al., 2026; Yavuz et al., 2025). Comparative research should include wind, solar, hydropower, bioenergy, geothermal, ocean energy, and hybrid systems without assuming that results from one technology apply to others (Robledo-Abad et al., 2017; Tian et al., 2024).

Fourth, life-cycle and supply-chain measurement should be strengthened by identifying where materials and labor originate, measuring end-of-life pathways, and connecting energy-system scenarios with life-cycle and land-use effects while reporting assumptions and uncertainty (Ahlbäck et al., 2026; Humpenöder et al., 2018; Luderer et al., 2019).

Fifth, justice and distribution should be assessed as outcomes rather than as general principles. Studies should examine who participates in decisions, who owns assets, who receives jobs and revenues, which groups bear land and environmental burdens, and whether affected groups can actually alter siting, design, ownership, benefit sharing, or approval, as opposed to being merely consulted (Batra et al., 2025; Long et al., 2026; Sovacool, 2021).

Sixth, evidence syntheses should develop more transparent approaches to assessing confidence across heterogeneous designs, separating qualitative, conceptual, modeled, observational, and causal evidence and publishing the rationale for structured ratings of evidence strength, agreement, and confidence (McCollum et al., 2018; Whittemore & Knafl, 2005). Seventh, researchers should test transboundary and intergenerational effects directly, using comparative life-cycle studies and longitudinal designs to examine whether early employment or access effects persist and how end-of-life outcomes emerge over asset lifetimes (Ahlbäck et al., 2026; Hernandez et al., 2020).

7.5 Limitations

This paper is a conceptual integrative synthesis, not a completed systematic review with reproducible database-specific queries, record-level screening, and a PRISMA flow diagram (Snyder, 2019; Whittemore & Knafl, 2005). The discovery search returned 239 candidate records, but that figure is not an included-study count, and not all candidates underwent formal eligibility screening. The synthesis gives greater weight to a

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purposive set of highly relevant full-text sources, which may omit relevant studies and introduce selection bias.

The evidence itself is heterogeneous in technology, geographic scope, outcome definition, time horizon, and study design, which precludes a single quantitative estimate of renewable energy's effect across the SDGs (McCollum et al., 2018; Robledo-Abad et al., 2017). Some sources map potential interactions while others measure project outcomes or model scenarios, and these cannot be treated as interchangeable. Social and justice outcomes are quantified less consistently than many energy and environmental measures, and findings from specific regions or technologies may not generalize globally (Batra et al., 2025; Long et al., 2026). The coding of sources in Figure 3 and of pathways in Figure 5 reflects the author's interpretive judgment and should be replicated by independent coders in future work. Finally, the framework is a synthesis proposal rather than an empirically validated causal model; its pathways and propositions require testing through comparative project studies, longitudinal data, mixed methods, life-cycle analysis, and context-sensitive impact evaluation (Klemm et al., 2024; Yavuz et al., 2025).

8. Conclusion

Renewable energy can support progress toward multiple SDGs, but its wider effects depend on technology, life-cycle stage, context, governance, service quality, and the distribution of benefits and burdens (Batra et al., 2025; Klemm et al., 2022; McCollum et al., 2018; Tian et al., 2024). Existing reviews and mapping studies establish important parts of this picture, while impact evaluations show that access and deployment do not automatically produce broader socioeconomic outcomes (Aklin et al., 2017; Almulhim & Abubakar, 2026; Yavuz et al., 2025).

The proposed framework connects context and governance to deployment attributes, life-cycle activities, mediating pathways, target-level outcomes, distribution, and feedback over time. Its principal analytical safeguard is the distinction between stated alignment and potential interaction, on the one hand, and outputs, observed outcomes, and attributable impacts, on the other. The framework is intended to guide transparent review, project assessment, and empirical testing—not to certify all renewable energy as sustainable or to replace technology- and place-specific evidence. Future work should complete a reproducible search and screening process and test the six propositions advanced here across technologies, regions, and scales.

Ethics Statement

This study adhered to all ethical standards of research during the conducting of this study. We collected data from secondary sources, and no human participants were involved in the collection of data. Therefore, there is no conflict of interest of any human participant to this study.

Author's Contributions

All authors participated in ideation, development, and writing the manuscript. All authors read and approved the final manuscript.

Conflict of Interest Statement

The authors declare that there is no conflict of interest regarding the publication of this article.

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Data Availability

The datasets generated and analysed during the current study are available from the corresponding author upon reasonable request. The authors are committed to transparency and will provide detailed methodological information and analysis protocols upon request.

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