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Renewable Energy Transition Pathways and Net-Zero Strategies

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Abstract: This article synthesizes current evidence on renewable energy transition pathways and the design of net-zero strategies, with emphasis on three interdependent levers: (i) recent technological advances shaping renewable deployment and system integration, (ii) the strategic role and constraints of CO_2 capture technologies within power and energy systems, and (iii) the policy architecture required to translate technical potential into durable emissions outcomes. Building on a systems perspective, the paper frames decarbonization as a sequencing problem in which rapid expansion of variable renewables (solar PV and wind) must be co-optimized with enabling infrastructure, transmission and distribution upgrades, inverter-based stability services, storage and demand-side flexibility, to maintain reliability as fossil generation declines. The investigation further evaluates carbon management options, including post-combustion and pre-combustion capture for point sources and emerging CO_2 removal pathways, highlighting that feasibility is governed by capture rates, energy penalties, transport-and-storage access, and robust monitoring, reporting, and verification. Finally, the article assesses how high-impact policy instruments, carbon pricing, clean electricity standards, competitive procurement via auctions and long-term contracts, grid and permitting reform, methane and non-CO_2 regulations, and end-use electrification mandates, interact to reduce investment risk, accelerate deployment, and avoid emissions lock-in. The resulting framework clarifies how technology evolution, infrastructure readiness, and policy credibility jointly determine the cost, pace, and integrity of pathways consistent with mid-century net-zero objectives.

Keywords: Renewable energy transition pathways, Net-zero strategies, Grid integration and flexibility, Carbon capture and storage (CCUS), Climate and energy policy instruments.

1.Introduction

Annual global energy-related CO_2 emissions attained an unprecedented level of 38 gigatonnes (Gt) in 2024. Under the Current Policies Scenario (CPS), emissions are projected to remain broadly at this plateau, implying that 2050 emissions are approximately 10 Gt lower than in the 2019 vintage of the same scenario [1,2]. By contrast, in the Stated Policies Scenario (STEPS), emissions decline to below 30 Gt by mid-century. These divergent trajectories translate into markedly different long-run climate outcomes: the CPS pathway is consistent with an end-of-century (2100) temperature increase approaching 3 °C, whereas STEPS correspond to an outcome of roughly 2.5 °C. In the updated Net Zero Emissions (NZE) Scenario, persistently elevated emissions in recent years, coupled with slower-than-anticipated deployment across several mitigation domains, yields a more gradual emissions-reduction profile to 2030 relative to earlier editions [3,4]. In light of these dynamics, a temporary exceedance ("overshoot") of the 1.5 °C threshold is now assessed as unavoidable. Accordingly, peak warming in the NZE pathway remains above 1.5 °C for multiple decades, with temperatures returning to below 1.5 °C by 2100 only under assumptions of an exceptionally rapid energy-system transformation and the large-scale deployment of CO_2 removal options that are not yet demonstrated at commensurate scale [5,6].

A pathway capable of averting the most acute climate risks remains technically attainable, underpinned by accelerating innovation and diffusion across several pivotal low-carbon technologies. However, a decade after the Paris Agreement was adopted in December 2015, the durability of formal, country-level political commitments appears uneven [7,8]. In this context, the United States initiated a renewed withdrawal from the Paris Agreement following an executive action taken on 20 January 2025, signalling a material weakening of multilateral engagement by a major emitter. Against this backdrop, the 2025 cycle of nationally determined contributions (NDCs) communicated to date provides limited aggregate uplift beyond trajectories already embedded in the Stated Policies Scenario (STEPS) [9,10]. Specifically, for countries that had submitted updated NDCs by November 2025, total energy-related emissions were approximately 20 Gt in 2024; full implementation of these NDCs would reduce emissions to around 15–17 Gt by 2035, an 11–25% decline that is broadly consistent with STEPS outcomes [11,12].

Renewable energy transition pathways describe structured, time-bound sequences through which energy systems shift from fossil-dominant supply toward high shares of low-carbon electricity, typically anchored in rapid scale-up of solar PV, wind, hydropower, and complementary firm low-carbon resources [13,14]. In contemporary systems analysis, credible pathways are increasingly defined not by generation build-out alone, but by the co-evolution of enabling infrastructure and operational capabilities: accelerated transmission expansion, enhanced distribution hosting capacity, grid-forming and grid-following inverter controls, and a portfolio of flexibility resources (short- to long-duration storage, demand response, interconnection, and flexible clean generation) [14,15]. Pathway design therefore requires reliability-constrained planning that explicitly accounts for resource adequacy, seasonal and diurnal variability, congestion, and extreme-weather resilience, while optimizing investment sequencing to avoid stranded assets and lock-in effects. As renewable penetration rises, the marginal value of additional variable renewable energy (VRE) becomes system-dependent, making integrated planning, rather than technology-by-technology deployment targets, essential to minimizing total system costs and curtailment while preserving stability and quality of supply.

Figure 1 conceptualizes the renewable-energy value chain as a coupled exploitation–production–utilization system that is continuously shaped by climate change and ecological risk. At the upstream end (exploitation), growing resource scarcity and inelastic demand intensify pressures on mineral extraction and supply security, while environmental externalities, such as greenhouse gas emissions, electronic waste, and air/soil pollution, emerge if circularity is weak. In the midstream (production), climate-driven meteorological variability and microclimate/ecological process changes directly affect renewable output and operational performance, highlighting the importance of forecasting and resilient system design. Downstream (utilization), the system confronts unbalanced resources and stochastic risk (e.g., variability, extremes), which can propagate into ecological damage if deployment and operation are not managed responsibly [16,17].

A key contribution of the diagram is its emphasis on interactions and flows: "information flow" links decision-making across all stages, "material flow" reflects supply chains and recycling loops, and "energy flow" represents generation, delivery, and storage. The bottom panel consolidates this into actionable "challenges and solutions": for exploitation, strategies such as recycling/reutilization, high-performance materials, and life-cycle/material-flow analysis reduce upstream impacts and improve supply resilience; for production, multi-timescale variability prediction, extreme-climate warning systems, and sensor collaboration enhance operational robustness; and for utilization, variable renewable management via cooperative planning, transmission and microgrids, and distributed flexible resources supports reliability while limiting environmental harm [18].

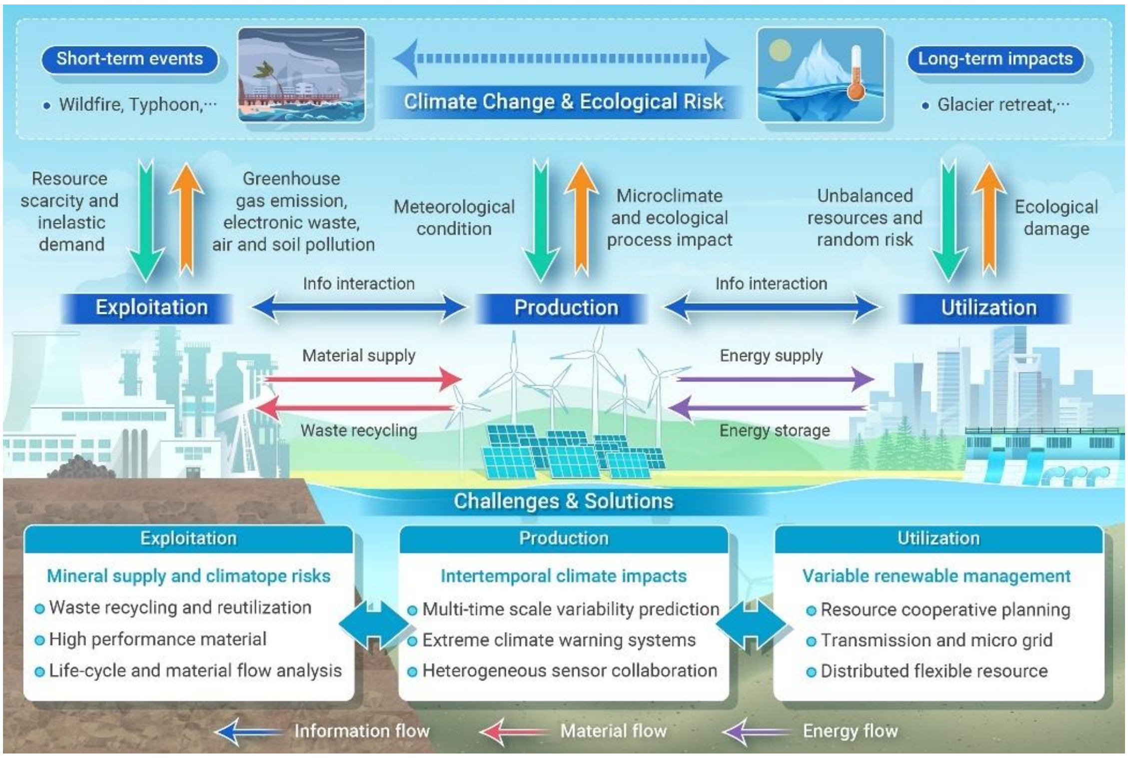

Figure 1. The renewable-energy value chain as a coupled exploitation–production, utilization system that is continuously shaped by climate change and ecological risk [18].

Net-zero strategies extend these pathways beyond the electricity sector to encompass economy-wide emissions abatement through a hierarchy of measures: energy efficiency and conservation, deep electrification of end uses, decarbonization of remaining fuels and feedstocks via green hydrogen and sustainable bioenergy, and targeted carbon management for residual emissions [19,20]. The core strategic challenge is aligning near-term actions (to 2030) with long-run net-zero integrity (to 2050/2060) by prioritizing "no-regrets" investments, clean power, grids, efficiency, methane abatement, and electrified mobility/heating, while reserving higher-cost or less mature options for applications where alternatives are limited (e.g., cement process emissions, some chemical feedstocks, high-temperature industrial heat, and long-distance aviation/shipping) [21,22]. Robust net-zero strategies also require governance mechanisms that translate ambition into delivery: enforceable standards and procurement frameworks, credible carbon pricing or equivalent incentives, measurement/reporting/verification (MRV) for non-CO_2 gases and carbon removals, and just-transition policies to manage distributional impacts on households, workers, and fossil-dependent regions [23-25]. In high-ambition scenarios, carbon dioxide removal plays a balancing role rather than a substitute for mitigation, underscoring the importance of minimizing residual emissions through structural transformation rather than reliance on large-scale removals that remain uncertain in cost and scalability.

A substantial body of literature has investigated renewable energy transition pathways and the design of net-zero strategies. The report article [26] indicated that global renewable power capacity reached 2,838.8 GW by the end of 2020, with 259.6 GW added during 2020. The installed base was dominated by hydropower (1,170 GW; ~41.2% of total capacity), followed by solar PV (760 GW; ~26.8%) and wind (743 GW; ~26.2%), which together accounted for ~52.9% of total installed renewable capacity. In terms of annual expansion, solar PV (139 GW) and wind (93 GW) drove the vast majority of new additions, contributing 232 GW combined (~89.4% of total 2020 additions). Hydropower additions were comparatively modest at 19.4 GW (~7.5%), while bio-power added 8 GW (~3.1%). Geothermal (0.1 GW), concentrating solar power (0.1 GW), and ocean power (0.002 GW) remained niche contributors, together representing a negligible share of annual growth.

According to [27], the study indicated a sustained acceleration in renewable deployment, with aggregate capacity projected to exceed 1,000 GW by 2050 and a pronounced inflection, approaching exponential growth, emerging around 2045. Over the same period, the PSI increases by 20% (from 50 in 2020 to 60 in 2050), reflecting gradual strengthening of enabling policy frameworks, while renewable energy investments rise from USD 10 billion to USD 25 billion, indicating expanding capital mobilization. In parallel, energy-related emissions are projected to decline monotonically to net-zero by 2050, consistent with long-term decarbonization objectives. Uncertainty analysis suggests a ±5% margin of error around the projections, primarily attributable to variability in policy execution, macroeconomic conditions, and the pace of technological learning and deployment.

Employing a niche-management framework, this study [28] undertakes a national census of renewable energy cooperatives (RECs) to evaluate their prospective contribution to Canada's net-zero greenhouse gas emissions objectives. Drawing on a systematic review of more than 250 organizational websites and 27 semi-structured interviews with representatives of RECs and cooperative associations across Canada, the analysis indicates that the REC sector remains largely confined to a marginal niche. Notwithstanding these data constraints, the available evidence suggests that RECs accounted for no more than approximately 73 MW in 2021, equivalent to less than 0.05% of Canada's total installed generation capacity. Moreover, the sector experienced marked contraction, with the number of RECs declining by 44% (n = 40) between 2016 and 2021. Although some consolidation through mergers was observed, the dominant pattern is one of organizational fragility: many cooperatives operate under persistent capacity constraints, rely heavily on volunteer labor, and frequently face conditions that compel them to dissolve or discontinue operations.

According to [29], Saudi Arabia's commitment to achieving a net-zero economy by 2060 represents a strategic inflection point for accelerating economic diversification beyond hydrocarbons while strengthening long-term resilience and sustainability. The results further indicate that early action yields substantial long-run economic advantages relative to delayed implementation. Specifically, initiating policy measures sooner reduces cumulative policy costs by approximately 38–72% over the 2025–2060 period, primarily because earlier deployment accelerates learning effects, avoids high-cost retrofits, and enables more orderly retirement and replacement of carbon-intensive assets. Collectively, these findings suggest that timely, credible policy execution can mitigate the macroeconomic challenges of decarbonization, support industrial diversification and competitiveness, and contribute to global emissions reductions, thereby reinforcing Saudi Arabia's trajectory toward a durable and economically robust net-zero future.

This article contributes to the renewable energy and climate mitigation literature by presenting an integrated, systems-level framework that links (i) recent technological advances in renewable generation, storage, grid digitalization, and inverter-based stability, (ii) the conditional but strategically important role of CO_2 capture and carbon management across power and industrial point sources, and (iii) a cohesive policy package that converts technical feasibility into implementable net-zero pathways. Unlike studies that treat technology deployment, carbon capture, or policy design in isolation, the paper explicitly analyzes their interdependencies, showing how declining technology costs can be offset by grid and permitting bottlenecks, how CCUS viability hinges on infrastructure and MRV integrity, and how policy credibility affects financing costs and deployment speed.

2.Recent Trends in Technological Advances

The 2023–2025 period has been characterized less by single "breakthrough" inventions and more by rapid industrialization, scale-up, and system integration of technologies required for deep decarbonization. On the supply side, solar PV and onshore wind continue to consolidate as the dominant sources of new low-carbon electricity, supported by incremental gains in component performance, manufacturing learning, and project execution [30, 31]. On the demand side, electrification technologies, most notably heat pumps and electric mobility, are increasingly shaped by policy design, electricity pricing, and grid readiness rather than technical feasibility alone. At the system level, the defining technological trend is the acceleration of flexibility and stability solutions: grid-scale batteries, advanced inverters, digital control platforms, and transmission expansion (including HVDC and interconnection reinforcement) [32, 33]. These technologies respond to the operational realities of variable renewable energy (VRE), where reliability is maintained through fast-response services, congestion management, and more sophisticated forecasting and dispatch. In parallel, climate-specific mitigation technologies and practices, particularly methane detection/abatement, carbon management (CCUS), and early carbon dioxide removal (CDR) markets, are evolving toward higher integrity measurement, reporting, and verification (MRV), reflecting rising expectations for demonstrable emissions outcomes and credible net-zero claims. Figure 1 illustrates recent trends in technological advances.

Figure 1. Recent Trends in Technological Advances.

Ref.	Technology domain	What is advancing (recent trend)	What this change (system / climate impact)	Practical indicators / evidence
[34] [35] [36]	Utility-scale solar PV	Higher module performance and better balance-of-system design (bifacial, trackers, high-voltage inverters).	Lower delivered cost per kWh; faster deployment; higher value when paired with storage and grid upgrades.	Global weighted-average solar PV LCOE stabilised around USD 0.043/kWh in 2024; installed costs continue to fall in many markets.
[37] [38] [39] [40]	Onshore wind	Larger rotors and taller hub heights; improved aerodynamic controls; better forecasting and grid-code capabilities via power electronics.	Higher capacity factors and improved grid support; reduced curtailment and balancing needs.	IRENA reports continued cost reductions in installed costs for onshore wind between 2023 and 2024
[41] [42] [43] [44]	Offshore wind	Turbine scaling and project industrialisation continue, but the main "advance" is redesigning auctions/contracts to manage supply-chain and financing risks.	Strategic decarbonisation option for dense coastal demand; near-term build depends strongly on bankable procurement and permitting.	IRENA indicates offshore wind installed costs were relatively stable between 2023 and 2024 compared with other renewables.
[45] [46] [47] [48]	Grid-scale battery energy storage (BESS)	Rapid expansion of lithium-ion grid storage; improved energy management systems (EMS), forecasting, and market participation for ancillary services and arbitrage.	Enables higher variable renewable energy (VRE) penetration by providing fast frequency response, ramping, peak shifting, and congestion support.	IEA notes grid-scale batteries are projected to account for the majority of storage growth; global grid-scale battery capacity reached ~28 GW by end-2022 and has continued to expand rapidly.
[49] [50] [51]	Long-duration storage (LDS)	Increased pilot-to-early-commercial activity across sodium-ion, flow batteries, iron-air, compressed/thermal storage; improved bankability via capacity contracts.	Addresses multi-hour to multi-day balancing needs; improves reliability at high VRE shares and reduces dependence on peaking fossil capacity.	Growing number of procurements explicitly targeting 8–100+ hour solutions; performance guarantees and degradation models improving for project finance.
[52] [53] [54] [55] [56] [57]	Inverter-based grids (grid-forming, advanced controls)	Grid-forming inverter controls and stability services from inverter-based resources (IBR); wider deployment in microgrids and increasing focus for large grids.	Supports system stability with higher shares of IBR (less synchronous inertia); enables stronger frequency/voltage performance from renewables and storage.	Grid-forming controls increasingly treated as a key stability tool for renewable-rich power systems in the research and operator landscape.

[58] [59] [60] [61]	Transmission and interconnection (HVDC, digitalization)	HVDC buildout and interconnection planning; digital tools (dynamic line rating, automation) to raise utilization of existing networks.	Reduces congestion, lowers curtailment, improves adequacy and geographic smoothing of VRE output.	Grid constraints and connection queues are widely recognized as critical bottlenecks; upgrades are increasingly prioritized in system plans.
[62] [63] [64] [65]	Distributed energy resources (DER) and virtual power plants (VPPs)	Aggregation platforms, smart inverters, and behind-the-meter batteries; improved DER forecasting and dispatch.	Turns small assets into system-level flexibility; reduces peak demand and defers some network reinforcement.	More markets are formalising participation rules for aggregated DER in ancillary services and capacity mechanisms.
[66] [67] [68]	Heat pumps (buildings electrification)	Efficiency improvements and better cold-climate performance; smarter controls and load shifting; however, adoption is sensitive to policy and relative energy prices.	Large near-term decarbonisation lever in buildings; increases importance of clean grids and demand-side flexibility.	IEA notes major regional sales volatility in 2024 (e.g., EU sales drop in H1 2024) driven by policy and market conditions.
[69] [70] [71] [72] [73] [74]	Low-emissions hydrogen and electrolysers	Manufacturing scale-up and improved stacks/BOP integration; stronger emphasis on certification, offtake contracts, and project bankability.	Potential pathway for hard-to-electrify sectors; deployment pace constrained by costs, infrastructure, and limited projects reaching FID.	IEA: installed water electrolyser capacity reached 1.4 GW by end-2023 and could reach ~5 GW by end-2024; only a small share of announced capacity is at FID/under construction.
[75] [76] [77]	Methane detection, measurement, and abatement	Better leak detection and repair (LDAR) using continuous monitors, drones, and satellites; increasing MRV and regulatory frameworks.	Fast, high-impact climate mitigation (short-lived climate pollutant); often low-cost abatement with co-benefits for safety and air quality.	UNEP and IEA track progress, but emphasise that implementation gaps remain versus 2030 targets under the Global Methane Pledge.
[78] [79]	Carbon capture, utilisation and storage (CCUS) and CO2 infrastructure	Shift from single-point projects to hubs and shared CO2 transport/storage; improved monitoring and storage appraisal; stricter performance expectations.	Key option for some industrial point sources and potentially blue hydrogen; effectiveness depends on high capture rates and robust storage integrity.	Momentum is increasingly tied to CO2 network buildout and regulation (site permitting, long-term liability, monitoring).
[80] [81]	Carbon dioxide removal (CDR) and MRV	Improved MRV for removals (durability, additionality); early scaling of engineered removals procurement; better remote-sensing data streams.	Strengthens credibility of net-zero claims; supports compliance-grade accounting when standards are robust.	Market trend increasingly values high-durability removals and stronger verification; standards tightening across voluntary and emerging compliance contexts.

Overall, recent technological advances indicate that the energy transition is entering a phase where deployment speed and system operability are as decisive as device-level efficiency. The cost and maturity trajectory of solar PV, wind, and batteries strengthens the economic case for rapid renewable expansion; however, achieving high VRE penetration increasingly depends on grid modernization, permitting and interconnection reform, and market structures that monetize flexibility and stability services. Electrification solutions such as heat pumps remain pivotal for near-term emissions reduction but require supportive policy and consumer economics to sustain adoption. Meanwhile, hard-to-abate sectors continue to drive interest in low-emissions hydrogen and CCUS, yet these options are constrained by bankability, infrastructure, and performance requirements, suggesting that near-term progress will come from targeted, high-value applications rather than universal deployment.

3.CO_2 Capture

Carbon dioxide (CO_2) capture technologies are a central component of many decarbonization pathways because a substantial share of global emissions arises from large, continuous point sources, notably fossil-fuel power plants and heavy industry [82, 83]. While wind and solar generation have near-zero direct operational CO_2 emissions, power systems and industrial value chains still contain "hard-to-abate" segments where electrification is technically constrained, economically challenging, or limited by infrastructure and process chemistry [84, 85]. CO_2 capture addresses this gap by separating CO_2 from gas streams, either after combustion (post-combustion capture from flue gas), before combustion (pre-combustion capture from high-CO_2 process streams such as hydrogen production via SMR/ATR), or by capturing CO_2 from very dilute sources such as ambient air (direct air capture) [85, 86]. Moreover, the captured CO_2 must then be compressed, transported, and permanently stored in geological formations or mineralized, with measurement, reporting, and verification (MRV) ensuring long-term integrity [87-91]. **Table 2** demonstrates CO_2 Capture technologies for power and energy systems.

Table 2. CO_2 capture technologies for power and energy systems.

Ref.	Emission source	Typical CO_2 stream	Capture approach (technology)	Typical capture rate (design)	Key energy/cost implications
[92] [93] [94]	Coal-fired power plants	Dilute flue gas (lower CO_2 concentration)	Post-combustion capture (amine solvents; emerging solid sorbents)	≈90% typical; higher (≈95–98%) technically feasible	Higher capture rates generally increase energy use and unit cost per tonne captured
[95] [96]	Natural-gas combined cycle (NGCC)	More dilute flue gas than coal	Post-combustion capture (amines) with optimized heat integration	≈90% typical; higher feasible with higher energy penalty	Often higher $/t than coal due to dilution; depends strongly on capacity factor
[97] [98]	Cement (calcination + combustion)	Flue gas with significant process CO_2	Post-combustion capture; also oxy-fuel/calciner integration options	≈90%+ commonly targeted	High relevance because process emissions are hard to avoid;
[99] [100]	Hydrogen from natural gas (SMR/ATR)	High CO_2 concentration process stream	Pre-combustion capture (shift + physical solvents)	Often ≥90% designs	Typically, more favorable than dilute flue-gas capture; requires robust methane control
[101] [102] [103]	Bioenergy (biomass power/ethanol) + CCS (BECCS)	Flue gas or fermentation CO_2	Post-combustion (power) or fermentation capture (high purity)	High (configuration-dependent)	Potential net-negative CO_2 if biomass supply chain is sustainable and MRV is rigorous
[104] [105]	Direct Air Capture (DAC)	Ambient air (~0.04% CO_2)	Solid sorbents or liquid solvents + regeneration	High capture fraction of processed air, but energy intensive	Highest energy and cost burden due to very dilute feedstock
[106] [107]	Renewables (wind/solar)	No CO_2 stack stream during operation	Not captured at plant; mitigation focuses on low-carbon manufacturing and recycling	N/A	Emissions are upstream/life-cycle rather than operational

CO_2 capture technologies can deliver meaningful emissions reductions when deployed in the right applications under the right system conditions. Technically, capture rates around ~90% are common in commercial designs, and higher capture levels are achievable, albeit with increasing energy demand and cost; consequently, optimizing capture rate requires balancing climate outcomes against system efficiency and project economics. Strategically, the most robust near-term use cases tend to be high-concentration CO_2 streams (e.g., natural gas processing and hydrogen production) and process-emissions-dominated industries such as cement, where alternatives are limited. In the power sector, CCUS can support firm low-carbon generation in some systems, but its competitiveness is highly sensitive to utilization, fuel prices, and policy incentives, and it must be evaluated alongside renewables-plus-storage, transmission expansion, and demand-side flexibility. Across all cases, the defining success factors are rarely the capture unit alone: projects typically require reliable CO_2 transport and storage infrastructure, strong MRV and monitoring obligations, and long-term commercial arrangements that de-risk capital investment.

4.Policy

Governments seeking to accelerate renewable energy deployment and reduce greenhouse gas (GHG) emissions increasingly rely on integrated "decarbonization packages" rather than isolated interventions. This reflects the multi-dimensional nature of energy transitions: while renewable generation costs have declined substantially, the pace of deployment is often constrained by non-price barriers, including permitting delays, grid interconnection bottlenecks, financing risk, and the persistence of incumbent fossil-fuel advantages. Effective policy design therefore combines economy-wide incentives that internalize emissions costs with sector-specific instruments that create bankable demand for clean electricity, de-risk capital investment, and ensure that enabling infrastructure, particularly transmission, distribution, and flexibility resources, expands in parallel. Figure 2 highlights the policy.

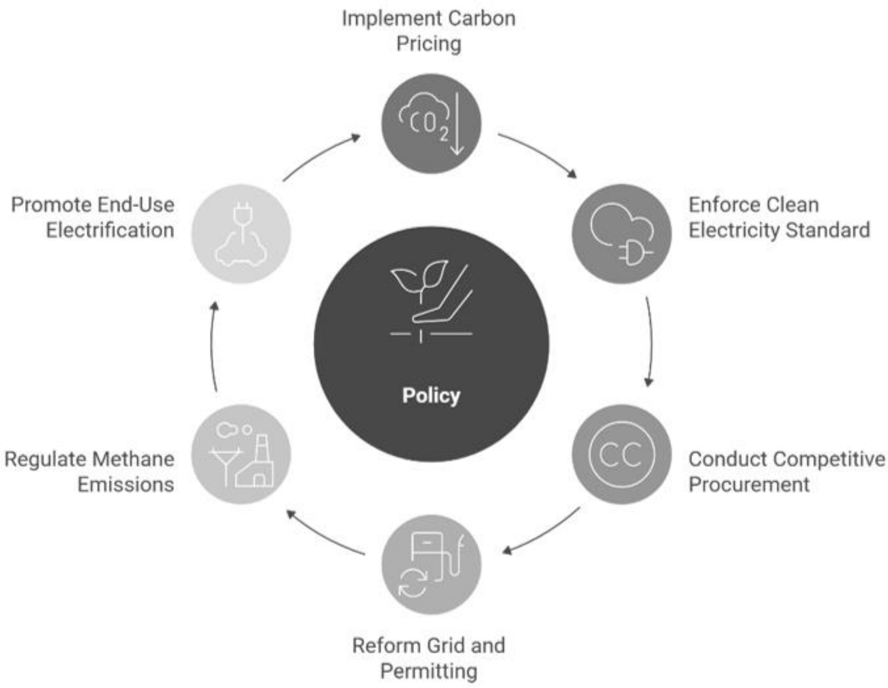

Figure 2. Policy.

A. *Carbon pricing (Carbon tax or Emissions Trading System)*

Carbon pricing reduces greenhouse gas emissions by assigning an explicit monetary cost to each tonne of CO_2-equivalent emitted, thereby internalizing climate externalities and shifting investment toward lower-carbon technologies. In practice, a carbon tax provides price certainty by setting a fixed charge per tCO_2e, while an emissions trading system (ETS) provides quantity certainty by establishing a cap and allowing market trading of allowances to determine the carbon price. When designed with credible long-term trajectories, robust monitoring and enforcement, and appropriate protection for vulnerable households and trade-exposed industries, carbon pricing strengthens the business case for renewables, energy efficiency, electrification, and low-carbon industrial processes.

B. *Clean Electricity Standard / Renewable Portfolio Standard (RPS)*

A Clean Electricity Standard or Renewable Portfolio Standard mandates that electricity suppliers procure an increasing share of their generation from renewable or low-carbon sources by specified dates, creating predictable and bankable demand for clean power. Compliance is typically managed through eligible technology definitions and certificate-based accounting, which enables flexibility while maintaining an enforceable target. As a result, these standards can accelerate renewable deployment at scale, reduce the emissions intensity of the grid, and provide a strong foundation for economy-wide decarbonization once end-use sectors electrify.

C. *Competitive procurement: Renewable auctions and long-term contracts (CfDs / PPAs / FiTs)*

Competitive procurement mechanisms, such as renewable energy auctions and long-term contracts including contracts for difference (CfDs), power purchase agreements (PPAs), or feed-in tariffs (FiTs), are among the most effective policies for rapidly scaling renewables at low cost. Their central benefit is reducing revenue uncertainty, which lowers the cost of capital and, consequently, the levelized cost of electricity for capital-intensive assets like solar, wind, and storage. When procurement rules are transparent, penalties for non-delivery are credible, and grid connection responsibilities are clearly allocated, auctions and contracts translate national targets into investable pipelines and disciplined project execution.

D. *Grid and permitting reform for renewables and transmission*

Grid and permitting reforms address one of the most persistent barriers to rapid decarbonization: the gap between renewable project availability and the ability to connect and deliver energy reliably. These reforms typically include streamlining environmental and land-use approvals, enforcing time limits for permitting and interconnection studies, standardizing technical requirements, and planning transmission proactively to unlock high-quality resource zones. By reducing delays, curtailment risk, and network congestion, grid and permitting reforms directly increase the effective penetration of renewables while maintaining system reliability and enabling larger volumes of private investment.

E. *Methane (CH_4) and non-CO_2 regulations (oil and gas, waste, agriculture)*

Methane and other non-CO_2 greenhouse gas regulations deliver fast climate benefits because methane has high near-term warming potency and many mitigation measures are operationally straightforward. Policies commonly focus on leak detection and repair (LDAR), bans or limits on routine flaring and venting, equipment performance standards, landfill gas capture, and improved agricultural waste management. With strong measurement, reporting, and verification (MRV) requirements and enforcement capacity, these regulations can provide some of the most cost-effective and immediate emissions reductions available, often with co-benefits in safety, air quality, and reduced product loss.

F. *End-use electrification standards and mandates (transport, buildings, and industry)*

End-use electrification policies reduce emissions by shifting energy demand from direct fossil fuel combustion to electricity, which can be progressively decarbonized through renewables and other low-carbon generation. In transport, this often involves fuel economy and CO_2 standards, zero-emission vehicle mandates, and charging infrastructure programs; in buildings, it includes building energy codes, appliance efficiency standards, and heat-pump incentives or requirements; and in industry, it combines performance standards with targeted support for electrification, low-carbon heat, and, where necessary, hydrogen or carbon capture. When aligned with grid expansion and clean electricity targets, electrification policies ensure that renewable growth translates into economy-wide emissions reductions rather than remaining confined to the power sector.

Taken together, these six instruments form a coherent policy architecture that can convert decarbonization ambition into measurable emissions outcomes. Carbon pricing and clean electricity standards establish the strategic direction and strengthen the investment signal; auctions and long-term contracts translate targets into financeable projects at scale by lowering revenue uncertainty and the cost of capital. Grid and permitting reforms address the binding "real economy" constraints that increasingly determine deployment speed, while methane and non-CO_2 regulations deliver rapid climate benefits and reduce near-term warming through enforceable operational controls. Finally, electrification mandates and standards ensure that clean electricity growth drives economy-wide abatement by displacing direct fossil fuel use in transport, buildings, and industry. The effectiveness of this policy package ultimately depends on credible governance, robust measurement, reporting, and verification (MRV), enforcement capacity, transparent market rules, and equity-oriented measures that protect households and support affected workers and regions.

5.Conclusion

Renewable energy transition pathways capable of supporting net-zero outcomes are increasingly well-defined in technical terms: they require rapid scale-up of renewables, parallel investment in grids and flexibility, and operational reform to sustain reliability under high shares of inverter-based generation. Recent technological advances, particularly in solar PV, wind, grid-scale batteries, digital dispatch, and advanced inverter controls, have strengthened the feasibility and reduced the cost of deep power-sector decarbonization; however, the binding constraints are progressively shifting toward interconnection queues, transmission congestion, permitting timelines, and market designs that inadequately value flexibility and stability services. Within this context, CO_2 capture occupies a targeted but consequential role. It is most defensible where emissions are structurally difficult to eliminate, high-concentration process streams, cement and select heavy-industrial sources, and specific firm-capacity applications, provided that projects are embedded within credible CO_2 transport and storage networks and governed by stringent MRV. Overreliance on capture or CO_2 removal as a substitute for near-term mitigation increases transition risk, as large-scale deployment remains sensitive to cost, infrastructure availability, and long-term storage assurance.

Policy, therefore, is the decisive integrator of net-zero strategies. The six high-impact instruments examined operate as a complementary package: carbon pricing and clean electricity standards set directionality; auctions and long-term contracts reduce financing costs and scale deployment; grid and permitting reform removes delivery bottlenecks; methane and non-CO_2 regulations secure rapid climate benefits; and electrification mandates ensure renewable expansion translates into economy-wide abatement. The central implication is that net-zero strategies are not single-technology roadmaps but governance-and-infrastructure programs that must be sequenced to avoid lock-in, minimize total system cost, and preserve credibility. Where governments implement these instruments coherently, aligning incentives with buildable pipelines, robust enforcement, and equity-oriented transition measures, renewable energy pathways can deliver rapid emissions reductions while maintaining reliability and enabling an orderly transition to mid-century net-zero.

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