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Review

Synergistic Integration for Energy Sector Decarbonization: Leveraging Solar, Storage, Power Systems, and Carbon Capture

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Received: 3 September 2026; **Revised:** 3 November 2026; **Accepted:** 5 November 2026; **Published:** 24 November 2026

Abstract: The energy transition towards low carbon energy systems is an essential step in achieving the climate targets of the world and sustaining the future of the energy system. This narrative review is aimed at evaluating the synergies between four components of the energy transition: solar energy, energy storage, power-system modernization, and carbon capture utilization and storage (CCUS). The review will focus on advancements in energy storage technologies such as lithium-ion batteries, flow batteries, and green hydrogen as they complement each other in solving the issue of the intermittency of renewables, balancing supply and demand of energy, and long duration storage of energy. In addition, the review will explore how smart grid technologies make it possible to monitor the power system and increase its flexibility and resilience. Though CCUS can have the potential to reduce emissions of the appropriate processes and energy sources, it still does not receive much attention and its usage level is relatively low compared to what is needed to achieve the global decarbonization. According to the estimates of the International Energy Agency, in the early 2025 the operational carbon capture capacity worldwide had already exceeded 50 million t of CO_2 annually.

Keywords: Decarbonization; Solar Energy; Energy Storage; Smart Grids; Power Systems; Carbon Capture; Renewable Energy

1. Introduction

Demand for energy in the global arena has seen a continuous rise over the past few decades, driven by industrialization, urbanization, and population growth. In 2023, global primary energy consumption reached a record 620 exajoules (EJ), up from 607 exajoules in 2022, a rise of roughly 2%, according to the Energy Institute's Statistical Review of World Energy [1]. Despite growing investment in clean energy, fossil fuels still accounted for 81.5% of the

primary energy mix in 2023, only marginally down from 82% in 2022. Looking ahead, the IEA's 2025 World Energy Outlook projects that under a Current Policies Scenario, global energy demand will climb by roughly 90 exajoules by 2035, about a 15% increase from present levels, with continued growth through mid-century unless policy shifts substantially [2]. This rising demand continues to drive greenhouse gas emissions [3]. The IPCC's Special Report on Global Warming of 1.5 °C states that limiting warming to 1.5 °C above pre-industrial levels requires CO_2 emissions to fall by about 45% from 2010 levels by 2030, reaching net-zero around 2050 a benchmark that remains the reference point for most national climate pledges [4]. The 2022 energy crisis, triggered by Russia's invasion of Ukraine, exposed the risks of fossil-fuel dependence: European gas prices spiked and supply security became a political priority, accelerating the continent's push toward renewables and energy independence [5]. Power generation remains the single largest source of energy-related CO_2 emissions. Solar has been central to that shift [6]. The international levelised cost of electricity (LCOE) for utility-scale solar PV projects which became operational from 2010 to 2023 was about 90% lower, dropping from USD 0.460/kWh to USD 0.044/kWh as reported by IRENA, 2024 [7]. But solar's intermittency has made storage essential to grid reliability. Global battery storage deployment grew by 42 GW in 2023 alone, an increase of more than 130% year-on-year, and utility-scale battery capacity exceeded 124 GW by 2024, per IEA data [8]. Hydrogen and thermal storage remain complementary but earlier-stage solutions. Persistent challenges aging grid infrastructure, cybersecurity threats, and inconsistent regulatory frameworks across jurisdictions continue to slow the pace of this transition [9].

Simultaneously, there is growing interest in CCUS technologies, which have particular relevance to cement, steel, and petrochemical industries/sectors where emissions are difficult to abate through electrification alone [10]. **Figure 1** highlights the major regions and countries with active CCS deployment of global distribution of operating commercial carbon capture and storage (CCS) facilities in 2025 [11]. The IEA reports that more than 50 million t (Mt) of CO_2 per year of capture and storage capacity was in operation by the first quarter of 2025, while the current project pipeline indicates a substantial further expansion of capture and storage capacity around 430 Mt of CO_2 per year by 2030 [12]. Despite advances in CO_2 capture technologies, including emerging adsorption-based approaches using metal-organic frameworks (MOFs) that offer high surface areas and tuneable chemical properties, large-scale deployment remains constrained by capture costs, energy requirements, and the availability of CO_2 transport and storage infrastructure [13]. Capture costs vary substantially according to the CO_2 source and concentration [14]. For relatively pure or highly concentrated streams, such as those associated with natural-gas processing and some industrial processes, capture costs can be approximately USD 15–25 per t of CO_2 [15]. For more dilute industrial flue-gas streams, including those from cement production and power generation, costs can increase to approximately USD 40–120 per t of CO_2 [16]. Direct air capture remains substantially more expensive because CO_2 is present at very low concentrations in ambient air [17].

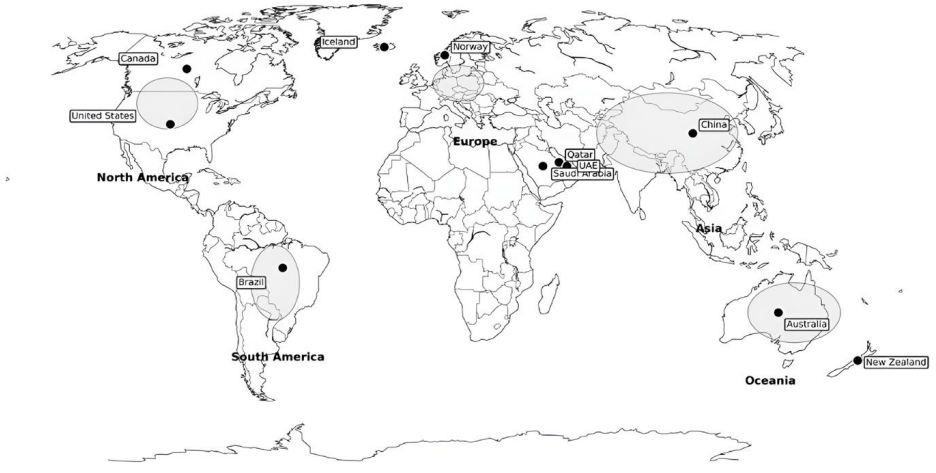


Figure 1. Operating Commercial Carbon Capture and Storage (CCS) Facilities in 2025: Global Distribution of Operating Commercial CCS Facilities, showing key regions and countries where CCS is deployed. The black dots represent facility locations, and the shaded ovals represent the regions of deployment.

The decarbonization of the energy industry is a complex process that needs to incorporate several different dimensions. These include incorporating solar energy and renewable energy, the incorporation of energy storage, the upgrade of the power infrastructure to handle fluctuations in production, and the application of carbon capture technology to reduce residual emissions. This process will depend on cooperation on the global level and investment in innovation.

1.1. Conventional to Renewable Energy Transition

The development of renewable energy technologies, particularly solar energy, has gained significant importance in global decarbonization efforts. Numerous peer-reviewed studies have highlighted the potential of renewable energy to reduce greenhouse-gas (GHG) emissions by displacing fossil-fuel-based electricity generation [18]. Global solar photovoltaic (PV) capacity has expanded rapidly over the past decade and a half [19]. According to the International Renewable Energy Agency (IRENA), global installed solar PV capacity reached approximately 1,419 GW by the end of 2023, following the addition of about 346 GW during 2023 alone [20]. The global weighted-average levelized cost of electricity (LCOE) for newly commissioned utility-scale solar PV decreased by approximately 90%, from USD 0.460/kWh in 2010 to USD 0.044/kWh in 2023 [21]. In 2023, the global weighted-average LCOE of solar PV was approximately 56% lower than the weighted-average cost of fossil-fuel-fired electricity generation, demonstrating the increasing economic competitiveness of solar power [22]. Mendes et al. [23] have further demonstrated the potential contribution of renewable energy deployment to limiting global warming to below 2 °C, although the magnitude of this contribution depends on the pace of deployment, energy-system integration, technological development, and complementary mitigation measures. Beyond its environmental benefits, renewable energy has also become an important source of employment and economic activity [24]. According to IRENA and the International Labour Organization (ILO), global renewable-energy employment increased from 13.7 million jobs in 2022 to 16.2 million in 2023, while solar PV employment increased to approximately 7.1 million jobs in 2023, accounting for about 44% of global renewable-energy employment [25].

1.2. Decarbonization Techniques

Solar PV and wind are the most developed and utilized renewable technologies. They compete with the fossil fuel energy sources on the cost level in many countries due to the economies of scale and technological improvements [26]. Nevertheless, because of the intermittent character of these technologies, battery energy storage or pumped hydro storage systems should be used, and they improve the stability of the grid but have the limitations in terms of infrastructure and environment. It is capital-intensive and is not yet widely deployed, but it is vital for abating emissions that cannot be reduced otherwise. Another technology with negative emissions is BECCS, but it is restricted in its deployment due to the lack of land and biomass. Green hydrogen is an attractive decarbonization pathway for difficult-to-decarbonize sectors like heavy industry and long-haul transportation. The adoption of green hydrogen is based on reduction of costs for electrolysis and renewable electricity used. Smart grids and DSM ensure the efficient utilization of energy and the integration of renewables, thus providing better flexibility [27]. Finally, electrification of end uses, mainly of transport and heating, makes use of renewable energy to decarbonize demand-side applications.

1.3. Solar Energy and Energy Storage Systems

As indicated by **Figure 2**, solar energy leads among renewable energy generation technologies with more than 1,200 GW of installed capacity globally in 2023 [28]. The global weighted-average LCOE for utility-scale solar PV fell to $0.044/kWh in 2023, with the most competitive markets achieving $0.03–$0.04/kWh, making it one of the most cost-effective sources of power generation in much of the world [22]. Although solar energy is developing rapidly, its intermittency is still a critical issue. The solution to this problem includes implementing energy storage solutions. Battery pack prices fell 89% between 2010 and 2021, reaching roughly $132/kWh by 2021 [29]. Prices have continued to fall since, reaching approximately $108/kWh by 2025, a cumulative decline of about 93% since 2010 [30]. Other emerging energy storage technologies include flow, solid-state, and thermal batteries. Nevertheless, the widespread use of long-duration energy storage (LDES), often referred to as storage that can supply electricity for 10 h or longer—is limited by cost, scale, and infrastructure challenges. It depends on both the technology used and its intended application.



Figure 2. Statistics regarding solar and energy storage technologies: (**a**) Global Solar Capacity (GW); (**b**) Lithium-Ion Battery Cost (USD/kWh); and (**c**) Lithium-Ion Energy Storage Penetration (%).

The conventional power grid system was engineered mostly for centralized power production and hence encounters difficulties in accommodating decentralized sources of renewable power. The smart grid relies on digital communications, analysis, and automation to control fluctuations in order to strike a balance between supply and demand. The global investment in electricity grids stood at approximately USD 330 billion in 2022, while the digital aspect of the investments was a fraction of this, as shown in **Figure 3**. The investments aim at modernizing the grid as well as integrating the distributed energy resources (DERs) [31,32].

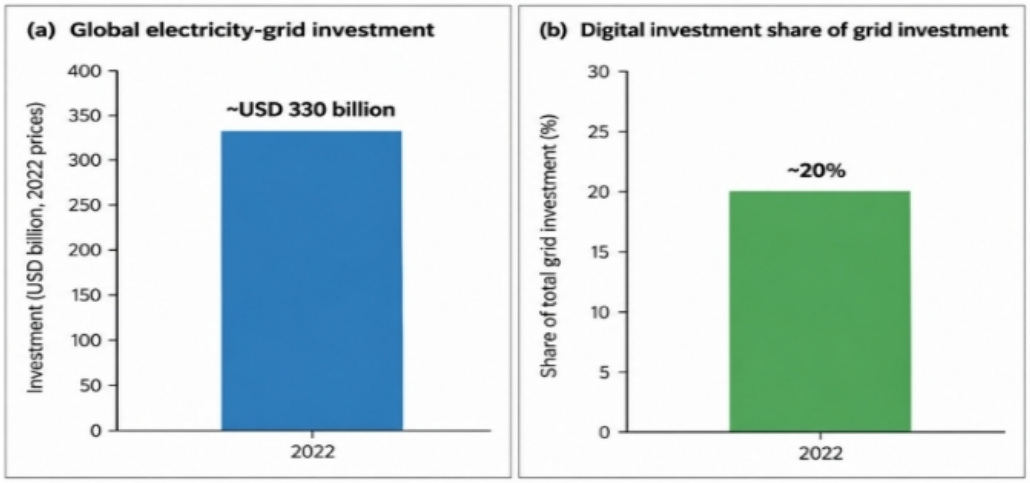


Figure 3. Indicators of grid investments and digitalization: (**a**) global investments in electricity grids (billion USD, 2022 prices) for 2022 and (**b**) digital investments as a share of total grid investments (%) for 2022.
Source: IEA, World Energy Investment 2023 and Digital Investments in Grid Technologies, 2015–2022.

1.4. Carbon Capture and Storage (CCS)

CCS technologies are key to reducing emissions from difficult-to-abate sectors such as cement production, steel manufacturing, and fossil-fuel-based power generation. As of 2023, CCUS facilities worldwide had the capacity to capture more than 40 million t of CO_2 per year; this had grown to approximately 50 operating facilities with roughly 51 million t/year of combined capacity by 2024 (**Figure 4**) [12]. To align with a net-zero pathway, the IEA's Net Zero Emissions by 2050 Scenario calls for global CCUS capture and storage capacity to reach approximately 1 billion t of CO_2 per year by 2030 [33]. The cost of capturing CO_2 can widely vary depending on the concentration of the source stream as well as the configuration of the plant. According to the IEA, the indicative cost of capturing CO_2 is about USD 15–25 per t of CO_2 in case of relatively pure or high concentration of the stream (natural gas processing stream), in comparison to about USD 40–120 per t of CO_2 when dealing with diluted sources like flue gases from cement manufacturing and power plants.

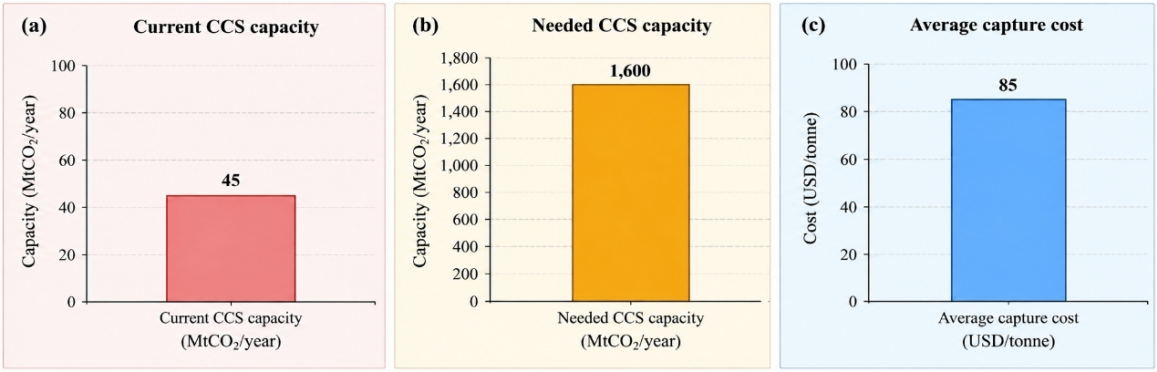


Figure 4. Statistical indicators for carbon capture and storage (CCS): (**a**) current global CCS capture capacity ($MtCO_2$/year), (**b**) required CCS capacity ($MtCO_2$/year), and (**c**) average CO_2 capture cost (USD/t). Each indicator is presented in a separate panel with its own axis and units.

1.5. Challenges in Achieving a Low-Carbon Energy Sector

While renewable energy provides much potential for addressing climate change, the development of a low-carbon energy sector poses certain challenges. One of these challenges lies in the intermittent nature of renewable energy sources like solar and wind energy. According to research, the efficiency of photovoltaic systems might be reduced by 20–30% because of clouds. Also, the generation of wind power depends on the wind speed, so the capacity factor usually equals 30–40% [34]. Thus, an effective energy storage system should be used for maintaining stable energy provision. The price of lithium-ion batteries fell by 89% from 2010 to 2020 [35]. However, developing large-scale energy storage is still difficult from both economic and technological points of view. The updating of the power system is another major challenge. Any upgrade of the grid should take into account demand-supply balancing, voltage regulation, and system inertia, which pose problems due to the inherent variability of renewable energy sources.

On top of that, there are various barriers from the regulatory and policy perspective. Studies show that inconsistent policies and failure on the side of governments to commit themselves to any actions in the long term may deter private companies from investing in the renewable energy sector [36]. This is due to changing feed-in tariffs or lack of carbon price schemes, for example. One of the most critical barriers is cost. Although LCOE of solar PV has dropped to \$0.03–\$0.06 per kWh in the leading countries, the upfront investment cost is still rather high [37].

There have been many challenges with the implementation of CCS technology as a means of mitigating carbon dioxide emissions because of economic and technological limitations. Despite developments in projects, worldwide operational capacity for capturing and storing CO_2 was still only slightly above 50 million t per year in early 2025, the IEA reports [12]. This is considerably lower than the deployment envisaged in net-zero scenarios [38]. The cost of CCS technology is between \$15–120 per t of CO_2, and thus is not competitive without financial incentives [39]. Lastly, there are social and political aspects that play a big role in determining the path of decarbonization. Social opposition against renewable energy projects such as wind farms and power transmission lines can prevent their implementation. Inadequate public knowledge can also impede energy efficiency initiatives. Political instability and changing policies in developing countries are also a concern.

Figure 5a–d illustrates that the combination of solar, storage, smart grids, and CCS technology provides substantial synergies. For instance, the combination of solar storage with smart grid management results in increased reliability of the network and provides demand-side flexibility. Just as excess renewable energy could be used for the generation of hydrogen fuel using electrolysis, this energy can be utilized in carbon capture and utilization and storage (CCUS). These are different channels that play different roles in a low-carbon energy system. **Tables 1** and **2** demonstrate that several important research gaps are currently important for developing further steps to decarbonize the energy industry. The first problem is that the long duration of energy storage must be considered because of the seasonal fluctuations of renewable energy production. The current technologies like lithium-ion batteries provide cost-effective storage on a short term, but they are inadequate for 10+ h or multiple days that are required in some regions.

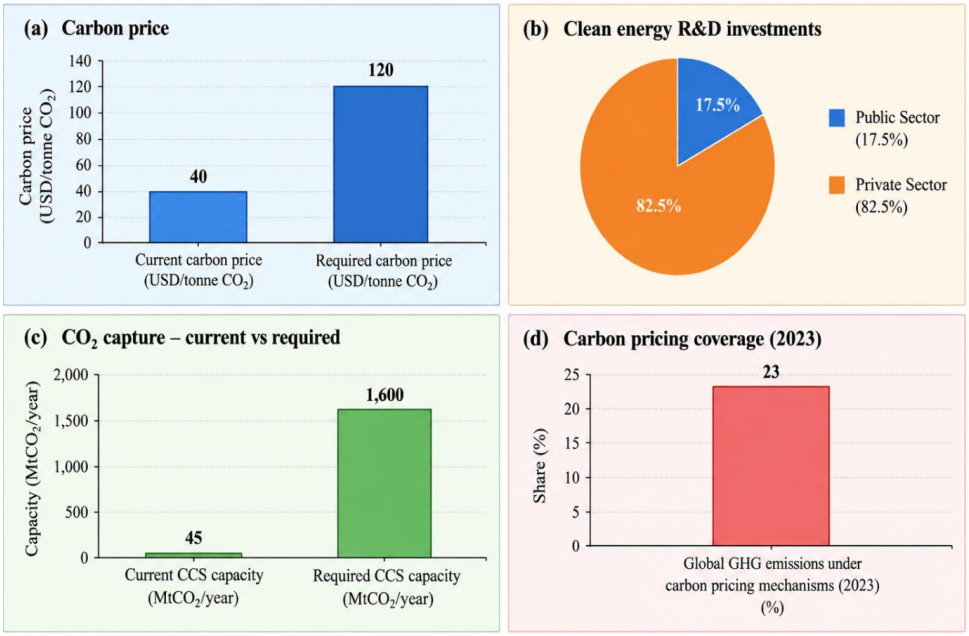


Figure 5. Selected indicators of carbon pricing, clean-energy research and development (R&D), and carbon capture and storage (CCS): (**a**) current and required carbon prices (USD/t CO_2), (**b**) reported shares of public- and private-sector clean-energy R&D investment (%), (**c**) current and required CCS capacity ($MtCO_2$/year), and (**d**) share of global greenhouse gas (GHG) emissions covered by carbon pricing mechanisms in 2023 (%).

Table 1. Synergies from Technology Integration.

Technology Combination	Synergy/Benefit
Solar + Energy Storage + Smart Grids	Increases grid resiliency, helps with demand-side management, and increases flexibility for incorporating variable renewable energy sources.
Renewable Electricity + Hydrogen Production	Harnesses green power to generate hydrogen gas using electrolysis, which helps with energy storage for prolonged periods and de-carbonizing certain industrial sectors.
Renewable Electricity + CCS/CCUS	Emissions related to the energy consumption for capturing and compressing CO_2 can be decreased, depending on the power source and the configuration of the carbon capture process.

Table 2. Key Research Gaps in Energy Decarbonization.

Area	Current Status	Research Need
Long-Duration Energy Storage	Dominated by lithium-ion; limited to short durations	Develop cost-effective solutions for 10+ h and seasonal storage
Carbon Capture & Storage (CCS)	30 facilities capturing >45 $MtCO_2$/year (IEA, 2021)	Scale up to 1.6 $GtCO_2$/year by 2030; reduce cost; expand CO_2 transport/storage
Grid Integration of DERs	DERs growing at 10–15% annually in advanced economies	Develop standardized grid protocols for seamless interoperability
Socioeconomic Models for Smart Grids	Limited understanding of user behavior	Build robust models to align policy and technology with consumer needs

It is imperative that new low-cost technologies of CO_2 capture as well as transportation and storage networks are developed. In addition, the absence of grid standards for DER integration, which are increasing in developed countries at a rate of 10–15% per year, makes it harder to achieve interoperability. Finally, the creation of appropriate socioeconomic models is important in order to study consumer behavior within the smart grids framework. These issues need to be solved with proper research (**Table 3**).

Table 3. Policy Interventions with Supporting Data.

Policy Intervention	Current Status	Required Action
Carbon Pricing	Covers 23% of global emissions; avg. price \$26/t CO_2 (2023)	Raise to \$75/t CO_2 (IMF recommended)

Table 3. *Cont.*

Policy Intervention	Current Status	Required Action
Financial Incentives (e.g., U.S. IRA)	Tax credits up to \$85/t CO_2 for industrial CCS	Expand globally to encourage large-scale CCS and storage adoption
Interoperability Standards for Smart Grids	DERs growing fast, but no universal standards	Mandate standards to ensure efficient grid communication and reduce costs
Public-Private Partnerships (PPPs)	Global public energy R&D spending was nearly USD 44 billion in 2022 (IEA, 2023); corporate R&D by listed energy-related companies also rose by 10% that year	Strengthen coordination between public research programmes and private-sector innovation to accelerate technology development and deployment

To promote the decarbonization of the energy sector, a number of policy initiatives should be based on specific numerical goals and economic instruments. A carbon tax continues to be a useful tool in the reduction of greenhouse gas emissions; however, its impact will depend on how broad the price is, the price level and the presence of other supporting policies. The International Monetary Fund has noted that carbon prices could range to about USD 75 per t of CO_2 by 2030 as one such indicator [40] (**Table 3**). Secondly, the provision of economic incentives for energy storage and CCS application will facilitate their adoption; for example, the US Inflation Reduction Act provides tax credits of up to \$85 per t CO_2 for geological storage of carbon captured by industry.

Thirdly, imposing standardization of smart grids is important to deal with the increasing share of distributed energy resources (DERs) that are being deployed at a rate of 10–15% each year in developed countries [41]. PPPs can help ensure smooth communication among devices, grid reliability, and cost reduction in integration. It is clear from **Table 3** that the support of public-private partnerships is essential to facilitate research and development in clean energy. Public R&D expenditure in clean energy stood at \$44 billion in 2022 globally while the private sector spent more than \$130 billion [42].

This review seeks to shed light on the way forward to achieve sustainability and a low carbon energy future by reviewing the present status, developments and problems of these important technologies. Gap bridging, effective integration, and creation of favourable policy environments will be fundamental towards achieving the goal of decarbonization of the planet. This review presents an exhaustive analysis of the technologies that have been acting as catalysts to achieve decarbonization of the global energy sector. Solar energy, energy storage, power system integration, and CCS are some of the technologies that are included in this review.

2. Review Methodology

A comprehensive narrative review approach was adopted to explore the integration of solar energy, energy storage, modernization of the power system, and CCUS in the decarbonization of the energy sector. Literature sources were found by searching via Google and Google Scholar, by browsing related journals' websites, and by reading institutional and technical reports. The used literature sources are cited in the manuscript references section, while the search results were kept by the authors. The literature was concentrated on the solar photovoltaic technologies, energy storage technologies, development of the smart grid, power system modernization, CCUS, and on the technoeconomic aspects of the integrated decarbonization. Literature sources were selected depending on their relevance to the research topic and their contribution to the knowledge of technological advances, performance parameters, cost parameters, integration opportunities, barriers to the implementation of those technologies, and implications of policies. Selected literature sources were organized in the themes of solar energy, energy storage, modernization of the power system, CCUS, and integration opportunities. The data provided were qualitatively analyzed to compare technology advancement, economic aspects, deployment trends, and interactions within systems. Where possible, the quantitative figures were compared in the light of the sources they came from taking into consideration.

3. Growth and Adoption Trends in Solar Energy

There has been an exponential rise in the deployment of solar energy over the past two decades, which has become an important player in decarbonizing the world. **Tables 4** and **5**, according to the International Renewable Energy Agency [43], the installed capacity of the world in terms of solar photovoltaic (PV) increased from just 23 gigawatts (GW) in 2009 to more than 1,200 GW by 2023 (**Figure 6**). The dramatic increase 18.7% in 2023 (**Table 6**) can be due to three main factors: reduction in cost of PV, awareness of climate change, and global effort through

policy tools like feed-in tariff (FIT), investment tax credit (ITC), and RPS.

Table 4. Global Installed Solar PV Capacity.

Year	Installed Solar PV Capacity (GW)
2009	23
2013	139
2017	402
2020	713
2023	1,200

Table 5. Global weighted-average LCOE of newly commissioned utility-scale solar PV projects, selected years (2010–2022).

Year	LCOE of Solar PV (USD/kWh)
2010	0.460
2013	0.197
2016	0.116
2019	0.060
2022	0.050

Table 6. Reduction in global weighted-average LCOE of utility-scale solar PV projects relative to 2010.

Year	LCOE ($/kWh)	% Reduction Since 2010
2010	0.460	0.0
2015	0.132	71.3
2020	0.067	85.4
2023	0.044	90.4

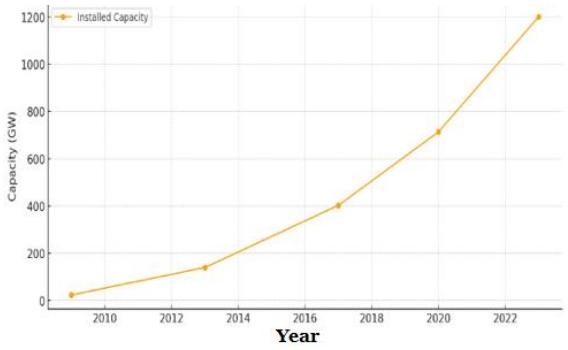


Figure 6. Global Installed Solar PV Capacity Growth (2009–2023).

Table 5 and **Figure 7** clearly demonstrate that the Levelized Cost of Electricity (LCOE) of large-scale Solar PV technology has drastically decreased, with more than 88% reduction from 2010 to 2022. According to **Table 6** [43], the LCOE for solar globally was reduced from about $0.378/kWh in 2010 to less than $0.045/kWh. India, China, and the USA are just some of the countries where the LCOE of solar is under $0.03/kWh (**Table 7**) under favorable circumstances. The cost-competitiveness of solar energy has allowed it to compete against traditional energy sources based on fossil fuels even without subsidies in many places. Many scientific sources [44] point out that solar, along with wind energy, batteries and modern grid infrastructure, is capable of meeting most of global electricity needs by mid-century.

Apart from large-scale use, solar power is revolutionizing the process of rural electrification (**Figure 8**). According to the World Bank (2022), off-grid solar power systems have provided electricity access to over 420 million people, particularly in Sub-Saharan Africa and South Asia, at the least cost. Such decentralized systems contribute to sustainable development goals through poverty reduction, the replacement of diesel generators, and better health and education results. Apart from being a green and scalable energy source, solar energy is also a necessary part of global climate change goals. **Figure 9** shows reduction in the global weighted-average LCOE of newly commissioned

utility-scale solar PV projects between 2010 and 2023, reflecting falling module and system costs and improving efficiency (IRENA, 2024).

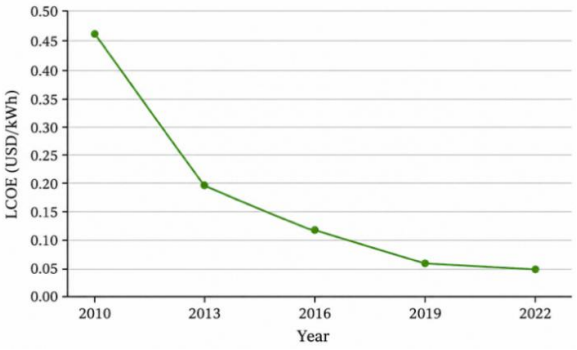


Figure 7. Decline in the global weighted-average LCOE of newly commissioned utility-scale solar PV projects between 2010 and 2022.
Source: Adapted from IRENA (2024).

Table 7. Solar Electricity Prices in Key Countries (2023, Utility-Scale Projects).

Country	LCOE Range ($/kWh)	Notes
India	$0.025–$0.035	One of the lowest globally
China	$0.026–$0.032	Driven by large-scale PV deployment
USA	$0.028–$0.035	Incentivized by tax credits and state policies
UAE	$0.0135	Record low bid in 2021 project
Chile	$0.021	Supported by strong solar resource

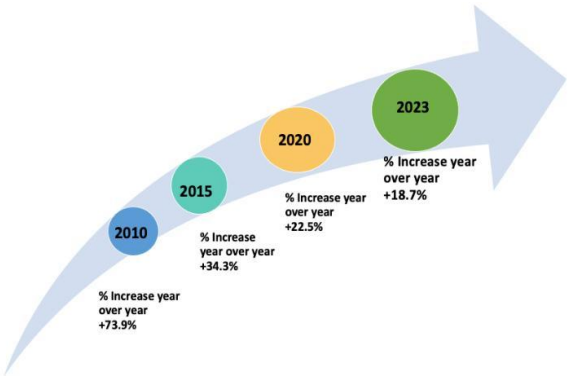


Figure 8. Increase in the capacity over year.

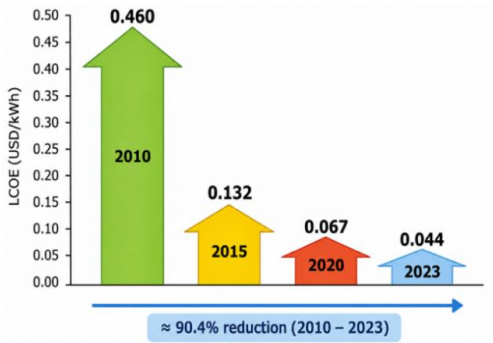


Figure 9. Reduction in the global weighted-average LCOE of newly commissioned utility-scale solar PV projects between 2010 and 2023.
Source: Adapted from IRENA (2024).

3.1. Technological Advancements in Solar Photovoltaic (PV) Systems

The data presented in **Table 8** indicates that technological developments in the area of solar photovoltaics (PV) have revolutionized the energy sector, increasing the efficiency and reducing the cost of harnessing solar energy. The advancements made possible by significant research and development activities over the last two decades have resulted in breakthroughs in the form of new materials including monocrystalline silicon, passivated emitter and rear cell (PERC), and perovskite solar cells, increasing the efficiency of commercial PV modules from 12% in the early 2000s to over 22% in 2023 [45].

Table 8. Advancements in Solar Photovoltaic (PV) Systems.

Technological Advancement	Description	Key Benefits
Monocrystalline and Polycrystalline Silicon Cells	Improved manufacturing processes for silicon-based cells.	Higher efficiencies (20–22%) in commercial PV modules.
Thin-Film Solar Cells	Technologies like CdTe and CIGS offering lightweight and flexible alternatives.	Cost-effective, versatile applications.
Bifacial Modules	Modules that capture sunlight on both sides.	Increases energy yield by up to 30%.
Perovskite Solar Cells	Emerging technology integrated into tandem cells for improved performance.	Potential efficiencies over 30%, lower costs.
Solar Tracking Systems	Single-axis and dual-axis systems that adjust panel orientation.	Boosts energy capture by 10–25%.
Building-Integrated Photovoltaics (BIPV)	Solar panels integrated into building materials like windows and roofs.	Urban-friendly, dual-purpose energy generation.

Cost reductions have been equally impressive. There was an approximate decline of 90% in the LCOE value of new utility scale solar photovoltaic projects across the world over the 2010 to 2023 period from USD 0.460/kWh to USD 0.044/kWh. In addition, the LCOE of 2023 represented a decline of 12% from 2022 where it was USD 0.050/kWh. These efficiency improvements and cost reductions have driven widespread uptake, with installed solar PV capacity growing from just 40 GW in 2010 to 1,200 GW in 2023 [28]. Flexible thin-film solar panels and BIPV have broadened applications into infrastructure, transport, and mobile devices. These developments confirm solar PV as an essential technology for decarbonization, energy security and sustainable development goals.

3.2. Energy Storage in Solar Based Systems

The production of intermittent solar energy due to variations in the seasons and day-to-day basis is one of the major problems associated with its usage. The Energy Storage System is vital to help overcome this problem, and this helps to ensure that the excess energy produced when there is abundant sunlight is stored and can be used in times when the amount of sunlight is insufficient (**Table 9**).

Table 9. Comparative Technical and Economic Characteristics of Energy-Storage Technologies.

Parameter	Lithium-Ion Batteries	Flow Batteries	Pumped-Storage Hydropower (PSH)	Hydrogen Storage
Round-trip efficiency	Typically 85–95%	Approximately 60–85%, depending on chemistry and system design	Approximately 70–85%, depending on plant configuration	Generally lower for electricity-to-hydrogen-to-electricity pathways; often approximately 25–45%
Capital expenditure (CAPEX)	Modular systems; costs depend on power rating, storage duration, installation and battery chemistry	Costs depend on electrolyte, tanks, power-conversion equipment and storage duration	High initial investment due to reservoirs, civil works, turbines and site development	Requires electrolysers, hydrogen storage and reconversion equipment; costs depend strongly on storage method and scale
Levelized cost of storage (LCOS)	Often competitive for short-duration applications and frequent cycling	Potentially attractive for longer-duration stationary storage, depending on utilisation and system design	Project-specific; long operating life can help offset high initial costs	Highly dependent on electricity input costs, electrolyser utilisation, storage method and reconversion efficiency
Cycle life and operating life	High cycle life, but degradation, temperature and battery augmentation affect service life	Can support frequent cycling; lifetime depends on electrolyte chemistry, membranes and maintenance	Infrastructure can operate for several decades with appropriate maintenance	Depends on electrolyser, storage and reconversion equipment; hydrogen storage duration depends on the storage method
Typical storage duration	Commonly used for approximately 1–8 h, with longer-duration configurations available	Suitable for multi-hour applications, including longer-duration stationary storage	Typically hours to days, depending on reservoir capacity and system design	Potentially suitable for multi-day to seasonal storage, depending on storage capacity and end-use equipment
Main applications	Frequency regulation, rapid response, and daily renewable-energy shifting	Stationary storage, renewable-energy integration and frequent cycling	Bulk energy storage, peak shifting and grid balancing	Long-duration or seasonal energy storage and industrial feedstock

Table 9. *Cont.*

Parameter	Lithium-Ion Batteries	Flow Batteries	Pumped-Storage Hydropower (PSH)	Hydrogen Storage
Principal limitations	Battery degradation, thermal management, fire safety and material supply chains	Lower energy density, system complexity and sensitivity to project scale	Geographic constraints, permitting, environmental impacts and high upfront costs	Low electricity-to-electricity efficiency and the need for hydrogen infrastructure

Moreover, storage is vital for stability and resilience of power grids because the proportion of energy generation using solar and other renewable resources is continuously growing. Storage systems provide solutions to problems of energy excess and grid congestion, making demand-response possible.

Lithium-ion batteries are currently the most prevalent energy storage system in use due to their energy density, typically around 90–95% efficiency rate, and rapidly falling prices (**Figure 10**). Lithium-ion batteries can be applied in residential, commercial, and utility scales [46]. Small form factor and rapid charging capability make them appropriate for smartphones, electric cars, and solar energy storage. Nonetheless, there are several challenges associated with lithium-ion batteries, including shorter lifetime than that of other battery types, possibility of catching fire due to the risk of thermal runaway and environmental concerns regarding usage of cobalt and lithium in the batteries.

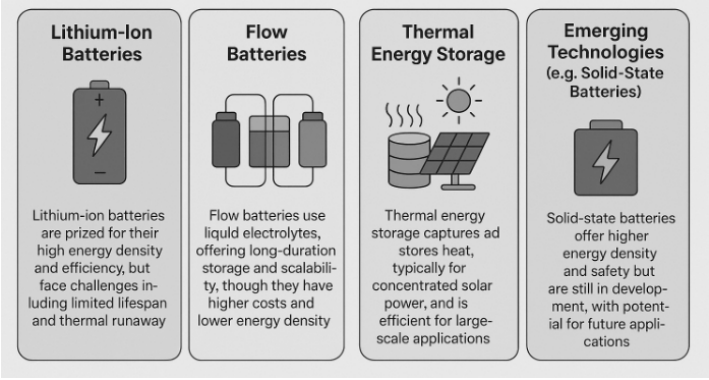


Figure 10. Types of Storage Technologies.

The electrolyte is stored in an external tank in a flow battery system, which makes its installation scalable and highly appropriate for large-scale applications such as long-duration energy storage applications (**Figure 10**). The technology has many benefits compared to lithium-ion batteries; these include increased longevity and greater capacity for deep discharge without damaging the battery cells [47]. Nonetheless, there are some challenges in using the technology since it is relatively expensive and less energy-efficient. Nevertheless, flow batteries have potential in the energy systems of the future.

Thermal energy storage consists of storing thermal energy through collecting heat from the sun via using substances such as molten salts or phase change materials. This technique is mainly used in concentrated solar power (CSP) systems since it allows the storage of energy for up to several hours or even days and thus electricity production even when there is no sun available. This technique is highly efficient and cost effective on a large scale [48].

Unlike conventional batteries which use either a liquid or gel-like electrolyte, solid-state batteries (SSBs) incorporate solid electrolyte materials which have multiple benefits such as 2–3 times higher energy density, higher thermal stability, and a much lesser likelihood of flammability [49]. According to Bloomberg NEF (2023), solid-state batteries can provide energy densities up to 500 Wh/kg as opposed to 250–300 Wh/kg offered by current Li-ion batteries [50]. The increased energy density is likely to enhance the range of electric cars, as well as cut down the charging time to under 15 min [51].

4. Renewable Energy Systems Integration for Decarbonisation

With the evolution of the global energy scene towards sustainability, the integration of renewable energy into the current power generation system has come to be both an essential as well as a tough requirement (**Figure**

11). Such a development requires a new vision about how electricity is generated, distributed, and used. The key innovations include smart grids, grid modernization, and the effective use of distributed energy resources (DERs).

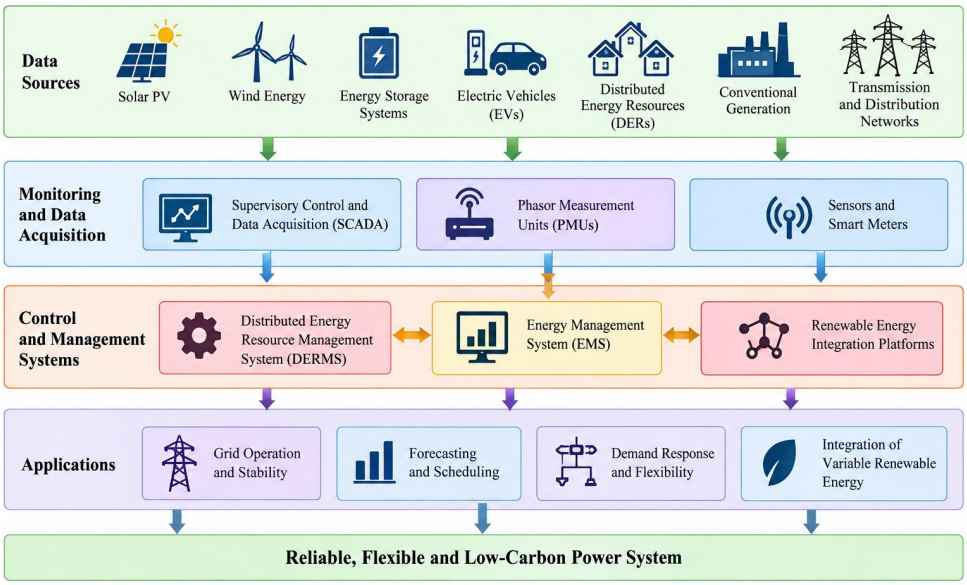


Figure 11. Power Systems Integration Tools.

Smart Grids Revolution

From **Figure 12**, it is clear that smart grids are digitally enhanced electric power systems, which integrate highly evolved information technology and automation technologies. They help in balancing electricity generation, transmission and consumption. These intelligent grids play an essential role in assembling the renewable energy sources like solar and wind because their nature is variable. From 2014 to 2022, investment in smart grid was in excess of $300 billion indicating the importance of digital grid modernization [31]. The concept of smart grids is also motivated by the factor of digitalisation involving the use of millions of sensors, AMI and IoT based devices. In 2022, approx. 1.2 billion smart meters were installed globally [52]. These meters provide useful information about the functioning of grids and electricity consumers. These meters can measure electricity consumption in real time and provide useful information for maintenance and faults sensing and forecasting energy demand. Thus, energy loss is minimised considerably. For example, the U.S. Department of Energy stated that there was 20–30% decrease in outage time in regions where full-fledged smart grids are operating.

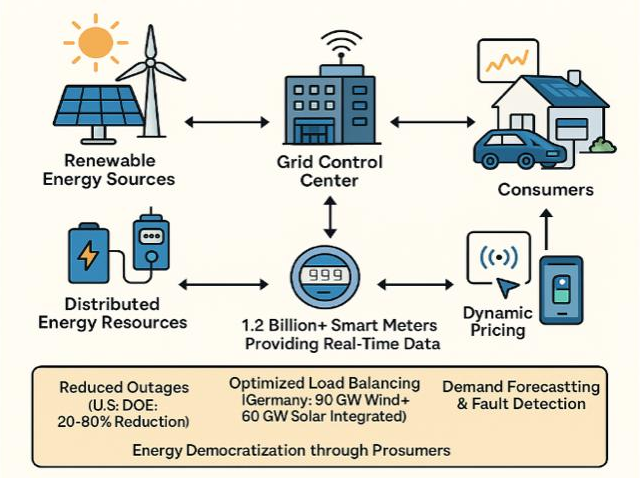


Figure 12. Smart Grids-Digitalized, Intelligent Electrical Networks.

The use of smart grids also improves load balancing by incorporating distributed energy resources, battery energy storage systems, and electric vehicles that coordinate together with the central systems. In the case of Germany, through the use of smart grids, the integration of over 50 GW of wind power generation and 60 GW of solar PV into the national grid system has been achieved, while maintaining its stability [41]. For the consumers, the use of smart grids provides dynamic pricing, energy control, and prosumers.

In this regard, smart grids have helped in decentralizing and democratizing energy systems. In general, smart grids are facilitating a clean and resilient future of energy. **Table 10** indicates that grid modernization consists of the upgrade of physical as well as digital infrastructure of existing electrical networks in order to cater to the changing energy needs, especially the incorporation of renewable energy sources. The total amount of investment in the global electricity grids amounted to $337 billion in 2022, of which 30% was invested in digital upgrading [53]. It is important for two-way power flows for incorporating distributed energy resources into the grid. Some of the upgrades include advanced substations, protection systems, and voltage regulation.

Table 10. Key Data on Grid Modernization and DER Integration.

Aspect	Metrics	Source/Year
Global grid investment (2022)	$337 billion	IEA, 2023
Share of digital upgrades	>30% of total grid investment	IEA, 2023
Projected U.S. DER capacity (2025)	387 GW (≈33% of total U.S. grid capacity)	Wood Mackenzie, 2021
Global transmission losses	5–10% of electricity lost during transmission	IEA, 2023
DER contributions	Rooftop solar, wind micro-turbines, batteries, smart loads	NREL, 2022
Two-way power flow infrastructure	Requires upgrades to substations and automation systems	NREL, 2022
Key benefits of DERs	Decentralization, flexibility, localized backup power	NREL, Wood Mackenzie, IEA

The DERs play a pivotal role in the process of decentralization of power generation. By 2025, the cumulative capacity of DERs in the United States will reach 387 GW (**Figure 13**), accounting for one-third of the total grid capacity [54]. The process of decentralization does not only decrease the dependence of the system on centralized plants; it also increases the resiliency and flexibility of the system. The use of DERs helps to decrease the transmission losses, which usually constitute 5–10% of the total electricity loss worldwide [55]. Moreover, the process of using DERs allows for provision of localized backup electricity during peak load times and emergencies, thus decreasing the probability of blackouts. Overall, the process of grid modernization is crucial for creation of a resilient and flexible power system of the future. However, despite the advantages that could be provided by modern grids and grid modernization, there are significant problems associated with integration of renewable energy into existing power systems. One of the biggest challenges related to renewable energy sources is their variability and intermittence. For instance, solar output can drop by up to 70% within minutes during cloud cover [56] requiring rapid response mechanisms for achieving grid stability (**Figure 14**). This issue can be tackled through the use of advanced forecasting systems and artificial intelligence predictive models.

However, energy storage plays an equally important role in mitigating these swings but is relatively expensive and underutilized (**Figure 14**). As of 2023, worldwide storage capacity on the grid level stood at 28 GW and according to estimates of the International Renewable Energy Agency [57], it needs to grow up to 500 GW in order to meet climate objectives by 2030. The first constraint is aging equipment around much of the world. In the US, more than 70% of the transmission lines and transformers are over 25 years old [58] and were not designed to handle two-way power flows that distributed generation entails. Such a condition significantly restricts regions' capacity to incorporate decentralized renewable energy systems effectively. Regulatory schemes add additional constraints since they rely on archaic assumptions related to centralized fossil fuel power networks. They create inflexible market systems and slow permitting procedures. Over 60% of the world's nations do not have regulatory means to promote peer-to-peer energy transactions [59].

DR systems have proved to be a very important answer to the above challenges. Over 20 GW of DR capacity was switched on in the US alone in 2022 [60]. DR systems enable the consumers to respond to the availability of renewables by adjusting their electricity consumption pattern and thus contribute towards both flexibility of the grid as well as reduced dependence on fossil fuels.

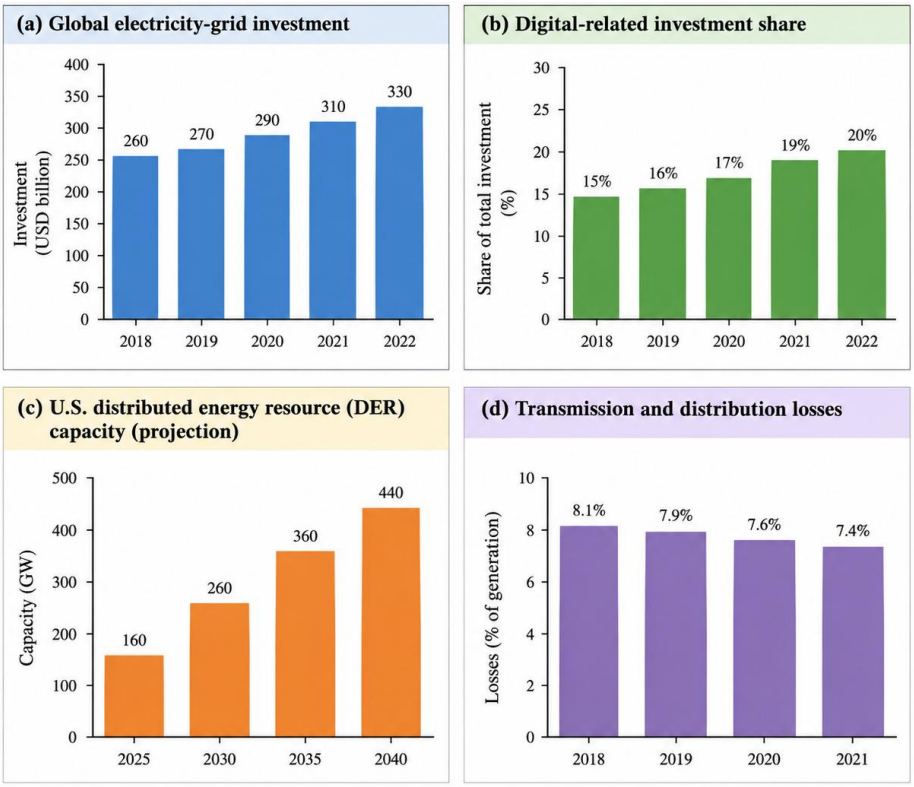


Figure 13. Indicators concerning grid modernization and DER adoption: (**a**) Investment in electricity grids globally (in USD billions); (**b**) Digital investments as a percentage of overall grid investments; (**c**) Expected capacity of distributed energy resources in the United States (in gigawatts); and (**d**) Transmission and distribution losses (% of generation). The above indicators are shown in different panels since they use different units and come from different sources.

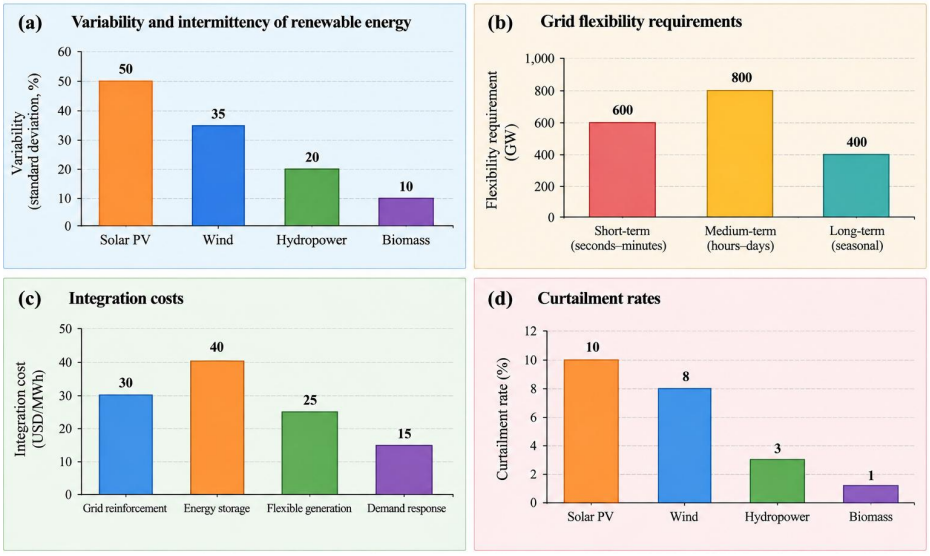


Figure 14. Challenges of integrating renewable energy: (**a**) variable/intermittent nature of renewable energy sources; (**b**) flexibility demands in the short-, medium-, and long-term timeframes; (**c**) main types of costs associated with renewable integration, such as reinforcing the network, energy storage, flexible generation, and demand response; and (**d**) curtailment of renewable energy. The numerical measures have been provided only if the geographical region, reporting period, unit, and source were known.

5. Carbon Capture and Storage (CCS)

As the world speeds up its attempts at mitigating the impact of climate change, Carbon Capture and Storage (CCS) has become an essential technology, especially in those industries which have difficulty decarbonising their emissions. Even as renewables and electrification continue to decrease the carbon footprint in many industries, there remain some industries such as cement, steel production and chemicals manufacture that present difficulties [61]. In those difficult to decarbonise industries, carbon capture and storage offers an alternative path in terms of capturing carbon dioxide (CO_2) emissions from these sources and stopping them from being released into the atmosphere. The carbon capture stage is the first stage in the CCS process, which involves separating the carbon dioxide from the emissions produced by industrial operations and energy production [62]. **Figure 15** demonstrates that there are three main methods of capturing carbon:

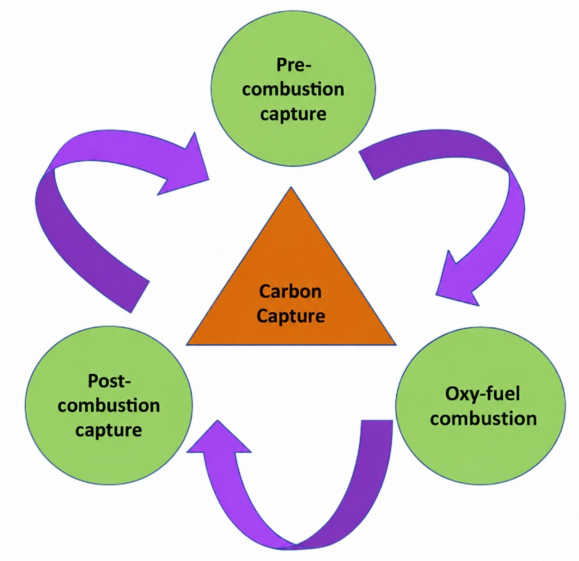


Figure 15. Carbon Capture Stages.

In pre-combustion capture technology, the fossil fuel feedstock is converted to a hydrogen and CO_2 rich mixture prior to combustion. The CO_2 is subsequently separated out and captured. Pre-combustion capture technology is frequently utilized in industrial applications and gasification power stations. In post-combustion capture technology, the CO_2 is extracted from flue gases once the fossil fuels have been burnt. This technology is highly useful for upgrading or retrofitting current power generation plants and is among the most extensively studied and utilized technologies. Oxy-fuel combustion burns the fuel in pure oxygen instead of air and results in flue gas that consists of mainly water vapor and CO_2. This allows for easier separation and extraction of CO_2. These capture technologies differ greatly in their efficiency, cost, and applicability, yet are equally important in reducing carbon emissions in sectors where there is no viable substitute.

5.1. Carbon Storage and Utilisation

The next stage is the storage or use of the CO_2 after it has been captured. The geologic storage technique is the most advanced and used method with successful experience in long-term storage (**Figure 16**). According to the Global CCS Institute [57], more than 260 million t of CO_2 have been injected and securely stored worldwide from the beginning of commercial-scale operations [63]. Geologic storage includes the injection of CO_2 into deep geological reservoirs such as saline aquifers and depleted oil/gas fields. Saline aquifers represent a very promising option due to large potential storage capacity. According to the U.S. Department of Energy estimates, the potential CO_2 storage capacity in saline formations in North America exceeds 2,600 billion t. Such reservoirs provide the required pressure conditions and sealed rocks to store CO_2 for thousands of years. Depleted oil and gas fields provide the already installed infrastructure, thus saving costs. The Sleipner and Snøhvit projects in Norway have injected more than 1 million t of CO_2 per year into the saline aquifers since the end of the 1990s without any leakage [64]. These

examples emphasize the practicality of geological storage as a backbone of CCS technologies, which are needed to achieve the net-zero goals defined by the Paris Agreement [65].

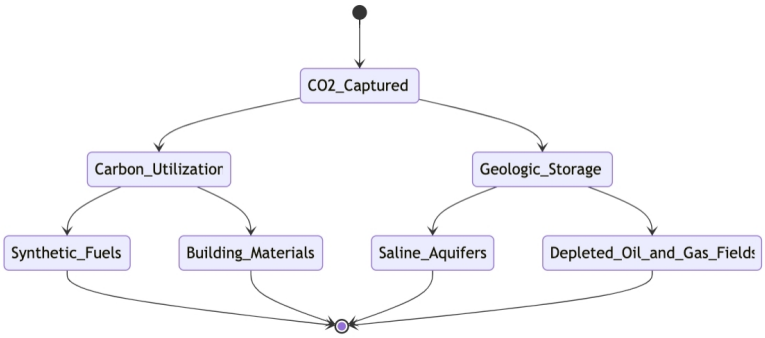


Figure 16. Geologic storage.

Apart from storage, there is a trend developing in utilizing carbon through various uses for captured CO_2. Such uses include synthetic fuels where CO_2 is reacted with hydrogen to form low carbon fuels to fuel engines and transport, and building materials where CO_2 is reacted with cement to increase the strength of the material. Even though it is at a developmental stage for many uses, there is great potential for circular economies using carbon.

5.2. CCUS Economic and Policy Framework

However, even though technically feasible, CCS is economically difficult. According to the International Energy Agency [60], the costs of CCS range from $50 to $100 per t of CO_2 captured, depending on various parameters, including the method used for capture, distance to store, and geological characteristics of the place. In industries characterized by high carbon emissions but low margins, such costs may prove to be very high.

In order to overcome this economic disparity, there needs to be proper policy backing. The feasibility of CCUS is not limited to the cost of capturing the CO_2 but is also linked to the energy consumption needed for the separation, compression, transportation, and storage. The cost of capture is determined by the concentration of CO_2 in the emission, method of capture, and level of integration with the hosting facility. This could affect the operational cost and electricity generated from the power plant using carbon capture. The use of renewable energy will assist in minimizing the emissions related to the operation of CCUS, while common infrastructure and improved integration could assist in reducing costs. It is therefore important that CCUS be assessed from the whole chain of capture, transportation, and storage. The U.S. Internal Revenue Code section 45Q grants tax credits of $85 per t of CO_2 captured and stored, and $60 per t if used [66]. This has been a driving force behind more than 100 active CCS projects currently being undertaken in the U.S. Also, the EU innovation fund and Canada's clean fuel regulations are some other financial schemes that can help promote the implementation of CCS technology. It is necessary to clarify regulatory issues. Issues related to liability, environmental monitoring, and site management need to be enforced for gaining public trust.

6. Integration of Solar Power, Energy Storage and CCUS Technologies

As the world moves towards zero emissions, the combination of technologies that complement each other (as shown in **Figure 17**) such as solar technology, energy storage, and carbon capture and storage provides a means to achieve a sustainable energy future. While each of the above technologies is individually effective, when combined, their synergies can make energy security much easier.

6.1. Synergies between Solar, Storage, and CCS

As an energy source, solar is clean, renewable, and economically viable. In 2023, the weighted average LCOE of electricity from utility-scale solar PV has declined to $0.044/kWh, a 29% decrease from 2019 and 89% lower than that of 2010 [67]. However, due to the intermittent nature of the energy source and generation only when there is sunlight, it creates an issue in terms of power system reliability. Energy storage technologies are necessary to

offset the issue of intermittency. The process of energy storage involves charging batteries with excess solar energy during times of maximum sunlight and discharging at times of peak demand or lack of sunlight, such as night or cloudy weather. As shown in **Figure 18**, Lithium-ion batteries are extensively used in grid-level storage owing to their high efficiency and quick response. Round-trip efficiencies of Lithium-ion batteries are usually 90%–95%, although the efficiency will vary depending on the system design, operation, and additional load [68]; Round-trip efficiencies of Lithium-ion batteries are 90–95% with a sharp reduction in price from $1,200/kWh in 2010 to less than $140/kWh in 2023.

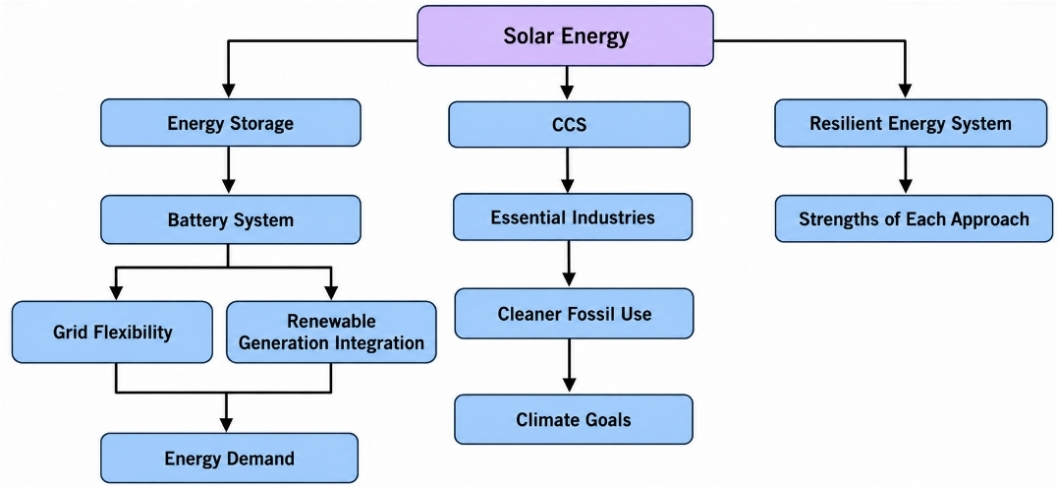


Figure 17. The interrelated uses of solar energy, energy storage, and carbon capture and storage (CCS) in providing flexibility in the energy system, lowering industrial emissions, and contributing to climate objectives. The function of energy storage is to aid in incorporating variable renewable energy sources into the power grid, while CCS will lower CO_2 emissions from certain industrial processes if it is done efficiently.

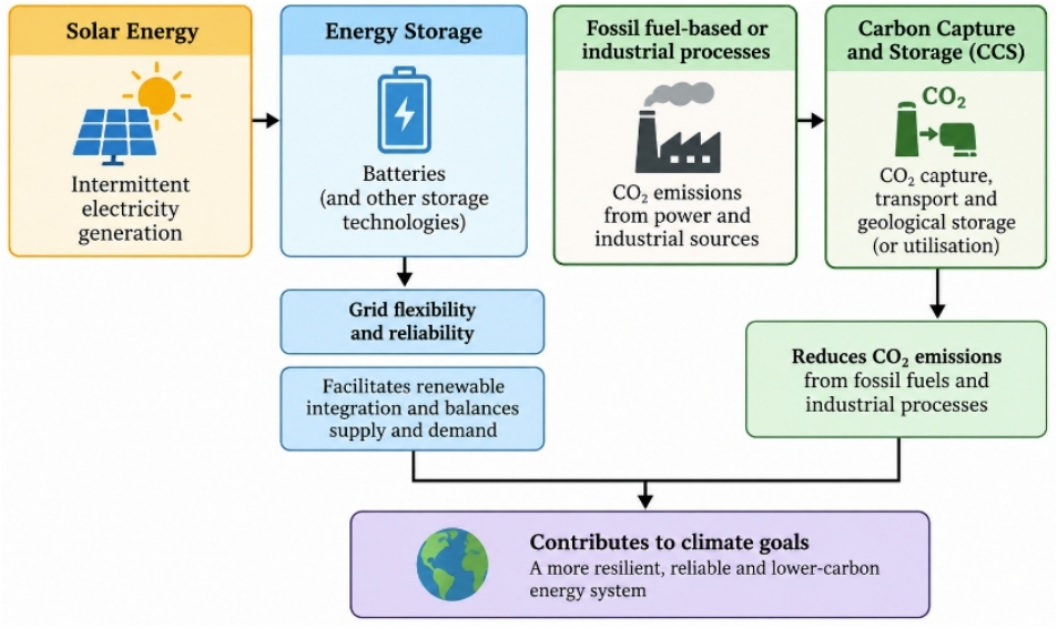


Figure 18. Synergies between Solar, Storage, and CCS.

Some flow-battery systems can exceed 10,000 cycles, depending on chemistry and operating conditions and are well-suited for LDES use. The lack of adoption can be attributed to their lower energy density (20–40 Wh/L) and relatively high initial capital expenditure, however, with new chemistry, cost reductions of up to 40% could be

possible by 2030 [69]. Solid state batteries, while still in R&D stage, offer energy densities above 400 Wh/kg, shorter charge time, and increased thermal stability in comparison with conventional lithium-ion batteries. Despite current manufacturing challenges, predictions of their commercial application in EVs and grid-scale energy storage are for the 2030–2035 period [70]. However, storage systems help to overcome temporal issues in renewable energy production—they do not solve the problem of emissions from the industrial sector that constitutes 30% of total carbon dioxide emissions globally, with steel and cement being responsible for more than 13% [71].

This is where Carbon Capture and Storage (CCS) enters the scene as a parallel solution that becomes important in this respect. CCS technology captures CO_2 emitted from flue gases or industrial processes and either stores it in geological deposits or uses it in other industrial processes. According to figures provided by 2023, there are 41 operational CCS plants in the world which capture some 49 million t of CO_2 per year, although this is still far short of the 1.6–2.3 billion t/year required by 2030 under the IEA NZE scenario [72].

Moreover, the plants which use natural gas and have CCS technology can be used as a flexible source of energy production to back up renewables. One example of this is the Petra Nova project in the United States, which proved the viability of the technology of capturing more than 90% of CO_2 emissions from a coal power plant, which would correspond to 1.4 million t of CO_2 per year [73]. Although the project has been suspended because of economic considerations, it is an example of how technologically feasible the process can become if favourable policies and market conditions exist. As shown in **Figure 19**, the combination of solar energy, storage and CCS technologies creates an efficient system.

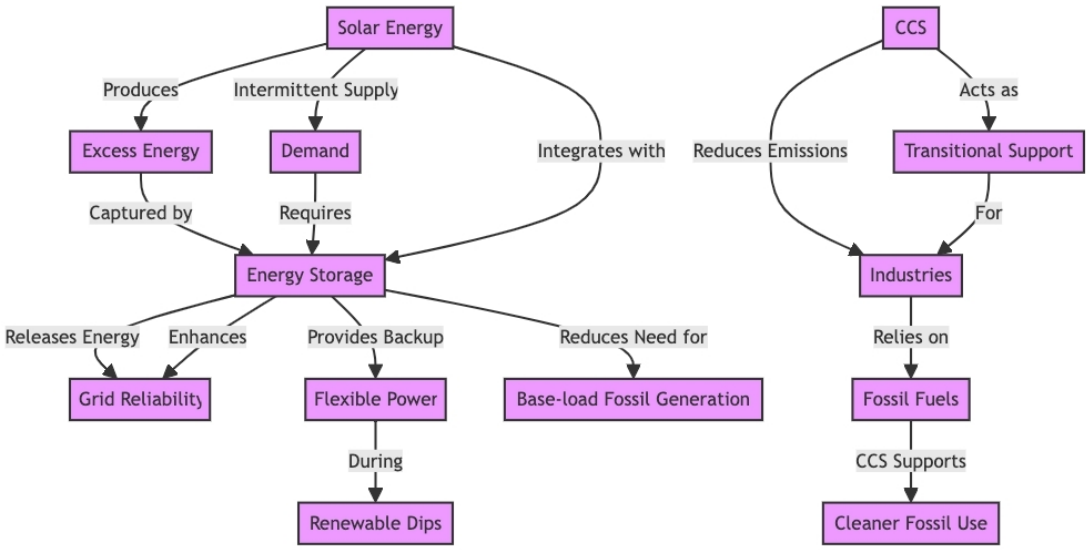


Figure 19. Relationship between Solar, Storage, and CCS-interconversion.

6.2. Case Studies of Resilient, Low-Carbon Energy Systems

Internationally, there have been several innovative integration initiatives that have proven the viability of the application of renewable energy, energy storage, and carbon capture and storage (CCS) for developing robust, low-carbon energy systems (**Figure 20**).

California is the leading region in terms of deployment of solar-plus-storage systems worldwide due to its supportive policies and goals of decarbonization. One of such example is Moss Landing Energy Storage Facility which belongs to Vistra Energy (**Table 11**). In 2024, the facility had a reported battery capacity of 1.6 GWh, which makes it one of the largest installations of lithium-ion batteries [74]. Combining large-scale solar energy generation with batteries can make it possible to deliver power generated from solar panels at evening hours, thus minimizing usage of natural gas-powered peakers. At present, the solar + storage combination in California can provide multi-hour dispatchable renewable energy to address diurnal and transient grid issues. According to the California Energy Commission, more than 6 GW of battery storage has been deployed in California by the end of 2023, which is ten times more compared to 2020, with expectations of 12 GW in 2030 [75].

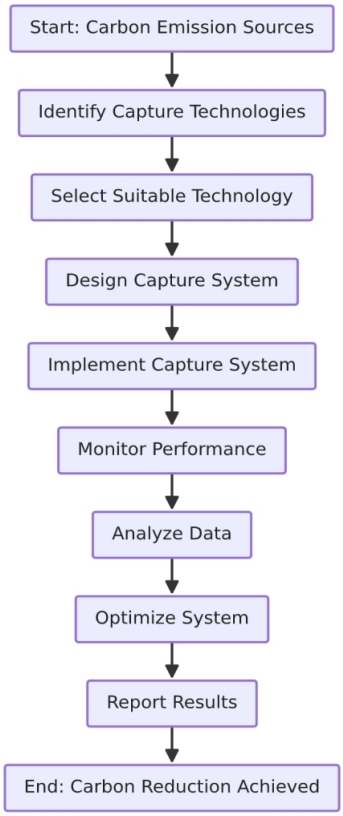


Figure 20. Outcomes of integration projects.

Table 11. Global Case Studies on Renewable Storage and CCS Integration.

Country/Location	Project/Initiative	Key Technologies	Capacity/Impact	Insights
California, USA	Moss Landing Energy Storage Facility	Solar + Lithium-ion Battery Storage	1.6 GWh battery capacity (Vistra, 2024); >6 GW battery storage online by end-2023; projected 12 GW by 2030	Enables dispatchable solar power during peak hours; reduces reliance on gas plants
Norway	Norcem Cement Project (Longship Initiative)	Industrial CCS + Hydropower + Offshore Wind	400,000 t CO_2/year capture (CCS); 90% of electricity from hydropower; target: 30 GW offshore wind by 2040	Industrial decarbonization and clean electricity in parallel; part of EU Green Deal alignment
Texas USA	Petra Nova CCS Project	Post-combustion CCS (Coal Plant) + EOR	1.4 million t CO_2/year (2017–2020)	Technically successful but halted due to low oil prices; highlighted the importance of strong economic policy backing
Queensland Australia	Kidston Renewable Energy Hub	Solar + Pumped Hydro Energy Storage (PHES)	50 MW solar; 250 MW/2,000 MWh PHES; >400 PHES sites mapped (total 300 GWh potential)	Uses abandoned gold mine pits as reservoirs; enables multi-day storage for seasonal grid needs

Industrial CCS integration can be seen in the example of Norway, where one of the projects that is part of the larger Longship CCS project is the Norcem Cement Project [76]. Norcem plans on capturing 400,000 t of CO_2 per year and transporting it via the Northern Lights offshore CO_2 storage infrastructure beneath the North Sea. At the same time, Norway is continuing to grow its renewable energy sources capacity.

The Petra Nova CCS Project in Texas was the largest post-combustion CCS project in the world installed on a coal-fired power plant, with a capture rate of 1.4 million t of CO_2 annually [77]. Although the project later had to be discontinued due to the low cost of oil (the project utilized the technology of enhanced oil recovery), it proved that such projects were technically feasible and that there was a need for more economic approaches to CCS [78]. The experiences from the Petra Nova project have affected further directions in U.S. policy and led to tax incentives under the Inflation Reduction Act, providing a tax credit of $85 per t for geological storage and $60 per t for utilization [79].

One example in which solar energy is complemented by pumped hydro energy storage (PHES) is the Kidston Renewable Energy Hub in Queensland, Australia, showing a case-specific way of making the grid resilient. The Kidston hub has a solar power capacity of 50 MW and 250 MW/2,000 MWh of PHES that makes excellent use of abandoned mine pits for storing water, providing a unique reuse of old infrastructure [80]. While lithium-ion batteries can only store energy for days, PHES has an important advantage of storing energy for weeks, which is necessary to deal with energy shortages in winter (**Figure 20**). There are around 400 potential PHES sites in Australia that have a storage capacity of over 300 GWh [81].

7. Environmental and Economic Footprints

The shift towards green energy systems holds immense consequences for the environment and economy. While a lot of attention goes towards amazing technologies that are involved in producing solar panels, wind turbines and carbon capture facilities, it is important to see how they change our environment and economy. The implementation of renewable energy, energy storage and carbon mitigation technologies not only helps in lowering greenhouse gas emissions, but also creates many opportunities for sustainable development, creating jobs and economic revival (**Table 12**). Probably the main environmental benefit of using renewable energy technologies is the decrease in the amount of greenhouse gases emitted [82]. By 2023, about 73% of global CO_2 emissions come from the energy sector, and fossil fuel sources—coal, oil and natural gas—are the major contributors [83]. In its turn, renewable energy sources—solar, wind, hydro and biomass—emit almost no carbon dioxide during their use. For example, the lifetime emissions from the production of solar photovoltaic energy systems are 20–50 g CO_2-eq/kWh against more than 900 g CO_2-eq/kWh from coal-based power plants [84].

Table 12. GHG Emissions and Air Pollutant Reduction by Technology.

Technology	GHG Emissions (gCO_2-eq/kWh)	Air Pollutants Reduction (%)
Coal Fired Power	950	0
Natural gas	450	20
Solar PV	40	95
Wind (on shore)	12	98
Hydropower	24	90
Biomass	18	85
Carbon Capture (CCS)	100	70

Figure 21 shows that carbon capture and storage (CCS) further supports decarbonization by enabling emissions reductions in sectors that are hard to electrify, such as cement, steel, and aviation. Current global CCS capacity captures about 49 million t of CO_2 annually, but the IEA estimates this must increase to 1.6 billion t by 2030 to stay on track for net-zero goals [85].

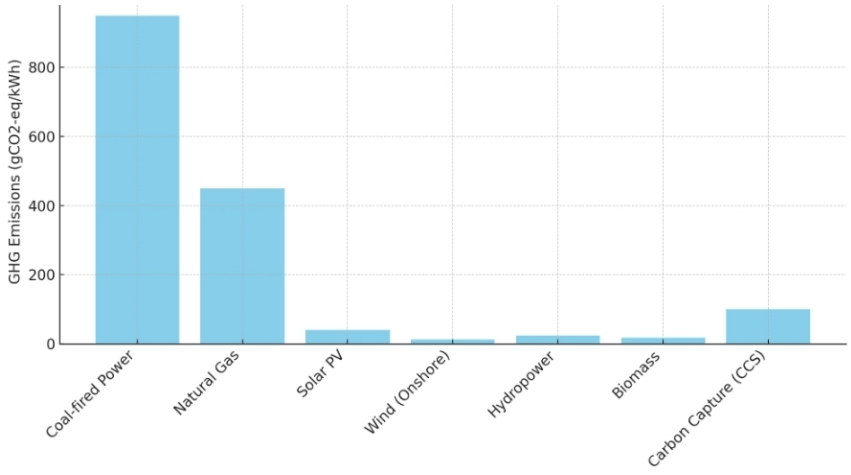


Figure 21. GHG Emissions per kWh by Energy Technology.

The shift away from fossil fuels also leads to improved air and water quality. Coal-fired power plants emit sulphur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (PM2.5)—all linked to respiratory diseases and premature deaths [86]. The World Health Organization (WHO) attributes around 7 million premature deaths annually to air pollution. Transitioning to renewables drastically reduces these pollutants, promoting public health and reducing healthcare costs. Biodiversity and ecosystem health also benefit. Fossil fuel extraction damages habitats, contaminates water, and endangers species. In contrast, well-sited renewable installations such as floating solar farms, offshore wind, and agrivoltaics offer low ecological footprints while coexisting with nature. Moreover, mitigating climate-related risks—like sea level rise and extreme weather—helps preserve biodiversity long-term.

From **Figure 22**, it is evident that although clean energy transition requires a significant amount of investment at the start, it carries enormous potential for economic renewal and benefits in the long run. Increasing numbers of studies have highlighted that clean energy transition is not only an ecological requirement but an economic one as well. According to the International Energy Agency [87], the LCOE for utility-scale solar PV had decreased by 85% from 2010 to 2022, becoming cheaper than coal and natural gas in numerous areas. Likewise, Bloomberg NEF (2023) [88] points out that prices of lithium-ion batteries dropped from above $1,200/kWh in 2010 to $139/kWh in 2022, which enhanced economic viability of energy storage systems.

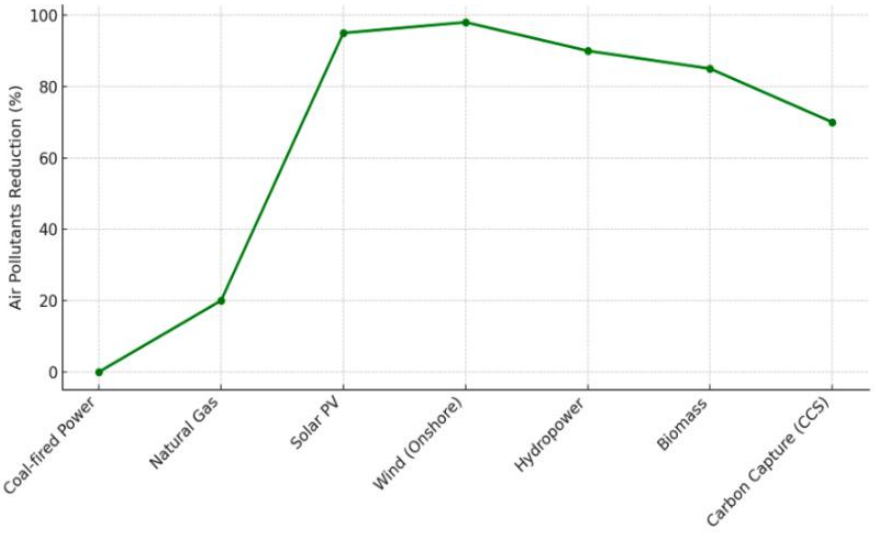


Figure 22. Air Pollution Reduction Potential by Technology.

Capital investments in renewables, batteries, and CCS technologies are expensive—costs of building solar farms are approximately $1 million per MW installed, while CCS technologies cost $50–$100 per t of CO_2 [89]. At the same time, there are significant benefits through lower expenses on fuel, reduced maintenance, and earnings from carbon credits. The role of strategic incentives such as the U.S. Inflation Reduction Act and the EU Green Deal in justifying economics is critical, as they reduce payback periods and attract investment.

In addition, clean energy is a powerful job generator. For instance, according to IRENA [90], in 2022, 12.7 million jobs were related to the global renewable energy sector, which was an increase from 11.5 million jobs in 2019. Employment in solar PV (4.9 million), wind (1.4 million) and bioenergy (3.6 million) are prevalent jobs in this area [91]. Moreover, unlike fossil fuels, those jobs are geographically diverse and more resistant to automation.

Challenges and Future Directions

Although the renewable energy sector has seen significant progress, certain key areas of R&D have yet to be tackled that prevent the full realization of the integration of renewables. The next generation batteries such as solid state, metal-air, and flow batteries have better efficiency and life cycle compared to lithium-ion batteries, but are mostly laboratory-based inventions which need considerable research investment for scaling up. For instance, solid state batteries are still twice as costly ($1,000/kWh) as lithium ion batteries [92]. In the realm of carbon capture and storage (CCS) technology, there are only 45 million t of CO_2 captured annually, whereas we need 1.6 billion t annually

for the net-zero emissions pathway by 2030 [93]. Research on the topics of direct air capture (DAC), bio-capture, and carbon-to-product processes is crucial. Currently, the cost of DAC is between $600–$1,000 per t of CO_2 making it economically nonviable (Global CCS Institute) [94], AI and machine learning can also be leveraged much more than they currently are in clean energy systems. There is significant potential in demand forecasting, grid optimization, and real-time DER (Distributed Energy Resources) management using AI and machine learning. Several studies indicate that the full integration of AI could help cut energy costs by 10%, while improving reliability [95]. In terms of socio-technical research, there is a need for research related to the concept of just transition, which encompasses re-skilling workers and providing equitable access to energy. The ILO expects around 24 million green jobs by 2030 but also foresees 6 million job losses in the fossil fuel industries [96].

Policy obstacles hinder rapid implementation of new environmentally friendly technologies. As of 2023, only 23% of total CO_2 emissions were subject to carbon pricing, and the mean carbon price stood at ~$26 per t CO_2, which is substantially less than $75/t$CO_2$ suggested by the IMF in order to meet the targets of the Paris Agreement [95]. Regulations in most countries do not offer enough flexibility to accommodate dynamic integration of DERs, and, therefore, development of smart grids lags behind expectations. At the same time, R&D expenditure is relatively small. In 2022, global public investment into R&D was $35 billion, out of which only a negligible portion went to CCS and long-term energy storage projects [96]. Overcoming the existing obstacles would require well-targeted policy incentives, creation of platforms for international knowledge exchange, and private-public partnerships [97]. Development of carbon markets, regulation strategies, and infrastructure investments—particularly regarding transportation and storage of carbon—would be instrumental in accelerating the transition.

8. Conclusions

The decarbonization of the energy industry is not only an essential tool in combating climate change but also a path towards a sustainable energy future. The combination of technologies such as solar energy use, energy storage, and carbon capture and storage provides a holistic perspective on how to become net zero. Technological progress has led to significant cost reductions in solar and wind energy and made them comparable to fossil fuel production, whereas energy storage and carbon capture provide security and emission reduction, respectively. Examples from California, Norway, Texas, and Australia show that with the appropriate policies and infrastructure, both environmental and economic goals can be achieved. However, the adoption of these innovations is still contingent on strong policy support, investment, and regulations. The shift towards renewable energy sources is more than an environmental necessity, it also opens up new possibilities for economic growth and sustainable development by creating jobs and revitalizing regions.

Author Contributions

Conceptualization, S.S., N.S.R., and A.K.; methodology, S.S., Y.G., and G.K.; software, S.S.; validation, S.S., A.K., and G.D.; formal analysis, S.S.; investigation, A.K. and G.D.; resources, S.S. and N.S.R.; data curation, S.S.; writing—original draft preparation, S.S. and N.S.R.; writing—review and editing, S.S., G.K., and G.D.; visualization, Y.G. and G.D.; supervision, A.K. and G.D. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

We don’t have any data for public availability. All details are available in manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

During the preparation of this work, the authors used Claude 5.5 Sonnet in order to improve the language, readability, and overall clarity of the manuscript text. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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