

Investment Barriers and Technological Innovations in Modern Energy Infrastructure

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ABSTRACT

Objective: This literature review aims to explore the connection between investment barriers and technological innovations within modern energy infrastructure. **Method:** Peer-reviewed literature as well as credible reports from 2005 to 2026 was selected in Scopus, Web of Science, and Google Scholar databases on such topics as investment barriers, grid infrastructure, renewable energy, energy storage, smart grids, digitization, and predictive technologies. **Results:** The results show that technological innovation significantly enhances economic competitiveness, flexibility, and reliability of energy systems. Notable in this regard is the reduction in the installed cost of utility-scale battery energy storage by 93% from 2010 to 2024. In addition, 91% of new utility-scale renewable power generation added in 2024 produced electricity at a lower cost than any new fossil fuel-based technology. However, technological advancements are not enough to promote the installation of such infrastructure since high cost of financing, policy risks, grid constraints, supply chain risks, insufficient institutional capacity, and uneven access to capital are still major barriers. **Novelty:** Moreover, advances in digital technologies are now opening up new opportunities through the use of smart meters, predictive maintenance, digital twin, and intelligent forecasts.

INTRODUCTION

The energy infrastructure of the modern world plays a very important role in development, industry productivity, energy security, technology, and sustainability. The global energy infrastructure is currently going through a dramatic change owing to deployment of renewables, electrification, distributed generation, electric mobility, energy storage, smart grids, and digital technologies. In contrast to the traditional energy infrastructure based on centralized generation and more or less predictable consumption, modern energy infrastructure becomes more connected, decentralized, flexible, and digitalized [1]. The shift affects not only electricity generation but also transmission, distribution, storage, monitoring, maintenance, and consumption. The investment in modern energy infrastructure requires continuous investment in renewables generation, transmission, distribution, storage, grid automation, communication, and advanced controls [2]. The process of investment is affected by the following factors: high initial costs, cost of financing, regulatory uncertainty, long-term permits, exchange rates, supply chains, lack of access to finance, and lack of technical skills [3], [4].

Technological innovation is also enhancing the economic and operational efficiency of contemporary energy systems. Renewables have become economically competitive due to technological learning, scaling of manufacturing, improvements in efficiency, and reductions in project cost. In 2024, 91% of the new capacity from

renewables installed in utility-scale projects was less expensive in producing electricity than the least-cost fossil-fuel-based option that could be built in the same year, indicating that renewables are becoming more economically viable [5]. Energy storage systems are another component of modern energy infrastructure which help with renewable energy integration, peak load management, frequency regulation, energy storage, balancing and resiliency [2], [6]. From 2010 until 2024, the installed cost of utility-scale battery energy storage has reduced by 93% due to advances in manufacturing, battery technology, efficiency in the use of materials, and production process. Furthermore, smart metering, sensors, automated substations, digital twins, predictive maintenance, intelligent forecasting and monitoring are opening up new possibilities of making better use of assets and enhancing their reliability and operational efficiency [7]. However, digitalization poses new challenges such as cybersecurity, data management, interoperability, workforce, and organizational capability.

Grid modernization is a crucial link between technology and infrastructure as the rise in renewable energy usage necessitates the creation of transmission and distribution infrastructures that are able to cope with variability of production, bi-directional flow, integration of storage capacity, demand flexibility, and rising electricity demand [8]. Insufficient grid capacity might lead to congestions, delayed connections, reduction in renewables, operational inefficiencies, and unreliability of the grid [9]. While there has been plenty of research devoted to renewables, energy storage, smart-grids, digital transformation and infrastructure modernization, the factors of investment and technological innovations are often considered independently and do not reflect the interaction of financial issues and technological advancements in terms of infrastructure reliability and investment payback [7]. Consequently, this literature review focuses on analyzing key investment barriers and technological innovations that define the current state of energy infrastructure.

RESEARCH METHOD

For the purpose of this literature review, the structured and thematic literature review approach was used to consolidate the current evidence about the barriers to investments and innovative technologies for modern energy infrastructure. Pertinent literature published during the period from 2005 to 2026 was searched using Scopus, Web of Science, and Google Scholar by using such keywords as modern energy infrastructure, investment barriers, renewable energy, grid modernization, energy storage, smart grids, digitalization, predictive maintenance, technological innovation, and energy-system resilience. Peer-reviewed research articles, review papers, and reputable institutional reports dealing with the financial, technological, operational, institutional, and policy aspects of modern energy systems have been sought. Papers were chosen based on their substantial relevance to the research objectives. Duplicate documents, non-scientific material, and publications with low relevance have been eliminated. Retrieved

documents were further filtered by reading titles, abstracts, and the papers themselves in order to assess their relevance and consistency with the aims of this literature review [10]. In the end, the selected evidence was synthesized into a number of thematic categories, such as investment and financial barriers, grid infrastructure, renewable energy innovations, energy storage, smart grid development, digitalization, predictive maintenance, and future infrastructure needs [11].

RESULTS AND DISCUSSION

Result

Investment and Financial Barriers

Investment is one of the basic determinants for the development of energy infrastructure in contemporary times. However, the issues of accessibility, affordability, and geographical spread of funds are significant problems, as illustrated in Figure 1 below. The move towards more sustainable energy systems around the world has seen a rise in investments, although there are still large differences between developed and developing countries in terms of investments. Markets of emerging market and developing countries, excluding China, attract only 18% of global investment in clean energy despite the increasing demand and the need for energy infrastructure in these countries [12]. The disparity reflects the fact that technological attractiveness of the solutions does not necessarily mean equal investment opportunities. Projects implemented in countries with difficult financial situation can experience difficulties such as high financing cost, unstable currencies, underdeveloped financial markets in the country, lack of credit, institutional inefficiency, and high perception of regulatory and political risk [7], [13], [14]. Thus, investment barriers can be defined by two interrelated aspects: technological affordability and investment accessibility. Affordability of technology is associated with decreases in the cost of equipment, power generation, storage, and operations, while accessibility of finance refers to whether project developers are able to secure financing in a manner that is economically and regulation-wise acceptable [15]. While decreasing the cost of technology might enhance the economics of the project, the prohibitive cost of financing, poor revenue model, and underdeveloped banking industry could still keep it from getting implemented [16].

Investment and Financial Barriers

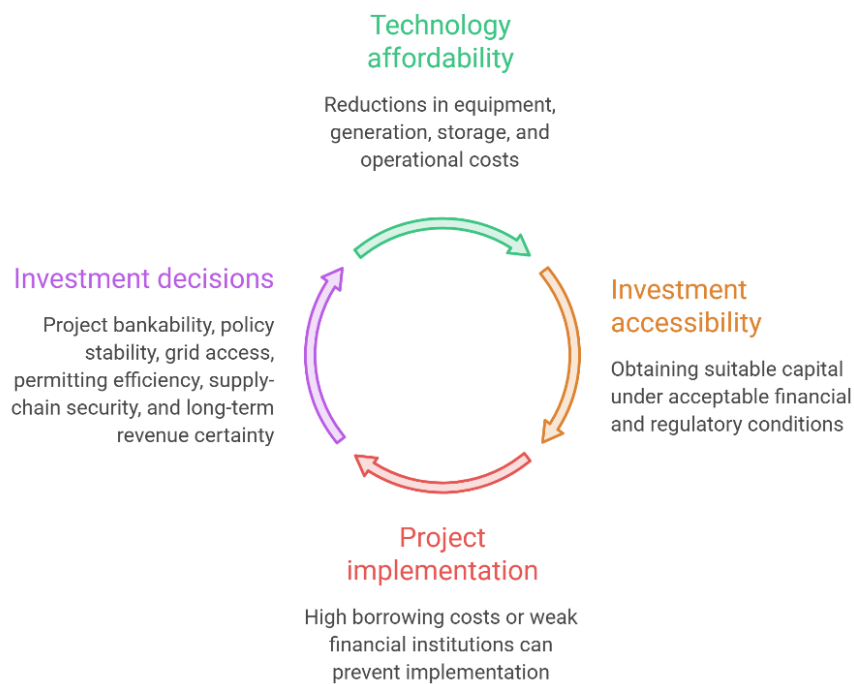


Figure 1. Investment and Financial Barriers

Grid Infrastructure and Operational Constraints

The fast growth of renewable energy has made it much more critical to have adequate transmission and distribution infrastructure. Traditional electrical networks were built on the assumption of centralized generation, predictable flow of power, and more or less stable patterns of consumption as illustrated in Figure 2 below. Modern networks should be able to take into account renewable sources of energy that are not concentrated geographically, the variable production of electricity, two-way flow of electricity, distributed energy sources, electric transportation, battery storage and flexible demand. Among other things, this change poses certain demands on the capacity, balance, control and flexibility of the infrastructure. One of the main problems that arise is the uneven geographical distribution of investment in grids. Developed countries and China take 80% of all expenditures on electricity networks globally [17], [19], [20]. Grid congestion, connection delays, transmission loss, curtailment of renewable power sources, overloaded grids and reliability issues may affect the economic value of additional power plants. Therefore, increasing the renewable power generation capacity without developing the supporting grid infrastructure can result in infrastructure bottlenecks and decreased efficiency of the investments into energy generation and supply [21]. Grid development thus necessitates a shift from a traditional approach to network growth to smart infrastructure development. High-voltage power lines, advanced transformers, automation of substation, flexible distribution systems, energy storage solutions, demand response, and monitoring technology must be developed as an interlinked system. Real-time monitoring and control will facilitate improved network

visibility, grid congestion detection, electricity flow optimization, and increased reaction speed for changes in power production and demand [15,22].

Modern Grid Development Requirements

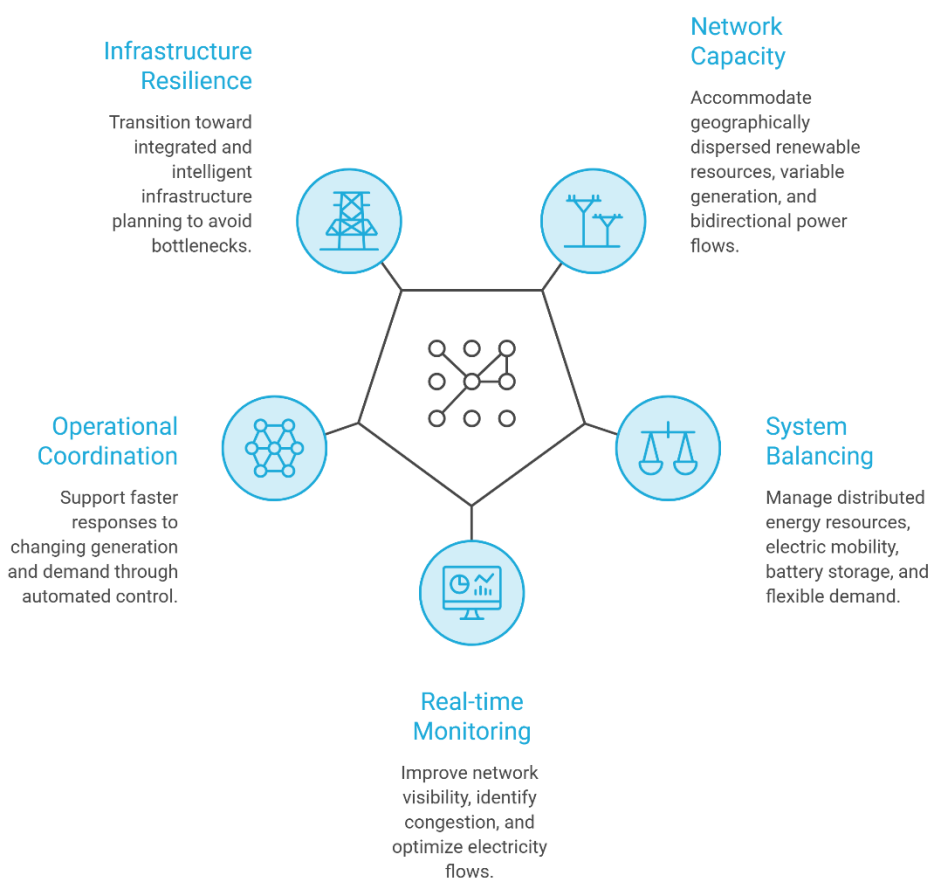


Figure 2. Grid Infrastructure and Operational Constraints

Renewable Energy Transformation and Cost Competitiveness

Technological progress has transformed the economic standing of renewable energy in the modern energy landscape as demonstrated in Table 1. Innovations in manufacturing, efficiency of equipment, project design, logistics management, resource use, and economies of scale have brought down the cost of renewable-energy technologies greatly. From 2010 to 2024, the weighted average cost per unit of installed capacity of utility-scale solar photovoltaics fell by 87%, and the cost of the electricity generated by the projects went down by 90% [23], [24]. This is an example of the impact of learning and deployment on infrastructure economics. The increasing competitiveness of renewable energy has its implications for investments. Cost savings in power generation may increase the attractiveness of projects, decrease fuel price risks, and ensure better predictability of operational costs in the long term. In 2024, 91% of utility-scale power capacity from renewable energy sources had a lower cost of electricity production compared to the least expensive new capacity from fossil fuels [25]. These are some examples of how renewable technologies are increasingly competing in economic terms against traditional energy sources, not only in terms of environmental benefits. The

efficient use of renewable energies needs to be supported by adequate grid infrastructure, energy storage, forecasting capabilities, flexible generation, demand-side response and modern grid management systems [26]. The economics of projects are also dependent on funding conditions, quality of resources, available space, licensing issues, connection to the grid and supply chain conditions. Therefore, the economic potential of renewable energies should be evaluated at the level of the system. In this case, an economical generation technology might offer very little value in practical terms if there is no way to transmit, store and manage the generated electricity [27]. On the other hand, integrating renewables with adequate storage and grid management might enhance its reliability and overall value.

Table 1. Renewable energy transformation and cost competitiveness

Aspect	Evidence	Investment implication
Solar PV cost	Installed cost declined 87%	Improved project affordability
Electricity cost	LCOE declined 90%	Stronger economic competitiveness
Renewable competitiveness	91% of new utility-scale renewable capacity in 2024 was cheaper than the lowest-cost new fossil alternative	Increased investment attractiveness
Technological innovation	Advances in efficiency, manufacturing, materials, and scale reduced costs	Lower project and operational risks
Grid integration	Requires transmission, forecasting, storage, and flexible management	Coordinated infrastructure investment is essential
Storage and flexibility	Storage supports energy shifting, balancing, and renewable integration	Enhances system reliability and asset value
Project constraints	Financing, permitting, land, grid connection, and supply chains affect project viability	Cost reductions alone cannot ensure deployment
Future investment	Integrated renewable generation, storage, grid modernization, and digital management	Supports resilient and sustainable energy systems

Energy Storage and System Flexibility

The significance of energy storage has grown over time because as more renewable power plants come online, there is an increased need for flexibility in both time and operations, as depicted in Figure 3 below. Solar or wind energy does not always occur at times when electricity use reaches its peak, and balancing the demand for electricity becomes a problem [28]. Battery energy storage could help with that issue by making it possible to move electricity through time, handling peak load, frequency regulation, congestion, offering backup generation and ensuring grid stability. The technology

serves not just as one more tool but as a key enabler, making the value of renewable electricity higher. Innovation has greatly reduced the cost-effectiveness of battery storage solutions. Since 2010 until 2024, the average installed cost of utility-scale battery energy storage decreased by 93% [3], [14], [29]. Such impressive savings were achieved due to scaling up of production, advances in battery technology, material efficiency gains, optimization of production processes and learning effects. Reduction in cost has led to the establishment of renewable-energy storage hybrids where solar or wind energy is complemented by battery capacity to allow for a more flexible production of electricity. This has allowed for better management of the gap between production from renewables and demand for electricity [30]. However, reduction in the cost of technology does not guarantee that investments in storage will be made widely. Investments in storage tend to occur in countries where there are good financial systems, electricity market, regulation, and infrastructure [31].

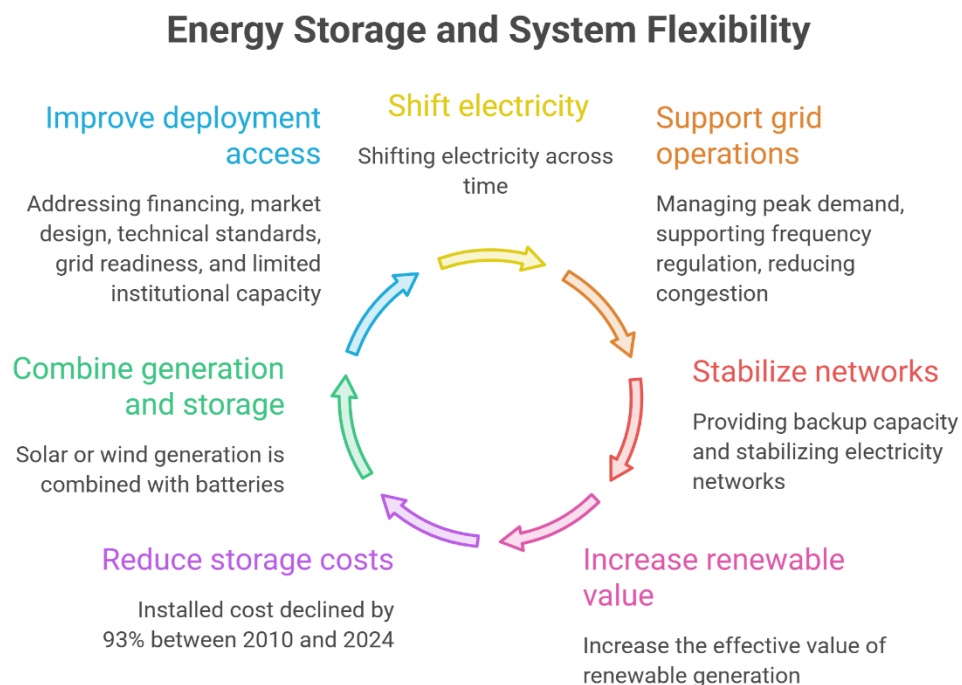


Figure 3. Energy Storage and System Flexibility

Smart Grids, Digitalization and Predictive Technologies

The advent of digitalization is changing the traditional passive nature of energy infrastructure into smart systems that can be monitored continuously, controlled automatically, troubleshoot faults, predict future events, and make decisions. Smart meters, sophisticated sensors, automated substations, communications systems, digital twin, intelligent forecasting, and predictive maintenance are becoming key elements in modern energy management [32], [33]. They can enhance infrastructure visibility, optimize power flows, sense faults, minimize unexpected interruptions, and help in managing complicated energy infrastructures more effectively. Predictive maintenance is especially useful because conventional methods of maintenance often depend on reactive approach to equipment fault or failure [34]. However, through condition-based

monitoring and predictive analysis, it is possible to sense equipment faults prior to their occurrence. Based on energy management practices, it has been found that predictive-maintenance software can save maintenance costs by 25%, minimize downtime by 35%, and prevent equipment failures by 70%. In connection with investments, there are certain benefits in innovations, which can improve the efficiency of infrastructure throughout its life cycle and reduce uncertainties in case of unexpected failures of this infrastructure [7], [18]. Digital technologies provide considerable opportunities for the integration of renewable energy into the grid. Forecasting technologies can be used in order to forecast the production of energy produced by solar power plants and wind power stations, whereas digital controls would allow for coordination of different sources of energy, energy storage facilities, and demand response [35].

Discussion

The findings of this review indicate that technological innovation and investment conditions are closely interconnected in shaping the development of modern energy infrastructure. The declining cost of renewable energy technologies and battery storage has significantly improved the economic attractiveness of low-carbon energy systems. In particular, the substantial reduction in solar photovoltaic and battery storage costs demonstrates how technological learning, manufacturing scale, material efficiency, and improved production processes can enhance project affordability. However, improved technological affordability does not automatically translate into successful infrastructure deployment. High financing costs, limited access to capital, regulatory uncertainty, supply-chain risks, weak institutional capacity, and inadequate grid infrastructure can continue to reduce the feasibility of otherwise economically competitive technologies. This suggests that investment accessibility remains as important as technological affordability in determining whether energy projects can be implemented.

The review also shows that grid infrastructure plays a central role in determining the practical value of renewable energy investments. The rapid growth of variable renewable generation requires transmission and distribution systems capable of handling geographically dispersed resources, bidirectional electricity flows, energy storage, electric mobility, and flexible demand. Without adequate grid expansion and modernization, additional renewable generation may contribute to congestion, connection delays, curtailment, transmission losses, and reduced system reliability. Therefore, investments in generation should be coordinated with transmission, distribution, storage, monitoring, and control infrastructure. This reinforces the need to assess renewable energy projects at the system level rather than only on the basis of generation costs.

Energy storage further strengthens the flexibility and reliability of modern energy systems by enabling electricity to be shifted across time, supporting peak-load management, frequency regulation, congestion reduction, and renewable-energy integration. The major decline in battery storage costs increases the potential for combining renewable generation with storage. Nevertheless, the review indicates that

storage deployment is more likely to occur where financial systems, electricity markets, regulation, grid readiness, and institutional capacity are sufficiently developed. Consequently, technological cost reductions alone cannot guarantee widespread investment.

Digitalization also expands the operational capabilities of modern energy infrastructure. Smart meters, advanced sensors, automated substations, digital twins, intelligent forecasting, and predictive maintenance can improve infrastructure visibility, optimize electricity flows, identify faults, reduce unexpected interruptions, and support more efficient asset management. These technologies can improve the life-cycle performance of energy infrastructure and reduce operational uncertainty. Overall, the findings suggest that the transformation of energy infrastructure depends on the combined development of technology, finance, regulation, institutional capacity, and grid infrastructure. A coordinated life-cycle approach is therefore necessary to ensure that technological innovation is translated into reliable, resilient, and economically viable energy infrastructure.

CONCLUSION

Fundamental Finding: The findings of this review indicate that technological innovation and investment conditions are closely interconnected in shaping the development of modern energy infrastructure. The declining cost of renewable energy technologies and battery storage has significantly improved the economic attractiveness of low-carbon energy systems. However, improved technological affordability does not automatically translate into successful infrastructure deployment. High financing costs, limited access to capital, regulatory uncertainty, supply-chain risks, weak institutional capacity, and inadequate grid infrastructure can continue to reduce the feasibility of otherwise economically competitive technologies. **Implication:** This suggests that investment accessibility remains as important as technological affordability in determining whether energy projects can be implemented. Therefore, investments in generation should be coordinated with transmission, distribution, storage, monitoring, and control infrastructure. This reinforces the need to assess renewable energy projects at the system level rather than only on the basis of generation costs. Overall, the findings suggest that the transformation of energy infrastructure depends on the combined development of technology, finance, regulation, institutional capacity, and grid infrastructure. **Limitation:** Nevertheless, the review indicates that storage deployment is more likely to occur where financial systems, electricity markets, regulation, grid readiness, and institutional capacity are sufficiently developed. Consequently, technological cost reductions alone cannot guarantee widespread investment. **Future Research:** A coordinated life-cycle approach is therefore necessary to ensure that technological innovation is translated into reliable, resilient, and economically viable energy infrastructure.

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