Gyaneshwar Sharma, Vikash Singh, Sadanand Singh, and Pavan Kumar

Empowering the future via energy storage: roadmap of renewable energy mission

Abstract: As the world aims for prompt transitions toward a low-carbon and prosperous economy, the efficient and skillful integration of multiple renewable energy sources is crucial. Energy storage technologies play a vital role in this transition, enabling the widespread adoption of intermittent renewable energy sources. This study presents a comprehensive roadmap for the sustainable development of renewable energy harvesting and the deployment of energy storage solutions, aligning with global renewable energy ambitions. We discuss key challenges, opportunities, and innovative strategies for harnessing energy storage to empower a cleaner, more resilient energy future. By addressing the technical, economic, and policy aspects of energy storage, this work aims to inform stakeholders and policymakers, facilitating the creation of a sustainable, renewable energy-powered world.

Keywords: Renewable energy, sustainability, green technology, grid integration, decarbonization

8.1 Introduction

As a result of several international issues, driven by the recent emergence of political conflicts, the global community has recently faced a steep upsurge in the shortage of fossil fuels and a significant rise in their prices. The price of natural gas, oil, and electricity has reached unprecedented levels. This imbalanced nature of energy distribution has led to an energy crisis all around the globe. However, from a sustainability point of view, natural fossil resources may not be considered promising due to their limited availability. Our imprudent dependency on nonrenewable energy resources will certainly lead to an energy crisis in the coming years if reliable and efficient alternatives to nonrenewable energy are not devised on an urgent basis. It is very hard to envisage life and perform routine duties without energy. In essence, energy has acquired a prime position in our daily routine and plays an essential role in everyday

Gyaneshwar Sharma, Department of Physics, Tilak Dhari PG College, Jaunpur 222002, India, e-mail: gyaneshwar.jnu@gmail.com
Vikash Singh, Department of Physics, Tilak Dhari PG College, Jaunpur 222002, India
Sadanand Singh, Physics Department, Kashi Naresh Government PG College, Gyanpur, Bhadohi 221304, Uttar Pradesh, India
Pavan Kumar, Department of BSH, Faculty of Engineering and Technology, Datta Meghe Institute of Higher Education and Research, Wardha 442001, India, e-mail: pavan2012iitk@gmail.com

https://doi.org/10.1515/9783111289076-008

life. Currently, fossil fuels are the most reliable resource of energy, but they are responsible for the emission of greenhouse gases that are harming our climate and causing a recurrence of extreme weather events around the world, from wildfires in the USA and scorching summers in India to stormy weather in Asia, unprecedented heavy rainfall in the UK, and rising sea levels, floods, and droughts. Since 2010, India has been experiencing an unprecedented increase in natural disasters related to climate issues, such as drastic fluctuations in weather patterns, which have caused heavy rainfall and flooding in various provinces, and the 2021 land subsidence crisis in Joshimath – a popular tourist town in the north-eastern state of Uttarakhand. The glacial lake outburst flood in Sikkim in October 2023 led to the collapse of a hydroelectric dam, killed more than 100 people, and affected more than 88,000 people [1]. For decades, pollution in New Delhi has been occurring at an alarming level during the winter, but the government does not seem quite serious about addressing it due to the lack of an administrative organization to align the efforts of various ministries and state governments to find a suitable solution to this recurring hazardous situation. This could be seen as symptomatic of a policy drag that affects India's climate action.

The occurrence of extreme weather events has become more frequent in recent decades. The Himalayan range plays a pivotal role in shaping India's climate. The Indian Himalayan region serves as a vital habitat for over 50 million people, providing them with livelihoods, ecosystem services, and cultural heritage. Any disruption to the delicate balance of the Himalayas would have far-reaching consequences, impacting the lives of millions of people not only in India but also across the entire subcontinent [2]. From the evidence, it is interpreted that humankind is playing a principal role in climate change.

India made a landmark commitment at COP26 in the UK, pledging to achieve net-zero emissions by 2070. To be more realistic about net-zero carbon emissions, India presented its long-term strategy for low carbon development at COP27 in Egypt, outlining a strategic roadmap for the economy and key sectors to support this ambitious goal. During COP28, India highlighted its domestic initiatives toward mitigating climate impact by reducing carbon emission intensity by 30% between 2005 and 2019, while nonfossil fuel electricity capacity increased by 40%. At COP29, India responded strongly in favor of equity, climate justice, and sufficient financial support for developing nations. In a proactive approach, India set a target of 500 GW of energy from renewable resources and a bold and ambitious goal of reducing carbon intensity of GDP by 45% by 2030 [3].

8.2 Strategic plans and roadmap

For sustainable development, the purpose of energy has changed and become multifaceted. Undoubtedly, the production and processing of energy must be ethical, reasonable, resilient, reliable, innocuous, and aligned with human-rights values. Sustainability in energy can be assessed [4]:

- Ensuring cooperation among stockholders from diverse markets and sectors, including developers, financiers, and civil society, in a more sustainable fashion.
- Revisiting the sustainability and future fitness of conventional energy systems.
- Enabling energy players to shape transition pathways. Which technologies, prototypes, and actions will align with our vision?
- As destructive conflicts become more frequent among nations due to the rapid depletion and scarcity of resources allocated in finite amounts on our planet, the transition to renewable energy becomes increasingly imperative.

8.2.1 Phase-out of fossil fuels

A major goal was to gradually phase out the use of fossil fuels in favor of zero-carbon-emission empowerment of renewable energy resources. The developed nations are sincerely devoted to reducing their dependence on these nonrenewable resources. At the United Nations Climate Change Conference (COP28), the stakeholders unanimously passed a resolution to be greener and more efficient in energy harvesting and proposed accelerating the phase down of fossil fuels. However, this process puts intense pressure on the interested nations because of the huge shifts in interest from well-established fossil fuel technology and the need to reorient the flow of the economy away from fossil fuels. To be free of carbon emissions, there is a need for collective effort – no one should be excluded. For action, all actors must work collectively toward the transition from fossil fuels to clean energy. A strategic plan, full engagement, and proper action by the governing bodies, all levels of society, and public and corporate consumers, should be implemented in association with efficient and intelligent technologies.

8.2.2 Solar energy expansion

Solar energy is one of the most rapidly growing major renewable energy sources. Recent technological innovations, along with improved efficiency, safety, and cost-effectiveness, are playing vital roles in making renewable energy more accessible and popular [5–8]. India's solar installed capacity has exceeded 90.76 GW as of September 30, 2024. This signals a positive shift where solar energy increasingly becomes a key power source, not just an alternative. India aims to derive 40% of its energy from solar-based systems by 2030, which is evident that India's solar future is bright. In India, it is becoming the prime destination for a green energy revolution. Leading innovations are empowering solar energy production with greater efficiency – ~20% efficient and causing a significant drop in costs. In 2018, solar PV power costs dropped by 13%, helping India meet its renewable energy goals. Costs could decrease by another 15–35% by 2024, making solar investments even more attractive. India is endowed with immense solar energy potential. About 5,000 trillion kWh per year of energy is incident over India's land area, with most parts receiving 4–7 kWh/m^2 per day. Solar photovoltaic power can be effectively harnessed providing huge scalability in India [9]. The future of sustainable energy in India looks bright. The industrial age gave us the understanding of sunlight as an energy source.

8.2.3 Wind energy development

Wind power is a cheap, green energy option to generate electricity from renewable sources. Wind energy capacity has been scaled up with the emergence of novel technologies at lower costs, which play a significant role in the design of more efficient turbines and the development of larger-scale wind farms. India is quite rich and has significant potential for wind energy, with an estimated 302,000 MW of onshore capacity and 70 GW of offshore capacity [10]. Offshore wind projects are gaining popularity due to their potential for generating substantial amounts of clean energy.

8.2.4 Hydropower optimization

Hydropower is quite resilient and self-reliant. Energy production does not have a mandate regarding foreign exchange policy [11]. Once the construction phase is over, energy production becomes free of cost. Hydropower is equally suited for remote areas and also has the potential to enrich irrigated agriculture, food production, tourism, etc. Many countries are looking to maximize the potential of hydropower, including the modernization of existing hydropower plants and exploring new locations for dams.

8.2.5 Bioenergy utilization

Biofuels have great potential to boost the rural economy by exercising the distinguished crop innovation. As bioenergy is largely derived from existing crops, no additional effort is needed. Only proper management will provide significant value to the climate. The biomass used for energy production is fantastic and more sustainable in nature because it is produced from waste materials: ethanol from wheat, sugarcane, molasses, and corn; biodiesel from oilseeds; and methane from manure [12, 13].

Biomass and biofuels are being explored as viable renewable energy sources. Research focuses on sustainable ways to utilize waste organic materials for energy production. Yet, in reality, the greenness of biofuel is not clear; certain studies reveal that biomass energy has a deeper footprint on our climate, ecosystems, and communities than fossil fuels [14]. Since the beginning of civilization, the production of crops has been an integral part of human life. Crop-oriented biofuel energy generation seems twofold and quite promising in nature.

8.2.6 Geothermal energy expansion

Unlike wind and solar energy, geothermal plants generate power at a constant rate, without regard to space or weather conditions. Geothermal energy is also more affordable than conventional energy. However, geothermal systems are more expensive to install than other systems [15]. Over time, however, they will provide the homeowner with cost-free services. Geothermal energy is used in over 40 countries today. China, the USA, Turkey, Sweden, Indonesia, Iceland, Japan, New Zealand, Germany, and the Philippines are the main consumers of geothermal energy. Similarly, India needs to improve its clean energy potential to meet rising electricity demand while avoiding reliance toward coal-based energy plants. To date, geothermal energy is an underutilized resource, despite being used since the Paleolithic Age. Geothermal resources are natural reservoirs of hot water, with different temperatures at different depths. This hot water and steam can be accessed through geothermal facilities and used to generate electricity by driving turbines.

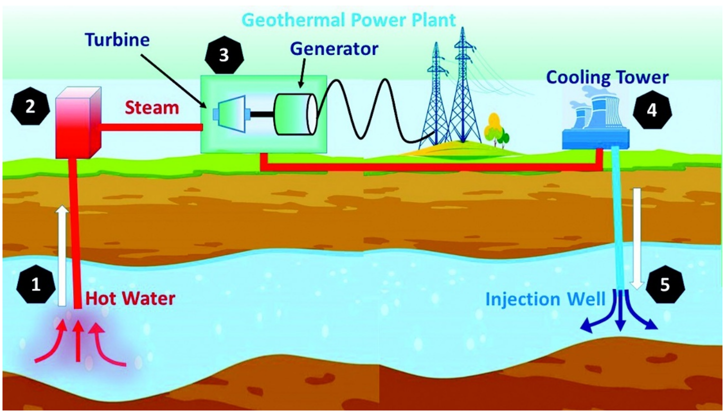

Figure 8.1: Schematic diagram of the geothermal energy harvesting process [16].

The whole operation may be divided into five steps (Figure 8.1). First, identify a suitable and sufficient amount of water resources in thermal active regions, such as volcanoes, hot springs, or geysers. Next, conduct drilling at a specified site to access the hot water and steam. The flow of steam will operate the turbine and generate electricity. The geothermal fluid is extracted from the well and circulated through a heat exchanger. In the heat exchanger, the thermal energy from the geothermal fluid is transferred to a secondary fluid, typically a working fluid such as isobutane or supercritical carbon dioxide. This secondary fluid, which has a lower boiling point than water, is vaporized by the heat from the geothermal fluid. The vaporized secondary fluid then expands through a turbine, driving an electrical generator. As the turbine spins, electricity is produced. The secondary fluid is subsequently cooled and recirculated back to the heat exchanger, completing the flow cycle. Geothermal energy is a renewable energy resource, just behind solar, wind, and hydropower, with the potential to increase electricity generation from the existing 16 billion kWh to 47.7 billion kWh by 2050 [17].

8.2.7 Investment in energy storage

Developing efficient and cost-effective energy storage methods, such as electrochemical systems, hydro energy storage, and other grid-scale energy storage technologies, is a critical aspect of the roadmap to ensure stable and reliable renewable energy integration. Energy storage has proven effective in supporting a clean and modern electricity grid and in helping to achieve the ambitious goals for renewable energy and power system resilience. The energy storage roadmap has a broader aim to facilitate the electricity system in terms of security, reliability, affordability, environmental responsibility, and innovation.

The growing interest in grid-scale energy storage has a multifaceted perspective, including addressing the high capital costs associated with managing peak electricity demand and/or power failures to ensure the availability of electricity at all times without interruption. For efficient operation, an energy scheme requires investments in the development of grid technology and the integration of various intermittent renewable energy sources, such as solar and wind, which are intermittent and fluctuating. The use of electricity storage is warranted by the capacity restrictions of grids [18, 19].

The roadmap for energy storage includes a market size estimation and the identification of potential market segments. The United States aims to achieve 6 GW of energy storage by 2030 – equivalent to 20% of its expected peak load – helping enable it to meet 70% of electricity demand with renewable energy. According to NITI Aayog, India’s energy storage sector suffers from a lack of centralized testing facilities. This disintegration may lead to unreliable remarks. NITI Aayog is planning a roadmap based on a public-private partnership [20].

8.2.8 Smart grid implementation

Smart grid technologies are being adopted to optimize the integration of renewable energy sources into the existing power grid, making it more resilient and efficient. Electrical energy storage offers two other important advantages. First, it separates electricity generation from user load, making it easier to regulate supply and demand. Second, it provides a sustainable solution to store energy in the form of local grids or microgrids, which leads to more secure grid operation and viable energy security [19].

8.2.9 Electrification of transportation

The roadmap for renewable energy also included efforts to transition the transportation sector from fossil fuel-powered vehicles to electric vehicles (EVs) and to promote EV infrastructure. The global EV market is expected to grow from $255.54 billion in 2023 to $2,108.80 billion by 2033, with a CAGR of 23.42%. The Indian EV market is expected to grow from $3.21 billion in 2022 to $113.99 billion by 2029, with a CAGR of 66.52% [21]. More or less, at present, all major countries heavily rely on fossil fuels for road transportation accounting for around 75%. However, they are attempting to reduce the consumption of conventional energy resources due to authoritative mandates for carbon footprint reduction. This suggests that there is a huge opportunity toward maximizing the electrification of transportation.

8.2.10 Public awareness and policy support

Governments and organizations were working to raise awareness about the benefits of renewable energy and implementing supportive policies, incentives, and subsidies to accelerate the transition. Various nations have operational economies that are purely reliant on oil and gas exports. The migration of the world from the well-established fossil fuel economy seems to be a catastrophic situation for oil-rich nations. These nations must agree to move away from coal, oil, and gas, which are considered “gifts from God,” as claimed by the President of the host nation, Azerbaijan, during the COP-29 conference held on November 11–22, 2024 [22]. Currently, geopolitical uncertainty and distraction make keeping countries united and unanimous on climate policy critical. The big culprit is the uneven investment between rich and poor nations. Another problem was observed due to China. During the COP-29 meeting, China did not play a leading role. The world’s largest carbon emitter – China, was largely silent at this year’s COP and only gave consent regarding the amount of climate finance it provides to developing countries. In addition, the role of the United States in addressing climate change is already doubtful due to the shifting attention of elected President Trump. Campaigners, organizations, and policymakers should work together to address the climate problem with effective local action and implement practical initiatives that reduce pollution and climate impacts. Media can play a huge role with its shaping power, which can usefully attract public attention to accelerate climate mitigation – the efforts to reduce or prevent the emission of greenhouse gases that are heating our planet – but it can also be used to do exactly the opposite [23].

8.2.11 International collaboration

The roadmap involved fostering international cooperation and partnerships to address global climate change challenges and promote the adoption of renewable energy technologies worldwide. From a planetary health perspective, the successful roadmap for the energy transition is the complete transformation of the global energy sector from fossil-based to zero-carbon sources by 2050, reducing energy-related CO_2 emissions to mitigate climate issues and limit global temperature increases to within 1.5° of preindustrial levels [24]. To achieve this goal within the specified timeframe, nations and institutions should realize both national and regional commitments and accelerate their decarbonization schemes for energy transition.

8.3 Renewable energy in Indian perspective current scenario

As a developing nation, India has previously relied heavily on coal to meet its energy demands. However, India has always been concerned about the consequences of non-renewable energy and is committed to strengthening alternative energy sources for sustainable growth. Today, India is managing power generation systems and pursuing its goals toward the immediate shift of energy generation with a more significant share of renewable energy. India has witnessed a remarkable surge in renewable energy capacity, with a 250% growth between 2014 and 2021. This impressive expansion has propelled India to the fourth position globally in terms of installed renewable energy capacity.

Presently, India is capable of fulfilling 40% of its energy demand from renewable energy resources (48.55 GW from solar, 40.03 GW from wind, 4.83 GW from small hydro, 46.5 GW from large hydro, 10.62 GW from biopower, and 6.78 GW from nuclear) [25]. Due to its renowned economic opportunities and natural resources, India is progressively emerging as a prime destination for investment in renewable energy resources. India is currently promoting energy storage projects with the aim of meeting its ambitious target of expanding renewable energy capacity to 500 GW by 2030 [26]. With the implementation of energy storage, the cost of energy storage is expected to become more economical, decreasing from the current rate of INR 5.5–6.5 per unit.

This initiative will also foster the development of large-scale battery energy storage systems by encouraging competitive bidding to drive down costs. The government anticipates that the storage scheme will generate private investments worth INR 56 billion (approx. US$680.47 million) through this initiative. Additionally, the government will provide support in the form of funding and certain incentives to stakeholders involved in critical ventures that are economically unviable in nature. India has achieved 37 MWh of storage capacity by leveraging battery technology. However, there is a need to scale up battery storage to 236 GWh, in addition to implementing 27 GW of pumped storage projects by 2031–2032. To meet this target, India will require investments of around US$200 billion to establish renewable energy generating assets by 2030.

8.4 Energy transition road map and road blocks

Conservative estimates suggest that around 13 million Indians rely on the coal-driven economy for their livelihood. A sudden transition away from coal could have devastating economic consequences, particularly in states like Jharkhand, which hold the majority of India's coal reserves. The coal-dependent economies of these regions risk collapse, emphasizing the need for a carefully managed and gradual transition [27]. India's transition to energy is not straight forward.

India's quest for a just energy transition and climate resilience is complex, with myriad challenges. Its development path has been fueled by coal, yet it seeks to take decisive steps to invest in the reduction of coal consumption. The deep correlation of the country's economy with coal is quite evident. There must be a balance between development aspirations and environmental imperatives. While there is a compelling case for developed nations to provide financial support to developing countries transitioning to cleaner energy, there is also a need to resist pressure for a rapid transition that could threaten the livelihoods of millions reliant on fossil fuels. India and other developing countries are urging the global community, particularly developed economies, to acknowledge their unique challenges and priorities in navigating the net-zero carbon transition.

To reach the climate goal by 2070, India must adopt a sustainable energy roadmap with enhanced efficiency in all processes and activities, paying full attention to every detail. It is quite urgent to align with climate change initiatives and renewable energy for the sake of the economy and economic independence from fossil fuel supply.

8.5 Role of energy storage in green energy

Energy storage is playing an increasingly crucial role in green energy systems. The green energy mission can be strengthened by simplifying the intermittent mechanism of renewable energy generation and enhancing the overall reliability and efficiency of green energy deployment [28, 29]. The performance of electricity generation from solar and wind technology is severely limited by weather conditions and the availability of wind and daylight. Energy storage technologies enable the capture and retention of excess energy produced during favorable conditions, which can then be utilized during power failures, peaks in demand, or when renewable energy sources are not available [28–31].

Some key roles of energy storage in green energy.

8.5.1 Storing excess energy

Solar panels and wind turbines often produce more electricity than is needed at certain times. Energy storage systems, such as batteries, allow the excess energy to be stored and used later, ensuring that renewable energy is not wasted.

8.5.2 Load balancing

Energy demand fluctuates throughout the day, and traditional power plants must adjust their output accordingly. With energy storage, the produced energy can be stored when the generated energy exceeds demand and sourced when demand exceeds the generated amount, helping to balance the load on the grid.

8.5.3 Grid stability and reliability

Energy storage provides grid operators with the ability to smooth out fluctuations in renewable energy generation, making the grid more stable and reliable.

8.5.4 Backup power

Energy storage systems can supply a desirable amount of energy during emergencies or grid outages. This capability enhances the resilience of the grid and improves energy security.

8.5.5 Enabling off-grid solutions

In remote areas or during disasters, energy storage can be used with renewable energy sources to create off-grid systems, providing electricity to places where traditional power infrastructure is unavailable.

8.5.6 Integration of renewables

Energy storage can help integrate a higher share of renewable energy into the grid. As renewable energy sources become more prevalent, energy storage becomes increasingly important for managing the variability and intermittency of these sources.

8.5.7 Reducing peak demand

Energy storage can be used to shave off peak demand periods, reducing the need for expensive and polluting peaker plants, which are often used to meet short-term high electricity demands.

8.5.8 Time shifting

Energy storage allows utilities and consumers to buy electricity when it is cheaper (during low-demand periods) and use it during high-demand periods, reducing electricity costs and promoting efficiency.

8.5.9 Environmental benefits

By facilitating the efficient use of renewable energy, energy storage reduces the need for fossil fuel-based power plants, leading to lower greenhouse gas emissions and a cleaner environment. [28]

8.5.10 Incentivizing investment in renewable energy

Energy storage makes renewable energy projects more attractive to investors by mitigating risks associated with intermittent energy generation. While energy storage technologies have made significant progress, further advancements and cost reductions are needed to fully unlock the potential of green energy and create a more sustainable and resilient energy future. Research and development efforts are ongoing to improve energy storage technologies and enhance their integration into existing energy systems.

8.6 Importance of energy storage

Due to imbalanced power supply during odd situations and from a sustainability point of view, energy storage seems to be more relevant and convenient in addressing the scarcity of energy. In addition, energy storage may serve as a potential add-on toward efficient energy harvesting from renewable energy resources, helping to meet demand and increase the energy efficiency of working systems [28–31]. Energy storage can ease energy transmission and distribution. There is an open opportunity toward the development of efficient energy storage systems, which would be more economical due to the reduction in the cost of transporting generated/harvested energy. Energy storage can save operational and maintenance charges of the grid and provide certain benefits to consumers who are well-equipped with energy storage in their state-of-the-art living and occupational setups (Figure 8.2). Energy storage provides greater flexibility to ensure the availability of power supply to consumers whenever and wherever they need it, without any interruption. Energy storage has the ability to smoothen the demand and deliver power in the absence of intermittent resources such as wind and solar. Thus, energy storage is an add-on technology. When solar and wind energy are not available, the stored energy will be there to fulfill the energy gap.

Comparison of conventional grids and battery energy storage systems for balancing renewable energy, highlighting the advantages of energy storage in terms of efficiency, cost, and emissions.

8.7 Ferroelectrics: energy harvesting materials

Since the discovery of ferroelectricity, ferroelectric materials have been playing a significant role in technology and continuously propelling advancements in areas such as power electronics, capacitors, memory storage, energy harvesting, energy storage, imaging, and actuation due to their inherent ability to demonstrate spontaneous polar functionality. For electrical energy storage technology, a dielectric with special characteristics is desirable. Batteries can supply energy at a certain rate for an extended period of time. From an application point of view, batteries are considered a suitable source of energy where low power is required to drive a device. Capacitors, on the other hand, instantaneously release the entire amount of stored energy at an enormous rate.

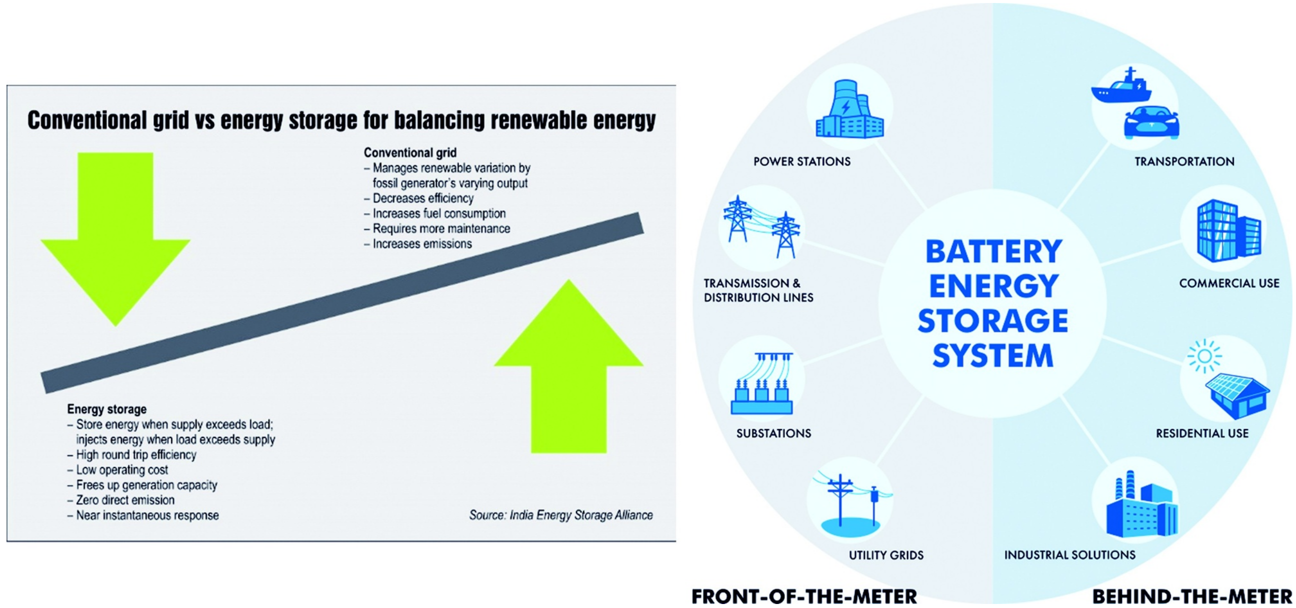

Figure 8.2: The futuristic role of energy storage [32].

Table 8.1:

Source	Energy density (Wh/kg)	Power density (W/kg)
Battery	10–300	500
Capacitor	< 30	10^8
Super-capacitor	< 30	10^1–10^6

A super-capacitor possesses high-energy storage density. However, its low power density does not make it suitable for certain applications where high power density is desired, for example, high-power electronics, electron guns, active armor, and directed energy weapons (Table 8.1). To fulfill the requirements of high-power electronics, capacitor-based efficient energy storage devices are in urgent demand. With the unprecedented development in technology, dielectric materials with high energy-storage efficiency are highly desirable candidates in power electronics for potentially high discharge mechanisms [33]. The dielectric system with high energy storage capacity is less explored. However, there are physical approaches that may be employed to enhance energy storage performance. Here, we will discuss the mechanisms for enhancing energy storage. Based on their response toward an externally applied electric field, dielectric materials may be classified into linear dielectrics, piezoelectric, pyroelectric, ferroelectric, and relaxor.

8.7.1 Linear dielectric material

Dielectrics are insulating materials by nature, that is, ideally, no current will flow through the dielectric system when electrical voltage is applied to its two terminals [30]. However, at the microscopic level, charge redistribution yields significantly important phenomena – especially when its capacitive feature is taken into consideration. When an electric field is applied across the dielectric specimen, it transforms into an electrically polarized system due to the separation of positively charged nuclei and negatively charged electrons of electrically neutral atoms. The whole system becomes polarized due to the shifting of electron clouds toward the positive voltage. Dielectric materials that exhibit a linear variation of polarization with the external field follow the same polarizing path upon the reversal of the field, and their polarization becomes zero upon the removal of the field. All dielectric materials are insulators, but a good dielectric is one that gets easily polarized.

8.7.2 Piezoelectric material

The piezoelectric effect was first discovered by Jacques and Pierre Curie in 1880. Piezoelectric materials are a technologically important class of materials, which exhibit linear electromechanical responses when subjected to external electrical or mechanical stimuli [34–38]. Piezoelectrics exhibit coupling between mechanical and electrical energy. Under the application of mechanical stress, the specimen produces electrical voltage, and under the application of electrical voltage, it produces a mechanical effect. Piezoelectrics play a significant role in electronic devices and gadgets such as energy harvesting, generation and storage, sensors, accelerometers, ultrasonic transducers, biomedical, structural, and environmental applications, filters and resonators, and micro-electromechanical systems [34].

8.7.3 Pyroelectric materials

Pyroelectric materials exhibit the generation of an electrical signal when the specimen is subjected to thermal variation due to having a nonzero value of polarization in the absence of an electric field. This phenomenon is known as the pyroelectric effect. The spontaneously polarized bulk material may be equivalently transformed in to capacitor form, having bound surface charges of opposite nature. Thermal variation causes a reduction in the degree of polarization as well as a drop in the bound charge density of opposite surfaces. Under open-circuit conditions, electrical voltage is generated across the surface, and under short-circuit conditions, current flows through the external circuit. Experimentally, pyroelectric current (I_{pyro}) is determined as

$$I_{\text{pyro}} = \frac{dq}{dt} = p \cdot A \cdot \frac{dT}{dt} \tag{8.1}$$

where $p = \frac{dP}{dT}$ is the pyroelectric coefficient, A is the geometrical area of the conducting electrode, and dT/dt is the rate of change of temperature of the specimen.

8.7.4 Ferroelectric material

Ferroelectrics are materials that exhibit spontaneous electric polarization due to the naturally parallel alignment of their constituent dipole moments. When induced polarization is linearly proportional to the applied external electric field, this class of materials is called dielectrics. There are certain materials that exhibit a nonlinear dependence of polarization on the electric field [39–43]. Such materials are termed ferroelectrics. In addition, ferroelectrics demonstrate a peculiar polarization curve characterized by a hysteresis loop. The ferroelectric state of the specimen is quite sensitive to its history. When the externally applied field is removed, the polarization of the ferroelectric system remains nonzero, and the orientation of polarization can be switched by reversing the direction of the field [41–43].

8.8 Principle of energy storage

Electrical energy storage is designed to play key roles toward lowering electricity costs by storing energy, improving the reliable supply of energy with greater flexibility and security during failures caused by disasters, and promoting a green and sustainable approach. More importantly, energy storage may support solar and wind energy renewable schemes by favoring the decarbonization and decentralization of loads on the electric grid. Since renewable energy generation can be intermittent and variable, energy storage systems can store excess energy when generation is high and deliver it when generation is low, enabling a more reliable and consistent power supply from renewable sources.

The key principles of energy storage include the following.

8.8.1 Conservation of energy

The fundamental principle of energy storage is to identify the appropriate method to convert ambient energy into a more suitable form of energy. Energy storage systems adhere to this principle by capturing and storing energy in a form that can be easily retrieved and converted back into its original form.

8.8.2 Conversion efficiency

Energy storage systems aim to maximize the efficiency of the energy conversion process. Most energy conversion processes suffer from weak energy conversion efficiency and are considered inefficient from an application point of view. Higher efficiency ensures that minimal energy is lost during the storage and conversion process, maximizing the usefulness of the stored energy.

8.8.3 Energy density

Energy density is an important principle in energy storage, referring to the amount of energy per unit volume that can be stored. Higher energy density enables more energy to be stored in a compact and lightweight manner, which is particularly important for portable and mobile applications such as EVs.

8.8.4 Charge and discharge rates

Energy storage systems should be capable of both charging (storing energy) and discharging (retrieving energy) at desirable rates. The charge and discharge rates determine how quickly energy can be stored or released, and they can vary depending on the specific technology or system used for energy storage.

8.8.5 Environmental impact

Energy storage systems should be capable of reducing their footprint on environmental impact. This includes considerations such as the use of environmentally friendly materials, efficient manufacturing processes, and responsible end-of-life disposal or recycling methods for energy storage devices.

8.9 Theory of energy storage of ferroelectrics

Ferroelectric materials are known for their ability to exhibit spontaneous electric polarization, and the direction of polarization can be reversed by the application of an electric field. This property allows them to store and release electrical energy, making them suitable for storage applications. The theory of energy storage in ferroelectric materials involves the interaction between the electric field, polarization, and the energy stored in the material. When a ferroelectric material is subjected to an electric field, the electric dipoles within the material align in response to the applied field, resulting in the development of a net polarization. This alignment process is known as polarization switching or domain reorientation. The energy required to switch the polarization depends on the characteristics of the ferroelectric material and the strength of the applied electric field. The energy stored in a ferroelectric material arises from two main contributions:

8.9.1 Electric field energy

The stored energy in a dielectric system is proportional to the square of the applied electric field strength. The electric field energy is stored when a ferroelectric material is exposed to the field. This stored energy can be released when the polarization is reversed by an opposite electric field, which allows the material to act as an energy storage device.

8.9.2 Domain wall energy

Ferroelectric materials consist of multiple domains, each with a distinct polarization direction. Domain walls separate these domains. The movement of domain walls during polarization switching involves the reorientation of the material's polarization and incurs energy due to the creation and annihilation of domain walls. The energy associated with domain wall motion contributes to the overall energy storage capability of the ferroelectric material.

To enhance the performance of ferroelectric materials toward energy storage applications, various factors can be considered, such as material composition, crystal structure, domain engineering techniques, and temperature control. Optimizing these factors can help achieve higher energy density, improved charge-discharge efficiency, and better cycling stability in ferroelectric energy storage devices. It is worth noting that the theory of energy storage in ferroelectric materials is a complex and active area of research, and different theoretical models and experimental techniques are employed to understand and predict the behavior of these materials in energy storage applications.

8.9.3 Energy storage performances

Energy storage characteristics refer to the properties and parameters that describe the performance of an energy-storage system. These characteristics provide valuable information about the storage capacity, efficiency, and other important aspects of the system. Some key energy storage characteristics include:

8.9.4 Energy storage density

Energy density is the amount of energy that can be stored per unit volume or mass of a storage medium. It is a crucial characteristic as it determines the storage capacity of the system. Recoverable energy density, also known as usable energy density or practical energy density, refers to the amount of energy that can be effectively stored and retrieved from an energy storage system within a given volume or mass. It represents the energy that is available for use, taking into account losses or limitations that may occur during the storage and retrieval processes.

8.9.5 Recoverable energy storage

Recoverable energy density is the estimation of the actual usable amount of energy in a storage system. It provides a more realistic estimation of the energy storage capability of a system. Recoverable energy density is an important parameter during the evaluation of storage characteristics for a specific application. It provides a more accurate assessment of the usable energy capacity, allowing for a better understanding of the actual energy available for use and the practical performance of the storage system. Loss energy density refers to the energy that is dissipated or lost during the application or removal of a field. It represents the energy that is not recoverable or usable for the intended purpose due to loss. The efficiency of an energy storage system represents the ratio of the useful energy output to the energy input. It accounts for losses that occur due to charging or discharging.

The recoverable energy W_{rec}, energy loss W_{loss}, and efficiency η are determined graphically from the isothermal ferroelectric hysteresis loop using mathematical relation:

$$W_{\text{rec}} = \int_{P_r}^{P_{\max}} E \cdot dP \tag{8.2}$$

$$W_{\text{loss}} = \int_{0}^{P_{\max}} E \cdot dP - \int_{P_r}^{P_{\max}} E \cdot dP \tag{8.3}$$

$$\eta = \frac{W_{\text{rec}}}{W_{\text{rec}} + W_{\text{loss}}} \% \tag{8.4}$$

It is important to note that loss energy density represents the energy that is dissipated or lost within the storage system itself. It does not account for losses that may occur during energy transmission or due to other external factors. Losses should be minimized in energy storage systems to maximize the usable energy and overall system efficiency.

8.9.6 Power density

Power density quantifies the rate of delivery of energy in a storage system. It estimates how quickly the energy can be accessed when needed. Higher power density ensures rapid charging and discharging processes. An energy storage system with higher power density is desirable for applications with high power requirements.

8.9.7 Cycle life

Cycle life refers to the maximum number of cycles of charging and discharging up to which the storage system can perform without significant loss in efficiency. It indicates the system's endurance, durability, and longevity. An extended life is desirable to ensure a reliable and long-lasting energy storage solution.

8.9.8 Dielectric materials for energy storage

Dielectric materials play a significant role in energy storage applications, particularly in capacitors and dielectric energy storage devices. These materials are chosen for their ability to store electrical energy in an electric field, thanks to their unique dielectric properties. According to empirical considerations, there are four classes of dielectric materials, namely dielectric-glass-ceramics, relaxor ferroelectrics, antiferroelectrics, and polymer-based ferroelectrics, which are considered the most proven candidates for next-generation applications (Figures 8.3 and 8.4). Here, we provide a systematic analysis and state-of-the-art advances in the storage performance of these materials.

Based on physical prerequisites, the materials required to demonstrate efficient energy storage activity exhibit high values of saturation-polarization, low remnant polarization, and high electrical breakdown field. There are various classes of dielectric materials, for example, anti-ferroelectrics, dielectric-glass-ceramics, relaxor ferroelectrics, and polymer-based ferroelectrics that seem to be more favorable than the conventional ferroelectric systems due to their high values of remnant polarization [33].

Ferroelectric polymers exhibit certain additional advantageous properties, for example, flexibility, process ability, and the lightweight nature of polymers. These materials can be synthesized and easily tuned to possess high dielectric constants and excellent charge storage capabilities, making them suitable for energy storage applications. Here are some key aspects of polymer ferroelectric materials for energy storage:

8.9.9 High energy density

Polymer-based ferroelectrics exhibit the potential to demonstrate large energy storage performance due to their high dielectric constants. By incorporating ferroelectric polymers into capacitors, higher energy densities can be achieved compared to traditional dielectric materials.

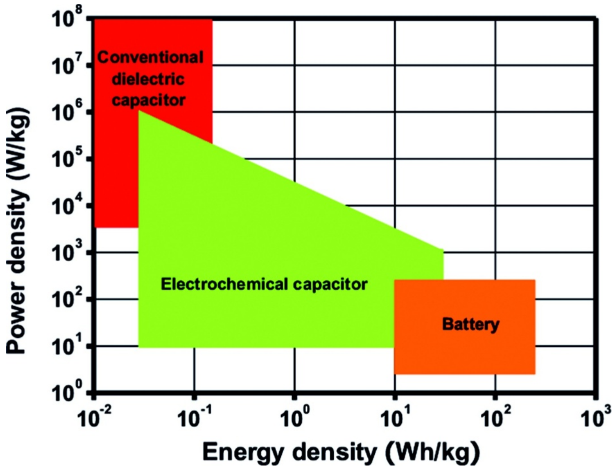

Figure 8.3: Performance of various energy storage systems [33].

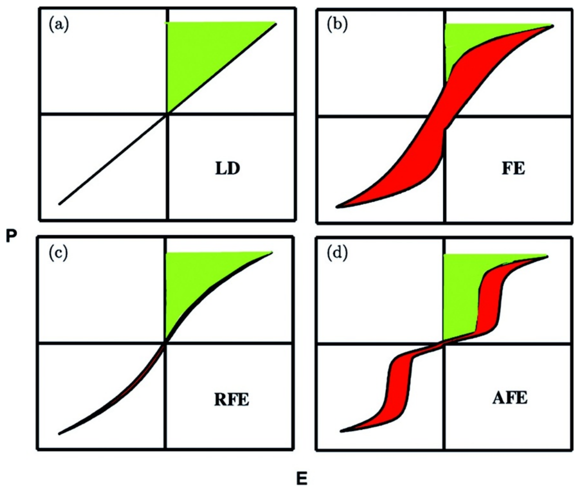

Figure 8.4: Energy storage performance of materials: (a) dielectrics, (b) ferroelectrics, (c) relaxors, and (d) antiferroelectrics. The green and red areas represent recoverable energy density and energy loss, respectively [33].

8.9.10 Reversible polarization

One of the key advantages of ferroelectric polymers is their polarization switching. When an electric field is applied, the constituent dipoles align, resulting in the storage of electrical energy. This energy can be released when the electric field is removed or reversed. The reversible nature of the polarization makes ferroelectric polymer materials suitable for repeated charge and discharge cycles.

8.9.11 Flexibility and formability

Polymer ferroelectric materials offer flexibility and formability, allowing them to be shaped and integrated into various device configurations [44]. They can be processed using techniques such as spin coating, solution casting, or inkjet printing, enabling the fabrication of thin films, coatings, or complex device structures.

8.9.12 Low cost and scalability

Polymers are generally less expensive compared to inorganic ferroelectric materials, such as ceramics. Additionally, the manufacturing processes for polymer ferroelectric materials are often less complex and more scalable, making them attractive for large-scale production.

8.9.13 Multifunctionality

Polymer ferroelectric materials can exhibit other desirable properties such as high breakdown strength, good thermal stability, and mechanical flexibility. These additional functionalities make them suitable for diverse applications beyond energy storage such as sensors, actuators, memory devices, and optoelectronic devices.

While polymer ferroelectric materials hold great potential for energy storage, there are still challenges to overcome. Some of these include stability over long-term cycling, polarization fatigue, and the need for higher operating temperatures compared to traditional dielectric materials. Ongoing research efforts are focused on addressing these challenges and further optimizing the performance of polymer ferroelectric materials for practical energy storage applications.

8.9.14 Dielectric strength

The dielectric strength of a polymer ferroelectric refers to the maximum electric field or voltage that the material can withstand before experiencing electrical breakdown. This property is significant in applications where high electric fields are present, such as in capacitors, actuators, and memory devices. The dielectric strength of a polymer ferroelectric can vary depending on the specific polymer used, its composition, processing conditions, and any additives or fillers incorporated into the material. Some commonly used polymer ferroelectrics include poly(vinylidene fluoride) (PVDF) and PVDF-based copolymers, such as poly(vinylidene fluoride-trifluoroethylene) (PVDF-TrFE) and poly(vinylidene fluoride-chlorotrifluoroethylene) (PVDF-CTFE). PVDF, for instance, is known for its high dielectric strength, typically in the range of 200–300 MV/m. PVDF-based copolymers like PVDF-TrFE and PVDF-CTFE also exhibit good dielectric strength, often similar to or slightly lower than PVDF. It is important to note that the dielectric strength of a polymer ferroelectric can be influenced by factors such as sample thickness, temperature, frequency of the applied electric field, and the presence of defects or impurities within the material. Additionally, the orientation and crystalline structure of the polymer can also impact its dielectric strength.

8.10 PVDF

PVDF is found to crystallize in various forms based on the linking of functional groups with the structural back bone. PVDF exhibits the repeating unit $(–CH_2–CF_2–)_n$. The overall properties of PVDF material can be tuned significantly in a variety of ways [37, 38]. The length and linking of the carbon chain provide a fertile ground toward the realization of broad physical properties. As more monomers are included, the length of the chain increases, and the designed materials attain a soft, waxy phase. When the length of the chain is maintained above 1,000, a flexible solid structure is obtained. It is typically a semicrystalline material with 50% amorphous nature. It has a highly regular structure in which the monomer vinylidene fluoride units are connected in a head-to-tail fashion. There is a very low probability of the occurrence of a head-to-head arrangement. On the basis of linking the functional –H and –F groups to the polymer chain (–C–C–), PVDF materials are found to crystallize in different phases, that is, α, β, γ, δ, and ε [45]. However, the underlying physical characteristics are very sensitive to the crystalline structure, that is, the symmetry of –H and –F group attachment.

Among these, α and β conformations are the most general and important classes of polymorphs of PVDF [46–48]. The α-phase is synthesized under normal crystallization conditions, while the β-phase is formed by crystallization under pressure or by mechanical distortion of polymer films. The α is the thermodynamically stable structure. The β-phase can be derived from the α-phase via induced crystal phase transition. The formation of polar β-PVDF involves mechanical extension and electrical poling with a suitable strength of the electric field. Mechanical elongation of the material induces the transition of the original spherulitic structure into a crystal array, which forces the molecules to acquire their most extended conformation structure, that is, the polar β-phase, in which all of the underlying dipole moments are spontaneously aligned in the same direction.

For comparison, the relevant parameters of leading piezoelectrics and β-phase PVDF are provided in Table 8.2. The comparative study suggests that β-phase PVDF exhibits an outstanding mechanical response as well as a high piezoelectric response. This excellent property of β-phase PVDF is attributed to its small Young's modulus and very low acoustic impedance. The low acoustic impedance parameter, in comparison to its inorganic counterparts, makes it highly suitable for acoustic sensors used in underwater operations and biological tissue applications [37, 38, 41]. Its high effective coupling coefficient enables PVDF materials to be utilized in wide bandwidth applications. Due to its excellent thermal and mechanical stability, along with a simple fabrication process, it empowers a smooth and low-cost production of PVDF on a large scale.

Table 8.2: Comparison of material parameters of PZT and β-PVDF [46, 47].

Material	PZT	β-PVDF
Density (g/cm^3)	7.55	1.78
Acoustic velocity (m/s)	3,603	2,200
Young's modulus (GPa)	1200	3
Acoustic imp (10^6 kg/m^2 s)	27.2	2.7
Efficient coupling coefficient k^2_{eff} (%)	20.25	14
Piezoelectric coefficient d_{33} (pC/N)	289–380	−24 to 34
Coefficient of thermal expansion (10^{-6})	1.75	42–75

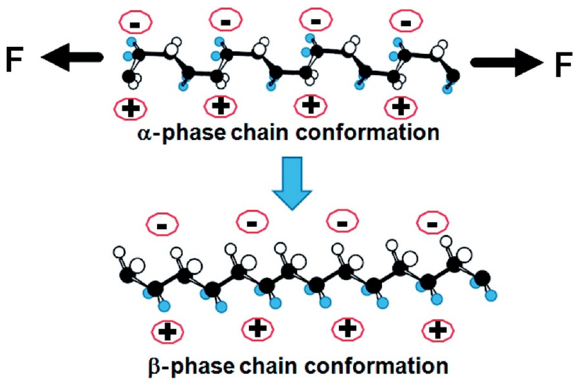

Figure 8.5: Conversion of α-PVDF into β-PVDF conformation [46].

8.11 Optimization of energy storage property

The low energy storage density of common ferroelectric materials has significantly hindered their energy storage application areas. For efficient energy storage performance, the materials should possess high energy density and dielectric strength, and they must also be nonhazardous and cost-effective [49]. The energy storage characteristics of ferroelectric materials can be influenced and modified through various methods and techniques. Here are some approaches to altering the energy storage characteristics of ferroelectrics.

8.10.1 Material composition

The energy storage characteristics of ferroelectric materials can be altered by adjusting their chemical composition. Modifying the elemental composition or doping the material with impurities can affect properties such as the dielectric constant, polarization, coercive field, and energy density [40, 43]. Different compositions can be explored to optimize specific energy storage characteristics.

8.10.2 Crystal structure and phase transitions

Ferroelectric materials exhibit different crystal structures and may undergo phase transitions at specific temperatures. By controlling the crystal structure or inducing phase transitions, the energy storage properties can be modified [35, 36]. For example, changes in the Curie temperature or the presence of multiple phases can influence the energy storage behavior.

8.10.3 Domain engineering

Ferroelectric materials consist of domains, each with a distinct polarization direction. Domain engineering techniques, such as domain wall manipulation or domain switching, can be employed to modify the energy storage characteristics [36]. Creating and controlling domain structures can enhance energy storage performance by optimizing domain wall motion and polarization switching behavior.

8.10.4 Electric field and temperature control

The energy storage characteristics of ferroelectrics can be influenced by the applied electric field and temperature. Varying the strength and duration of the applied electric field during polarization switching can affect the energy storage capacity. Similarly, temperature control can modify the phase transition behavior and alter the energy storage properties [30].

8.10.5 Thin film deposition and interface engineering

Ferroelectric thin films offer additional opportunities for tailoring energy storage characteristics. Techniques such as chemical vapor deposition, physical vapor deposition, and pulsed laser deposition can be used to deposit thin films with controlled thickness and interfaces [39, 40]. Interface engineering at the film-substrate or film-electrode interfaces can optimize energy storage performance by enhancing charge transfer and reducing losses.

8.10.6 Composite and hybrid structures

Combining ferroelectric materials with other materials or integrating them into composite or hybrid structures can provide additional flexibility in modifying energy storage characteristics. Hybrid structures can offer improved energy density, enhanced charge transport, reduced losses, or tailored dielectric properties [41].

8.10.7 External fields and stimuli

Applying external fields or stimuli, such as mechanical stress, strain, or magnetic fields, to ferroelectric materials can influence their energy storage properties. These external factors can induce changes in polarization and alter the energy storage characteristics.

8.12 Challenges and difficulties

Some of the primary difficulties in renewable energy include:

8.11.1 Intermittency

Many renewable energy sources, including solar and wind power, exhibit intermittency because they rely on weather patterns and the time of day. This intermittency can render them less dependable as primary energy sources unless accompanied by efficient energy storage solutions.

8.11.2 Grid integration

The incorporation of renewable energy into pre-existing electrical grids can pose significant challenges. The grid needs to be upgraded to handle variable sources of power, which can be both expensive and time-consuming.

8.11.3 Resource availability

The availability of renewable energy resources varies by location. For example, areas with limited sunlight or wind are less suitable for solar or wind power generation. This can limit the widespread adoption of these technologies.

8.11.4 Land and space requirements

Deploying extensive renewable energy installations, such as solar and wind farms, demands substantial land or space allocation, often resulting in land-use conflicts, particularly in densely populated regions.

8.11.5 Environmental impact

Although renewable energy sources are generally cleaner than fossil fuels, they still have some environmental impacts. For instance, the production and disposal of solar panels and wind turbine blades can generate waste.

8.11.6 Cost

While the cost of renewable energy technologies has been decreasing over time, the initial investment can still be high. Governments and industries need to explore certain alternatives to make these technologies more accessible to a broader range of consumers.

Technological challenges: Developing and scaling up new renewable energy technologies can be technically challenging and time-consuming. To make renewable energy technology user-friendly, research and development are ongoing to improve efficiency and reduce costs:
- Public interest in the development of sustainable energy
- Support and incentives for ESS investments
- Safety in operations
- Cost of maintenance and energy deliverability should be further reduced

- Parallel installation of a storage system with the main supply.
- Development of international standards for the selection and implementation of harvesting techniques
- Weak grid
- Availability of land and space
- Ease of operation and continuous space for technological growth
- To ensure sustainability in materials.
- Installation infrastructure requirements.

Despite these difficulties, there is a growing recognition of the need to address climate change and reduce our dependence on fossil fuels. As a result, governments, researchers, and industries are actively working to overcome these challenges and accelerate the transition to a more sustainable energy future.

8.13 Conclusions

The future of global economic growth is closely related to the rapidly developing global market. Wind, solar, biomass, and geothermal energy harvesting are highly desirable today for their cost-effective characteristics and are making a considerable contribution toward broader commercialization. Due to the inconsistency in the availability of renewable energy resources, a broad spectrum of renewable energy sources, combined with efficient energy harvesting technology, should be integrated to avoid the condition of energy insecurity. Current communication and information technology is highly reliant on the Internet of things. To meet the demand for an uninterrupted power supply to components, local energy generation and storage systems must be installed alongside the devices. Ferroelectric systems provide a reliable solution toward autonomy in the generation and storage of electrical energy. Ferroelectric energy devices are capable of generating hundreds of kilovolts and supplying power up to the megawatt range. However, ferroelectric energy storage is not yet available for commercial low-power applications. Proper implementation of ferroelectric energy applications will provide a sustainable solution for renewable energy technology. Stakeholders are well aware that there is an urgent need for ambitious government policies to meet bold climate targets, ensure a healthy planet, and build a sustainable economy.

References

[1] Disasters triggered over half million internal displacements in India in 2023, https://indianexpress.com/article/india/disasters-displacements-india-2023-report-9328685

[2] India at COP-28: Highlights of 28th Conference of Parties, https://static.pib.gov.in/WriteReadData/specificdocs/documents/2023/dec/doc20231212285701.pdf

[3] Outlook 2025: India's renewable sector strides unabated, industry leaders optimistic on future, https://m.economictimes.com/industry/renewables/outlook-2025-indias-renewable-sector-strides-unabated-industry-leaders-optimistic-on-future/amp_articleshow/116770737.cms, Dec. 29, 2024.

[4] The Future of Sustainability 2024/25: Reimagining the Way the World Works, https://www.forumforthefuture.org/the-future-of-sustainability-2024-25

[5] Solar Overview, https://mnre.gov.in/en/solar-overview/.

[6] Bioenergy in a Changing Climate, https://www.climatehubs.usda.gov/bioenergy-changing-climate.

[7] Dangerous delusions: biomass is not a renewable energy source, https://www.oneearth.org/dangerous-delusions-biomass-is-not-a-renewable-energy-source/.

[8] A Student's Guides to Global Climate Change, https://archive.epa.gov/climatechange/kids/solutions/technologies/geothermal.html.

[9] Geothermal Energy: An Underutilised Source of Renewable Energy, https://knowhow.distrelec.com/energy-and-power/geothermal-energy-an-underutilised-source-of-renewable-energy/.

[10] Dunn B., Kamath H., and Tarascon J.-M. Electrical Energy Storage for the Grid: A Battery of Choices. Science. *2011*;334:928–35.

[11] Pomerantseva E., Bonaccorso F., Feng X., Cui Y., and Gogotsi Y. Energy storage: The future enabled by nanomaterials. Science 2019; 366: eaan8285.

[12] Sharma Y S, NITI Aayog lays out the roadmap for emerging energy storage technologies- Economics Times, https://economictimes.indiatimes.com/industry/renewables/niti-aayog-lays-out-the-roadmap-for-emerging-energy-storage-technologies/articleshow/111805442.cms, Jul. 17, 2024.

[13] Gür T. M. Review of electrical energy storage technologies, materials and systems: challenges and prospects for large-scale grid storage. Energy Environ Sci. 2018;11:2696–767.

[14] Economics Times, "With 23% CAGR Global EV Market to Soar to USD 2018 billion by 2033: Report," https://economictimes.indiatimes.com/industry/renewables/with-23-cagr-global-ev-market-to-soar-to-usd-2108-billion-by-2033-report/articleshow/113763420.cms, Sep. 28, 2024.

[15] McGrath M, Huge deal struck but is it enough? 5 takeaways from a dramatic COP29, https://www.bbc.com/news/articles/cp35rrvv2dpo.

[16] Quiñones L., Five ways media and journalists can support climate action while tackling misinformation, https://news.un.org/en/story/2022/10/1129162, Oct. 03, 2022.

[17] Energy transition outlook, https://www.irena.org/Energy-Transition/Outlook.

[18] Renewable Energy Report, https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1785808.

[19] India eyes 500 GW renewable power by 2030, https://economictimes.indiatimes.com/industry/renewables/india-eyes-500-gw-renewable-power-by-2030/articleshow/114242361.cms?from=mdr.

[20] D'Souza S M, India's Pathways to a just Energy Transition, https://thediplomat.com/2024/12/indias-arduous-path-to-just-energy-transition/.

[21] Energy storage economic benefits, https://www.energystorage.org/benefits.

[22] R Walawalkar, Enabling Ecosystem: NESM aims to boost indigenous manufacturing of energy storage systems, https://renewablewatch.in/2018/07/20/enabling-ecosystem.

[23] Hao X. A review on the dielectric materials for high energy-storage application. J Adv Dielectr. 2013;03:1330001.

[24] Wu T, Jin H, Dong S, Xuan W, Xu H, Lu L, Fang Z, Huang S, Tao X, Shi L, Liu S. A flexible film bulk acoustic resonator based on β-phase polyvinylidene fluoride polymer. Sensors. 2020;20(5):1346.

[25] Koseki Y., Aimi K., and Ando S. Crystalline structure and molecular mobility of PVDF chains in PVDF/PMMA blend films analyzed by solid-state 19F MAS NMR spectroscopy. Polym J. 2012;44:757–63.
[26] Lim, J. Y., Kim, S., and Seo, Y. Enhancement of β-phase in PVDF by electrospinning. AIP Conf Proc. 2015;1664:1.
[27] J. Y. Lim, J. Kim, S. Kim, S. Kwak, Y. Lee, and Y. Seo. Nonisothermal crystallization behaviors of nanocomposites of poly(vinylidene fluoride) and multiwalled carbon nanotubes. Polymer. *2015*;62:11–18.
[28] Yang L., Wang H., Fang S., and Li M. Research progress on energy storage performance enhancement strategies for polyvinylidene fluoride-based composites. J Alloys Compd. 2023;960:170831.