Graduate Journal of Interdisciplinary Research, Reports & Reviews
(Grad.J.InteR^3)
ark:/85846/JPR3.2024AR.02030150
https://doi.org/10.5281/zenodo.15087049

ISSN(E): 2584-2919
Vol.02, No.03 (2024)
pp.150-163

Aspects of Energy Efficiency and the Execution of Modern Technologies for Achieving Net Zero

Debdutta Mandal[1,2], Jyoti Bhattacharjee[3], Debarati Mitra[1], and Subhasis Roy[3,*]

[1]*Department of Chemical Technology. University of Calcutta, Kolkata-700009, West Bengal, India.*
[2]*Calcutta Institute of Technology. Uluberia, Howrah-711316, West Bengal,India.*
[3]*Department of Chemical Engineering, University of Calcutta, KolkataDepartment of Chemical Engineering, University of Calcutta, Kolkata-700009, West Bengal, India.*
[*] Email: srchemengg@caluniv.ac.in (corresponding author)

(Received:08-01-2025; Accepted: 27-02-2025; Published Online:21-03-2025)

ABSTRACT:

Background: The energy efficiency and conversion technologies play a vital role for achieving net zero emission as well as environmental sustainability. As our nation and industries attempt to mollify the influence of weather trade, the optimizing the power usage and transition to purifier assets has predominant.

Purpose: The chapter discusses energy performance measures, a spectrum of strategies to reduce electricity consumption, as well as easy behavioural modification to advance technology solutions.

Methods: The mission not only aims for lower greenhouse fuel emissions but also the development of energy conversion technologies, which are crucial for decarbonizing the energy system by allowing the hybridization of renewable energy sources such as solar, wind, biomass, and hydroelectric power.

Results: For innovation, the chapter outlines the hybrid renewable energy storage system like smart grids, electrification, batteries, and other storage technologies that allow the storage of excess energy generation during peak production times.

Conclusions: The transition to net zero is a holistic method that considers not only cost-effective technological improvements but also policy frameworks, financial incentives, and public engagement strategies to accelerate adoption at scale. The article concludes by portraying that the race for achieving net zero is not an assignment; however, it is a possibility to transform our energy landscape into a cleaner one for our future generations.

Keywords: Netzero emissions, Energy efficiency, Energy security, Hybrid Renewable Energy Generation System

1. Introduction

Net-zero carbon emissions are no longer a distant goal; it is an urgent global mandate driven by the escalating threats of climate change. Nations, industries, and institutions worldwide are under immense pressure to transition from fossil fuel-based energy systems to sustainable, low-carbon alternatives. The 2015 Paris Agreement has established the platform for cooperation at the global level through the goal of limiting the increase in global temperature to 1.5°C [1, 2], but this will require unprecedented levels of energy efficiency and technological innovation to meet this target [2]. Carbon dioxide emissions from energy use account for almost 75 percent of all GHG emissions, which clearly puts energy efficiency and advanced technologies at the heart of the journey toward net-zero [2, 3]. The cheapest and fastest way to reduce emissions is energy efficiency, oftentimes termed as "the hidden fuel" because it is the one that can traverse all sectors, that is, industrial processes, transport, and residential use. This also demands high-end technologies, which involve renewable energy systems, smart grids, energy storage, and carbon capture, utilization, and storage. In that case, these new solutions would save energy but redefine production, distribution, and consumption patterns in the energy industry [3, 4]. Advancements in metamaterials and phase-change materials (PCMs) are enabling novel passive heating and cooling possibilities with much greater energy efficiency in buildings. Smart materials regulate temperature through very minimal energy input, hence reducing the need for conventional HVAC systems. The development of blockchain platforms for energy trading ensures efficient and transparent decentralized energy distribution with lower transmission loss and better energy efficiency in general. Blockchain also ensures immutable carbon accounting systems, which guarantee accurate record-keeping of emissions reductions across various sectors [5].

1.1. Redefine Energy Efficiency in the Context of Net Zero

Traditionally, energy efficiency means doing more with less; that is, getting more out of using less amount of energy for doing essentially the same thing or arriving at the same result. In the context of net zero, the definition becomes broader and requires more holistic changes in the system involved in producing, distributing, and consuming energy. It integrates digital technologies such as artificial intelligence (AI), machine learning (ML), and the Internet of Things (IoT) to optimize energy use in real-time. For instance, smart buildings with IoT sensors can adjust heating, cooling, and lighting dynamically based on occupancy and weather conditions, which greatly reduces energy waste [5, 6]. Additionally, new breakthroughs in the energy efficiency of their installation would also come through innovative ideas such as installing a heat recovery system and employing materials with low thermal conductivity and precision manufacturing has been discussed. At the transportation end, the growth in the usage of electric vehicles and energy-efficient public transport should also be considered. These changes seem to indicate that energy efficiency has gradually evolved from being only an idea to being a multilateral approach of technology, behavior, and policy [6, 7].

1.2. Modern Technologies Driving Energy Efficiency

The transition to a NetZero future is speeded up by the fast development and deployment of modern technologies aimed at improving energy efficiency. Key technologies are: It is the renewable energy of technological systems, including solar energy and wind energy, hydro energy, and geothermal. These systems provide clean sources of sustainable energy while helping to reduce GHG emissions significantly. Advances in PV materials, offshore wind farms, and floating design for solar farms have optimized the yield and scalability of renewable systems. Decentralized power systems, for instance, in microgrids and community-based solar projects, will allow points of generation and consumption closer to the source to minimize the loss in transmission and improve energy supply security [7, 8]. This chapter discussed a disruptive approach to energy distribution and management, Smart grids involve digitally enabled grids with the use of sensors, advanced metering infrastructure, and real-time data analytics that optimize energy flow, detect and respond to outages, and allow seamless integration of renewable energy sources. AI and ML allow for the prediction of energy demand patterns, thus balancing supply and demand through utilities. This way, the demand side management programs will encourage consumers to shift their energy use from peak periods, thereby easing the burden on the grid and eventually reducing overall energy consumption. Smart Grids: Leveraging digital communications technologies to manage and monitor the flow of electricity, enhancing grid reliability, and allowing for variable renewable energy sources.Applying the Internet of Things (IoT), artificial intelligence (AI), and big data analytics to maximize energy efficiency in industrial operations. Research has established that these technologies can significantly boost the efficiency of net-zero supply chains. Energy storage technologies, particularly lithium ion batteries, are of paramount importance in balancing supply and demand from intermittent renewable. More advanced battery technologies include solid-state batteries, flow batteries, and hybrid energy storage systems. Advanced battery technologies provide greater energy density, longer lifetimes, and safety improvements. All these innovations open the way to grid-scale energy storage for the integration of renewable and the stability of the grid. Some of the emerging technologies like hydrogen storage and thermal energy storage may provide solutions to large scale, long-duration energy storage [8, 9]. CCUS technologies are essential for mitigating emissions from hardhearted sectors such as the cement, steel, and petrochemical industries. These technologies capture CO_2 emissions at the source and either store them underground or utilize them in value-added products like synthetic fuels, chemicals, and building materials. Solvent-based capture, membrane separation, and direct air capture technologies have improved the efficiency and cost-effectiveness of CCUS systems. Also, carbonaceous chains are now being developed that give an economic incentive to capture and use CO_2, changing it from a waste product to a valuable resource as shown in the article [10]. Strong policy frameworks supporting the deployment of energy-efficient technologies and encouraging reductions in emissions are important in achieving net zero. Ambitious targets should be set by governments, financial incentives provided, and standards for carbon emissions and energy efficiency regulated. Instances include building codes that enforce designs for energy efficiency, appliance standards that mandate minimum levels of performance, and vehicle fuel economy standards [10, 11]. Another significant innovation is the use of AI and ML in energy prediction and demand management. As per the latest reports, AI-driven predictive analytics can help reduce industrial energy consumption by 10-20% through load balancing and real-time dynamic adjustments. Similarly, blockchain-based use in peer-to-peer (P2P) decentralized energy trading simplifies peer-to-peer transactions and helps reduce transmission loss and local energy market participation. Moreover, there are other technologies that can contribute significantly to reducing energy consumption and energy costs. Experimental implementations of blockchain microgrids have shown a 15% reduction in grid overload and transmission inefficiencies. Furthermore, new nanostructured thermoelectric materials have demonstrated high performance in waste heat recovery, converting waste industrial heat into utilizable electricity. Studies on doped 2D materials such as MXenes and perovskites have demonstrated over 40% efficiency enhancement compared to conventional bulk thermoelectric materials. Concurrently, green hydrogen production via single-atom catalysts (SACs) has considerably reduced the overpotential for water splitting, thus improving the feasibility of hydrogen as a clean fuel [12]. To ensure the seamless adoption of net-zero strategies, policy frameworks and subsidy regulations must align with technological advancements. Governments globally are increasingly looking towards carbon pricing policies, renewable portfolio standards (RPS), and industrial decarbonization transition plans to accelerate uptake. Cases of net-zero industrial clusters in Europe and Asia highlight how sectoral integration of carbon capture, utilization, and storage (CCUS) and electrification of high-temperature processes can cut emissions by over 60% within a decade. This review outlines the latest trends in energy-efficient technologies and their deployment strategies to achieve net-zero emissions. Another important economic incentive for firms to reduce their carbon footprint is given by carbon pricing mechanisms in the form of carbon taxes and candelabra systems. These policies internalize the environmental cost of carbon emissions, thereby making energy-efficient and low-carbon technologies more competitive. International cooperation and harmonization of policies across borders are also of utmost importance to drive global progress toward net zero.

2. Distinct Strategies to Minimize Emissions

Net-zero emissions will require a more comprehensive approach involving emerging technologies, policy reforms, and measures specific to different sectors. Various strategies for reducing emissions include several methods that may be applied for reducing carbon intensity in various sectors. Among those strategies, there are clean energy technologies, optimization of energy efficiency, and carbon capture and storage (CCS). Besides, behavioural change and circular economy are the main triggers for emission reduction. This chapter deals with decarbonization as an essential approach: various industrial routes of CO_2 emissions and several perspectives of decarbonization leading to net zero transition [11, 12].

2.1. Decarbonization

Decarbonisation refers to the reduction of carbon dioxide (CO_2) emissions in all sectors of the economy by substituting high-carbon energy sources with low or zero-carbon alternatives. It is an approach toward curbing climate change by lessening the emission of greenhouse gases without sacrificing economic growth. This change in energy production, industry, transportation, and city planning would require a system change in a low-carbon economy. Innovations in renewable energy, electrification, hydrogen technologies, and carbon management are the crucial enablers of decarbonisation. In the following sections, we present various industrial routes for CO_2 emissions and explore different aspects of decarbonisation, emphasizing the technological and economic pathways to achieve net zero [12, 13].

2.1.1. Various Industrial Routes for CO_2 Emissions

Industrial sectors account for the largest share of global CO_2 emissions, amounting to nearly 30% of total emissions. Each industrial sector is unique in terms of the particular challenges and opportunities for decarbonisation depending on its energy intensity, raw material use, and process design. The major industrial routes to CO_2 emissions are as follows:

The largest source of CO_2 emissions is the power generation sector, mainly because of the dependence on fossil fuels like coal, natural gas, and oil. The combustion processes of thermal power plants emit considerable amounts of CO_2 . A major step toward the decarbonisation of power generation involves switching to renewable sources of energy, such as solar, wind, hydropower, and nuclear energy. Moreover, the integration of grid-scale energy storage systems will make renewable energy more reliable and stable and decrease dependency on fossil fuels [13, 14].

I **Cement Industry** The cement industry is considered to be one of the biggest CO_2 emitters and is said to cause about 8% of the world's emissions. The two primary sources of emissions are calcinations, which liberates CO_2 from limestone ($CaCO_3$), and fossil fuel combustion for heating kilns. Decarbonisation strategies for the cement industry include alternative binders like geopolymer cement, industrial by products such as fly ash and slag, and carbon capture and utilization (CCU) technologies to sequester CO_2 emissions.

II **Steel Production** This industry happens to be one of the most energy-intensive, accounting for almost 7% of global CO_2 emissions.The traditional blast-furnace-based oxygen-furnace route in steel production relies upon coke as the reducing agent. Therefore, its usage contributes significantly to carbon emissions through the generation of CO_2. Other potential replacement paths that can potentially help offset emissions levels are direct reduced iron using green hydrogen, and some other electric arc furnaces work under renewable electricity, in the respective cases. Stronger recycling of steel will lower carbon footprint as one takes up the circular economy principle [14, 15]. Petrochemical and Refining Industry The petrochemical and refining industry is emitting CO_2 due to the transformation of crude oil and natural gas into fuel and chemical end-use products. Main emission activities related to the petrochemical industry involve process heat, hydrogen, and flaring. Bio based feedstock substitutions along with electrification of process heat as well as carbon capture, and utilization or storage are strategies that can help mitigate the carbon footprint of this sector. Renewable hydrogen electrolysis integrated into refining is another strategy that can effectively bring the emissions down. Transport contributes about 14% to global CO_2 emissions due to the combustion of fossil fuel in the internal combustion engine, which runs the vehicle. Decarbonisation in the transport sector can come through electrification, hydrogen fuel cells, and support for sustainable bio fuels. The upgrading of the public transportation infrastructure, a smart mobility system, or encouraging active transport, among others, are part of the solution in reducing carbon emissions from the transport sector. Agriculture and land use change releases nearly 18% of total global greenhouse gas emissions, most specifically in methane that comes from livestock, nitrous oxide from fertilizers, and CO_2 through clear-cutting. Decarbonisation of agriculture can be achieved through precision farming, sustainable land use management, and regenerative agriculture techniques. Besides sequestration in the soil, reforestation, and aforestation can be used to create natural carbon sinks [16, 17].

III **Integration of Renewable Energy: A Path towards Sustainable Energy System** Although energy efficiency reduces aggregate demand, the net-zero future depends on the mass deployment of renewable energy technologies. Solar photovoltaics, wind power, and hydroelectric power are getting economically competitive, but intermittency and grid stability are some of the challenges still to be overcome. Energy storage technologies such as batteries and hydrogen fuel cells address these issues, offering a safe and robust power supply. Sector coupling—linking electricity, heat, and transport—is also making the system efficient and flexible [17, 18].

IV **The Role of Digitalization and Smart Technologies** The adoption of newer technologies is key to enabling an easy transition to net zero. Digitalization using AI, IoT, and blockchain for efficient energy transmission, reducing the losses in the process, and enabling real-time energy management brings the best use of energy across the board. Smart meters, demand response systems, and peer-to-peer trading platforms educate and empower consumers and industries to participate as active actors in an efficient energy, dynamic energy system. Also, the use of digital twins of industrial processes makes it possible to simulate and optimize energy consumption profiles before actual use.

2.1.2. *Diversification of Decarbonisation*

Decarbonization encompasses various strategies that aim to tackle different issues, including technological enhancement, economic interest, and political policy and social inclusion. Each of these plays a crucial role in making the economy into a low-carbon economy, as shown in the article [18].

I **Technological Innovation** Technological innovation is at the core of decarbonisation. Breakthrough technologies in producing green hydrogen, advanced energy storage systems, and next-generation nuclear reactors provide solutions for reducing carbon emissions. In addition, digital technologies such as AI, block chain, and IoT can be optimized to help improve energy consumption, enhance the management of the grid, and monitor real-time emissions in industries.

II **Energy Efficiency** Improving energy efficiency is a cost-effective and immediate strategy for reducing emissions. Energy efficiency measures can be implemented across industrial processes, buildings, and transportation systems to minimize energy consumption and associated emissions. Technologies such as high efficiency motors, waste heat recovery systems, and smart building management systems can significantly enhance energy efficiency, contributing to overall emission reductions [19, 20].

III **Carbon Capture, Utilization, and Storage (CCUS)** CCUS technologies play an important role in decarbonising hard toabate sectors by capturing CO2 emissions from industrial processes and power generation. The captured CO2 can be stored in geological formations or used for various applications, including EOR, chemical synthesis, and concrete production. Scaling up CCUS infrastructure and reducing its costs are needed to achieve widespread uptake. Indeed, the integration of renewable energy sources into the energy mix is an important step in decarbonization. Solar, wind, and hydropower are fast becoming the equivalent of fossil fuels by way of costs, leading the charge for clean energy. Still, given the intermittent nature of these renewable sources, adequate, robust energy storage solutions are needed such as lithium-ion batteries, flow batteries, and hydrogen storage to make for stable and dependable grids.

IV **Policy and Regulatory Frameworks:** Good policy and regulatory frameworks are a driving force behind the decarbonization process. Governments can introduce carbon pricing mechanisms, such as carbon taxes and cap and trade systems, to encourage a reduction in emissions. Setting very stringent emission reduction targets, providing subsidies for clean technologies, and establishing green financing mechanisms would accelerate the transition to a low-carbon economy [21, 22]. Public awareness and behavioural change are necessary for decarbonisation. Creating awareness among individuals and firms about the environmental effects of their actions and promoting eco-friendly practices can create a demand for low-carbon products and services. Awareness campaigns for energy conservation, eco-labeling, and green certifications help consumers make environmentally friendly choices. Decarbonization is a holistic strategy, therefore requiring an all-around approach to cut down on emissions in the sectors. Using technological innovation, energy efficiency improvement, renewable energy integration, and effective policy implementation, the industries will find a sustainable and low-carbon way forward. Net zero emissions will help in fighting climate change while also providing economic benefits, public health improvement, and resilience in the pursuit of a sustainable future for posterity.

3. Technological Appliances to Reduce Emissions

Net zero emissions are one of the most important objectives for mitigating climate change and promoting sustainable development. This objective calls for integrating advanced technological appliances across sectors such as industry, transportation, residential, and commercial domains. The technologies aim at reducing carbon footprints, improving energy efficiency, and transitioning to renewable energy sources. In this chapter, we introduce three new types of technologies that have emerged to become major contributors to reduction of emissions. Each type of technology is discussed concerning functionality, advantages, and limitations.

3.1. Different Types of Technology

3.1.1. Carbon Capture, Utilization, and Storage (CCUS)

Carbon Capture, Utilization, and Storage involves the capture of carbon dioxide emissions in the industrial process or power generation from being emitted into the air. Once captured, it is either geologically stored or used for various applications across industries in enhanced oil recovery, concrete production, or chemical synthesis. CCUS is successful at places where decarbonization proves to be challenging as in the production of cement, steel, and chemicals [22, 23].

3.1.2. Green Hydrogen Production Technologies

Green hydrogen, which is produced by the electrolysis of water using renewable energy, is one of the versatile energy carriers for decarbonizing multiple sectors. The electrolysis technologies include proton exchange membranes, alkaline electrolyzers, and solid oxide electrolyzers. These enable the production of hydrogen with a minimal environmental footprint. Green hydrogen is a fuel for transportation, feedstock for industrial processes, and an energy storage medium to balance intermittent renewable energy sources.

3.1.3. Energy Efficient Smart Grids

Smart grids are advanced electrical networks that integrate digital communication and automation technologies to enhance the efficiency, reliability, and sustainability of energy distribution. Smart grids optimize energy consumption through real-time data from smart meters, sensors, and DERs such as solar panels and wind turbines. Thus, smart grids are critical in reducing emissions and supporting the transition to renewable energy systems through demand-side management, energy storage integration, and grid stabilization [23, 24].

3.2. *Advantages and Disadvantages*

3.2.1. Carbon Capture, Utilization, and Storage (CCUS)

Benefits:

Substantial Emission Mitigation: CCUS captures up to 90% of CO_2 emissions from industrial sources, which is an indispensable measure for achieving net zero goals.

Existing Infrastructure Compatibility: CCUS can be integrated into existing power plants and industrial facilities without requiring significant infrastructure changes.

Economic Opportunities: Using captured CO_2 in many industries will create new streams of revenue and promote circular economy practices.

Disadvantages:

High Costs: The capital and operating costs for CCUS technologies are still very high, which has been the major limiting factor for large-scale deployment of these technologies.

Energy Intensity: The energy demand for capture and storage is quite high, and some of the emission reduction benefits are offset by these energy inputs.

Storage Risks: The long term permanence of CO_2 storage sites is unknown, and leakage could jeopardize the environment benefits of the technology [25, 26].

3.2.2. Green Hydrogen Production Technologies

Advantages:

Zero Emissions: When produced using renewable energy, green hydrogen is a fuel that has zero emissions and may replace fossil fuels in any application.

Multi Sector Usage: Hydrogen is applicable across transport, industry, and storage in the energy sector as well, and this makes hydrogen an enabler of sector coupling.

Energy Security: Using green hydrogen helps reduce importation of fossil fuel, increasing the energy security of any nation that is endowed with high levels of renewable resources.

Benefits More costly for green hydrogen production is due to electrolysis mainly now instead of the traditional ways of making hydrogen.

Infrastructure Hurdles: Hydrogen requires specific infrastructure to be distributed, stored, and transported. This is not available very much yet.

Energy Losses: The energy efficiency of the use of hydrogen after the electrolysis is lesser compared to the direct use of electricity because there is energy loss associated with it [26, 27].

3.2.3. Smart Grids with High Energy Efficiency

Greater Energy Efficiency: Smart grids optimize energy distribution and consumption, thus reducing waste and generally improving the efficiency of the system.

Renewable Integration: Embedding distributed energy resources helps smart grids integrate more renewable energy to reduce dependence on fossil-based ones.

Increased Reliability: Realtime monitoring as well as automation improve grid reliability and resilience by minimizing outages and ensuring a stable energy supply.

Disadvantages:

High Upfront Investment: The infrastructure of a smart grid calls for high initial investment in hardware, software, and communication networks.

Cyber security Risks: Smart grids are vulnerable to cyber attacks due to their digital nature which can compromise grid stability and data privacy.

Complexity and Interoperability: In a smart grid, diversity in technologies and devices increases complexity and interoperability problems.

These advanced technologies are critical tools that industries and governments will have to leverage in reducing their emission output to net zero and ultimately meeting their targets. Each of these technologies carries a specific problem forward and needs to be mitigated by research, innovation, and policy support. Its complete and successful implementation into life requires a balanced view and resolution of environmental, economic, and social issues [27, 28].

4. Future Outlooks and Challenges

4.1. *Integration of Renewable Energy Sources*

The future of net zero is largely dependent on the integration of renewable energy sources, such as solar, wind, and hydropower, into national grids. These sources have immense potential but pose a significant challenge in terms of variability. Solar and wind power generation is intrinsically intermittent, leading to fluctuations that may destabilize the grid. Future technologies will need to focus on enhancing the reliability of renewable energy through advanced forecasting algorithms, demand response systems, and hybrid energy solutions that combine multiple sources to maintain consistency. Additionally, nations will need to collaborate on cross-border energy trading to balance supply and demand across regions with varying renewable capacities [26, 29] as shown in Figure 3 of the article [29].

4.2. Energy Storage Innovations

Achieving a low-carbon economy will depend on breakthroughs in energy storage technologies. The technology that has dominated until today has been lithium ion; however, its very low energy density and a rather high cost, paired with its reliance on some relatively rare materials, create long-term sustainability issues. Future innovations likely to represent alternative solutions may involve the development of solid state batteries, flow batteries, or even hydrogen-based storage systems. However, scaling these technologies to full-scale deployment will require overcoming issues related to cost, lifecycle performance, and integration into existing infrastructure. Decentralized storage systems are also likely to be a critical part of the solution, enabling energy consumers to become energy producers and storage providers in local microgrids.

4.3. Electrification of Transportation

The electrification of transport is the major strategy towards reducing emissions in one of the most polluting sectors [30, 31]. The future is only more electric vehicles with the growth of battery technology, the development of charging infrastructure, and smart grid integration. However, several challenges are still on the way to complete electrification because producing EV batteries is still a very energy-intensive process and is dependent on finite resources like cobalt and lithium. Additionally, charging infrastructure has to be scaled up dramatically to keep pace with demand, particularly in rural and underdeveloped regions. Policymakers and industry will need to work together to make the shift to electric mobility equitable and just, and to develop and test alternative forms of propulsion for heavy-duty transportation, like hydrogen fuel cells.

4.4. Carbon Capture, Utilization, and Storage (CCUS)

Technologies for carbon capture, utilization, and storage (CCUS) will be instrumental in reducing the emissions of difficult-to-decarbonize industries, including cement, steel, and chemical manufacturing. The future outlook for CCUS is scaling up deployment from pilot projects to full-scale industrial applications [31, 32]. However, several challenges need to be overcome, including high capital costs, energy penalties associated with capture processes, and a lack of a comprehensive CO_2 transportation and storage infrastructure. Such technologies as direct air capture (DAC), mineralization, and carbon to products would add value and economics to CCUS. There should be supportive policy on carbon pricing and incentive regimes, so the governments encourage them and create incentives to boost their scale and use.

4.5. Digitalisation and Smart Energy Management

This digitalization of energy shall also help in realizing the target of reaching net zero. The use of smart grids, Internet of Things (IoT) devices, and artificial intelligence (AI) algorithms will allow real-time monitoring, predictive maintenance, and optimized energy consumption throughout sectors of industries, commercials,and residential sectors. This widespread adoption of digital technologies gives rise to some critical questions regarding data privacy and protection, cybersecurity, and power requirements of data centres in scale [32, 33]. This includes bridging the digital divide, thereby ensuring that all communities fully realize the advantages of smart energy technologies and are a part of the net-zero transition.

4.6. Energy Efficiency in the Built Environment and Retrofitting

This means that nearly half the Earth's energy usage and releases come from its built environments. The future will also require ultra-efficient buildings, which include improved insulation, energy efficient heating, ventilation, and air conditioning, and renewable energy systems integrated into their design. Retrofits of existing buildings to increase efficiency standards will be considered a priority but are expected to pose challenges that are related to cost, technical complexity, and disruption to occupants. New financing mechanisms, green bonds, and energy performance contracts will be needed to ramp up the pace of retrofits. Moreover, smart building technologies that advance further and change the pattern of energy usage according to occupancy and prevailing weather conditions will also improve the overall efficiency of energy consumption [33, 34].

4.7. Development of Hydrogen Economy

Hydrogen is thought to be a fuel that can feed and decarbonise several industries, including transportation, industry, and power. The future hydrogen economy will depend on a large scale production of green hydrogen through electrolysis powered by renewable energy, but several barriers remain to be overcome, such as the high cost of electrolysis, the vast infrastructure required for hydrogen storage and transportation, and improving the efficiency and durability of fuel cells. Collaboration between governments, industry, and academia will be required to build a robust hydrogen supply chain and set up a regulatory framework that encourages investment and innovation in the hydrogen sector as shown in article [33].

4.8. Circular Economy and Waste-to-Energy Technologies

A circular economy approach will be critical for minimizing waste and maximizing resource efficiency in the pursuit of net zero. New advances would instead expand such waste-to-energy technologies encompassing anaerobic digestion, gasification, and pyrolysis to transform organic, inedible, and recyclable waste into useful products. However, the release of unintended emissions and resource exhaustion from these technologies must be mitigated. Policymakers will need to implement rules and incentives that encourage cross industry adoption of circular economy practices, as well as innovation in material recycling, bio products, and sustainable packaging solutions [33, 34, 35].

4.9. Decentralized Energy Systems and Community Participation

Decentralized energy systems, including microgrids and community-based renewable energy projects, represent a promising pathway for achieving net zero while promoting energy resilience and equity. The future will see more community participation in energy generation, storage, and management, thanks to the advancements in DERs and peer to peer energy trading platforms. However, regulatory frameworks, grid integration, and financing issues must be addressed to scale these systems. Empowering communities with the knowledge, tools, and financial support to participate in the energy transition will be crucial for ensuring an inclusive and just path to net zero [36, 37].

4.10. Policy and Regulatory Frameworks

Net zero will require a comprehensive and coherent policy and regulatory framework that harmonizes national and international efforts. Future policies will need to reconcile these competing demands of energy security, economic growth, and environmental sustainability. But ambitious climate policies are politically hard to implement because of questions of political will, stakeholder alignment, and public acceptance. The diverse set of stakeholders involved including industrialists, researchers, and civil society will be the responsibility of policymakers to interact with, formulating policies that are effective and equitable. International cooperation and harmonization of standards will also be very crucial for coordinating a global response to this crisis [37, 38].

4.11. Economic and Social Implications

A transition to a net-zero economy will have wide-reaching implications for the economy and for society. Although new job opportunities and economic growth will arise with the shift to clean energy technologies, it may also cause the displacement of jobs in traditional fossil fuel industries.The future demands proactive measures in managing this transition, including re-skilling and programs, social safety nets, and inclusive economic development strategies. Ensuring a just transition that leaves no one behind will be critical to keeping social cohesion and public support for zero policies. Designing low-energy or net-zero energy buildings (NZEBs) with high-performance insulation, energy-efficient windows, and state-of-the-art HVAC systems to dramatically reduce energy demands. Shifting from internal combustion engines to electric vehicles (EVs) that are more energy-efficient and can be fueled by renewable energy sources [38].

4.12. Nuclear Energy

Nuclear energy is a highly contentious but potentially crucial element of the future energy mix for achieving net zero. Next-generation nuclear technologies, small modular reactors,and advanced fusion reactors, among others, would promise the world with its safer, more flexible, and lower cost nuclear power, and challenges facing public perception, regulatory approvals, and waste management need to be addressed before realizing such huge potential from nuclear energy. Future efforts must focus on safer, more efficient, and sustainable nuclear technologies and successful restoration of public confidence through open communication and community engagement. On the technological, economic, social, and regulatory hurdles covered in the chapter, this will undoubtedly add toward energy futures that are cleaner, resilient, and fairer in all respects by all sorts of stakeholders from all walks of life [39, 40] With outstanding progress achieved, net zero is a challenging assignment that continues to require passionate innovation. The future would most probably witness breakthroughs for future-generation nuclear energy, bioenergy systems, and quantum computing for energy efficiency. Collaboration between the constituencies of government, industry, and academia is required to overcome financial and technological challenges. Synergistic thinking integrating efficiency, renewable energy, digitalization, and carbon management will build a lasting and climatically resilient future. Net-zero emissions are not an individual ambition but a global pledge that has to be addressed as a collective effort across all sectors. By focusing on energy efficiency, adopting cutting-edge technologies, and applying strict policy measures, the world can achieve a green and economically viable energy future. The transition to net zero is not merely an environmental imperative but also an opportunity to increase innovation, economic growth, and global resilience to climate change [40, 43].

5. Conclusions

Net-zero emissions will be achieved through a combination of energy efficiency and the deployment of modern technologies across sectors. Energy efficiency remains a cornerstone strategy, offering immediate and cost-effective reductions in carbon emissions. Optimizing industrial processes, enhancing building insulation, and promoting energy-efficient appliances can make great strides toward minimizing energy consumption while maintaining productivity. This reduces operational costs and eases the burden on renewable energy systems, accelerating the shift toward a low-carbon economy. However, the realization of these technologies needs to be accompanied by an effective ecosystem, including policy and regulatory frameworks, financial incentives, and public-private partnership. The government policies need to shift focus from creating regulatory regimes that are conducive to innovation, while financial institutions would need to provide accessible mechanisms for funding technology deployment. Another important area is the collaboration among industries, academia, and policy makers in bridging research and reality, so as to make sure that net zero goals are fully realized from emerging technologies. Despite the promising developments, many challenges remain. Scalability of some technologies in developing regions is limited due to high capital costs and low technical expertise. Furthermore, the intermittency of renewable energy sources underscores the necessity of robust energy storage solutions and smart grid infrastructure. These challenges require continued investment in research and development and the integration of circular economy principles to ensure the sustainability of resource utilization. In conclusion, the path to net zero is complex and dynamic, demanding a synergistic approach that leverages energy efficiency along with cutting-edge technologies. Fostering innovation, enhancing collaboration, and addressing implementation barriers will lead to a sustainable and carbon-neutral future that brings economic, environmental, and societal benefits on a global scale.

Acknowledgement

Author, S. Roy would like to acknowledge 'Scheme for Transformational and Advanced Research in Sciences [STARS]' [MoE-STARS/STARS-2/2023-0175] by the Ministry of Education, Govt. of India for promoting translational India-centric research in sciences implemented and managed by the Indian Institute of Science [IISc], Bangalore, for their support.

Authorship contribution: All authors have more or less equal contribution, the authors are accountable for the accuracy, originality, and integrity of the work.

Funding: MoE-STARS/STARS-2/2023-0175 by the Ministry of Education, Govt. of India.

Conflict of interest: Author has no conflict of interest with anyone.

Declaration: It is an original data and has not been sent or published anywhere.

Similarity Index: The authors hereby confirm that there is no similarity index in abstract and conclusion while overall is less than 10% where individual source contribution is 2% or less than it.

References

[1] Eon, R., & Lazarus, I. J. (2018). Energy-efficient building construction and embodied energy. In *Sustainability through energy-efficient buildings* (pp. 1–20). CRC Press.

[2] Mavrokapnidis, D., Mitropoulou, C. C., & Lagaros, N. D. (2019). Environmental assessment of cost-optimized structural systems in tall buildings. *Journal of Building Engineering, 24*, 100730. https://doi.org/10.1016/j.jobe.2019.100730

[3] Hedman, Å., Rehman, H. U., Gabaldón, A., Bisello, A., Albert-Seifried, V., Zhang, X., Guarino, F., Grynning, S., Eicker, U., Neumann, H. M., et al. (2021). IEA EBC Annex 83 positive energy districts. *Buildings, 11*(2), 130. https://doi.org/10.3390/buildings11020130

[4] Xiang, X., Ma, M., Ma, X., Chen, L., Cai, W., Feng, W., & Ma, Z. (2022). Historical decarbonization of global commercial building operations in the 21st century. *Applied Energy, 322*, 119401. https://doi.org/10.1016/j.apenergy.2022.119401

[5] Sun, Y., Wilson, R., & Wu, Y. (2018). A review of transparent insulation material (TIM) for building energy saving and daylight comfort. *Applied Energy, 226*, 713–729. https://doi.org/10.1016/j.apenergy.2018.05.086

[6] Yüksek, I., & Karadayi, T. T. (2017). Energy-efficient building design in the context of building life cycle. In E. H. Yap (Ed.), *Energy efficient buildings* (pp. 1–20). InTech.

[7] Zhou, Y., & Liu, Z. (2023). A cross-scale 'material-component-system' framework for transition towards zero-carbon buildings and districts with low, medium, and high-temperature phase change materials. *Sustainable Cities and Society, 89*, 104378. https://doi.org/10.1016/j.scs.2022.104378

[8] Bhattacharjee, J., & Roy, S. (2024). Synergistic insights: Electro-organic photocatalysis and nanostructures. *Chemical Papers, 78*(15), 8077–8105. https://doi.org/10.1007/s11696-024-03657-2

[9] Bhattacharjee, J., & Roy, S. (2024). A review on photocatalysis and nanocatalysts for advanced organic synthesis. *Hybrid Advances, 6*, 100268. https://doi.org/10.1016/j.hybadv.2024.100268

[10] Ampomah, W., Morgan, A., Koranteng, D. O., & Nyamekye, W. I. (2024). CCUS perspectives: Assessing historical contexts, current realities, and future prospects. *Energies, 17*(17), 4248. https://doi.org/10.3390/en17174248

[11] Bhakta, D., Gayen, D., Bhattacharjee, J., Chatterjee, R., Dastidar, P., & Roy, S. (2024). Repurposing industrial and agricultural wastes as sustainable alternatives in photovoltaic cells and dye degradation. *Chemistry Select, 9*, 1–15. https://doi.org/10.1002/slct.202402345

[12] Ruparathna, R., Hewage, K., & Sadiq, R. (2016). Improving the energy efficiency of the existing building stock: A critical review of commercial and institutional buildings. *Renewable and Sustainable Energy Reviews, 53*, 1032–1045. https://doi.org/10.1016/j.rser.2015.09.044

[13] Lee, D. Y., Seo, B. M., Yoon, Y. B., Hong, S. H., Choi, J. M., & Lee, K. H. (2019). Heating energy performance and part load ratio characteristics of boiler staging in an office building. *Frontiers in Energy, 13*, 339–353. https://doi.org/10.1007/s11708-019-0621-0

[14] Baldi, S., Michailidis, I., Ravanis, C., & Kosmatopoulos, E. B. (2015). Model-based and model-free "plug-and-play" building energy efficient control. *Applied Energy, 154*, 829–841. https://doi.org/10.1016/j.apenergy.2015.05.029

[15] Wang, Y., Zhao, F. Y., Kuckelkorn, J., Li, X. H., & Wang, H. Q. (2014). Indoor air environment and night cooling energy efficiency of a southern German passive public school building operated by the heat recovery air conditioning unit. *Energy and Buildings, 81*, 9–17. https://doi.org/10.1016/j.enbuild.2014.06.017

[16] Liu, Z., Zhou, Y., Yan, J., & Tostado-Véliz, M. (2023). Frontier ocean thermal/power and solar PV systems for transformation towards net-zero communities. *Energy, 284*, 128362. https://doi.org/10.1016/j.energy.2023.128362

[17] Swaminathan, S., Wang, X., Zhou, B., & Baldi, S. (2018). A university building test case for occupancy-based building automation. *Energies, 11*(11), 3145. https://doi.org/10.3390/en11113145

[18] Al Khaffaf, I., Tamimi, A., & Ahmed, V. (2024). Pathways to carbon neutrality: A review of strategies and technologies across sectors. *Energies, 17*(23), 6129. https://doi.org/10.3390/en172361

[19] Shaikh, A. A., Bhattacharjee, J., Datta, P., & Roy, S. (2024). A comprehensive review of the oxidation states of molybdenum oxides and their diverse applications. *Sustainable Chemistry for the Environment, 7*, 100125. https://doi.org/10.1016/j.scenv.2024.100125

[20] Bhattacharjee, J., & Roy, S. (2024). Review on green resources and AI for biogenic solar power. *Energy Storage and Conversion, 2*(1).

[21] Bhattacharjee, J., & Roy, S. (2024). Density functional waltz: Molecular theory of spin dynamics. *Journal of Physics & Optics Sciences*, 1–4. https://doi.org/10.47363/jpsos/2024(6)242

[22] Panwar, N. L., Kaushik, S. C., & Kothari, S. (2011). Role of renewable energy sources in environmental protection: A review. *Renewable and Sustainable Energy Reviews*, *15*(3), 1513–1524.

[23] Ordóñez, J., Jadraque, E., Alegre, J., & Martínez, G. (2010). Analysis of the photovoltaic solar energy capacity of residential rooftops in Andalusia (Spain). *Renewable and Sustainable Energy Reviews*, *14*(7), 2122–2130.

[24] Kammen, D. M., & Sunter, D. A. (2016). City-integrated renewable energy for urban sustainability. *Science*, *352*(5281), 922–928.

[25] Korkas, C. D., Baldi, S., Michailidis, I., & Kosmatopoulos, E. B. (2016). Occupancy-based demand response and thermal comfort optimization in microgrids with renewable energy sources and energy storage. *Applied Energy*, *163*, 93–104.

[26] Jiang, Z., & Rahimi-Eichi, H. (2009). Design, modeling and simulation of a green building energy system. In *Proceedings of the 2009 IEEE Power & Energy Society General Meeting* (pp. 1–7). Calgary, AB, Canada.

[27] Gunkel, P. A., Bergaentzlé, C., Jensen, I. G., & Scheller, F. (2020). From passive to active: Flexibility from electric vehicles in the context of transmission system development. *Applied Energy*, *277*, 115526.

[28] Omrany, H., Chang, R., Soebarto, V., Zhang, Y., Ghaffarianhoseini, A., Zuo, J., & Ghaffarianhoseini, A. (2022). A bibliometric review of net zero energy building research 1995–2022. *Energy and Buildings*, *262*, 111996.

[29] Gulagi, A., Ram, M., Bogdanov, D., et al. (2022). The role of renewables for rapid transitioning of the power sector across states in India. *Nature Communications*, *13*, 5499. https://doi.org/10.1038/s41467-022-33048-8

[30] Guo, D., & Zhou, C. (2016). Potential performance analysis and future trend prediction of electric vehicle with V2G/V2H/V2B capability. *AIMS Energy*, *4*(3), 331–346.

[31] Bhattacharjee, J., & Roy, S. (2023). Green remediation of microplastics using bionanomaterials. In *Remediation of Plastic and Microplastic Waste* (pp. 240–260). Elsevier.

[32] Bhattacharjee, J., & Roy, S. (2024). Synthesis of thermoelectric nanocomposites by incorporating reduced graphene oxide. *Archives of Advanced Engineering Science*. https://doi.org/10.47852/bonviewaaes42023514

[33] Chirosca, A.-M., Rusu, E., & Minzu, V. (2024). Green Hydrogen—Production and Storage Methods: Current Status and Future Directions. *Energies*, *17*(23), 5820. https://doi.org/10.3390/en17235820

[34] Zhou, Y., Cao, S., Hensen, J. L. M., & Hasan, A. (2020). Heuristic battery-protective strategy for energy management of an interactive renewables–buildings–vehicles energy sharing network with high energy flexibility. *Energy Conversion and Management*, *214*, 112891.

[35] Barone, G., Buonomano, A., Forzano, C., Giuzio, G. F., Palombo, A., & Russo, G. (2022). Energy virtual networks based on electric vehicles for sustainable buildings: System modelling for comparative energy and economic analyses. *Energy*, *242*, 122931.

[36] Bhattacharjee, J., & Roy, S. (2024). Applications, biomedical necessities, and green future of metallic nanoparticles. *Bentham Science Publishers*. https://doi.org/10.2174/9789815238846124010010

[37] Bhattacharjee, J., & Roy, S. (2024). Exploration of molybdenum oxide compounds—a review. *Catalysis Research*, *4*(3), 1–19. https://doi.org/10.21926/cr.2403011

[38] Huda, M., Koji, T., & Aziz, M. (2020). Techno-economic analysis of vehicle to grid (V2G) integration as distributed energy resources in Indonesia power system. *Energies*, *13*(5), 1162.

[39] Bhattacharjee, J., Bhakta, D., & Roy, S. (2024). Characteristics, applications, and limitations of nanocomposites in biosensing. In *Advances in Chemical and Materials Engineering* (pp. 161–191). IGI Global. https://doi.org/10.4018/979-8-3693-1094-6.ch006

[40] Bhattacharjee, J., Bera, S., Mondal, S., & Roy, S. (2024). Heavy metals and other chemicals removal by microalgae. In *Advances in Sustainable Applications of Microalgae* (pp. 183–201). Elsevier.

[41] Chandrasekhar, K., Lee, Y.-J., & Lee, D.-W. (2015). Biohydrogen Production: Strategies to Improve Process Efficiency through Microbial Routes. *International Journal of Molecular Sciences*, *16*, 8266–8293.

[42] Bhattacharjee, J., & Roy, S. (2025). A comprehensive review on integrated photo rechargeable batteries-supercapacitors, and their techno-economic feasibility. *Journal of Photochemistry and Photobiology*, *25*, 100257. https://doi.org/10.1016/j.jpap.2024.100257

[43] Bhattacharjee, J., & Roy, S. (2024). Exploration of molybdenum oxide compounds—a review. *Catalysis Research*, *4*(3), 1–19. https://doi.org/10.21926/cr.2403011

Copyright and License

How to Cite?

Debdutta Mandal et al. (2024). Aspects of Energy Efficiency and the Execution of Modern Technologies for Achieving Net Zero. *Graduate Journal of Interdisciplinary Research, Reports and Reviews*, 2(03), 150-163. Retrieved from https://jpr.vyomhansjournals.com/index.php/gjir/article/view/39

Authors ORCiD

Debdutta Mandal: `https://orcid.org/0009-0008-3100-9290`; debduttamandal23@gmail.com
Jyoti Bhattacharjee: `https://orcid.org/0009-0006-6835-2899`; jyotibhattacharjee651@gmail.com
Debarati Mitra: debarati.che@gmail.com
Subhasis Roy: `https://orcid.org/0000-0003-4197-535X`; srchemengg@caluniv.ac.in,
subhasis1093@gmail.com (Corresponding author)
