Carbon Footprints

Review

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Advancing energy efficiency: innovative technologies and strategic measures for achieving net zero emissions

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Abstract

To evaluate the essential role of energy efficiency in achieving net-zero emissions and combating climate change, this comprehensive review was conducted based on a thorough analysis of academic literature, diverse case studies, and industry reports, focusing on key energy efficiency sectors and technological advancements. It begins by outlining global efforts, including the Paris Agreement and the Sustainable Development Goals, which have driven initiatives to enhance energy efficiency across various sectors. The review examines key technological innovations, such as advanced manufacturing, energy-efficient building designs, transportation electrification, and smart grid integration contributing to energy savings and decarbonization. It also discusses policy frameworks, regulatory incentives, and financial mechanisms that encourage energy efficiency. The study provides the detailed outcomes of the different strategies and initiatives, showcasing successful case studies from different regions in transportation, urban planning, power generation, and industry. It illustrates how countries have effectively implemented energy efficiency measures to reduce emissions and meet climate goals. Additionally, the review explores the potential of emerging technologies, including artificial intelligence, big data, and blockchain, to optimize energy management, enhance grid flexibility, and promote further efficiencies. Despite these advancements, the review identifies several key barriers - financial, technological, and behavioral challenges that impede the widespread adoption of energy-efficient practices. Finally, it offers strategies to overcome these obstacles, emphasizing the need for tailored policies, innovative business models, and greater consumer engagement. This review underscores the importance of energy efficiency in achieving a sustainable, net-zero future by synthesizing successful case studies and highlighting emerging solutions.

Keywords: Energy efficiency, net zero emissions, innovative technologies, sustainable energy, strategic measures, decarbonization

INTRODUCTION

Countries around the world are setting new goals to achieve net zero emissions by 2050 or earlier, in line with the outcomes of COP29 held in November 2024. Since the energy sector is responsible for over 75% of global emissions, it is crucial to make changes in this sector to address the climate crisis. Continuing with a "business as usual" approach will not lead to the significant adjustments needed to successfully tackle this problem[1,2]. According to the IEA Sustainable Development Scenario, more than 40% of the necessary emissions reductions by 2040 can be achieved through energy efficiency. Consumption patterns are expected to increase significantly due to global growth and development in developing nations. The current energy system needs to be transformed to meet this demand. Energy efficiency, known as the "first fuel," offers many advantages to society, supports net zero energy goals at lower costs, and helps in managing this significant task[3].

According to the IEA Efficient World Scenario, global energy efficiency could increase fourfold by 2040, in recognition of the availability of affordable technology in the market. Further efficiency gains are being made possible by innovations such as the digitization of energy systems and behaviorally informed policies. Countries must focus on implementing comprehensive energy efficiency policies across their economies if they want to achieve climate targets without sacrificing economic growth[4,5]. Achieving ambitious goals requires a fundamental reassessment of the structures and procedures that underpin our economy, with the help of creative policies, cutting-edge technologies, and novel approaches to accelerate development. The energy industry is being transformed by a new generation of efficiency solutions brought about by digital technologies. These advances can support higher percentages of variable and distributed renewable energy, improve grid flexibility, and reduce production and distribution losses. Building energy management systems have also advanced in sophistication by integrating external data sources like traffic and weather trends. These cutting-edge devices can forecast energy use and improve responsiveness by utilizing artificial intelligence. Leveraging existing digital solutions has several potential benefits. IEA analysis suggests that by leveraging existing technology, it may be possible to make 3,070 terawatt-hours (TWh), or more than 12% of the world's electricity usage in 2018, more efficient[3]. Approximately 25% of the world's electricity consumption is expected to be accounted for by 2040, which is approximately double the current level. Governments can significantly expand the market for smart devices through information exchange, standardization, incentives, and restrictions[2]. Digitalization can play a crucial role in rapidly expanding urban areas, where new district energy, heating and cooling systems, high population density, and a growing number of electric vehicles can work together to optimize demand and consumption and support decarbonization efforts[6]. Achieving complete energy efficiency improvements, with the potential to reduce energy intensity per square meter by more than 50%, is essential for decarbonization[3,5]. These "deep retrofits" involve a combination of modifications to the building exterior, heating and cooling systems, and lighting that go beyond simple updates to heating systems or insulation. While some businesses are currently working on this important project, scaling up deep retrofits will require new business models. To make these improvements more affordable, companies like Energies Prong are using economies of scale to carry out major retrofits on entire neighborhoods at once. Changing consumer behavior will be essential to achieving aggressive climate targets, with the majority of the behavioral changes required to reach net zero by 2050 coming from changes in transportation choices. Reducing short-haul flights, increasing walking and bicycling, using ride-sharing services, adopting micro-mobility solutions like shared bikes and scooters, and lowering driving speeds are some ways to achieve this. Reaching net-zero goals will also depend on how quickly the world's passenger car fleet switches to electric vehicles, which are up to five times more efficient than conventional cars and reduce oil use[3]. Furthermore, Figure 1 highlights the key elements for achieving net-zero emissions through energy efficiency, including technological innovations and policy frameworks. It outlines the benefits of emissions reductions and the economic advantages while noting challenges like technological, financial, and behavioral barriers.

The novelty of this study resides in its comprehensive synthesis of the latest advancements in energy efficiency technologies and their pivotal role in achieving net-zero emissions. Unlike previous reviews that focus on isolated sectors or technologies, this study presents a holistic perspective on energy efficiency across various domains, including transportation, power generation, urban development, and industry. It integrates a variety of case studies, current policy frameworks, and emerging technologies such as blockchain, big data, and artificial intelligence, offering new insights into how these innovations can optimize energy management and expedite decarbonization. Furthermore, the study highlights the challenges - technological, financial, and behavioral - that impede the widespread adoption of energy-efficient practices and proposes actionable strategies to overcome these barriers. By merging sector-specific successes with a focus on cutting-edge technologies and global policy frameworks, this review provides fresh perspectives on how to achieve ambitious climate goals while fostering economic growth.

The specific objectives of this review are to (a) examine successful case studies from various countries that showcase energy efficiency initiatives in transportation, power, urban development, and industry. This will provide insights into how different regions are tackling energy challenges and making progress toward their climate goals; (b) explore the potential of emerging technologies, such as blockchain, big data, and artificial intelligence, to optimize energy management, enhance efficiency, and accelerate decarbonization; (c) identify the main technological, financial, and behavioral barriers that hinder the widespread adoption of energy efficiency measures and suggest strategies to overcome these challenges; and (d) assess the role of policies and regulatory frameworks in promoting energy efficiency improvements, and outline the essential strategies needed to achieve ambitious climate targets. Overall, this review offers a comprehensive overview of how energy efficiency can contribute to reaching net-zero emissions and global climate goals, addressing both the necessary technological innovations and strategic frameworks essential for success.

THE IMPERATIVE FOR ENERGY EFFICIENCY

Making energy efficiency a top priority is crucial to achieving India's environmental and climate goals. Due to the country's limited supplies and increasing demand, the primary energy consumption has increased from about 450 million tons of oil in 2,000 to 880 million tons by 2020[7]. The power sector needs to use technical improvements to increase efficiency to reach the goal of reducing the energy intensity of GDP by 45% by 2030, addressing these energy needs, and cutting emissions[8-10]. Numerous tactics can be used, such as legislative and regulatory actions, financial aid and incentives for owners and producers of energy-efficient machinery, and research and development expenditures to promote the creation of new energy-efficient items. However, the most basic and economical approach is still to educate and raise public knowledge about energy efficiency and conservation. In order to mitigate the consequences of climate

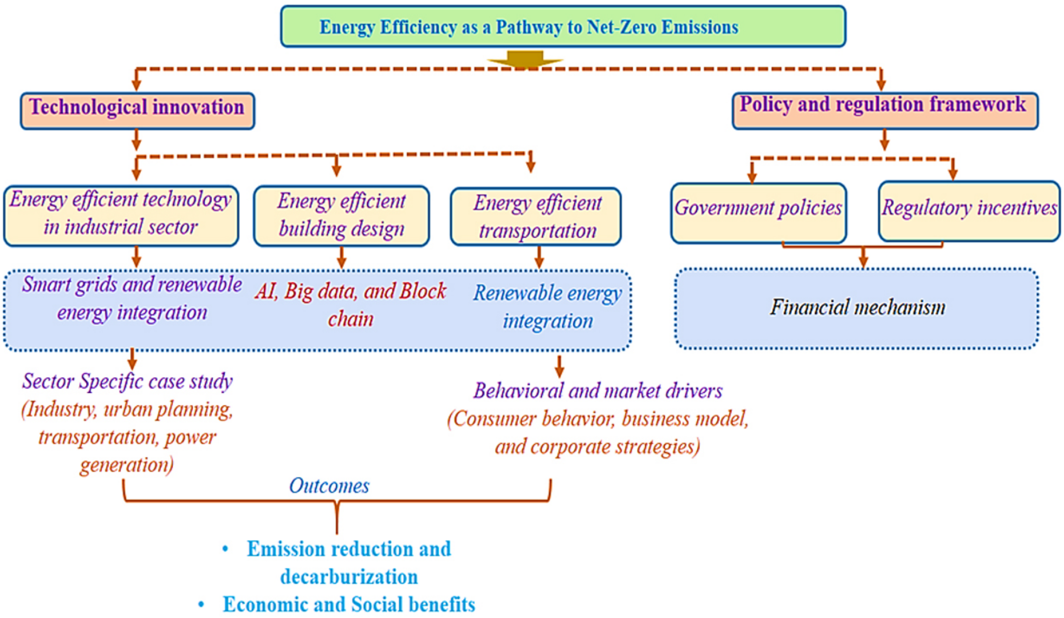

Figure 1. Different components for achieving net-zero emissions through the nexus of energy efficiency, technological innovations, and policy framework.

change and support the global energy transition, energy efficiency is essential. Energy efficiency initiatives have the potential to reduce emissions by as much as 55%, which is a big step in the direction of sustainable energy solutions. There is a lot of global potential in the transition to energy-efficient equipment like ceiling fans[3,11,12]. For example, energy-efficient fans run at roughly 25 watts, while conventional fans typically use about 70 watts. Even though this could seem like a little distinction, consider the broader implications. Changing to energy-efficient fans could cut electricity use by 45 watts per fan, assuming an average family uses three fans. With over a billion households using fans, the overall energy savings become incredibly substantial when this data is applied internationally. After the poorest performance in a decade, energy efficiency trends are expected to return to their ten-year norm. To reach the goals outlined in the IEA's Net Zero Emissions by 2050 Scenario, however, the rate of progress must double from its current level. Global energy intensity [Figure 2], a crucial measure of economic energy efficiency, is predicted to decrease by 1.9% in 2021, recovering from a meager 0.5% increase in 2020. The average yearly improvement in energy intensity over the last five years has been 1.3%, which is much less than the 4% goal set for the 2020-2030 timeframe in the Net Zero Emissions by 2050 Scenario and this improvement was 2.3% between 2011 and 2016[3,13,14]. In 2021, global energy demand is projected to rise by about 4%, returning to pre-pandemic levels as the economy recovers. The previous year saw challenges for energy efficiency due to decreased consumption and a shift away from less energy-intensive sectors like hospitality and tourism. While it is uncertain if this year's improved energy intensity indicates a stable recovery, there are positive signs, including increased government spending on efficiency, growing investments, and new climate commitments, which are tied to recovery strategies from the COVID-19 pandemic[15].

Advanced economies are the main beneficiaries of the unequal distribution of government investment in energy efficiency. Governments in other areas have a great chance to increase expenditure through recovery packages, which might boost employment and stimulate the economy. According to the IEA Net Zero Emissions by 2050 Scenario, concentrating on energy efficiency regulations from the start might increase investments in building retrofits, energy-efficient appliances, and other projects, thereby tripling the number of jobs created by 2030. This would result in several building works as well as the installation of hot

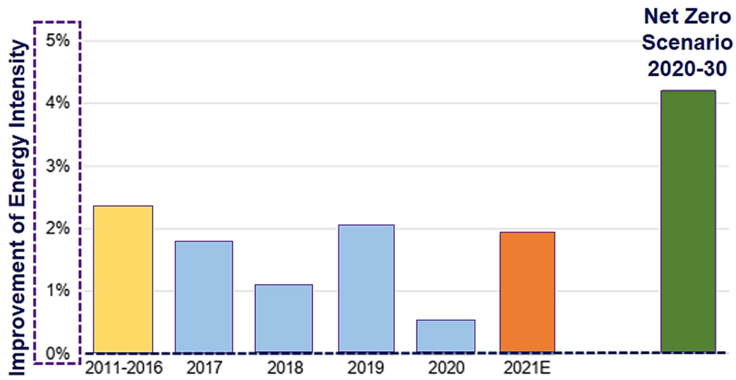

Figure 2. Year-wise energy intensity improvement (2011-2016 five-year average, Net Zero Emissions Scenario: IEA Net Zero Emissions by 2050 Scenario, 2020-2030 intensity improvements, ten-year average) [Modified after IEA[3]].

water, heating, and cooling systems. Even if a lot of these positions fit existing skill sets, governments can still help by funding training initiatives to increase access to these opportunities and lessen the likelihood of a skills shortage[3]. Efficiency initiatives have resulted in electricity consumption reductions equal to the sum of the electricity produced by solar and wind. According to an examination of nine major nations and regions [Figure 3], including the US, China, and the EU, efficiency requirements saved almost 1,500 TWh of electricity in 2018 - the same amount of electricity produced by wind and solar power combined in these locations that year. The impact is substantial in nations with the most well-established programs; appliance efficiency initiatives save roughly 15% of overall electricity generation. China's current electricity use might have been cut in half, or 3,500 TWh, if other nations had improved their electricity consumption by the same 15%[16,17].

The reviewed studies offer diverse yet complementary insights into energy efficiency, highlighting the intricate relationship between technology, policy, and socio-economic development across various sectors and regions. Ibekwe *et al.* focuses on technological innovations in the industrial sector, particularly advanced manufacturing, artificial intelligence, and smart systems that enhance energy efficiency[18]. In contrast, Umoh *et al.* investigate the impact of green architecture and sustainable construction practices on reducing energy consumption in buildings[19]. Both studies emphasize the need for integrating technological solutions with supportive policy frameworks. Additionally, Oyewole *et al.* broadens the discussion by addressing the role of financial inclusion, demonstrating that access to financial services positively influences energy efficiency, especially in developing economies, although effects can vary by region[20]. Furthermore, Chen *et al.* analyzes the connection between energy efficiency, economic growth, and environmental sustainability, arguing that decoupling energy use from economic growth is essential for achieving long-term sustainability[21]. Meanwhile, Tang *et al.* conducted a regional analysis of energy efficiency in China, revealing significant disparities across provinces and the necessity for tailored policy interventions[22]. Together, these studies highlight the multifaceted nature of energy efficiency, illustrating how technological innovations, policy measures, and socio-economic factors must work in harmony to tackle global energy challenges and promote sustainable development.

By examining key countries across various regions, such as the European Union, the United States, China, India, and Brazil, this review highlights the distinct approaches to energy transition, renewable energy adoption, policy frameworks, and technological innovations. For example, the EU's ambitious Green Deal and carbon pricing mechanisms stand in contrast to China's substantial investments in renewable energy infrastructure[3]. Similarly, India's emphasis on large-scale solar projects and Brazil's focus on bioenergy

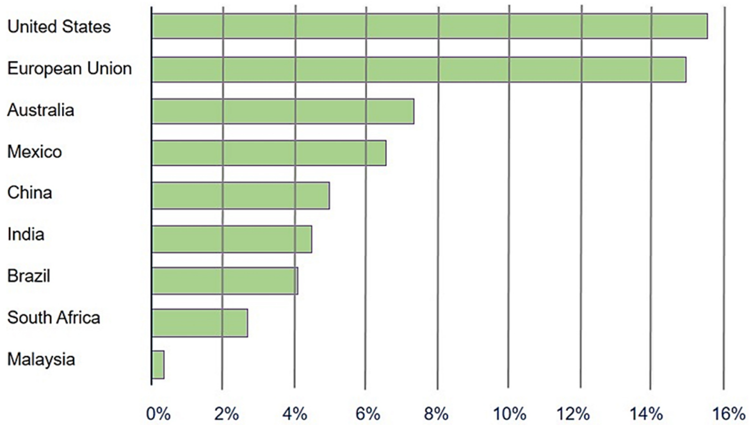

Figure 3. The impact of energy efficiency standards and labeling programs in selected countries [Modified after IEA[3]].

development illustrate diverse pathways tailored to the specific contexts of each nation. These comparisons underscore the challenges and opportunities that different countries encounter in their pursuit of net-zero emissions, providing a clearer understanding of global efforts and informing future strategies for expedited climate action.

TECHNOLOGIES FOR ENERGY EFFICIENCY

Energy-efficient technologies in the industrial sector

In the industrial sector, energy-efficient technologies are crucial for increasing output, reducing costs, and minimizing environmental impact. These technologies encompass a wide range of advancements, including high-efficiency motors that convert electrical energy into mechanical energy more effectively, variable frequency drives (VFDs) that adjust motor speeds to meet demand, and advanced process control systems that optimize manufacturing through realtime data analysis. Combined heat and power (CHP) systems significantly enhance efficiency by generating electricity and usable heat simultaneously, while waste heat recovery systems capture and reuse excess heat produced during manufacturing[23]. Energy management systems (EMS) provide comprehensive monitoring and optimization of energy use, enabling businesses to identify inefficiencies and implement targeted improvements. Additionally, incorporating renewable energy sources like wind and solar helps achieve sustainability goals and reduces dependence on fossil fuels[24,25].

Despite the many benefits, challenges such as high upfront costs, the need for specialized technical knowledge, and regulatory restrictions may hinder widespread adoption. However, advancements in artificial intelligence, the Internet of Things (IoT), and digitization could further enhance process optimization and predictive maintenance, making energy efficiency more practical and effective. Ultimately, adopting energy-efficient technologies is not only essential for meeting regulatory requirements but also serves as a strategic investment that can yield long-term financial and environmental benefits for businesses worldwide. Table 1 illustrates the detailed energy-efficient technologies in the industrial sector.

Energy efficiency in buildings

The global importance of reducing building energy use has increased significantly. This increase is primarily because a building's operational activities consume as much fossil fuel as other industries. Thus, adopting energy-efficient construction and operational practices is vital for developing sustainable cities in the future. Energy efficiency refers to a building's capability to perform the same functions while using less energy compared to buildings with inefficient energy use. It should be considered at every phase: design, material selection, construction, and operation[33,34]. The first step in creating an energy-efficient building is to

Table 1. Summarizing various energy-efficient technologies in the industrial sector

Technology	Description	Energy efficiency improvement	Advantages	Disadvantages	Limitations	References
Advanced process control (APC)	Utilizes data analytics to optimize industrial processes in real time	Optimizes process parameters for maximum energy efficiency, reducing waste and energy consumption by 10% to 20%	Increases efficiency, reduces waste, and improves quality	Requires significant data management and initial setup	Dependence on data quality and availability	Zanoli *et al.*,[26] Petrov and Novak[27]
Variable frequency drives (VFDs)	Controls motor speed by adjusting the frequency of power supplied	Adjusts motor speeds to match demand, saving 30%-60% energy in variable load applications	Reduces energy consumption, and improves motor lifespan	Initial installation costs can be high	Not suitable for all applications	Mitra *et al.*,[28]
High-efficiency motors	Motors are designed to operate more efficiently than standard motors	Energy savings of 2% to 8% reduce costs and heat generation, promoting sustainability	Energy savings of 2%-8%, lower operational costs	Higher upfront costs compared to standard motors	May require compatibility assessments with existing systems	Wei *et al.*,[29]
Waste heat recovery systems	Captures excess heat from processes and repurposes it for energy	Captures excess heat to reduce energy waste, improving efficiency by up to 30% and lowering heating costs and emissions	Reduces energy waste, and lowers energy bills	Requires investment in retrofitting existing systems	Effectiveness depends on process type and heat availability	Yan *et al.*,[30]
Combined heat and power (CHP)	Simultaneously generates electricity and useful heat from a single energy source	Achieves 60%-80% efficiency, reducing fuel consumption by generating heat and electricity from a single fuel source	High overall efficiency (60%-80%), reduces emissions	High initial capital cost, complex installation	Suitable primarily for large-scale applications	Catrini *et al.*,[23]
Energy management systems (EMS)	Software systems that monitor and optimize energy usage in industrial facilities.	Identifies energy inefficiencies and promotes strategies that can reduce energy consumption by 5% to 15%	Identifies inefficiencies, and facilitates better decision-making	Requires ongoing management and software updates	Success depends on user engagement and data integration	Segun-Falade *et al.*,[24] Al-Ghaili *et al.*,[25]
Insulation and heat recovery insulation	Reduces heat loss in industrial processes through improved insulation	Reduces energy losses by 40% by maintaining optimal temperatures.	Significant energy savings, and lower heating costs	Retrofitting existing systems can be costly	Effectiveness varies with insulation materials and conditions	Paraschiv *et al.*,[31]
Renewable energy integration	Incorporation of solar, wind, or biomass energy sources into industrial operations	Reduces fossil fuel dependence, lowering operational costs by up to 30% and cutting emissions, depending on the energy source and location	Reduces reliance on fossil fuels, and lowers operational costs	The initial investment can be substantial	Requires space and may be dependent on weather conditions	Erdiwansyah and Mahidin[32]

incorporate passive solar design techniques during the design phase[35,36]. During construction, it is essential to utilize low-energy building materials and less energy-intensive construction equipment. Regarding building operations, integrating renewable energy systems, such as photovoltaic electrification and water heating, must be part of the structure. Before construction commences, all passive solar solutions should be implemented in the design phase to achieve a nearly zero-energy passive building.

Rainwater harvesting, daylighting in buildings, and passive solar heating, and cooling are a few examples of sustainable design practices[37]. Passive buildings do not require complex designs, but they do require an understanding of window technology, local climate, and solar geometry[38]. When selecting passive solar design solutions, it is crucial to consider the climate of the project site. In hot, dry climates, passive cooling techniques such as groundwater heat exchangers, sun refrigeration, and wall and roof cooling should be incorporated into buildings. Conversely, in colder regions, passive heating designs like sunspaces, Trombe walls, and air handling systems should be utilized. To ensure energy efficiency and reduce the impact of global warming, it is essential to use materials with low embodied energy during construction. Embodied energy refers to the total energy consumed in every step of a building material's lifecycle, including mining, production, transportation, and management[35]. Fly ash bricks, fiber-reinforced bricks, stabilized adobe blocks, and various cement-replacement materials such as slag, fly ash, and silica fume, many of which are by-products from factories, are examples of low embodied energy building materials. Contractors around the world, especially in the Middle East, Europe, the USA, the UK, and India, are increasingly adopting these materials. In addition to using sustainable materials, it is important to incorporate energy-efficient appliances in buildings, including LED lights, fans, air conditioners, and refrigerators, to minimize energy consumption[39]. Energy-star-rated fluorescent bulbs are particularly popular because they are more durable and require 75% less maintenance than conventional bulbs. Moreover, implementing a lighting control system that automatically turns off lights helps further reduce energy waste, increasing overall energy efficiency.

Bioclimatic design plays a crucial role in enhancing energy efficiency by aligning buildings with their local temperature and environmental conditions. By utilizing natural resources such as sunlight, wind, and vegetation, this approach optimizes energy use throughout the year. Bioclimatic design reduces heat loss and the reliance on artificial heating or cooling systems while maximizing natural daylight and passive solar heating through careful placement of windows, overhangs, and thermal mass materials[40,41]. Furthermore, green walls and roofs improve insulation and mitigate the urban heat island effect, leading to cooler surroundings. Implementing natural ventilation techniques can significantly decrease the need for mechanical air conditioning. In summary, bioclimatic design not only reduces energy consumption and the carbon footprint of buildings but also creates healthier and more comfortable environments[42,43]. Moreover, different energy-efficient technologies applied in the building for energy efficiency are depicted in Table 2.

Energy-efficient transportation

To reduce greenhouse gas emissions and achieve sustainable mobility, energy-efficient transportation is essential[51]. As the world's population grows and urbanization increases, the demand for effective transportation systems rises. This situation requires innovative solutions to reduce energy consumption while enhancing accessibility and mobility.

One of the main strategies for energy-efficient transportation is the adoption of public transportation systems, such as buses, trains, and subways. These systems can significantly decrease the number of individual cars on the road, which in turn lowers overall energy consumption and alleviates traffic congestion. Additionally, integrating electric vehicles (EVs) into transportation networks marks a significant shift away from less environmentally friendly options, especially when these vehicles are powered by renewable energy sources. To support this transition, it is crucial to develop EV charging infrastructure[52].

Another effective approach is to promote active transportation modes like walking and cycling[53]. This can be achieved by constructing bike lanes, pedestrian-friendly streets, and safe crossing points. These initiatives not only reduce energy use but also enhance public health and decrease air pollution.

Improving energy efficiency also relies heavily on advancements in traditional vehicle fuel technologies, such as hybrid systems and enhanced internal combustion engines[54]. Automakers are increasingly investing in research and development to create lighter, more aerodynamic vehicles that consume less fuel and emit fewer pollutants.

Table 2. Different energy efficient technologies for energy efficiency of the buildings

Strategy	Description	Energy efficiency improvement	Advantages	Disadvantages	References
Passive solar design	Utilizes building orientation and thermal mass to optimize solar energy use	Strategic design can cut heating and cooling energy use by up to 50% in temperate climates	Reduces heating and cooling costs, enhances natural light	Requires careful planning, effectiveness varies by climate	Bekele and Atakara[35] Salem and Elwakil[36]
High-performance insulation	Uses advanced materials to minimize heat transfer	Reduces heat loss or gain by up to 70% and lowers energy consumption for heating and cooling by 20% to 30%	Lowers energy consumption, improves comfort	Higher initial cost, effectiveness depends on the installation	Abdelrady *et al.*,[44]
Energy-efficient windows	Incorporates multiple glazing and coatings to reduce heat loss	Reduce heating and cooling energy demand by 10%-25%, depending on window type and climate, for lower utility bills	Reduces energy costs, and enhances daylighting	Higher upfront costs, require proper installation	Liu *et al.*,[45]
LED lighting	Replaces traditional bulbs with energy-efficient LED fixtures	Achieve 75% energy savings compared to incandescent bulbs and 50% compared to CFLs, leading to significant cost reductions	Significant energy savings, longer lifespan	Initial investment may be higher	Olajiga *et al.*,[46]
Smart building technologies	Integrates IoT devices for realtime energy monitoring and management	Cut energy consumption by 10%-30% with smart heating, cooling, and lighting controls based on occupancy	Optimizes energy use, enhances comfort	Requires tech investment and training	Parekh[47]
Natural ventilation	Designs to maximize airflow and reduce reliance on HVAC systems	Cut HVAC energy use by 30%-40% in mild climates by enhancing air circulation and reducing mechanical cooling	Lowers energy costs, improves indoor air quality	May not suit all climates, requires careful design	Schulze and Eicker[48] Salihi *et al.*,[49]
Renewable energy systems	Installs solar, wind, or geothermal systems for onsite energy generation	Lower utility bills and reduce grid dependence by generating 30%-50% of a building's energy needs, based on the system and location	Reduces grid dependence, lowers utility bills	High initial installation costs, space requirements vary	Erdiwansyah and Mahidin[32]
Green roofs and walls	Uses vegetation to insulate and manage heat	Boost energy efficiency by reducing summer heat gain and improving winter insulation, potentially cutting energy use by 10%-20%	Improves energy efficiency, mitigates stormwater runoff	Maintenance needed, potential structural concerns	Besir and Cuce[50]
Energy management systems	Software for monitoring and optimizing energy usage across systems	Can achieve energy savings of 5%-20% by identifying inefficiencies and automating energy use	Identifies inefficiencies, promotes sustainable practices	Ongoing management is required, upfront costs may apply	Segun-Falade *et al.*,[24] Al-Ghaili *et al.*,[25]
Bioclimatic design	Adapts building design to local climate, utilizing natural resources for energy efficiency	Lowers energy demand by 20%-40% by using natural resources like sunlight and wind, and by optimizing building design for local climates	Enhances comfort, reduces energy demand, and utilizes renewable resources	Requires thorough climate analysis and skilled design, may limit architectural styles	Bera *et al.*,[40] Bera *et al.*,[41]

Innovative transportation management techniques, such as ridesharing, carpooling, and mobility-as-a-service (MaaS) platforms, help to reduce energy consumption by increasing vehicle occupancy and minimizing unnecessary trips[55]. Intelligent transportation systems (ITS) enhance this further by utilizing data analytics and realtime information to optimize traffic flow, decrease congestion, and improve route planning, ultimately lowering energy usage across the transportation network.

Encouraging the use of alternative fuels such as natural gas, hydrogen, and biofuels can reduce our dependence on fossil fuels and lessen the environmental impact of transportation[56]. Governments play a critical role in this transition by implementing laws and incentives that support research and development, encourage investment in energy-efficient technology, and assist in building sustainable infrastructure. Public awareness campaigns also inform citizens about the benefits of energy-efficient transportation, fostering behavioral changes that align with sustainability goals.

A comprehensive strategy for energy-efficient mobility should include public transportation, electric and alternative fuel vehicles, active transportation methods, and intelligent traffic management systems. By integrating these approaches, communities can address the challenges posed by urbanization and climate change, while developing sustainable transportation systems that enhance residents' quality of life, reduce emissions, and conserve energy. As we move toward a more sustainable future, energy-efficient transportation will be essential for achieving global environmental goals and creating resilient, livable communities.

Furthermore, government incentives and the global push for cleaner transportation are driving the rapid growth of electric vehicle (EV) usage. With Europe, China, and the United States leading the charge, global EV sales reached over 10 million units in 2023, marking a 55% increase from the previous year[51]. According to the International Energy Agency[13], electric vehicles are expected to account for approximately 15% of all new car sales globally by 2024, and predictions indicate that they could reach 30% of the market by 2030. However, significant infrastructure challenges remain for the mainstream adoption of EVs. By 2030, the demand for EV charging stations is anticipated to quadruple, resulting in an estimated need for 60 million public charging stations worldwide. To meet this demand, governments and businesses are investing heavily in the development of EV charging networks. For instance, China is the global leader in EV infrastructure, having already established over 2 million charging stations, while the European Union has committed €2 billion to enhance its charging infrastructure. Despite these efforts, there are still hurdles to overcome to ensure fast, widespread, and affordable charging, particularly in rural and underdeveloped areas[52,53].

With the rise of electric buses and engineering vehicles, an alternative approach is being developed, particularly in urban areas. Electric buses, which now make up over 30% of the bus fleet in cities like Shenzhen, China, offer a potential solution to the infrastructural challenges faced by metropolitan transit systems[52]. To minimize downtime, these buses often utilize fixed-route fast-charging systems that recharge at specific terminals or depots. Additionally, at designated hubs, electric engineering vehicles, such as delivery trucks and construction machinery, are being equipped with high-capacity quick-charging technology. This model provides reliable and flexible options for heavy-duty and public vehicles while reducing the need for extensive public charging infrastructure. London's electric bus fleet currently includes over 300 fully electric buses, and this number is expected to grow as the city aims for a completely emissions-free fleet by 2037. Additionally, Volvo Construction Equipment has already introduced several electric excavators and wheel loaders across Europe. Cities can address the challenges of electric vehicle (EV) adoption and make significant strides toward sustainable transportation systems by developing charging infrastructure and implementing innovative solutions, such as fixed-location charging for buses and heavy machinery[54-56].

STRATEGIC MEASURES FOR ENERGY EFFICIENCY

Reducing energy use, lowering emissions, and achieving net-zero goals rely significantly on strategic energy efficiency initiatives. These initiatives encompass a wide range of strategies, including market-based approaches, technological advancements, and government regulatory frameworks. One key tactic is the implementation of building codes and energy efficiency standards, which ensure that new constructions and renovations meet specific energy-saving requirements[33]. Governments can further encourage businesses and consumers to adopt energy-efficient technologies by providing financial incentives such as grants, tax breaks, or subsidies. Moreover, the integration of EMS in buildings, infrastructure, and industries facilitates ongoing monitoring, control, and optimization of energy consumption[57]. Larger-scale digital solutions and smart grid technologies, such as big data and artificial intelligence, can enhance the efficiency of power distribution, reduce losses, and facilitate the integration of renewable energy sources. Policy initiatives like carbon pricing, emissions trading schemes, and energy performance labeling provide financial incentives for both producers and consumers, promoting energy efficiency. Moreover, behavioral interventions, including public awareness campaigns and demand-side management programs, are essential in encouraging energy-saving habits among individuals and businesses. Energy efficiency goals are further supported by efficient urban design, the promotion of energy-efficient public transportation, and the electrification of transportation fleets. Finally, encouraging global cooperation and information exchange can accelerate the adoption of best practices worldwide, ensuring that energy efficiency strategies are adaptable and scalable to different geographic and economic contexts. When combined, these strategic actions create a comprehensive approach to increasing sector-wide energy efficiency, reducing emissions, and striving toward a sustainable, net-zero future.

Achieving net-zero emissions requires a comprehensive strategy that focuses on several key areas [Figure 4]. This includes decarbonizing energy systems, electrifying essential sectors, improving energy efficiency, and employing carbon removal methods. Transitioning to renewable energy sources, enhancing efficiency in buildings and industries, adopting carbon capture technologies, and implementing circular economy practices are vital steps in this process. To drive global progress toward sustainability and climate resilience, policymakers, industries, and individuals need to work together. Strategies [Table 3], such as carbon pricing, promoting sustainable consumption, and increasing investment in clean technologies, will play a crucial role in net zero emission and energy efficiency.

RENEWABLE ENERGY CONSUMPTION PATTERN

Between 2024 and 2030, the use of renewable energy in the transportation, heating, and power sectors is expected to increase by almost 60% [Figure 5]. As a result, the proportion of renewable energy in total energy consumption will grow from 13% in 2023 to over 20% by 2030[59,60]. This expansion is attributed to ongoing legislative support in more than 130 countries, declining costs, and the increasing use of electricity for heat pumps and road transportation. More than three-quarters of this increase will come from power generation using renewable sources. Additionally, around 15% of the anticipated rise in demand for renewable energy will come from renewable fuels, such as hydrogen, e-fuels, and liquid, gaseous, and solid bioenergy[61,62]. The percentage of renewable energy in the electricity sector is expected to increase from 30% in 2023 to 46% by 2030. Solar and wind power are expected to be the primary drivers of growth in renewable energy. This rapid expansion will contribute to reducing carbon emissions in several energy-consuming sectors, including building heating, industrial operations, and electric vehicle charging, while also enhancing the electricity sector. By 2030, renewable hydrogen, produced using renewable electricity, is projected to meet about three-quarters of the demand for hydrogen[63,64]. The increasing use of renewable energy in transportation and heating is mainly driven by renewable electricity. It is expected that approximately 20% of heat demand will be met by renewable sources, including ambient heat, solar thermal, geothermal, and solid and gaseous biofuels. The transportation sector is also projected to see increased use of liquid biofuels in road, aviation, and marine transportation, along with some contribution from hydrogen and e-fuels, bringing the renewable energy share in this sector to 6% of total demand. Despite the growth in renewable energy, electricity will still represent a modest portion of global energy consumption, accounting

Table 3. Different strategic measures for achieving net-zero emissions and energy efficiency (Adapted from Lou and Hsieh[57]; Dai *et al.*,[58])

Strategic measure	Description	Actions	Sector focus
Transition to renewable energy	Transition from fossil fuels to clean, renewable energy sources such as solar, wind, hydro, and geothermal energy	Expand renewable energy infrastructure; Incentivize renewable energy adoption	Energy, electricity, transport
Energy efficiency improvements	Minimize energy consumption by utilizing efficient technologies, processes, and building designs	Implement energy-efficient appliances; Upgrade building insulation; Promote energy-efficient lighting	Buildings, industry, transportation
Electrification of different sectors	Transition from fossil fuel-based systems to electric systems powered by renewables (e.g., electric vehicles, electrified heating)	Promote electric vehicles; electrify heating and cooling systems	Transport, buildings, industry
Carbon capture, utilization, and storage (CCUS)	Capture CO_2 emissions from industrial processes and power generation, storing them underground or using them in other applications	Develop CCUS infrastructure; Invest in research for direct air capture technologies	Power generation, industry, cement
Sustainable agriculture & land use	Implement practices that reduce emissions from agriculture and land use, and enhance carbon sequestration	Promote regenerative agriculture; Protect forests and increase afforestation; Optimize land management	Agriculture, forestry, land management
Carbon pricing & market mechanisms	Implement policies to put a price on carbon to incentivize emission reductions across sectors	Introduce carbon taxes; Set up cap-and-trade systems; Encourage corporate carbon footprint reporting	Economy, finance, industry
Green financing & investment	Mobilize financial resources to support low-carbon technologies and sustainable infrastructure	Create green bonds; Promote sustainable investing; Direct subsidies and tax incentives to green tech	Finance, energy, industry
Circular economy	Promote resource efficiency by reducing waste, reusing materials, and recycling, reducing emissions linked to production and disposal	Design for product longevity; Increase recycling rates; Develop circular supply chains	Manufacturing, waste, construction
Behavioral and lifestyle changes	Encourage societal shifts toward sustainable practices and consumption patterns that reduce carbon footprints	Promote plant-based diets; Encourage sustainable travel habits; Foster a sharing economy	Households, transportation, industry
Green building standards and retrofits	Establish and enforce building codes and standards to ensure energy-efficient construction and retrofitting of existing buildings	Enforce energy codes for new buildings; Retrofit old buildings to meet efficiency standards	Buildings, construction, industry

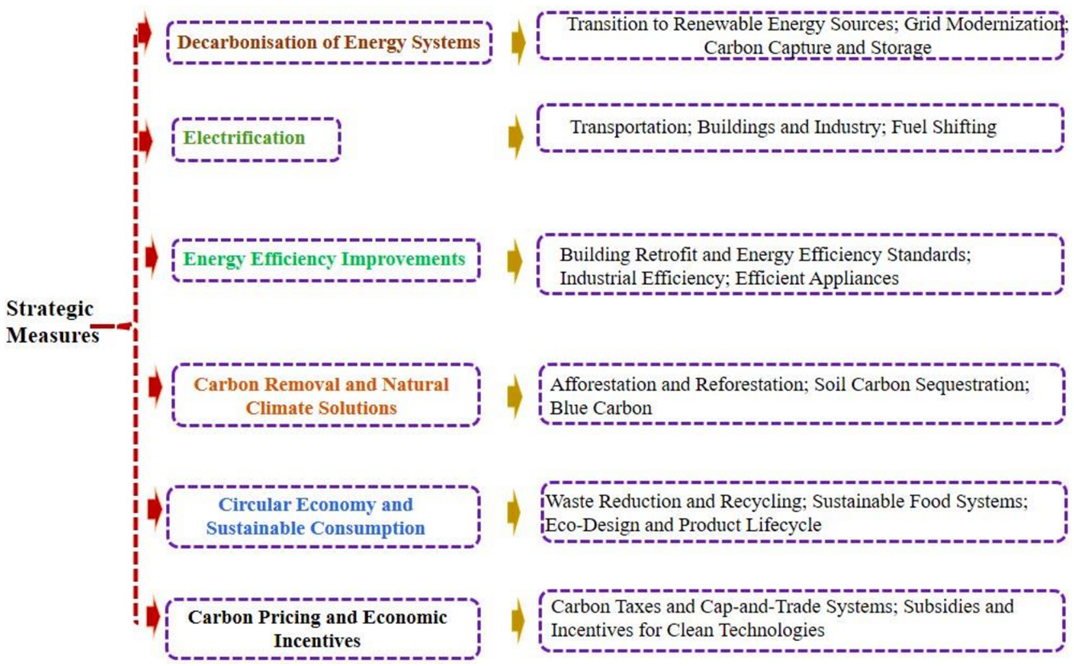

Figure 4. Different priority areas to achieve the net zero emission.

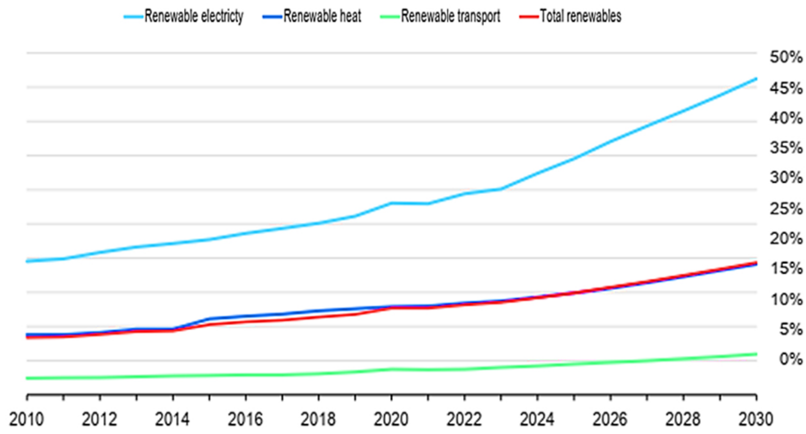

Figure 5. Share of renewable energy in global final energy consumption by sector [Modified after IEA[61]].

for 23% by 2030, which is only a 4% increase from 2023. To drive growth in the transportation and heating sectors, a diversified approach is needed. This includes accelerating electrification, improving energy efficiency, and expanding the supply of renewable fuels and other energy sources such as solar thermal and geothermal for heating purposes.

Renewable energy sources are predicted to generate 46% of the world's electricity by 2030, with solar PV and wind making about 30% of this total. Significantly, by that year, solar photovoltaics will overtake hydropower as the primary renewable electricity generation source, closely followed by wind[60]. By 2030, it is projected that variable renewables will account for two-thirds of the world's renewable electricity, compared to the current level of less than 45%. During this period, wind power is expected to almost double, while hydropower's share will decrease, and the proportion of solar PV in the world's power consumption will triple. Despite a slight decline in its share of total power output, hydropower generation is still expected to increase globally due to the commissioning of new projects, particularly in emerging and developing nations[65,66]. At present, less than 3% of energy is obtained from alternative renewable sources such as geothermal, concentrated solar, and biofuels. Projections suggest that 90% of the world's renewable energy will come from variable sources soon, leading to an increased need for flexibility in power systems. Despite the vital role that bioenergy, geothermal, and concentrated solar power play in integrating wind and solar PV into global electricity systems, their expansion remains limited[60]. Except for China, the renewable energy capacity in the Asia-Pacific region is expected to increase by more than 680 GW between 2024 and 2030, nearly doubling the growth rate observed from 2017 to 2023. It is anticipated that the region's total installed renewable capacity will grow by a factor of 2.2, surpassing the combined national goals of the participating countries. Almost half of this increase is projected to come from India, while the ASEAN region is expected to contribute another 14%. Two-thirds of this expansion will stem from utility-scale solar PV projects, accounting for more than 70% of the total additions in renewable energy capacity. This growth is primarily driven by India's extensive large-scale PV installations. In the rest of the region, the development of solar PV is evenly divided between large-scale and distributed applications, except in India. To account for the slower-than-expected growth in the ASEAN region, the regional forecast has been revised upward by 15% from the previous year, promising developments in Korea and India[61].

India is expected to nearly triple its renewable energy capacity from 2022 to 2030, maintaining its status as the third-largest renewable energy market. The country will add 350 GW between 2024 and 2030, more than three times the capacity of the previous six years, with utility-scale photovoltaic (PV) systems accounting for

60% of this growth. In the first half of 2024, a record 33 GW of capacity was awarded, over 50% more than the total for all of 2023[67]. This underscores that competitive auctions are the primary driver of large-scale project growth. This year, hybrid systems, which combine PV, wind, and storage technologies to reduce generation variability and facilitate system integration, received 40% of the capacity. As a leader in promoting hybrid plants, India is a strong example for other nations aiming to mitigate the impacts of variable renewable energy (VRE) on power system operations[68].

Recent studies offer a variety of perspectives on the factors influencing renewable energy consumption, utilizing different methodologies and focusing on various geographic regions. For example, Nyantakyi *et al.* concentrate on West African countries and find that economic growth and environmental taxes have a positive impact on the adoption of renewable energy, while financial development has a negative effect[69]. They emphasize the importance of strong institutions and regulatory frameworks. Furthermore, Li *et al.* expand this analysis by examining renewable energy consumption in China, incorporating the roles of international trade and production structures[70]. Their findings underscore the growing significance of optimizing both energy consumption and industrial structures to foster renewable energy growth. Recently, Pata *et al.* adopted a different approach by investigating the relationships among renewable energy types, economic growth, and environmental quality in the USA[71]. They identify a bidirectional causality between renewable energy consumption and economic growth, illustrating that renewable energy can enhance environmental quality. Lazzari *et al.* focus on the practical optimization of Renewable Energy Communities (RECs), demonstrating how advanced optimization methods can reduce energy waste, increase self-consumption, and minimize CO_2 emissions[72]. Dai *et al.* provides a comparative analysis of energy policy uncertainty, revealing that instability in energy policy can hinder the uptake of renewable energy and obstruct energy transitions in G7 countries[73]. Despite their diverse methodologies, nearly all studies emphasize the critical importance of policy frameworks and technological innovations in promoting the adoption of renewable energy. They highlight the necessity for region-specific strategies and stress the need for stable and effective energy policies to achieve sustainable energy transitions worldwide.

The growth of renewable energy adoption can be attributed to ongoing legislative support in over 130 countries. This support includes a combination of financial incentives, subsidies, and regulatory measures designed to accelerate the use of renewable energy technologies[61]. Many nations have established renewable energy targets or mandates that require a specific percentage of energy generation to come from renewable sources. In addition, governments often provide tax breaks or subsidies to lower the initial capital costs of renewable energy projects, such as wind and solar farms, which improves the feasibility of these technologies[61]. Furthermore, investments in renewable energy are encouraged through mechanisms like feed-in tariffs or power purchase agreements that guarantee fixed rates for renewable electricity. Carbon pricing schemes and environmental taxes also motivate businesses to reduce GHG emissions, supporting the transition to cleaner energy sources. These combined legislative efforts help eliminate financial barriers to renewable energy adoption, especially in developing countries where cost is a significant challenge. Overall, these regulations create a stable and predictable market for renewable energy investments, ensuring continued growth and facilitating the global transition to a low-carbon economy.

ENERGY CONSUMPTION IN DIFFERENT BUILT ENVIRONMENTS

Despite the urgent need to address climate change, CO_2 emissions and global energy consumption continue to rise[74,75]. Increases in wealth and population driven by globalization have fueled this growth. However, these effects have largely been mitigated by improvements in efficiency, allowing wealth to grow faster than consumption. Over the past 20 years, energy demand and emissions have increased at similar rates, hindering decarbonization efforts[76]. Nevertheless, growth rates have slowed since 2013, and the COVID-19 pandemic has significantly impacted emission trends, suggesting that a stabilization may be underway[77]. Regional disparities highlight the divisions in the world. For example, in 2019, non-OECD developing nations accounted for about 53% of global economic activity, supported 82% of the world's population, and represented approximately two-thirds of global consumption and emissions[78]. In contrast, individuals in industrialized countries (OECD) had incomes four times higher, with around three times more emissions and per capita consumption[79]. While this also leads to increased energy demand, the gap is narrowing as emerging economies in developing countries work to improve living standards. Fortunately, as these poorer nations strive to reduce inequality, it is expected that decreases in consumption and emissions in developed regions will offset increases in those areas.

Buildings, transportation, industry, and smaller operations like farming and forestry are the main sectors consuming energy globally. In 2019, total energy consumption reached 9.1 Gtoe, with buildings as the largest consumers, followed by transportation and industry. Since 2000, energy use in buildings has grown annually by 1.2%, driven by population growth, increased built area, and more time spent indoors, a trend that has persisted even during the COVID-19 pandemic and the 2008 economic downturn[80]. Future projections suggest that energy use in buildings will continue to rise, especially in developing nations, unless stricter regulations are enforced. Buildings account for about one-third of global energy consumption and 25% of CO_2 emissions[81,82]. In high-consuming countries like Russia (42%), the EU (41%), Japan (37%), and the US (34%), these figures are even higher. This significant impact has made buildings central to climate policies due to their potential for improving energy efficiency and utilizing renewable energy[83]. The energy consumption patterns of the different built environments based on different components are summarized in Table 4.

Several studies have examined energy use in buildings, highlighting the sector's importance as the largest energy consumer in the world. However, researchers have faced challenges due to data limitations that impede comprehensive analysis. Pérez-Lombard *et al.* identified buildings as significant energy consumers in various countries and noted the difficulties in data availability, which hinder more detailed assessments[85]. Ürge-Vorsatz *et al.* expanded on this by providing an overview of energy use in residential and commercial buildings as of 2010[87]. They pointed out essential factors that influence heating and cooling demands, including climate, building age, and energy prices. This overview was instrumental in outlining the diverse factors that affect energy consumption across different types of buildings.

Berardi[88] expanded on previous research by analyzing historical trends in energy use up to 2010, comparing regions such as the United States, the European Union, and the BRIC nations. He advocated for efficiency initiatives to mitigate rising energy demands. Building on his work, Allouhi *et al.* revisited energy use data from 2011 across countries such as the United States, Australia, China, and the European Union, providing deeper insights into energy-saving strategies[89]. They emphasized the need for more detailed data to effectively target policies, given the variability of energy use across different nations. Cao *et al.* further explored energy use and efficiency in China, the United States, and the European Union in 2012, with a particular focus on Zero Energy Buildings (ZEBs) as a potential model for reducing consumption[90]. In addition to broader regional studies, Lu and Lai[91] examined energy policies in the US, China, Australia, and the UK up to 2015. They emphasized the need for tailored policies to promote renewable energy, particularly in wealthier nations where the adoption of renewable energy is more feasible. Additionally, Guo *et al.* contributed to the discussion by analyzing energy consumption and emissions across several countries in 2017[92]. They suggested groupings based on specific policy needs and explored how factors such as population size and energy mix impact overall building energy demand. Despite ongoing efforts, challenges regarding data in the building sector continue, particularly in classifying building energy

 Bera *et al. Carbon Footprints* **2025**, *4*, 3 | https://dx.doi.org/10.20517/cf.2024.48

Table 4. Different factors that influence the energy consumption pattern of the built environment (Adapted from Wang *et al.*,[84]; Pérez-Lombard *et al.*,[85]; Wang *et al.*,[86])

Built environment factor	Residential areas	Commercial areas	Mixed-use areas	Key energy impact
Building orientation & design	South-facing windows for passive solar heating reduce HVAC needs	Optimized for daylighting, reduces lighting consumption	Mixed orientations balancing sun exposure & shading	Proper design can reduce heating, cooling, and lighting costs
Land use & land cover (NDVI)	Higher vegetation (green areas) reduces the urban heat island effect, lowering cooling costs	Green spaces can reduce energy consumption by lowering heat load	Green spaces can be integrated into high-density areas, providing cooling	High NDVI correlates with reduced cooling demand and energy savings
Urban green spaces (parks)	Urban parks provide natural cooling, reducing residential energy use for AC	Parks lower the heat load on buildings, saving energy in commercial spaces	Mixed-use areas with parks can lower the overall neighborhood energy consumption	Proximity to green spaces reduces reliance on mechanical cooling
Building configuration (aspect ratio, floor area)	Larger floor areas and compact designs increase energy use for heating/cooling	Taller buildings with poor insulation increase heating and cooling costs	Optimized mixed-use buildings can balance energy loads across different uses	Building size, insulation, and shape directly influence heating and cooling needs
Building materials (insulation, windows)	Well-insulated homes reduce heating and cooling demand	Commercial buildings with high-performance windows cut HVAC energy use	Mixed-use buildings require strategic material selection to balance energy efficiency	Advanced materials, like low-emissivity windows, improve energy efficiency
Building systems (HVAC, lighting)	Efficient HVAC and smart lighting reduce overall consumption	HVAC systems with zoning and smart controls reduce energy use	Mixed-use buildings often employ district heating and cooling, improving efficiency	Smart systems and efficient HVAC reduce energy use across all sectors
Density (floor area ratio)	Low-density areas may have larger energy needs due to dispersed energy sources	High-density buildings in commercial areas can share energy resources, improving efficiency	Mixed-use areas reduce transportation energy use and optimize shared infrastructure	Higher density generally leads to more efficient energy usage in commercial and mixed-use settings
Energy mix (fossil fuels *vs.* renewables)	Residential areas often rely on grid electricity; solar panels increase energy independence	Commercial buildings are increasingly incorporating renewable energy sources	Mixed-use buildings may use district energy or onsite renewables (solar, geothermal)	Renewable integration reduces reliance on fossil fuels, lowering overall consumption
Climate zone & external factors	In colder climates, buildings consume more energy for heating; in warmer climates, cooling dominates	Commercial areas in hot climates use more energy for cooling	Mixed-use areas in coastal regions may optimize natural ventilation to reduce cooling needs	Climate-specific design can drastically reduce energy demand, particularly for heating/cooling
Technology integration (smart controls)	Smart meters and thermostats help optimize energy consumption	Smart building technologies like lighting and HVAC controls reduce operational costs	Smart grids and integrated building systems improve energy efficiency across mixed-use spaces	Real-time monitoring and automated systems optimize energy consumption in all sectors

consumption. Many buildings are often grouped into a vague "Other" category, which obscures the true magnitude of their energy use. Although some datasets do differentiate between "Residential" and "Services," this distinction remains a temporary fix. For example, estimates indicate that nearly 10% of building energy consumption may include non-building services, such as postal services, water supply, and street lighting[93,94]. These inconsistencies complicate comparisons across different sectors and impede the development of targeted energy-saving strategies.

The energy mix in buildings is a crucial area of consideration, as it significantly affects both CO_2 emissions and primary energy consumption. Yang *et al.* examine how different energy sources, such as electricity, biofuels, natural gas, and renewables, impact building performance[95]. However, measuring the use of renewable energy, particularly biomass, remains challenging, especially in lower-income countries where biomass is heavily relied upon. Additionally, technologies like heat pumps, which increase electricity usage for heating, add complexity to the situation. Fossil fuels still dominate heating, while electricity is primarily used for cooling, given the limited market for gas-powered cooling systems[96,97].

Numerous studies have investigated the technological, environmental, and socio-economic factors that influence energy efficiency in buildings. For instance, Wang *et al.* explored how land use and building configuration affect energy consumption, revealing that the design and spatial arrangement of buildings significantly impact energy efficiency[84]. Additionally, Wang *et al.* focused on the influence of urban parks, demonstrating that proximity to green spaces can reduce energy consumption in urban areas[86]. These studies highlight the importance of incorporating spatial and design elements when evaluating energy use in buildings. In contrast, Arsecularatne *et al.* introduced Digital Twin (DT) technology as an innovative method for realtime monitoring and optimizing building energy usage[98]. This technology offers a data-driven solution by providing a digital replica of building operations, which enhances efficiency through continuous monitoring and adjustments. Meanwhile, Alimohamadi and Jahangir[99] approached the issue from a practical perspective, emphasizing the retrofitting of existing buildings in Iran using optimization algorithms and tools such as MATLAB and EnergyPlus. Their approach considers the local economic context, including energy pricing and subsidies, to ensure that retrofitting strategies are economically viable. Additionally, Chen *et al.* investigated household energy consumption patterns, providing a behavioral perspective on energy demand[100]. Their research emphasizes the significance of understanding consumer behavior and how factors such as socio-economic status, cultural practices, and awareness of energy efficiency affect household energy use over time. Overall, these studies highlight the complexity of reducing energy consumption in buildings. Technological advancements like Digital Twin technology and design interventions such as green spaces show promise, but there is no universal solution. The variety of approaches including optimizing infrastructure and promoting consumer behavior change underscores the need for a multifaceted strategy. Each study offers valuable insights while emphasizing the importance of addressing data challenges and tailoring solutions to the specific contexts of various regions and building types.

THE FUTURE OF ENERGY EFFICIENCY: PROSPECTS AND CHALLENGES

Prospects

The efficient use of energy has become crucial in the global fight against climate change, enhancing energy security, and fostering sustainable economic growth. The energy efficiency landscape is anticipated to evolve in the future due to various trends and emerging technologies. This comprehensive review examines key topics such as machine learning and artificial intelligence (AI), the importance of big data and analytics, blockchain technology, the potential of hydrogen, and other innovative solutions, as well as the overall opportunities for advancements in global energy efficiency.

Artificial intelligence and machine learning in energy management

• AI and machine learning are transforming energy management techniques by providing advanced methods to optimize energy use across various industries. These technologies utilize algorithms and data analysis to identify trends in energy consumption, enabling businesses to make more informed and efficient decisions[101].

• AI and machine learning algorithms can analyze large datasets collected from sensors, smart meters, and other sources to uncover patterns in energy use[102]. This analysis helps companies forecast demand trends and adjust their energy supply accordingly, optimizing overall energy consumption. For example, by understanding occupancy patterns, AI can control heating, ventilation, and air conditioning (HVAC) systems in commercial buildings, reducing energy usage during unoccupied hours.

• Predictive maintenance models powered by AI can anticipate equipment failures before they occur, allowing businesses to perform maintenance only when necessary. This proactive approach enhances the operational efficiency of energy-intensive equipment and minimizes downtime. For example, AI systems can monitor the performance of machines in manufacturing facilities in real time, identifying irregularities that could indicate potential breakdowns[103].

• Additionally, integrating AI with EMS enables realtime monitoring and control of energy usage across an organization[24]. By utilizing realtime pricing signals from the grid, these smart EMS can optimize power consumption and automate energy-saving measures, such as dimming lights during peak hours.

The role of big data and analytics

• The rise of big data has created new opportunities for improving energy efficiency[104]. Organizations can enhance their energy management processes by extracting insights from the vast amounts of data collected from various sources.

• With the widespread use of smart meters, IoT sensors, and smart devices, enormous volumes of energy data are generated daily. The challenge lies in efficiently gathering, integrating, and analyzing this data. Advanced analytics platforms can process this information, helping businesses identify inefficiencies and areas for improvement[104].

• By providing detailed insights into energy consumption patterns, big data analytics accelerates the process of energy audits. By comparing their performance to industry standards, organizations can set realistic goals for energy efficiency and track their progress over time. This data-driven approach fosters a culture of continuous improvement[105]. Utilities can also utilize big data to develop demand response plans that encourage customers to reduce or shift their energy usage during periods of high demand. Analytics can predict peak usage times and facilitate realtime communication with customers, offering incentives for reducing consumption, which helps stabilize the grid and optimize energy distribution[105].

Blockchain for Energy efficiency and decentralized energy markets

• Blockchain technology offers exciting opportunities for developing decentralized energy markets and enhancing energy efficiency. It can improve the overall effectiveness of energy infrastructure and enable peer-to-peer energy trading by facilitating secure and transparent transactions[106].

• With blockchain technology, customers can easily exchange any excess energy produced by renewable sources, such as solar panels, with their neighbors. This peer-to-peer trading model reduces reliance on centralized energy suppliers, fostering competition and driving down prices. By allowing consumers to sell their surplus energy at competitive rates, this system encourages the use of renewable energy sources[106].

• Blockchain technology ensures transparency, meaning that every transaction is accurately recorded and accessible to all participants. This transparency not only reduces the risk of fraud but also enhances stakeholder trust, leading to greater overall market efficiency. Additionally, smart contracts can automate transactions, simplifying processes and reducing administrative burdens[106].

The potential of hydrogen and other emerging technologies

• In the effort to decarbonize hard-to-electrify sectors, hydrogen has emerged as a promising alternative energy carrier. Alongside hydrogen, various cutting-edge technologies hold significant potential for improving energy efficiency[107].

• Hydrogen can be produced through methods such as electrolysis, which splits water into hydrogen and oxygen using renewable energy sources. This green hydrogen can then be used in fuel cells as a clean substitute for fossil fuels in industrial processes, transportation, and heating[108].

• The manufacturing of cement and steel are two major industries that can significantly reduce their greenhouse gas emissions by transitioning to hydrogen instead of relying on carbon-intensive fuels. Initiatives such as the European Commission's Hydrogen Strategy aim to promote the production and use of hydrogen across various sectors[108].

• In addition to hydrogen, other technologies like carbon capture and storage (CCS), smart grid technology, and advanced battery storage are essential for improving energy efficiency. Advanced batteries enable better integration of renewable energy into the grid, while CCS helps to lower emissions from fossil fuel consumption[109].

Numerous industries are already experiencing measurable benefits from the use of advanced technology in energy management. For example, AI-driven energy optimization has led to significant cost reductions. A pilot study conducted by Siemens in Germany found that implementing AI for demand response and predictive maintenance reduced energy consumption in manufacturing plants by 15%[101,102]. Additionally, BIG-DATA analytics have transformed energy audits. For example, AI-driven technologies can identify inefficiencies in real time and reduce energy waste in industrial settings by up to 20%[104,105]. Furthermore, a real-world example of blockchain technology in decentralized energy markets is the "Power Ledger" project in Australia. This initiative allows users to exchange surplus solar energy with their neighbors through blockchain, demonstrating the technology's potential to foster a more sustainable and decentralized energy model[106]. During its trial period, it successfully reduced grid dependency and increased the use of locally generated solar energy by 50%. Moreover, in industries that are difficult to electrify, hydrogen technologies are making significant strides in reducing emissions[107,108]. For instance, a joint venture between Shell and ITM Power in the UK has initiated a green hydrogen plant expected to cut carbon dioxide emissions by approximately 20,000 tons per year[107]. This effort aids in decarbonizing sectors that are challenging to reduce, such as industrial heating and heavy transportation. These examples illustrate that the integration of blockchain, AI, and BIG-DATA analytics is not just a theoretical concept but a practical reality that is actively shaping sustainability and energy efficiency for the future.

Challenges in achieving net zero

Combating climate change requires achieving net zero emissions through energy efficiency, but several obstacles may stand in the way. A multidimensional strategy including several stakeholders, such as governments, corporations, and communities, is needed to address these challenges.

• ***Initial costs:*** One major obstacle may be the initial outlay of funds needed for energy-efficient solutions. Many people and organizations could be reluctant to spend money on upgrades that, although eventually cost-effective, might not pay for themselves for years. This is especially true in developing nations with low financial resources.

• ***Technological integration:*** It might be difficult to incorporate new, energy-efficient technology into systems that already exist. Businesses frequently encounter difficulties while attempting to modify their current infrastructure, which may call for certain knowledge and abilities that are not always readily available in the labor market. Adoption may be further discouraged by downtime and extra expenses resulting from this integration.

• ***Lack of awareness:*** Advancement may be hampered by a general lack of knowledge about the advantages of energy efficiency. Many people are unaware of the significant financial and environmental savings that can result from energy-efficient measures. Both at the individual and organizational levels, this ignorance may lead to resistance to change.

• ***Regulatory barriers:*** Differing laws and policies in various areas might lead to misunderstandings and make it more difficult to put energy-saving initiatives into practice. If future regulatory frameworks or financial incentives are uncertain, businesses can be hesitant to invest in energy-efficient technologies. To encourage investment, a stable and unambiguous policy environment is necessary.

• ***Data gaps:*** It is challenging for stakeholders to identify and rank areas for improvement when there is a lack of information on energy consumption trends and efficiency prospects. It is difficult to quantify the effects of efficiency programs and convince stakeholders to invest when there is a lack of complete data on energy usage.

• ***Cultural resistance:*** Public and business willingness to embrace energy-efficient measures can be influenced by a wide range of cultural views on energy consumption. Targeted educational programs are required to modify attitudes in certain cultures because of a strong emphasis on consumption or resistance to altering long-standing behaviors.

• ***Market restrictions:*** In some markets, particularly in rural or underdeveloped areas, there may not be as much access to energy-efficient goods and services. Consumers and organizations may find it challenging to implement the required modifications to achieve energy efficiency if they do not have access to this technology.

• ***Economic pressures:*** Long-term sustainability objectives may lose focus and funding due to economic downturns or volatility. Organizations may put short-term financial worries ahead of energy efficiency initiatives during lean times, which would impede their progress toward net-zero objectives.

• ***Interconnected infrastructure:*** Energy efficiency initiatives frequently call for cooperation between multiple industries, including residential, commercial, and transportation. Because of their interdependence, complex systems can make it more difficult to apply efficiency gains because modifications made in one place may have unforeseen effects in another. Furthermore, the absence of standardized data and measurement techniques makes it challenging to identify and quantify energy inefficiencies, which poses a significant barrier to achieving net-zero emissions. For example, the IEA[61] reports that over 30% of energy consumption in industrial sectors remains unrecorded due to inadequate data collection methods and inconsistent reporting guidelines. This lack of data hinders businesses from setting specific targets for energy savings and emission reductions. An assessment of energy efficiency in the construction industry in China revealed that nearly 40% of energy efficiency programs lacked reliable baseline data. This deficiency made it difficult to evaluate the effectiveness of efficiency improvements and to attract additional funding. Moreover, the development of effective plans for overall emission reduction is complicated by insufficient data integration across various sectors, including industry, transportation, and energy. Although advancements in smart grid technologies are being made, the widespread adoption of standardized data collection and analysis methodologies is still in its early stages. Companies like Google and Microsoft have started using AI to gather and analyze energy usage data effectively.

CONCLUSION AND WAY FORWARD

Energy efficiency is a crucial strategy in the global effort to combat climate change and achieve net-zero emissions. This comprehensive review highlights the complex relationship between energy consumption and environmental impact, emphasizing that transforming the energy sector is essential for effectively addressing the climate crisis. With energy efficiency expected to play a significant role in reducing emissions, the need for comprehensive policies, innovative technologies, and increased public awareness has never been more urgent. The integration of advanced technologies, such as energy-efficient systems in industries and smart grid solutions, demonstrates the potential for substantial improvements in energy performance across various sectors. Case studies have shown that targeted initiatives can lead to significant reductions in energy consumption, illustrating the viability of energy efficiency as a key component of sustainable development.

As renewable energy sources continue to grow, their connection with energy efficiency becomes increasingly vital for reducing carbon emissions and creating resilient energy systems. Although there are challenges, such as financial obstacles and technical complexities, the advancement of digital technologies and innovative solutions offers new possibilities for improving energy efficiency. To meet ambitious climate goals, we must not only focus on technological progress but also encourage changes in societal behaviors and policy frameworks. By prioritizing energy efficiency, we can promote economic growth while making significant progress toward a sustainable, low-carbon future. This review serves as a call to action for governments, businesses, and individuals to recognize energy efficiency as a crucial element in transitioning to a sustainable energy landscape.

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Authors’ contributions

Conceptualization, Methodology, Literature search and review, Data curation, Formal data analysis, Writing-original draft: Bera, M.
Conceptualization, Methodology, Resources, Supervision, Visualization, Co-ordination, Writing-Review & Editing: Das, S.
Conceptualization: Garai, S.; Dutta, S.; Roy Choudhury, M.; Tripathi, S.; Chatterjee, G.
All co-authors read, commented, and approved the final manuscript.

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