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REVIEW

Charting the UK's path to net zero emissions by 2050: Challenges, strategies, and future directions

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Abstract

The authors explore the various obstacles and possible approaches that the UK may take to fulfil its goal of having net-zero greenhouse gas emissions by 2050. The paper thoroughly examines several aspects of this project, such as the modernisation of infrastructure, the energy transition, the economic effects, the obstacles to research and development, changes in behaviour, and the frameworks for policy and regulation. With a 44% decrease from 1990 levels by 2021, it showcases the UK's noteworthy achievement in lowering emissions and its ambitious initiatives, such as the £12 billion Ten Point Plan, to accelerate this development. The difficulties of switching from reliance on fossil fuels to renewable energy sources, their implications for the economy, and the necessity of green technology innovation are all covered in the article. It also discusses the behavioural sides of this shift, highlighting the need to change one's lifestyle and engage the public. To address these issues, the importance of international cooperation and policymaking is emphasised. Insights into potential remedies are provided by the article, which includes energy efficiency initiatives, investments in renewable energy, assistance for clean technology R&D, green funding options, public awareness campaigns, international cooperation, and regulatory frameworks. Every one of these alternatives is examined for possible effects and obstacles. The article concludes that reaching net zero in the UK is a complex but necessary objective that calls for a concerted strategy that strikes a balance between social and economic concerns and environmental sustainability.

KEYWORDS

electric vehicles, energy conservation, energy storage, greenhouse gas, renewable energy

1 | INTRODUCTION

There has been a remarkable increase in awareness of how human activity affects the climate since the turn of the 21st century. The burning of fossil fuels, deforestation, and industrial processes have increased greenhouse gas emissions, or GHGs, which has led to climate change. This poses a severe threat to the planet's ecosystems, human health, and the economy. As a result, the idea of "net zero" emissions, which aims to balance the quantity of GHGs released into the atmosphere with an equal amount removed, has become a significant objective for nations all over the world [1]. There is no denying the integrity of the evidence of climate change and its extensive effects. The past 10 years have been the warmest on record due to a steady increase in global temperatures. A series of environmental consequences, including melting polar ice caps, increasing sea levels, and a rise in the frequency and intensity of extreme weather events such as hurricanes, droughts, wildfires, and the destruction of natural ecosystems, have been brought on by global warming. In addition to posing a threat to human livelihoods, these changes have an adverse effect on agricultural water supplies and even raise the possibility of pandemics. Figure 1 reproduced from [2] shows the transition towards sustainability.

The scientific community has been instrumental in proving the connection between human activity and climate change, working through organisations such as the Intergovernmental Panel on Climate Change (IPCC). Their reports offer thorough evaluations of the state of science regarding climate change and have played a significant role in directing global policy. Global governments have united under the United Nations Framework Convention on Climate Change in reaction to these results (UNFCCC) [3]. The 2015 Paris Agreement, which committed 196 nations to keeping global warming well below 2 degrees Celsius, ideally, to 1.5 degrees Celsius above pre-industrial levels, marked a significant milestone in this path [4]. Achieving net zero entails striking a balance between the amount of greenhouse gases released into the environment and their removal. This idea is important because it acknowledges that, even though it might not be possible to totally stop all greenhouse gas emissions, we can offset these emissions by using different carbon sequestration techniques, including reforestation or carbon capture and storage technology. The net-zero concept reproduced from [5] is shown in Figure 2.

It is essential to get net zero to stabilise world temperatures. The IPCC estimates that in order to keep global warming to 1.5 °C, net human-caused carbon dioxide (CO2) emissions must decrease globally by roughly 45% from 2010 levels by 2030, and they must eventually reach net zero around 2050 [6]. In recent years, there has been a noticeable increase in the movement towards net zero. Net-zero aims are becoming a common feature of national strategies in many nations. For example, the European Union has set a goal to achieve carbon neutrality by 2050. Similar to this, the UK has made a legislative commitment to attain net-zero emissions of greenhouse gases by 2050 [7]. Even nations like Saudi Arabia and Russia, which have sizeable fossil fuel sectors, are beginning to recognise the necessity of making the shift to a net-zero future. There are possibilities as well as obstacles in the move towards net zero. The main block is changing the current energy systems, which are primarily dependent on fossil fuels. This necessitates a significant investment in the development of new technologies such as carbon capture and storage as well as in renewable energy sources such as wind, solar, and hydroelectric power. Economically speaking, the shift offers a chance for the development of new companies and the creation of jobs in the renewable energy industry. Additionally, it presents an opportunity to address problems such as energy security and reduce air pollution, all of which have significant positive health effects. Figure 3 reproduced from [8] shows the graph of CO_2 emissions per person.

The transition to net zero involves social and political concerns in addition to technical and financial ones. Individual behaviours, corporate procedures, and regulatory frameworks all need to change. Public understanding and support are required, and these can be developed through initiatives for awareness and education. One major worry in this transition is inequality. The developing world, which produces the fewest emissions worldwide, is frequently the one most susceptible to the effects of climate change. Therefore, equitable global climate action is required, with wealthy nations aiding developing nations in their shift to environmentally friendly technologies. For several decades, the United Kingdom has been progressing towards

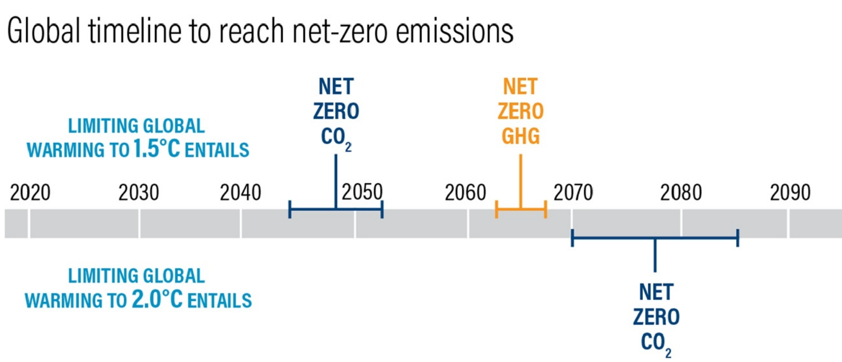

FIGURE 1 Transition towards sustainability.

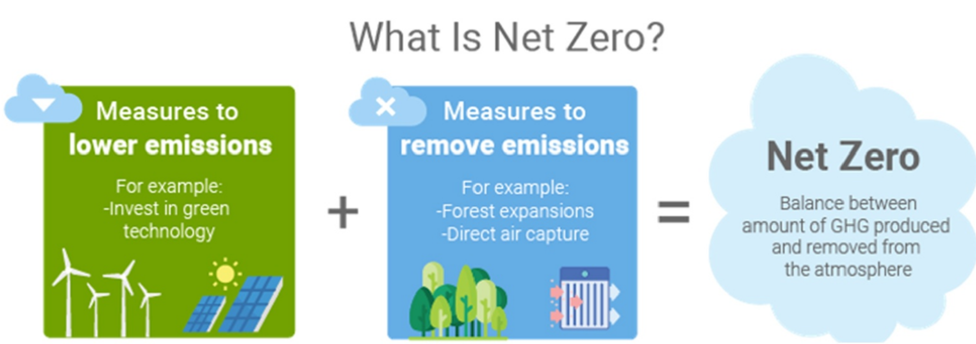

FIGURE 2 Net-zero concept.

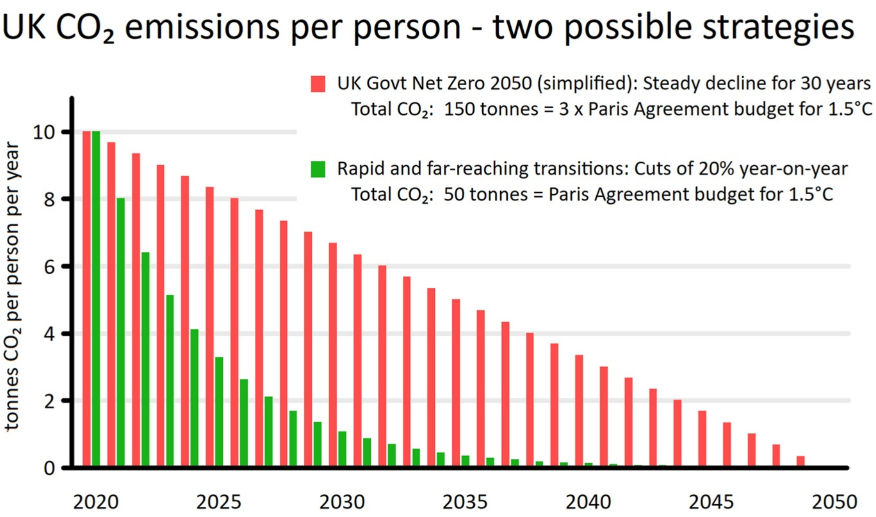

FIGURE 3 Graph of UK CO_2 emission per person.

environmental sustainability and lower carbon emissions. Initially, the historic Climate Change Act of 2008 established a legally mandated goal to cut greenhouse gas emissions by 80% by 2050 when compared to 1990 levels [9]. However, the UK government changed this goal in 2019 to reach "net zero" GHG emissions by 2050 in response to the mounting evidence of the effects of climate change and the growing imperative for more aggressive action globally [10]. The UK establishes itself as a pioneer in climate action by becoming among the first big economies to enact a net-zero aim, setting a standard that other countries can emulate.

Reaching net zero is anticipated to improve public health and the environment by resulting in cleaner air, less pollution, and healthier lifestyles. In the emerging "green economy," this goal is thought to spur innovation, green jobs, and sustainable technologies while also promoting economic growth. Energy security in the UK will be improved, and reliance on imported energy will be decreased by shifting from fossil fuels to renewable energy. The UK recognises its role in tackling the climate catastrophe and its effects, particularly on vulnerable groups and nations, as a historical contributor to global emissions [11].

The UK has achieved a substantial reduction in greenhouse gas (GHG) emissions, with a 44% decline from 1990 levels reported by 2021 [12]. The decrease was mainly accomplished by transitioning from coal-powered energy generation to renewable energy sources. In 2020, renewable energy sources such as wind, solar, and biomass will make up around 43% of the UK's electricity production, exceeding fossil fuels for the first time [13]. The UK possesses one of the world's largest offshore wind capacities, attracting substantial investments and demonstrating the nation's dedication to utilising its geographical strengths for producing renewable energy. The UK has introduced innovative policies and programmes such as the Carbon Pricing Mechanism and the Green Finance Strategy to encourage investment in green technologies and projects. The government's Ten Point Plan for a Green Industrial Revolution highlights crucial actions such as developing offshore wind, encouraging hydrogen production, and facilitating the shift to electric vehicles (EVs), aiming to stop the sale of new petrol and diesel cars by 2030.

In 2020, the UK had more than 24 GW of wind energy capacity installed, ranking it as the sixth-largest wind energy generator globally. The solar power capacity has surpassed 13 GW, with biomass and hydropower electricity adding to the renewable capacity [14]. Electric vehicle sales in the UK have been rapidly increasing, with electric cars accounting for over 10% of new car registrations in 2020. Meeting the government's goal of phasing out the sale of new petrol and diesel cars by 2030 will necessitate a substantial increase in the adoption rates of electric vehicles. In 2020, the UK's Carbon Price Support (CPS) was established at £18 per tonne of CO_2 to work alongside the EU Emissions Trading System (ETS) [15]. The UK has implemented its own emissions trading system (ETS) after Brexit to promote additional reductions in carbon emissions. The Committee on Climate Change projects that achieving net zero will necessitate an annual investment equivalent to about 1%–2% of the UK's GDP. This pertains to investments in renewable energy sources [16].

2 | CHALLENGES IN ACHIEVING NET ZERO IN THE UK

Figure 4 reproduced from [16] shows the common challenges in achieving a net zero in UK.

2.1 | Energy transition challenges

Fossil fuels such as coal, oil, and natural gas have long dominated the world's energy scene. The foundation of contemporary civilisation, economic expansion, and industrial progress has been these resources. However, the use of fossil fuels has adverse effects on the environment, especially when it comes to accelerating climate change [17]. For this reason, a move towards renewable energy sources is now necessary. Despite being required, this shift is fraught with difficulties.

FIGURE 4 Challenges in achieving net zero in the UK.

Since fossil fuels are very easy to collect and use, they have been the primary source of energy for centuries. Our homes, businesses, and transit networks are all run by them. However, there is a high environmental cost associated with this reliance. The primary source of carbon dioxide emissions, a significant greenhouse gas causing global warming, is the burning of fossil fuels. Fossil fuels continue to be a substantial contributor to the world's energy consumption despite increased awareness and the push for renewable energy sources. Fossil fuels are vital to many economies, particularly those in developing nations, for economic growth and stability [18]. Fossil fuels are the primary building block of the current energy generating, distribution, and consumption infrastructure. High energy output and the consistent ability to meet varying energy demands are features of fossil fuels. In 2021, the International Renewable Energy Agency (IRENA) stated that over 80% of new electrical capacity worldwide came from renewable energy sources, indicating a substantial transition towards renewables. The Global Energy Monitor reported that the operating capacity of renewable energy worldwide was approximately 2799 GW in 2020, showing growth compared to prior years [19].

2.2 | Infrastructure modernisation challenges

The UK has a great deal of difficulty in achieving net zero due to the requirement for massive infrastructure upgrades. Upgrading the energy grid to accept a more significant percentage of renewable energy is essential, and by 2050, this will require an expenditure of almost £40 billion [20]. With the transportation sector accounting for nearly 27% of the UK's total emissions in 2019, there needs to be a transition to electric vehicles (EVs) and a corresponding increase in the infrastructure for charging them [21]. This means that by 2030, there should be 300,000 public EV charging stations, up from about 35,000 in 2021 [22]. With over 29 million households in need of upgrades like insulation and low-carbon heating systems, upgrading existing structures for energy efficiency is a massive undertaking in the building and construction industry. The difficulty of creating and implementing cutting-edge technology, such as carbon capture and storage (CCS), which is required to decarbonise heavy industries, is another [23]. Realising the UK's ambitious net-zero ambitions would require not only significant financial investment but also coordinated regulatory frameworks, technical improvements, and public-private partnerships in addition to these infrastructure reforms. Even while technology is developing quickly, there are still certain obstacles to overcome, especially when it comes to energy storage and integrating renewable energy sources into the grid [24]. Inconsistent or antiquated policies and regulations may impede the adoption of contemporary infrastructure technologies and practices. The infrastructural systems that are in place now have been established for many years. Because massive systems have intrinsic inertia, it is generally tricky to transition these systems to more sustainable options [25]. The current labour market is not able to meet the growing need for a workforce knowledgeable in new technology and sustainable practices. Coordination amongst several stakeholders, including the public and private sectors as well as communities, is necessary for modernising infrastructure, but it cannot be easy. It is challenging to make sure that the advantages of contemporary infrastructure benefit every segment of society, especially disadvantaged and vulnerable groups.

2.3 | Economic challenges

The urgent need to address climate change will force a global shift towards a low-carbon, sustainable economy that will have far-reaching effects on many different economic sectors. This shift has substantial financial implications despite its primary environmental objectives. While some industries will have difficulties, others will see new opportunities. The UK faces formidable economic obstacles in its quest to achieve net-zero emissions by 2050. The largest of these is the significant financial outlay that will be necessary; according to the Climate Change Committee, 1–2 percent of the UK's GDP will need to be spent per year [26]. This amounts to billions of pounds annually in fields such as technology, infrastructure, and renewable energy. Additionally, the workforce and traditional industries are negatively impacted economically, especially in sectors that primarily rely on fossil fuels. This calls for investments in job retraining and regional economic diversification. Potential short-term effects of the shift on economic growth and competitiveness include how companies will respond to new laws and environmentally friendly technologies. Managing the costs that are passed on to consumers is another aspect of the transition to a low-carbon economy, especially in the energy and transportation sectors. The UK's net-zero plan is made more complex by the need to strike a balance between these economic objectives, provide fair access to green technologies, and minimise any regressive effects on lower-income households [27].

The most significant change will be seen in the energy sector, which is at the centre of the shift. The energy landscape will change as fossil fuels give way to renewable energy sources such as wind, solar, and hydro. Traditional producers of coal, gas, and oil may experience a drop in demand, which would affect their earnings and personnel. Infrastructure built using fossil fuels could become stranded assets. The advent of electric cars (EVs), biofuels, and public transportation networks is bringing about a revolution in the transportation industry, which is a crucial contributor to greenhouse gas emissions. Manufacturers who have made significant investments in internal combustion engines might find it challenging to make the switch [28]. A decline in oil consumption would have an impact on economies that depend on oil exports. To lessen its carbon footprint, the manufacturing sector will need to adjust to new materials and procedures. The adoption of greener technologies by industries will come with costs, and supply chains and customer preferences may shift as a result. Agriculture will need to adapt to sustainable techniques as it is both a cause and a sufferer of climate change. The productivity of agriculture may be impacted by farmers having to switch to crops that are climate-resilient and deal with shifting weather patterns [29].

A study by the Global Commission on the Economy and Climate revealed that ambitious climate measures might result in economic gains of at least $26 trillion by 2030. Studies show that moving towards a low-carbon economy necessitates substantial investment, with the International Energy Agency projecting a requirement of $1.6 trillion every year until 2030 [30]. The financial industry will be essential in helping to make the shift happen through insurance and investments. Financial institutions that rely on fossil fuels and other non-sustainable practices may need to review their investment portfolios. Buildings and construction-related activities need to become more energy-efficient because they contribute significantly to carbon emissions. Short-term costs for upgrading existing facilities and creating green may increase [31]. The shift will also affect the services industry, which includes retail, entertainment, and tourism. The service sectors will have to change to accommodate consumers' shifting inclinations towards sustainability. Through laws, rules, and public spending, governments will play a key role in guiding the shift. It will be challenging to manage the transition for impacted people and communities and to strike a balance between environmental regulations and economic growth [32]. The creation and application of new technologies are critical to the shift towards a low-carbon, more sustainable future. While technical breakthroughs could solve many of the problems caused by climate change, there are several obstacles to their development and general implementation. Comprehending these challenges is essential to formulating tactics for an effective shift.

2.4 | Research and development challenges

High Costs and Unclear Returns: Research and development (R&D) into new technologies, especially in the sustainability and renewable energy sectors, sometimes necessitate a sizeable initial investment with extended time horizons and uncertain payoffs. Significant obstacles stand in the way of research and development (R&D) as the UK attempts to achieve net zero by 2050. Accelerated innovation in green technologies is a crucial issue, particularly in fields like advanced nuclear power, hydrogen fuel, and carbon capture and storage (CCS), which are essential for decarbonising industries that are difficult to address [33]. The £1 billion Net Zero Innovation Portfolio is one example of increased investment. However, there is still a financing gap between what is currently available and what will be needed to meet the technological demands of a net-zero future. Scaling up experimental initiatives to commercially viable solutions is another difficulty; high costs and regulatory obstacles frequently impede this process. Government, academic, and business collaboration is vital yet complex; it calls for efficient procedures and well-defined policy frameworks [34]. There is also the problem of creating technologies that are not just efficient but also environmentally and socially responsible, striking a balance between innovation and concerns about the effects on the environment and public acceptability.

It can be difficult to efficiently coordinate the convergence of several scientific and engineering disciplines needed for many sustainable solutions. It might be challenging to move a technology from a prototype to a scalable product because of complicated engineering issues. It is frequently necessary to incorporate new technologies into an infrastructure that is either out-of-date or not built to support them [35]. Unpredictability exists in both consumer acceptance and market demand for new technology. Market pressures and consumer tastes, rather than a technology's technical superiority, sometimes decide its success. When externalities such as carbon pricing are absent, many emerging sustainable technologies find it challenging to compete with more established, less sustainable alternatives in terms of price. The International Energy Agency (IEA) stresses the importance of boosting research and development (R&D) funding for clean energy technology, noting that public expenditure on clean energy R&D increased by 13% in 2020. Progress in battery technology has significantly decreased the price of lithium-ion batteries by 97% in the past 30 years, facilitating the expansion of electric vehicles and renewable energy storage.

For developers and investors, the regulatory framework surrounding new technologies can be complex, shifting, and inconsistent across different jurisdictions. It can be challenging for new technologies to take off without government initiatives such as research grants, tax breaks, or subsidies that encourage their uptake and expansion. Particularly in the green sector, new technologies are frequently seen as high-risk investments. This may make it more challenging to get funding, especially in the beginning phases of development. New technology development can take longer than the usual investment horizon of venture capitalists and other investors to yield a return on investment. It is possible that the current infrastructure will not support new technologies well enough, requiring significant improvements or the creation of whole new infrastructure systems [36]. Creating a supply chain for new technologies can be pretty tricky, particularly if they need specialised or rare ingredients [37]. It can be challenging to strike a balance between the requirement for open knowledge sharing and collaboration and the protection of intellectual property (IP), especially in a global setting. There are obstacles to cross-border technology development collaboration, including disparate intellectual property laws, regulatory frameworks, and cultural differences. Because new technologies frequently call for specific knowledge and abilities, there is a labour shortage that must be filled through education and training initiatives. The skill gap is exacerbated in some areas by "brain drain," which is the departure of talented people in search of better chances elsewhere.

2.5 | Behavioural challenges

In the UK, reaching net zero requires overcoming major behavioural obstacles since lifestyle adjustments and public participation are essential. Promoting the general acceptance and use of green technologies, such as electric cars and energy-efficient home heating systems, is one of the main challenges. There is still some resistance, or inertia, among the populace in spite of government incentives because of things such as cost, habit, and ignorance [38]. It might be difficult to change eating habits to consume less meat because it increases greenhouse gas emissions; this calls for both cultural and educational changes. Changes in travel habits are also required; public transportation, walking, and cycling should be prioritised over driving. This transition necessitates a substantial shift in public perception in addition to infrastructure assistance. Research indicates that individual actions have the potential to account for up to 20% of the necessary emission reductions by 2050. This pertains to alterations in dietary habits, modes of transportation, and energy consumption within households. Studies on social norms and behavioural economics have demonstrated that interventions such as nudges can effectively change energy usage behaviours.

Getting people to understand the value of sustainable practices and how to put them into practice is one of the main obstacles. Generating enough incentives for people to adopt sustainable practices usually calls for material rewards [39]. It was creating and putting into practice behavioural nudges that successfully subtly promote more sustainable decisions. It is a big struggle to change the company culture so that sustainability comes before short-term profits. Adopting sustainable practices frequently necessitates significant adjustments to corporate structures, supply chains, and operations. It supports voluntary action beyond merely following the law while striking a balance with the requirement for regulatory compliance. Because financial cues have a powerful influence on both individuals and organisations, it is imperative to align economic incentives with sustainable behaviours by ensuring the organisations support and encourage tolerable practices at all scales, from local to international. Misinformation regarding sustainability and environmental challenges can spread quickly in the era of digital media, leading to distrust and uncertainty. It is crucial to build confidence in professional judgements, scientific data, and the efficacy of sustainable practices. People generally turn to their peers for indications of how to act. Therefore, it can be helpful to leverage the power of community and social groups to promote sustainable behaviour. It promotes sustainable practices using social marketing techniques in a way that is consistent with people's values and lifestyles [40].

There may be conflicts between the long-term nature of sustainability and the emphasis on shareholder value and short-term earnings. While challenging, creating precise and insightful metrics and reporting systems for sustainability initiatives is crucial for accountability and openness. Ensuring sustainability throughout the supply chain, particularly in worldwide markets, is a difficult challenge. Extensive public education and awareness-raising activities on environmental challenges and sustainable practices. Putting in place incentive systems, including tax exemptions, product subsidies for sustainability, and fines for non-sustainable behaviour. Using behavioural economics concepts to create treatments that promote long-term, sustainable behaviour. Promoting corporate responsibility through goals for sustainability, integration of sustainability into the main company plan, and leadership. Establishing laws and rules that support or require sustainable practices. It was supporting grassroot movements and community-led projects that advance sustainable living.

2.6 | Policy and regulation challenges

Regulation and policymaking are essential to the fight against climate change and the shift to sustainable behaviours. Nevertheless, there are many moving parts involved in creating, putting into effect, and upholding these rules and regulations. Numerous elements, such as political dynamics, economic interests, societal requirements, and technological advancements, give birth to these issues. A common difficulty for policymakers is striking a balance between environmental sustainability and economic growth [41]. Businesses and industries may oppose environmental protection policies if they have immediate financial consequences.

Diverse stakeholders, such as representatives of industry, environmental organisations, and the general public, have varying and perhaps contradictory agendas and interests. Depending on political philosophies, popular sentiment, and lobbying activities, political leaders' dedication to environmental issues might differ. Political cycles can place a premium on immediate results, which may not align with the long-term requirements of ecological sustainability. International cooperation is needed to address global environmental concerns, but geopolitical dynamics and divergent national interests can make this problematic [42]. Since environmental issues are frequently intricate and multidimensional, intelligent and nuanced regulating strategies are needed. Ensuring adherence to ecological standards can provide a challenge, particularly in areas where enforcement resources are scarce. Rapid technological development may surpass the pace at which pertinent regulations are formulated, resulting in regulatory framework gaps. Industries may need to make significant investments in new technologies or alter their operational procedures because of environmental restrictions. Market-based systems such as carbon pricing are challenging to implement and need to be carefully designed to be fair and prosperous. When creating financial incentives and subsidies to support sustainable activities, it is essential to strike a balance between issues of fiscal responsibility and market distortion as well as efficacy [43]. Socioeconomic disparities must be considered in environmental policies to ensure that the benefits and costs of ecological action are allocated equitably. Policies need to guarantee access to retraining and new employment possibilities while addressing the effects on employees in industries impacted by environmental legislation. It is not easy to effectively integrate scientific knowledge into policymaking, particularly considering the complexity and dynamic nature of environmental science. Policymakers must navigate uncertainty in ecological science to make well-informed judgements [44].

It takes good communication to convince the public of the significance and advantages of environmental policies. Policymakers face great difficulty in battling disinformation and public mistrust, particularly in the social media era. Environmental issues change with time, necessitating flexible and adaptive approaches. The process of creating policies should be dynamic, considering the knowledge gained from past decisions and adjusting to new facts and situations. These challenges are summarised in Table 1 below.

3 | POTENTIAL SOLUTIONS AND STRATEGIES

Figure 5 reproduced from [50] shows the common challenges in achieving a net zero in UK.

3.1 | Investment in renewables

Investing in renewable energy is essential for reducing the impact of climate change and guaranteeing a stable electricity supply. The worldwide shift towards renewable energy sources has resulted in notable progress and financial commitments in several technologies, such as wind, solar, and biomass. Offshore wind farms have experienced significant expansion

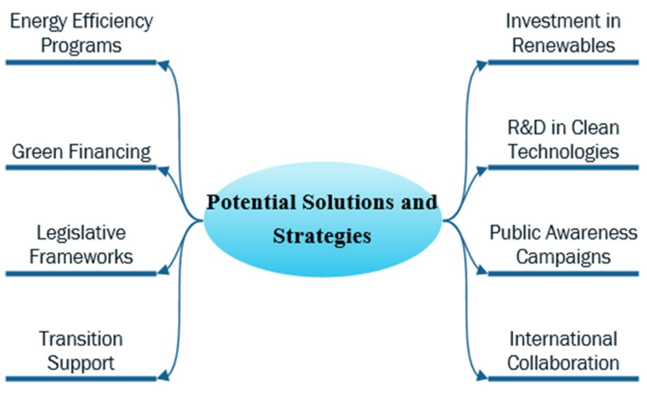

FIGURE 5 Potential solutions and strategies.

TABLE 1 Different challenges facts and figures.

Challenge type	Detail	Statistical facts and Figures	Ref
Energy transition challenges	Increase in renewable energy sources and reduction in fossil fuel use, with a focus on wind, solar, and biomass.	As of 2020, over 24 GW of wind power and 13 GW of solar power capacity. The UK aims for 40 GW of offshore wind by 2030.	[45]
Economic challenges	Financial investment and economic restructuring are required to support the transition, impacting various sectors.	Transition costs estimated at 1%–2% of GDP annually, with a potential for £50 billion in annual benefits from clean growth by 2030.	[46]
Behavioural challenges	Encouraging sustainable lifestyle changes and consumption patterns among the public.	A survey indicates only 12% of the UK population follows a low-carbon diet, emphasising the need for substantial behavioural shifts.	[47]
Infrastructure modernisation challenges	Upgrading the energy grid, transport systems, and buildings to be more energy-efficient and to support renewable energy.	£40 billion required for energy grid upgrades by 2050. A need for 300,000 public EV charging points by 2030 compared to 35,000 in 2021.	[48]
Research and development challenges	Innovation in green technologies, including carbon capture, storage, and utilisation (CCUS), and the development of scalable solutions.	The UK's R&D investment in CCUS and other green technologies is crucial, with a current allocation of £1 billion in the net-zero innovation portfolio.	[49]
Policy and regulation challenges	Developing comprehensive policies and regulations that accelerate the net-zero transition while ensuring economic stability.	The UK's ETS prices carbon emissions, aiming to reduce 68% of GHG emissions by 2030 relative to 1990 levels, but broader policy adaptation is required.	[50]

mainly because they can utilise more powerful and constant winds than onshore farms. By 2020, the United Kingdom had successfully implemented more than 24 GW (GW) of wind power capacity [51]. The country has set a target to achieve 40 GW by 2030, positioning itself as a prominent global player in offshore wind energy. This change has not only facilitated the reduction of greenhouse gas emissions but has also stimulated economic growth through job creation and investment attraction. Solar energy has shown significant progress, with the costs of photovoltaic (PV) systems declining by more than 80% since 2010. Global investments in renewable energy exceeded those in fossil fuels and nuclear power in 2020, reaching $366 billion [52]. Technological advancements have improved the practicality of solar and other renewable energy sources in energy storage, such as better battery systems. Biomass energy, a process that transforms organic substances into heat, electricity, or biofuels, has experienced advancements in efficiency and environmental sustainability. This form of energy promotes rural economies by harnessing local resources and minimising waste. By 2030, the investment in offshore wind is anticipated to surpass $810 billion, contributing to the ongoing growth of the worldwide renewable energy sector. These investments are crucial for attaining global climate objectives, such as the Paris Agreement's goal of limiting global warming to less than 2 degrees Celsius over pre-industrial levels [53]. Figure 6 shows the investment in renewable energy sources and their resulting capacities from 2020 to 2050. Offshore wind capacity, solar PV capacity, and biomass energy production are illustrated in blue, yellow, and green bars, respectively. The red dashed line indicates the overall investment in renewables, steadily increasing over time. Both offshore wind and solar PV capacities show significant growth, with offshore wind capacity reaching over 140 GW by 2050. Biomass energy production also increases, though at a more moderate pace.

3.2 | Energy efficiency programmes

Energy efficiency plays a crucial role in decreasing greenhouse gas emissions and energy usage in several sectors, such as residential, commercial, and industrial. Energy efficiency methods can substantially reduce energy expenditures and dependence on fossil fuels using less energy to accomplish the same tasks. Energy efficiency in residential structures can be significantly improved by enhancing insulation. Effective insulation can regulate indoor temperatures, minimising heating and cooling requirements. According to the US Department of Energy, adequate insulation can reduce up to 20% in heating and cooling expenses for houses. In addition, incorporating energy-efficient products, such as heating and cooling systems, refrigerators, and washing machines certified by ENERGY STAR, can further reduce household energy usage by 10%–50% [54]. Switching to LED lights in the commercial sector has been highly effective for optimising lighting systems. LED lights use at least 75% less energy and have a lifespan of 25 times longer than incandescent lighting. Industrial processes can conserve energy by deploying waste heat recovery systems, updating to high-efficiency motors and equipment, and leveraging smart sensors and IoT devices to monitor and optimise energy consumption [55]. The transportation industry is also vital for ensuring energy efficiency. The transition to electric vehicles (EVs), facilitated by measures such as tax incentives and investments in charging infrastructure, is crucial. According to the US Environmental Protection Agency (EPA), electric vehicles (EVs) are significantly more energy-efficient than conventional gasoline-powered vehicles. The EPA estimates that EVs convert approximately 59%–62% of the electrical energy obtained from the grid into power that moves the wheels [56].

In contrast, gasoline vehicles only convert about 17%–21% of the energy stored in gasoline into useable power [57]. In

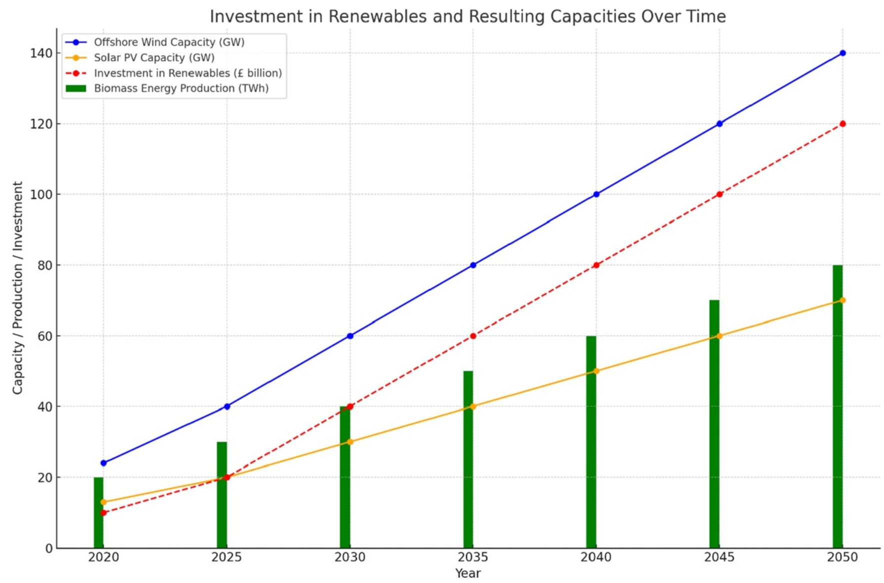

FIGURE 6 Investment in renewables and resulting capacities over time.

addition, improving the public transportation infrastructure by including electric buses and trains and encouraging non-motorised commuting methods such as cycling and walking can effectively decrease the overall energy consumption in the transportation sector. The predicted annual value of the global market for energy-efficient technology is expected to reach $250 billion by 2023, indicating a growing focus on energy efficiency [58]. Figure 7 depicts the trends in insulation upgrades and the adoption of energy-efficient appliances from 2020 to 2050. The blue bars indicate the number of homes with insulation upgrades, while the orange bars show the adoption of energy-efficient appliances in millions of units. The green line tracks the energy savings in TWh, showing a substantial increase over the years. Concurrently, the red dashed line represents the investment in energy efficiency, also rising, albeit at a slower pace compared to the energy savings achieved.

3.3 | Research and development in clean technologies

Research and development (R&D) in clean technologies are crucial for tackling the increasing effects of climate change and environmental degradation. These technologies include energy sources, energy efficiency, sustainable transportation, and waste management. They all help to decrease greenhouse gas emissions and encourage the sustainable use of resources. The global research and development (R&D) expenditure for renewable energy amounted to $30 billion in 2020, indicating a solid dedication to advancing innovation [59]. Significantly, solar photovoltaic (PV) technology improvements have resulted in a roughly 90% reduction in costs over the last 10 years, positioning solar power as one of the most cost-effective energy sources worldwide [60].

Furthermore, there has been a remarkable decrease of around 97% in the price of lithium-ion batteries over the past 3 decades. This reduction has been crucial in advancing energy storage and electric vehicle (EV) technology. The proliferation of electric vehicles (EVs) is especially remarkable, as seen by a 43% surge in sales in 2020, resulting in over 3 million new EV registrations globally [61]. Hydrogen fuel cells and carbon capture and storage (CCS) advancements are paramount. The UK has dedicated £1 billion to its Net Zero Innovation Portfolio to expedite the progress of these technologies. The Global Commission on the Economy and Climate has estimated that bold climate action may result in economic gains of at least $26 trillion by 2030, highlighting the significant economic potential of clean technology innovation [62]. This encompasses establishing a substantial number of environmentally friendly employment opportunities in renewable energy, energy efficiency, and sustainable transportation.

Moreover, incorporating smart grid technology and Internet of Things (IoT) devices in industrial operations helps optimise energy consumption and minimise inefficiencies, improving total efficiency. The International Energy Agency (IEA) emphasises the necessity of ongoing investment in research and development (R&D), highlighting that public expenditure on R&D for clean energy rose by 13% in 2020 [63]. Governments have a crucial role in promoting innovation by implementing regulations and providing incentives, such as tax credits, subsidies, and grants. These measures aim to stimulate private sector investment and encourage collaborations between the public and private sectors. International cooperation is crucial, as demonstrated by projects such as the International Solar Alliance, which seeks to generate $1 trillion

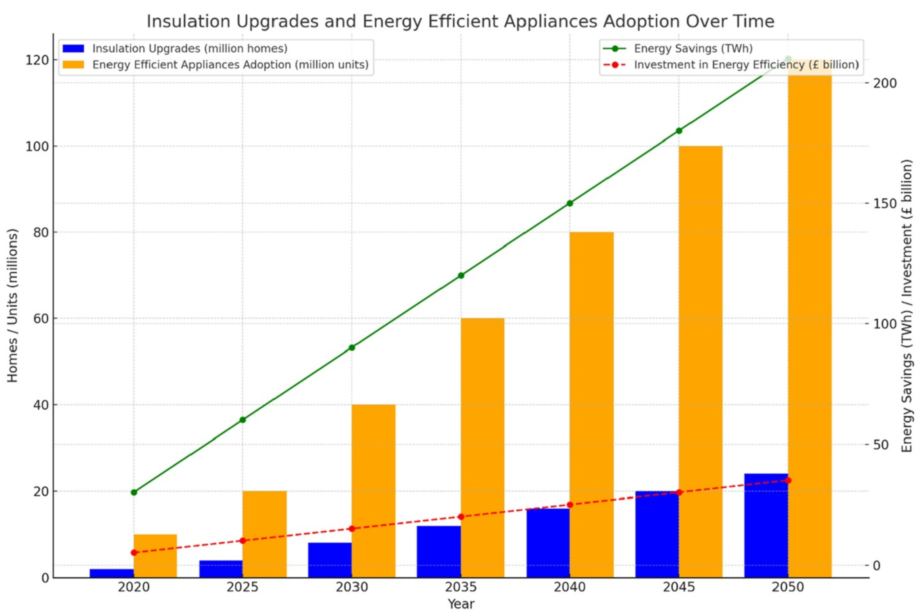

FIGURE 7 Insulation upgrades and energy efficient appliances adoption over itme.

in solar investments by 2030 [64]. Figure 8 presents the investments in Research and Development (R&D) for clean technologies such as Solar PV, Wind Energy, Battery Technology, and Hydrogen Technology from 2020 to 2050. Each technology's investment is displayed in blue, yellow, green, and red bars, respectively. The total R&D investment is shown by the purple dashed line, steadily rising to around £20 billion by 2050. The black line represents the expected CO2 reduction percentage, which increases more modestly, indicating a significant impact on emissions through these investments over time.

3.4 | Green financing

Green financing is crucial for expediting the shift towards a sustainable and low-carbon economy by supplying the required funds to back environmentally beneficial initiatives and technology. Financial tools, such as green bonds, loans, grants, and subsidies, are vital in reducing the significant upfront expenses and prolonged payback periods commonly linked to green initiatives. The global green bond market experienced an important milestone in 2020, with a remarkable surge in issuances amounting to $269.5 billion [65]. This notable achievement highlights the increasing interest among investors in funding climate and environmental initiatives. The Green Deal Investment Plan of the European Union seeks to generate a minimum of €1 trillion in sustainable investments by 2030, emphasising the significant dedication needed [66]. Tax incentives, including credits, deductions, and refunds, are efficient means of encouraging investments in renewable energy, energy-saving appliances, and environmentally-friendly construction methods. Feed-in tariffs (FITs) ensure that renewable energy producers receive set payments for the electricity they generate, thus increasing the appeal of investing in solar and wind power. Carbon pricing methods, such as carbon taxes and cap-and-trade systems, provide additional motivation for reducing greenhouse gas emissions by attributing a financial worth to carbon emissions. It is estimated that the worldwide green finance market, including green bonds and loans, will exceed $2.36 trillion by 2030 [67]. The extensive proliferation of electric cars (EVs) has been dramatically propelled by financial incentives, such as tax exemptions, and considerable expenditures in charging infrastructure. According to the International Energy Agency (IEA), reaching a state of net-zero emissions will necessitate annual investments of approximately $4 trillion by 2030, representing a significant rise from present levels [68]. Figure 9 illustrates the evolution of various green financing sources from 2020 to 2050. Green Bonds Issued, Green Loans Provided, and Subsidies and Grants are depicted as bar graphs in blue, orange, and green, respectively. The red dashed line represents the total green financing, showing a steady increase over the years, reaching approximately £350 billion by 2050. Additionally, the purple line indicates the percentage reduction in CO2 emissions attributed to green financing, suggesting a progressive increase, although at a slower rate compared to the financial growth.

3.5 | Public awareness campaigns

Public awareness campaigns are vital for promoting a widespread comprehension and implementation of sustainable practices, as they have a pivotal influence in changing human behaviours and attitudes towards the environment. Implementing educational programmes focused on sustainability from a young age may cultivate a sense of environmental responsibility. This can be achieved by integrating ecological

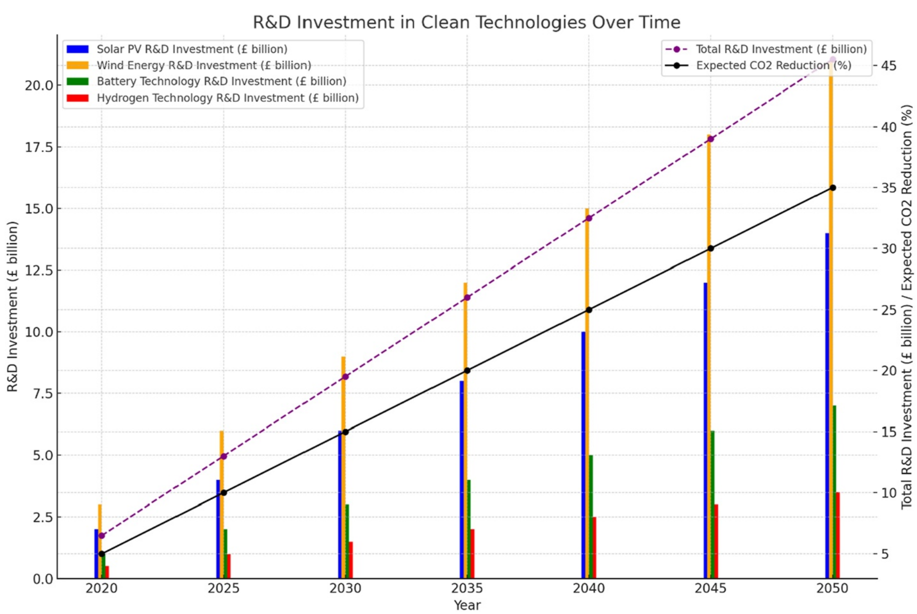

FIGURE 8 R&D investment in clean technologies over time.

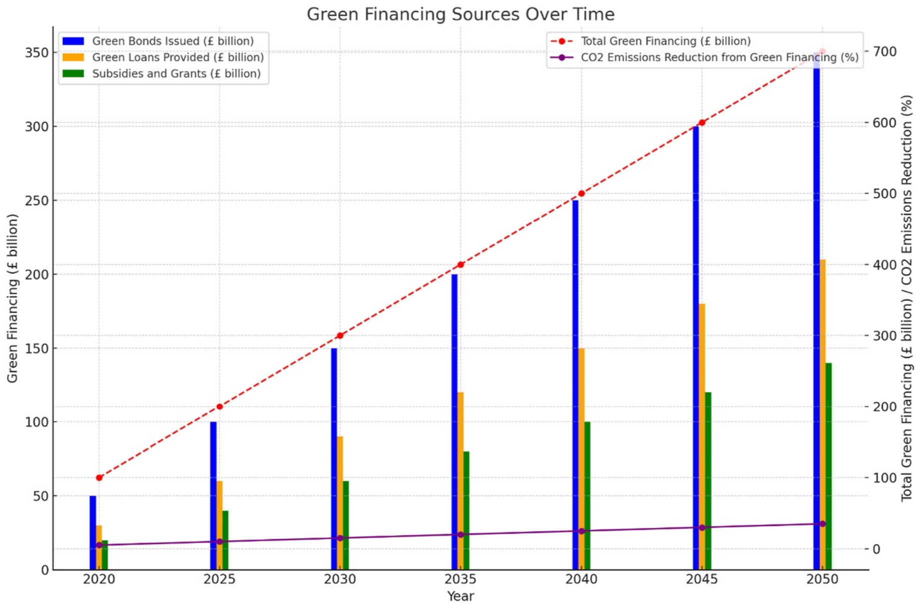

FIGURE 9 Green financing sources over time.

studies into the curricula of schools and institutions. Research conducted by the National Environmental Education Foundation revealed that ecological education led to a 27% improvement in students' environmental literacy and a 15% rise in pro-environmental actions [69]. The efficacy of media, encompassing public service announcements, documentaries, social media campaigns, and television programmes, is crucial in reaching extensive audiences and disseminating awareness regarding environmental challenges and sustainable practices. The Yale Programme on Climate Change Communication conducted a survey revealing that 72% of Americans acknowledge the existence of global warming, while 59% express concern about it [70]. This data highlights the significant influence of successful awareness initiatives. According to the International Energy Agency (IEA), energy efficiency measures resulting from more excellent public knowledge can decrease world energy usage by as much as 40% [71]. Local environmental concerns can be effectively addressed, and grassroots solutions can be promoted through community engagement through workshops, seminars, and interactive events. According to the Environmental Protection Agency (EPA), community-based programmes might reduce waste. Studies indicate that by 2050, individual activities have the potential to contribute up to 20% of the necessary emission reductions, underscoring the substantial influence of personal lifestyle modifications [72]. These activities encompass minimising energy usage, reusing materials, preserving water resources, and utilising public transportation. For instance, the Environmental Protection Agency (EPA) approximates that recycling has the potential to conserve up to 30% of energy in contrast to the production of new materials. The public endorsement of sustainable policies is essential; people who are knowledgeable about the subject matter are more inclined to promote environmental laws and corporate accountability.

Companies are compelled to implement eco-friendly methods due to the rising consumer demand for sustainable products fuelled by a growing awareness. The global organic food market is expected to reach $272.18 billion by 2027, exhibiting a compound annual growth rate (CAGR) of 12.2% [73]. This rise is mainly attributed to the increasing demand driven by well-informed customer preferences. Digital platforms, such as interactive websites, mobile apps, and online courses, offer convenient and captivating methods for individuals to acquire knowledge on sustainability. Virtual and augmented reality technologies can generate immersive learning experiences, enhancing the impact of sustainability education.

3.6 | Legislative frameworks

Legislative frameworks play a vital role in the worldwide endeavour to address climate change and decrease greenhouse gas emissions, directing economies towards a more sustainable and environmentally conscious future. These frameworks consist of rules and regulations targeting sectors such as energy, transportation, and industry. Carbon pricing mechanisms, such as carbon taxes and cap-and-trade systems, play a crucial role in these endeavours. Carbon taxes directly impose a financial burden on greenhouse gas emissions, motivating firms and individuals to decrease their carbon footprint. An example is Sweden's carbon tax, implemented in 1991 and now set at $137 per tonne of CO_2 [74]. Since its introduction, this price has resulted in a significant 27% reduction in emissions. Cap-and-trade systems, such as the European Union's Emission Trading System (EU ETS), establish a maximum emission threshold and enable the exchange of permits for emitting pollutants. The EU ETS has played a crucial role in achieving a

35% reduction in emissions from power plants and industrial facilities since 2005 [75]. Emission requirements for automobiles, power plants, and industrial sources are essential to regulatory frameworks. Adopting California's stringent vehicle emission rules by 14 other US states has substantially decreased the release of nitrogen oxides (NOx) and particulate matter (PM), enhancing air quality and public health [76]. Renewable energy requirements, such as renewable portfolio standards (RPS), oblige utilities to produce a designated proportion of their electricity from renewable sources. 29 states and the District of Columbia in the United States have adopted Renewable Portfolio Standards (RPS) laws, significantly growing renewable energy capacity. As an illustration, Texas, which has one of the most aggressive Renewable Portfolio Standards (RPS) programmes, has emerged as the top wind energy producer in the nation, generating more than 30 GW (GW) of wind power. Energy efficiency rules for homes, appliances, and automobiles are also crucial. By 2030, enforcing the appliance and equipment standards set by the US Department of Energy is estimated to result in a $2 trillion reduction in energy costs for consumers and a decrease of 7 billion metric tonnes in CO2 emissions.

The Paris Agreement, adopted by 196 nations, seeks to restrict global warming to below 2 degrees Celsius above pre-industrial levels, explicitly focusing on limiting the increase to 1.5 degrees Celsius. Countries must establish and revise their nationally determined contributions (NDCs) to decrease emissions. The existing commitments are expected to result in a 12% reduction in emissions by 2030 compared to the emissions that would occur under normal circumstances. However, attaining these objectives necessitates strong execution and adherence methods. The UNFCCC supervises worldwide climate policy, promotes international collaboration, and guarantees responsibility.

3.7 | International collaboration

Global cooperation is crucial worldwide to attain net-zero emissions, as climate change is a transnational problem necessitating synchronised efforts among countries. The UK's 44% reduction in emissions from 1990 levels by 2021 underscores the significance of collaborative efforts. The global carbon dioxide (CO2) emissions amounted to over 36.4 billion metric tonnes in the same year, highlighting the necessity for collaborative efforts [77]. The Paris Agreement, which 196 countries have approved, is a cooperative effort that seeks to restrict global warming to a maximum of 2 degrees Celsius above pre-industrial levels, with a particular emphasis on limiting the temperature to 1.5 degrees Celsius. To achieve these goals, nations have pledged to establish and revise their nationally determined contributions (NDCs) to reduce emissions. For example, the European Union has committed to decrease emissions by a minimum of 55% by 2030 compared to the levels recorded in 1990.

Similarly, China has set a goal to reach the highest point of its CO2 emissions by 2030 and attain carbon neutrality by 2060. The United States has pledged to decrease its greenhouse gas emissions by 50%–52% by 2030 compared to the levels recorded in 2005. The International Solar Alliance, a programme aimed at mobilising $1 trillion in solar power investments by 2030, is a prime example of the effectiveness of global collaborations. The Green Climate Fund, created under the framework of the United Nations Framework Convention on Climate Change (UNFCCC), aims to assist developing nations in decreasing emissions and improving their ability to withstand climate change impacts. Its target is to generate $100 billion per year by 2020. By 2020, the amount of money pledged to the fund had reached $10.3 billion. The collaboration encompasses technological innovation through projects such as Mission Innovation in which 24 nations and the European Commission have committed to doubling their clean energy research and development funding to $30 billion annually by 2021. Trade and investment policies are crucial in facilitating international collaboration. The Carbon Border Adjustment Mechanism (CBAM) of the European Union is scheduled to be implemented starting in 2023. Its purpose is to address carbon leakage by imposing a carbon price on specific imported goods from countries with less rigorous climate regulations. This project promotes global enterprises adopting environmentally friendly practices and ensures that international trade aligns with climate objectives. In addition, exchanging best practices and expertise via forums such as the Intergovernmental Panel on Climate Change (IPCC) and the Global Green Growth Institute (GGGI) assists governments in formulating efficient climate policies. The comprehensive reports of the IPCC offer crucial scientific insights that inform global and national climate policy. The GGGI assists member countries in attaining their climate targets by providing technical assistance and capacity building, particularly emphasising green growth and sustainable development. International cooperation is essential for addressing climate justice, as it ensures that vulnerable and low-income nations receive assistance in adapting to climate impacts and transitioning to sustainable energy systems. This involves tackling the consequences of loss and damage caused by climate change, with initiatives such as the Warsaw International Mechanism for Loss and Damage under the United Nations Framework Convention on Climate Change (UNFCCC) offering a structure for assisting nations with significant climate-related impacts.

3.8 | Transition support

Transition support is essential for facilitating a seamless and fair transition to a low-carbon economy by tackling this transformation's economic, social, and technical obstacles. Comprehensive transition programmes encompass significant monetary allocations, retraining of the workforce, creation of infrastructure, and revisions in policies. As per the International Labour Organisation (ILO), the green economy has the potential to generate 24 million new employment opportunities worldwide by 2030 [78]. However, this shift also entails the possibility of job reductions in conventional fossil fuel sectors. Hence, it is crucial to have robust support mechanisms in place to alleviate these effects and offer fresh prospects for the affected workers. Financial assistance is a fundamental aspect of endeavours to facilitate change. The primary objective of the European Union's Just Transition Mechanism is to allocate a minimum of €150 billion between 2021 and 2027 to assist regions that are most impacted by the transition [79]. The primary goal of this assistance is to promote economic diversification and generate employment opportunities.

Similarly, the United States has explicitly designated $16 billion in its American Jobs Plan to retrain people and foster fresh economic prospects in regions reliant on coal, oil, and gas [80]. The allocated monies are designated explicitly for reskilling programmes, educational initiatives, and job placement services. The objective is to facilitate the smooth transition of workers into developing green sectors, including renewable energy, energy efficiency, and sustainable agriculture. Infrastructure development is an essential element of providing support during a shift. Investing in contemporary and environmentally friendly infrastructure, such as public transportation, renewable energy installations, and energy-efficient buildings, not only stimulates economic expansion but also diminishes the release of greenhouse gases. According to the Global Infrastructure Facility, $94 trillion would be required by 2040 to fulfil global development objectives, with a substantial part allocated to sustainable infrastructure. Policy reforms are essential to establish a conducive climate for the transition. This involves implementing carbon pricing mechanisms, such as carbon taxes and cap-and-trade systems, which offer economic incentives for reducing emissions. Canada's carbon pricing proposal establishes a cost of $50 per metric tonne of CO2 in 2022, which will increase to $170 per metric tonne by 2030. These laws incentivise businesses to innovate and invest in environmentally friendly technologies while generating income that may be redirected towards supporting the shift to cleaner practices. Workforce development initiatives are crucial for providing people with the necessary skills for emerging green occupations. Based on the World Economic Forum's analysis, implementing upskilling and reskilling initiatives can contribute $6.5 trillion to the global gross domestic product (GDP) by 2030.

Additionally, it might generate 5.3 million new jobs by 2025. Programmes that prioritise the development of technical skills in renewable energy, energy efficiency, and sustainable practices are especially beneficial. According to the Solar Energy Industries Association (SEIA), the U.S. solar business had more than 231,000 employees in 2020 [81]. Job opportunities are anticipated to continue to increase as the sector expands. Global cooperation is crucial in facilitating a fair and equitable shift. The Climate Investment Funds (CIF) offer financial and technical support to poor nations, aiding their shift towards low-carbon economies and tackling social equality issues. By 2020, CIF has approved climate change projects totalling $8.3 billion across 72 countries, effectively mobilising an additional $61 billion in co-financing. The various strategies are summarised in Table 2.

4 | POLICY RECOMMENDATIONS

To achieve net zero by 2050, it is necessary to adopt a comprehensive approach that combines different evidence-based policies specifically designed for the unique circumstances of the UK. It is essential to prioritise allocating funds towards expanding renewable energy sources, namely in developing offshore wind farms and solar energy projects. The United Kingdom's significant offshore wind capacity, which is already among the highest in the world, has led to a 30% decrease in costs over the last 10 years. This has made offshore wind a feasible and competitive source of electricity. Furthermore, the progress in photovoltaic technology has greatly enhanced the effectiveness and cost-effectiveness of solar panels, hence bolstering the transition towards renewable energy. Investments in Germany have effectively boosted renewable energy generation and resulted in a 40% reduction in carbon emissions. This demonstrates the great potential of these technologies in driving meaningful progress towards achieving net zero. Implementing nationwide energy efficiency programmes for both residential and commercial buildings can significantly enhance efforts to reduce emissions. Denmark's energy efficiency initiatives have resulted in a 15% decrease in energy usage in residential buildings [90]. This has been achieved by implementing strict construction rules and providing financial incentives for upgrading older structures with improved insulation and energy-efficient appliances. The US Energy Star programme, responsible for certifying energy-efficient products, has achieved savings of over $430 billion in energy costs and has successfully prevented the release of more than 3 billion metric tonnes of greenhouse gas emissions since its establishment. These results demonstrate such initiatives' efficacy in reducing overall energy consumption and emissions. Encouraging the use of electric cars (EVs) and enhancing the availability of charging infrastructure are crucial in mitigating emissions from the transportation sector, which contribute significantly to the UK's carbon footprint. Due to Norway's assertive electric vehicle (EV) policies, which encompass generous tax incentives, toll and parking fee exemptions, and widespread charging infrastructure, EVs comprise more than 50% of new car purchases. Norway's methodology has substantially reduced transportation emissions, making it a useful source of lessons for the UK. The proposed prohibition on new petrol and diesel vehicles by 2030 in the United Kingdom, along with investments in electric vehicle infrastructure, has the potential to expedite this transition. Enhancing the UK's emissions trading system (ETS) and establishing effective carbon pricing mechanisms provide financial motivations for firms to embrace more environmentally friendly technologies. Since its inception, the European Union's Emissions Trading System (ETS) has played a crucial role in achieving a 20% reduction in emissions within participating industries. This success highlights the efficacy of market-based methods in addressing environmental concerns. The carbon tax in British Columbia, which is set at $40 per tonne of CO2, has successfully reduced emissions ranging from 5% to 15% [91]. This achievement demonstrates the

TABLE 2 Summary of various strategies.

Solution/ Strategy	Technical details	Statistical facts and Figures	Cost-effectiveness	Priority/Weight	Ref
Financial support	Allocation of funds to regions and sectors most affected by the transition	EU's just transition mechanism: €150 billion (2021–2027); US American jobs plan: $16 billion for retraining workers	High initial investment but essential for economic stability and job creation	High priority due to direct economic impact and job creation	[82]
Workforce development	Reskilling and upskilling programmes focused on green sectors	Potential to create 24 million new jobs globally by 2030 (ILO); US solar industry employs over 231,000 workers	Moderate investment, high return in terms of job creation and economic growth	High priority due to immediate impact on employment	[83]
Infrastructure development	Investment in sustainable infrastructure such as public transport and renewable energy	$94 trillion needed by 2040 for global infrastructure (global infrastructure facility)	High investment, long-term benefits in emission reduction and economic growth	High priority for sustainable development	[84]
Policy reforms	Implementation of carbon pricing mechanisms and regulatory frameworks	Canada's carbon pricing: $50 per tonne of CO2 in 2022, rising to $170 by 2030	Moderate to high investment, generates revenue for reinvestment	Medium priority due to the need for strong political will and economic adjustments	[85]
Renewable energy investments	Development of wind, solar, and other renewable energy sources	Global investment in renewable energy: $366 billion in 2020; cost of solar PV decreased by nearly 90% over the past decade	High initial cost, decreasing over time; significant long-term savings and emission reductions	High priority due to critical role in reducing emissions	[86]
International collaboration	Financial and technical assistance for developing countries	Climate investment funds (CIF): $8.3 billion approved, leveraging $61 billion in co-financing	Moderate investment, high impact on global emission reductions and equity	Medium priority, essential for global cooperation and equity	[87]
Public awareness campaigns	Education and engagement through media, schools, and community programmes	Potential to reduce global energy consumption by up to 40% (IEA); environmental literacy increased by 27% with education initiatives (national environmental education foundation)	Low to moderate cost, significant long-term impact on behaviour and policy support	High priority for sustaining public support and behavioural change	[88]
Energy efficiency programs	Enhancing insulation, adopting efficient appliances, optimising industrial processes	Projected to save consumers $2 trillion on energy bills by 2030 (US department of energy); energy efficiency market projected to reach $250 billion per year by 2023	Moderate cost, high return on investment in energy savings	High priority due to immediate and long-term benefits	[89]

capacity of carbon pricing to promote emission reductions without impeding economic growth. Augmented investment in research and development (R&D) for sustainable technologies, specifically carbon capture and storage (CCS) and hydrogen fuel cells, is needed to tackle emissions from challenging industries that are difficult to reduce. Japan's substantial investment in hydrogen technology, bolstered by government subsidies and collaborations with private enterprises, establishes it as a prominent international frontrunner. Hydrogen is anticipated to be pivotal in Japan's forthcoming energy plan. Moreover, the financing provided by the US Department of Energy for CCS initiatives has resulted in notable progress, as seen by pilot programmes that have successfully shown the practicality of capturing and storing substantial quantities of CO2 emitted by industrial sources. Extensive public awareness initiatives to advocate for sustainable practices and behaviours are also crucial. The "Act on CO2" campaign in the UK effectively enhanced public awareness regarding energy efficiency through television advertisements, internet resources, and community outreach. Consequently, there was a quantifiable rise in the implementation of energy-saving measures by families. The "Save Energy" campaign in Australia resulted in a 10% decrease in home energy consumption during its duration, showcasing the effectiveness of thoughtfully planned public awareness campaigns [92]. California's stringent vehicle emission restrictions, mandating automakers to create and sell a specific quantity of zero-emission vehicles, have decreased local air pollution and stimulated car manufacturers to develop new technologies, thereby helping the worldwide market. The UK's Climate Change Act of 2008 has played a crucial role in pushing national efforts and positioning the UK as a frontrunner in climate action. This legislation established legally binding targets for decreasing greenhouse gas emissions by a minimum of 80% by 2050, compared to 1990 levels.

Policymakers must traverse a complex landscape of technological, economic, and societal hurdles to meet the UK's ambitious net zero by 2050 ambition. This requires a gradual and deliberate method that combines immediate activities with long-term goals to ensure that efforts are effective and lasting. The precise policy proposals offer explicit direction for the next 25 years, outlining quick actions and those that can be implemented gradually, with timetables and prioritisation determined by urgency and impact. Table 3 shows different phases for net-zero achievement.

Table 4 lists different strategies and carbon metric benefits.

5 | FUTURE RESEARCH DIRECTIONS

Achieving a net-zero economy by 2050 requires significant collaboration among academia, industry, and government sectors. Future research should prioritise areas where technology advancements and system-level modifications can lead to substantial decreases in carbon emissions to reach the aim. Current carbon capture use and storage CCUS technologies are essential for decreasing emissions from heavy industry and power generation, although they are expensive and require a significant amount of energy. Research should prioritise enhancing the efficiency, scalability, and economic feasibility of these technologies. Advancements in materials science, including creating more efficient and cost-effective absorbents or catalysts, have the potential to lower expenses and enhance the effectiveness of CCUS procedures. Additionally, investigating biological carbon capture techniques such as increased photosynthesis or bioenergy with carbon capture and storage (BECCS) shows potential for sustainable carbon management. According to the Global CCS Institute, operational CCUS facilities worldwide absorb around 40 million tonnes of CO2 yearly as of 2020 [109]. This number must substantially rise to achieve the net-zero aim, emphasising the critical need for research in this field. Wind and solar power have made great progress but face limits due to their variability and the need for specific geographical locations for maximum performance. Future research must tackle these problems to guarantee a steady and varied renewable energy source. Advancing solar photovoltaics (PV) technology, including perovskite solar cells,

TABLE 3 Phases for net-zero achievement.

phase	Action	Technical aspect and policy recommendation	Expected impact	Ref
Immediate actions (2020–2025)	Accelerate renewable energy deployment	Increase wind (especially offshore) and solar capacity to exceed 40 and 20 GW by 2025. Implement subsidies and tax incentives and invest in R&D.	Substantial reduction in carbon emissions from the power sector, enhancing the UK's renewable energy capacity.	[93]
Immediate actions (2020–2025)	Enhance grid infrastructure and flexibility	Upgrade the grid for renewable inputs and incorporate intelligent technologies and energy storage, with investments of over £40 billion by 2050.	Improved grid reliability and ability to integrate renewable energy, facilitating a smoother transition to green power.	[94]
Immediate actions (2020–2025)	Promote electric vehicle (EV) adoption	Expand the EV charging network and provide incentives for purchase and manufacture, aiming for all new cars to be zero emissions by 2030.	Accelerated transition to electric transportation, reducing emissions from one of the most polluting sectors.	[95]
Medium-term actions (2025–2035)	Decarbonise heating	Transition to electric heat pumps and hydrogen heating, implementing a ban on new gas boilers and providing installation subsidies.	Significant reduction in residential and commercial heating emissions, moving towards cleaner, more sustainable heating solutions.	[96]
Medium-term actions (2025–2035)	Industrial carbon capture and storage (CCS)	Scale CCS technology in heavy industries with pilot project funding, incentives, and regulatory frameworks.	Mitigation of industrial emissions, enabling hard-to-decarbonise sectors to reduce their carbon footprint.	[97]
Medium-term actions (2025–2035)	Establish renewable energy communities	Support local renewable projects and energy-sharing with grants, regulatory amendments, and local government involvement.	Empowerment of local communities in energy production and sharing, enhancing national energy security and sustainability.	[98]
Long-term actions (2035–2050)	Achieve widespread carbon capture, use, and storage	Expand CCS technology across the power sector and hard-to-decarbonise industries, exploring uses for captured carbon.	Comprehensive reduction of emissions across sectors, utilising captured carbon in beneficial ways.	[99]
Long-term actions (2035–2050)	Complete the transition to sustainable transportation	Ensure all new vehicles are zero-emissions and expand public transport and active travel (cycling, walking) with infrastructure investment and planning reforms.	Complete elimination of emissions from transportation, promoting healthier and more sustainable urban mobility.	[100]
Long-term actions (2035–2050)	Support green innovation and jobs	Foster green technology innovation and workforce training for green industries, supporting up to 250,000 green jobs by 2030.	Creation of a robust green economy with sustainable jobs, driving innovation and ensuring a skilled workforce for the future.	[101]
Cross-phase actions	Public engagement and behavioural change	Engage the public in net-zero transition through awareness campaigns and promoting sustainable living practices.	Increased public support and active participation in the net-zero transition, leading to societal shifts in consumption and behaviour.	[102]
Cross-phase actions	Regulatory frameworks and international cooperation	Develop flexible regulations for net zero and enhance international technology exchange and climate finance.	Strengthened policy support for net-zero goals and enhanced global collaboration for climate action.	[103]

TABLE 4 Carbon metric benefits of different strategies.

Strategy	Economic costs (£)	Timeframes	Expected benefits	Carbon metrics benefits	Ref
Renewable energy deployment	£48 billion (by 2030 for offshore wind)	2020–2030	60,000 jobs in offshore wind by 2030, reduction in carbon emissions	Significant contribution towards the 40% reduction target by 2030	[104]
Grid infrastructure and flexibility	Over £40 billion (by 2050)	2020–2050	Improved grid reliability, higher renewable integration	Enables 100% renewable energy penetration in the power mix by 2050	[105]
Electric vehicle (EV) adoption	£1.3 billion (charging points) + £582 million (subsidies)	Immediate to 2030	Reduction in transportation emissions, boost in the domestic automotive industry	Aims for a 78% reduction in transport emissions by 2035 compared to 1990 levels	[106]
Decarbonising heating	£250 billion (by 2050)	Medium to long-term (2025–2050)	Significant emissions reduction in residential and commercial buildings	Aims to reduce heating emissions by 95% by 2050 compared to 1990 levels	[107]
Industrial carbon capture and storage (CCS)	Around £1 billion (initial CCS projects)	Medium to long-term (2020–2050)	Essential for decarbonising hard-to-abate industrial sectors	Could capture and store up to 30 million tonnes of CO2 annually by 2030	[108]

may increase efficiencies and reduce costs compared to existing silicon-based PV systems. Improving offshore wind technology to capture wind at deeper sea depths increases the possible locations for generating electricity.

Furthermore, investigating alternative renewable sources such as geothermal energy and tidal power could enhance the resilience of the energy portfolio. The UK aims to achieve 40 GW of offshore wind capacity by 2030. Innovations that reduce expenses and improve efficiency could make this goal more attainable and financially appealing.

To achieve a low-carbon economy by 2050, a significant progress in research and development is required in various areas. The University of Oxford's Oxford Photovoltaics group is at the forefront of advancements in renewable energy technologies in the UK. They have made significant strides in developing next-generation perovskite solar cells, which have the potential to achieve up to 30% efficiency and significantly reduce production costs compared to conventional silicon-based cells. In addition, the Grantham Institute at Imperial College London is improving the efficiency of offshore wind energy by developing new turbine designs. This is helping the UK maintain its status as the largest offshore wind market globally, with a capacity of over 10 GW as of 2020. The UK has plans to increase this capacity to 40 GW by 2030 [110]. The research on carbon capture and storage (CCS) is of utmost importance, and the scottish carbon capture and storage (SCCS) partnership at the University of Edinburgh is at the forefront of Europe in creating geological storage systems [8]. These solutions can store up to 10 million tonnes of CO2 annually by 2030. The University of Birmingham's Centre for Hydrogen and Fuel Cell Research is at the forefront of hydrogen technology, focusing on developing innovative methods for producing, storing, and using hydrogen. The ultimate goal is establishing hydrogen as a practical and sustainable alternative to fossil fuels in various industries and transportation. Hydrogen fuel cell vehicles can decrease greenhouse gas emissions by as much as 90% compared to traditional internal combustion engine vehicles. In addition, Loughborough University's Centre for Renewable Energy Systems Technology (CREST) places great importance on energy efficiency. They specifically concentrate on enhancing the energy efficiency of buildings, which has the potential to decrease energy usage in buildings by up to 30% [111]. The Green Homes Grant, implemented by the UK government, offers financial assistance of up to £10,000 per home to facilitate energy efficiency enhancements. This effort serves as a demonstration of legislative backing for such endeavours. However, particular areas still have considerable deficiencies, such as climate adaptation. Developing comprehensive urban resilience plans to tackle extreme weather events' growing occurrence and intensity is crucial. A study by the UK Met Office forecasts a 50% rise in heatwaves in the UK by 2050, highlighting the need for solid adaptation strategies. Moreover, it is imperative to engage in multidisciplinary research combining engineering, environmental science, and social sciences to create comprehensive answers for the complex issues surrounding the energy transition. Research conducted by the London School of Economics (LSE) highlights the significance of public involvement and changes in behaviour since evidence indicates that consumer actions can contribute to as much as 20% of the required reductions in emissions [112].

The bar plot in Figure 10 contrasts the current capacity or impact of different research areas with their future goals, illustrating a substantial increase needed across all sectors. Notably, Carbon Capture, Utilisation, and Storage (CCUS) technologies show a significant leap from 40 million tonnes of CO2 to a target of 200 million tonnes, indicating the critical importance of advancements in this field. The pie chart in Figure 11 provides a clear distribution of future goals among different research areas, highlighting the focus on specific technologies. For instance, the allocation emphasises the crucial roles of solar photovoltaic (PV) technology, offshore wind technology, and hydrogen technology in the future energy mix. The line plot in Figure 12 on the estimated cost reduction by the research area underscores the economic feasibility of these advancements. It shows potential cost reductions, particularly in hydrogen technology and energy storage, which could decrease costs by up to 60% and 80%, respectively [113]. The scatter plot in Figure 13 juxtaposes the current capacity or impact with future goals, colour-coded by

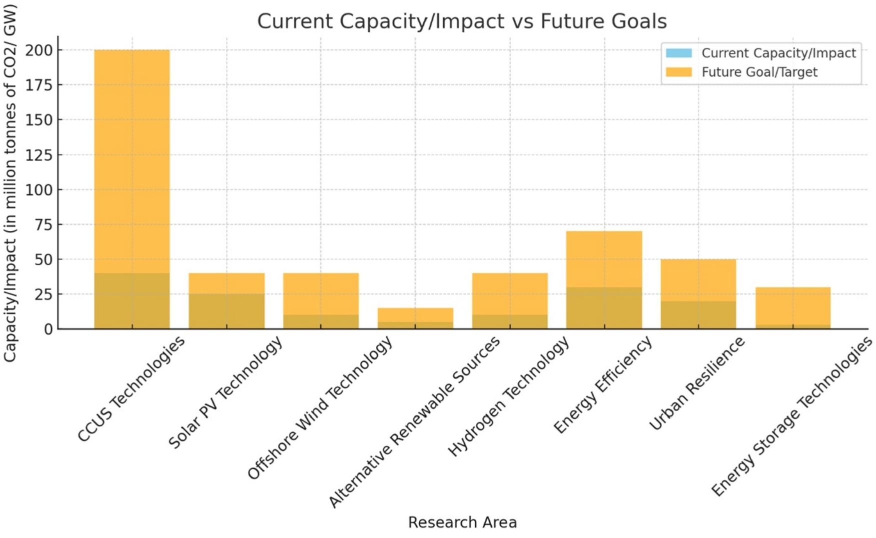

FIGURE 10 Current capacity/impact versus future goals.

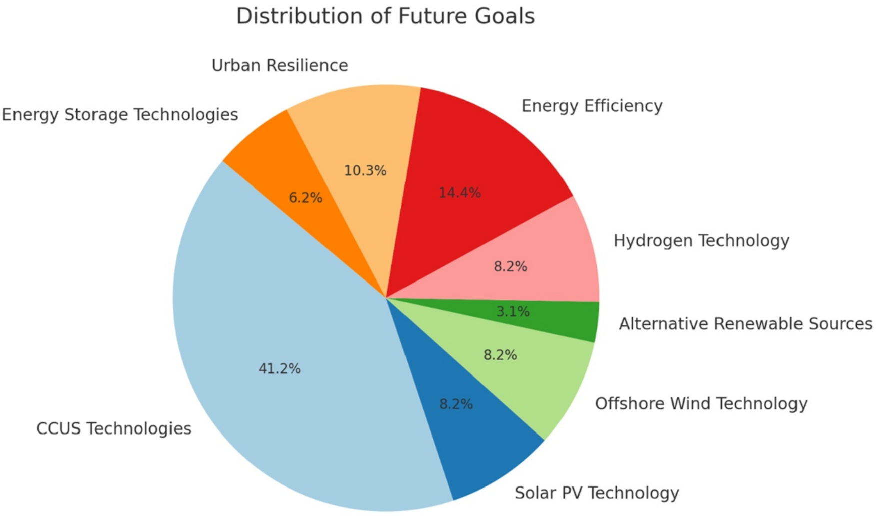

FIGURE 11 Distribution of future goals.

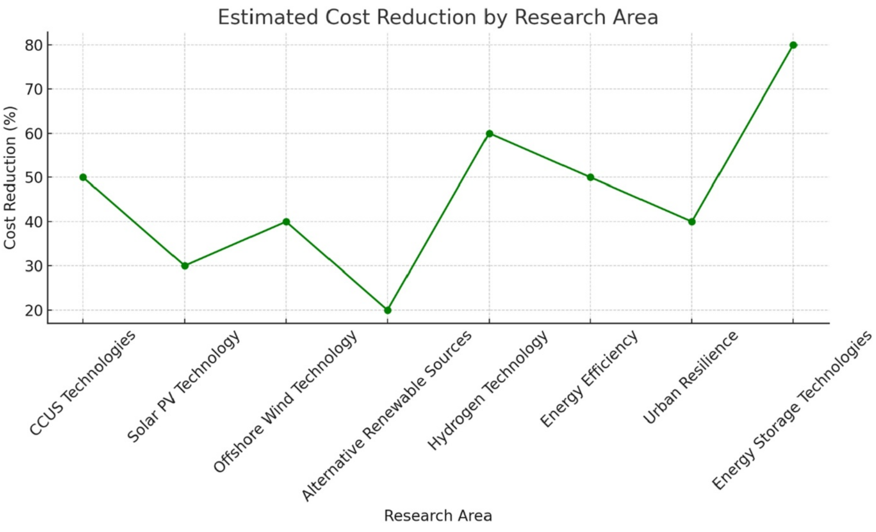

FIGURE 12 Estimated cost reduction by research area.

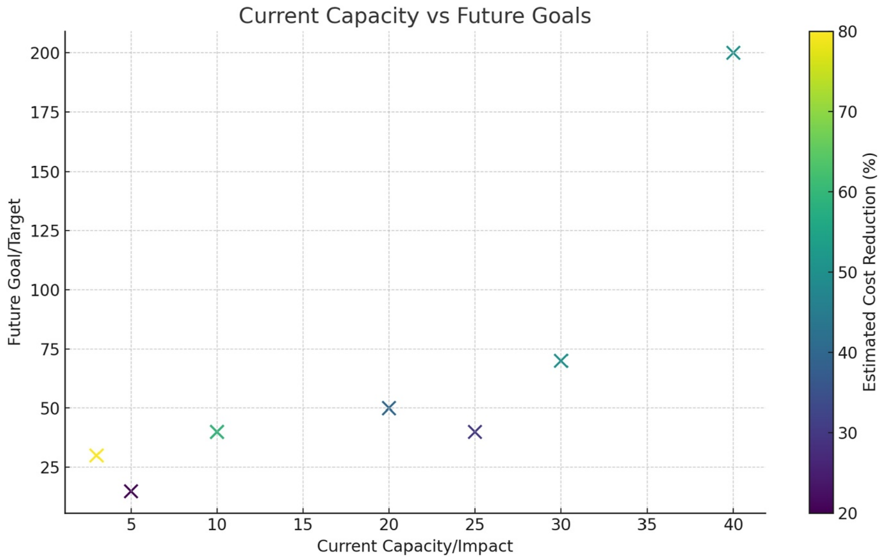

FIGURE 13 Current capacity versus future goals.

the estimated cost reduction percentage. This plot identifies research areas such as CCUS and offshore wind technology, which require significant improvements and offer substantial cost reduction opportunities [114–121]. Together, these visualisations underscore the multifaceted approach needed to achieve a net-zero emissions, emphasising technological advancements, economic feasibility, and targeted research efforts.

6 | CONCLUSIONS

The UK has set a challenging but essential aim to achieve net-zero emissions by 2050, which calls for a coordinated effort across all industries. Even though there has been a lot of progress, more innovation, sustainable economic growth, and societal reform are necessary to reach the next level. The key to this shift is striking a balance between modernising infrastructure and advancing renewable energy technologies at a rapid pace while limiting adverse economic effects and optimising jobs in green industries. The public's behavioural change towards sustainable habits, bolstered by efficient policy frameworks and education, is essential to success. International cooperation is still necessary since climate change is a worldwide issue that needs a coordinated response. The United Kingdom's dedication to this objective establishes a crucial standard in the global endeavour to tackle climate change, indicating that although significant obstacles exist, the advantages and prospects of a sustainable future are immense and attainable through joint effort and adaptability.

AUTHOR CONTRIBUTION

All authors contributed equally in preparation of this manuscript.

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CONFLICT OF INTEREST STATEMENT

None.

DATA AVAILABILITY STATEMENT

Data will be made available upon suitable request to corresponding author.

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