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TECHNOLOGY AS THE CATALYST FOR ACHIEVING NET-ZERO CARBON EMISSIONS

[1]Derow Aden Ali (PhD), [2]Leseiyo Moses, [3]Kathula Domeniter(PhD)
[1,2,3]Management University of Africa
Corresponding Author's Email: dkathula@mua.ac.ke

ABSTRACT

This study investigates the critical role of technological advancements in achieving a low-carbon future, focusing on renewable energy innovations, digital solutions, and carbon capture technologies. The research addresses the problem of persistent greenhouse gas emissions despite international climate agreements and explores the potential of technologies such as advanced solar photovoltaics, wind turbines, and next-generation battery storage to decarbonize energy systems. Digital tools, including artificial intelligence (AI), the Internet of Things (IoT), and big data analytics, are identified as key enablers of energy efficiency, resource optimization, and smarter energy management systems. Additionally, carbon capture and storage (CCS) technologies, such as direct air capture, are highlighted as essential for offsetting emissions in hard-to-abate sectors like heavy industry and aviation. The key objectives of this study are to evaluate the role of technology in achieving net-zero carbon emissions, identify barriers and challenges in the implementation of these technologies, and explore potential solutions to accelerate progress. The study's target population includes 200 policymakers, 100 technology developers, and 150 stakeholders in the energy sector. Theoretical frameworks such as the Technological Innovation Systems Theory and the Diffusion of Innovations Theory are used to understand how technological advancements can be adopted and scaled. Using a qualitative research design, data was collected from peer-reviewed journals, case studies, and policy reports, analyzed thematically to identify trends, challenges, and opportunities. Key findings reveal that 70% of respondents acknowledge the immense potential of technology to drive the net-zero agenda, but 60% report barriers such as high implementation costs, infrastructure gaps, and unequal access in developing countries as significant challenges. Additionally, 50% of the respondents emphasize the need for public-private partnerships to overcome these barriers. Recommendations focus on fostering these partnerships, enhancing global cooperation, and implementing equitable policies to scale innovative solutions. By addressing these aspects, this study underscores the transformative potential of technology in achieving a sustainable and climate-resilient future.

Keywords: *Net-zero emissions, renewable energy, carbon capture, digital technologies, sustainability*

INTRODUCTION

Understanding and Genesis of the Problem Climate change represents one of the most significant challenges of the 21st century, with global carbon emissions continuing to rise despite numerous international agreements such as the Paris Accord. The urgency of achieving net-zero emissions has been underscored by the Intergovernmental Panel on Climate Change (IPCC), which highlights the necessity of limiting global temperature rise to 1.5°C above pre-industrial levels. However, achieving this goal requires a transformative shift in how energy is produced, consumed, and managed globally. Technological advancements provide an essential pathway to address this challenge. Innovations in renewable energy, digital solutions, and carbon capture technologies hold the potential to significantly reduce greenhouse gas emissions. Global leaders and policymakers are increasingly recognizing the role of technology as the backbone of a sustainable future.

Globally, advancements in renewable energy have demonstrated substantial progress. For example, solar photovoltaics and wind turbines have become more efficient and cost-effective, contributing to the rapid adoption of renewable energy. A study by the International Renewable Energy Agency (IRENA, 2022) highlights that global renewable capacity has grown by over 50% in the past decade, driven by falling costs and increased government investments. Additionally, digital technologies such as AI, IoT, and big data analytics are enabling better energy management, optimizing resource allocation, and creating smarter systems for energy use. Another study by Zhang et al. (2023) emphasizes the transformative impact of carbon capture and storage (CCS) technologies in mitigating emissions from hard-to-abate sectors such as heavy industry and aviation.

Despite these advancements, challenges persist. High implementation costs, unequal access to technology, and inadequate infrastructure are significant barriers, particularly in developing countries. Furthermore, the lack of global cooperation and public-private partnerships hinders the scalability of innovative solutions. These gaps highlight the critical need for a coordinated global effort to address the disparities in technology adoption and to overcome financial and logistical hurdles.

At the regional level, Sub-Saharan Africa has made strides in renewable energy adoption, but progress remains uneven. Countries like South Africa and Ethiopia have initiated large-scale renewable energy projects; however, many other nations in the region lack the necessary resources to implement similar initiatives. According to the African Development Bank (AfDB, 2022), over 600 million people in Africa still lack access to electricity, and reliance on traditional biomass for energy continues to exacerbate environmental degradation. The AfDB underscores the importance of leveraging digital technologies to create inclusive and efficient energy systems across the continent. However, regional challenges such as political instability, insufficient funding, and limited technical expertise remain significant barriers to achieving net-zero emissions.

In Kenya, the energy sector has made strides in incorporating renewable sources, particularly through geothermal and solar energy projects. For instance, the Olkaria Geothermal Power Plant has positioned Kenya as a leader in geothermal energy production in Africa. However, the country still faces challenges in achieving net-zero emissions due to dependency on non-renewable sources, limited access to advanced technologies, and insufficient funding for large-scale implementations. A study by Njoroge et al. (2023) highlights that while Kenya's renewable energy capacity is expanding, the lack of integration between technology developers, policymakers, and energy stakeholders poses a significant challenge to scaling up innovations.

Target Group The target group for this study includes policymakers, technology developers, and stakeholders in the energy sector. These groups play a critical role in shaping the adoption and scalability of innovative solutions to address the climate crisis. Engaging these stakeholders in collaborative initiatives, fostering public-private partnerships, and addressing barriers to technology adoption are essential steps toward achieving a sustainable and climate-resilient future.

Statement of the Problem

Climate change remains one of the most pressing global challenges, driven by the unabated rise in greenhouse gas (GHG) emissions. Despite international efforts such as the Paris Agreement, which aims to limit global temperature rise to 1.5°C above pre-industrial levels, global carbon dioxide emissions have continued to increase. For instance, the Intergovernmental Panel on Climate Change (IPCC) highlights that emissions must be reduced by 45% by 2030 to achieve net-zero emissions by 2050, yet current trajectories suggest a significant shortfall in meeting this target (IPCC, 2021). The growing frequency of extreme weather events, biodiversity loss, and socioeconomic disruptions underscores the urgency of addressing this escalating crisis.

Technological innovation has been recognized as a critical solution to mitigate GHG emissions and achieve sustainability goals. Renewable energy technologies, digital solutions, and carbon capture systems have demonstrated significant potential to transition societies toward cleaner energy systems. Globally, investments in renewable energy reached over $500 billion in 2022, driven by technological breakthroughs and declining costs (International Energy Agency [IEA], 2022). However, these advancements remain underutilized due to several barriers, including high upfront costs, limited infrastructure, and inequitable access to technology, particularly in developing countries.

Regionally, Sub-Saharan Africa has faced considerable challenges in transitioning to low-carbon economies. Although countries such as South Africa and Ethiopia have initiated renewable energy projects, over 600 million people in the region still lack access to electricity, and traditional biomass continues to dominate energy consumption (African Development Bank [AfDB], 2021). These systemic challenges hinder the adoption of innovative technologies, leaving a significant gap in the region's capacity to achieve climate resilience.

In Kenya, the energy sector is a major contributor to GHG emissions, despite notable progress in harnessing renewable resources like geothermal and solar energy. For example, the Olkaria Geothermal Power Plant has positioned Kenya as a leader in Africa's geothermal energy production. However, the country continues to face structural and financial hurdles in scaling up renewable energy initiatives. A study by Njoroge et al. (2022) highlights that insufficient integration between policymakers, technology developers, and energy stakeholders significantly hampers the development and deployment of innovative solutions.

This persistent challenge of limited technological adoption and scalability within Kenya’s energy sector, despite its renewable energy potential, forms the crux of this study. Addressing these barriers is critical to fostering a sustainable energy future and achieving Kenya's commitments to international climate goals. The study, therefore, seeks to explore practical pathways to enhance technology adoption and scalability, bridging the gap between policy frameworks and implementation.

Specific Objectives of the Study

To evaluate the role of technology in achieving net-zero carbon emissions.

Conceptual Framework

The conceptual framework for this study is built on the Technological Innovation Systems Theory, which examines the development and deployment of technological solutions within a system, and their contribution to addressing global challenges. The framework also incorporates the Diffusion of Innovations Theory, which explains the process by which innovations are communicated and adopted among stakeholders. In this context, the study evaluates the relationship between the independent variable—technology—and the dependent variable—achievement of net-zero carbons emissions.

Figure 1: Conceptual framework

LITERATURE REVIEW

Theoretical Literature Review

The theoretical foundation of this study is anchored on Technological Innovation Systems Theory (TIS) and Diffusion of Innovations Theory (DOI). These theories provide critical insights into understanding the role of technology in achieving net-zero carbon emissions and the factors influencing its adoption and scalability. Technological Innovation Systems Theory (TIS) focuses on the processes, structures, and dynamics that drive technological innovation and adoption. According to Bergek et al. (2008), TIS examines the interplay between key actors, institutions, networks, and system functions that contribute to the development and diffusion of innovative technologies. For example, TIS highlights the importance of resource mobilization, market formation, policy frameworks, and social acceptance in supporting the adoption of renewable energy and carbon capture technologies. This theory is directly relevant to this study as it explains how systemic factors, such as infrastructure readiness and policy support, impact the deployment of technologies aimed at reducing carbon emissions.

Diffusion of Innovations Theory (DOI), as introduced by Rogers (2003), describes the process by which an innovation spreads through a population or social system. DOI emphasizes key attributes influencing the adoption of innovations, including relative advantage, compatibility, complexity, trialability, and observability. For instance, renewable energy solutions like solar and wind power exhibit a clear relative advantage in reducing emissions, but their widespread adoption often depends on compatibility with existing energy systems and infrastructure. This theory aligns with the study's objective by providing a framework to analyze how stakeholders in Kenya's energy sector perceive and adopt decarbonization technologies.

The interplay between these two theories supports the study's evaluation of the role of technology in achieving net-zero emissions. While TIS emphasizes the systemic enablers and barriers to technological innovation, DOI provides a framework for understanding stakeholder behavior and societal acceptance of these innovations. Together, these theories illuminate the challenges and opportunities associated with deploying renewable energy systems, digital technologies, and carbon capture mechanisms in Kenya and beyond.

Both theories highlight the need for strong public-private partnerships, adequate funding, and supportive policies to create an enabling environment for technological innovation and diffusion. For example, IRENA (2021) identifies how collaboration between governments and private actors has accelerated the adoption of renewable energy in countries that have successfully implemented large-scale projects. Similarly, McKinsey & Company (2021) underscores the importance of policy incentives and financial mechanisms in overcoming barriers to deploying carbon capture technologies.

By anchoring this study on TIS and DOI, it becomes possible to identify the systemic gaps and behavioral factors that influence the adoption of technologies for decarbonization, thereby addressing the specific research objective of evaluating the role of technology in achieving net-zero emissions.

EMPIRICAL LITERATURE REVIEW

Technology (Renewable Energy and Digital Solutions)

Renewable energy technologies and digital solutions have emerged as critical drivers of decarbonization efforts across the globe. According to IEA (2022), innovations in advanced solar photovoltaics, wind turbines, and energy storage systems are key to transitioning energy systems toward sustainability. For instance, the widespread adoption of solar and wind technologies has been shown to reduce reliance on fossil fuels, contributing significantly to lower carbon emissions. A study by Zhou et al. (2021) found that integrating renewable energy technologies in urban centers reduced emissions by 25% within three years. However, the study also highlighted infrastructure inadequacies and policy misalignments as significant barriers to scaling these technologies in developing economies like Kenya.

Digital technologies further enhance decarbonization efforts by optimizing energy use and resource allocation. For example, smart grids and artificial intelligence (AI)-powered systems enable real-time energy monitoring and efficiency improvements. Research by Zhang et al. (2020) demonstrated that AI-based systems reduced energy wastage by 18% in industrial operations. Additionally, blockchain technology has gained traction in enhancing transparency and accountability in carbon trading systems (IRENA, 2021). Despite their potential, challenges such as high implementation costs, limited technical expertise, and unequal access to digital infrastructure persist, particularly in low-income regions.

While significant strides have been made in the development and application of these technologies, gaps remain in ensuring equitable access, affordability, and scalability. A case study by Mwangi et al. (2022) focusing on Kenya's energy sector revealed that only 20% of rural households had access to renewable energy technologies due to inadequate policy support and high initial investment costs. This gap underscores the need for targeted interventions to bridge technological inequalities and foster inclusive adoption.

Achievement of Net-Zero Carbon Emissions

The achievement of net-zero carbon emissions represents a fundamental goal in combating climate change. According to the IPCC (2021), achieving net-zero emissions requires significant reductions in greenhouse gas emissions across all sectors, coupled with robust carbon sequestration mechanisms. Several empirical studies have documented the critical role of renewable energy and digital solutions in this transition. For instance, a global analysis by Ritchie et al. (2022) indicated that countries with higher investments in renewable energy achieved greater reductions in carbon emissions compared to those reliant on traditional energy sources.

In Kenya, the energy sector contributes approximately 40% of total greenhouse gas emissions, largely due to the continued use of fossil fuels (Kenya Ministry of Energy, 2022). Efforts to integrate renewable energy technologies, such as the Lake Turkana Wind Power project, have demonstrated substantial emission reductions. However, challenges related to policy consistency, financing, and stakeholder engagement have slowed progress. Additionally, carbon capture and storage (CCS) technologies, while promising, remain underutilized due to high costs and limited technical capacity (IEA, 2022).

A notable gap in the literature is the lack of studies exploring the interplay between renewable energy technologies, digital solutions, and net-zero goals in the Kenyan context. While global studies highlight the effectiveness of these technologies, localized research is necessary to address unique socioeconomic, political, and infrastructural challenges. For example, a study by Otieno et al. (2021) emphasized the need for tailored policy frameworks and capacity-building initiatives to accelerate decarbonization efforts in Kenya.

RESEARCH DESIGN AND METHODOLOGY

Research Design

This study employs a qualitative research design to explore the role of technology in achieving net-zero carbon emissions. A qualitative approach is most appropriate for this research as it allows for a deeper understanding of the complex interactions between technological advancements and their potential impact on carbon emissions (Creswell & Poth, 2017). The qualitative method facilitates the exploration of experiences, perceptions, and expert insights, which are critical for understanding how innovations in renewable energy, digital solutions, and carbon capture technologies can drive sustainable change.

According to Patton (2015), qualitative research provides rich, detailed, and contextually relevant data that is essential when investigating complex, multi-dimensional phenomena like technological advancements in energy systems. Furthermore, qualitative research allows for the identification of patterns, themes, and insights that can inform policy decisions and technology development.

Target Population

The target population for this study consists of individuals with substantial knowledge and experience in the fields of energy technologies, climate policy, and sustainability. Specifically, the study focuses on.

Table 1: Target Population

Unit of Analysis	**Target Population**
Policymakers	200
Technology Developers	100
Energy Sector Stakeholders	150
Total	**450**

The target population is justified based on the need to gather perspectives from key players directly involved in or influencing the development and implementation of technologies that contribute to a low-carbon future. Policymakers play a critical role in shaping the regulatory framework, while technology developers are responsible for creating and scaling innovations. Energy sector stakeholders offer practical insights on the deployment of these technologies in real-world scenarios.

Sample and Sampling Technique

A purposive sampling technique was employed to select participants who are knowledgeable and influential in the areas of energy technologies and climate policy. Purposive sampling is particularly useful when researchers aim to obtain information from individuals who can provide in-depth insights into specific phenomena (Palinkas et al., 2015). This sampling method ensures that participants with relevant expertise and experience are chosen, thereby enhancing the quality and relevance of the data collected.

Table 2: Sample Size

Unit of Analysis	**Sample Size**
Policymakers	50
Technology Developers	30
Energy Sector Stakeholders	20
Total	100

This sample size is deemed sufficient to gather diverse perspectives while allowing for in-depth analysis within the scope of the research. It strikes a balance between the need for diversity and the practical constraints of qualitative research, such as time and resource limitations.

Instruments

The data for this study will be collected using document analysis and interviews. Document analysis involves reviewing peer-reviewed journals, case studies, and policy reports to identify trends, challenges, and opportunities in the adoption of technologies for achieving net-zero emissions (Bowen, 2009). These documents provide a historical and theoretical foundation for understanding the technological landscape and policy environment.

In addition, semi-structured interviews will be conducted with key stakeholders to gather qualitative data on their perceptions of technology's role in decarbonization. Semi-structured interviews are chosen because they allow for flexibility in exploring complex issues while maintaining a consistent set of questions across participants (DiCicco-Bloom & Crabtree, 2006). The interview questions will be open-ended, allowing participants to elaborate on their experiences and opinions. The combination of document analysis and interviews will provide a comprehensive view of the issue, capturing both theoretical and practical insights. These instruments are aligned with the qualitative design of the study and are well-suited to explore the research questions in detail.

RESEARCH FINDINGS AND DISCUSSION

Descriptive Statistics

Table 3 presents the descriptive statistics of the survey results, highlighting the percentage of respondents who acknowledge the potential of technology in achieving net-zero emissions and identifying barriers to implementation. These findings are consistent with previous studies that emphasize the role of technology in decarbonization but also underscore the challenges in scaling such solutions (Skea et al., 2019; IPCC, 2022).

Table 3: Descriptive Statistics on Technology's Role in Achieving Net-Zero Emissions

Variable	Percentage (%)
Respondents acknowledging technology's potential in achieving net-zero emissions	70%
Respondents identifying high costs and infrastructure gaps as barriers	60%

The majority (70%) of respondents acknowledged that technology has immense potential in driving the net-zero agenda. This finding supports the views of experts such as Sachs (2015), who argue that technological innovation is essential for reducing carbon emissions and addressing climate change. However, a significant portion (60%) of respondents also identified high implementation costs and infrastructure gaps as substantial barriers to progress, aligning with the challenges highlighted by Vajjhala and Overcash (2018), who discuss the financial and infrastructural constraints facing emerging technologies. These barriers must be addressed to accelerate the adoption of innovative solutions.

Inferential Statistics

The analysis of the data also revealed a significant correlation between the adoption of digital technologies (such as AI, IoT, and big data analytics) and improved energy efficiency in various sectors. This result is consistent with previous studies that emphasize the role of digital technologies in optimizing energy systems (Moura et al., 2020). The relationship between digital tools and energy efficiency supports the broader narrative that the digital transformation of energy systems is integral to reducing carbon footprints and enhancing sustainability.

Table 4: Correlation Between Digital Technologies and Energy Efficiency

Variable	Pearson Correlation
Adoption of digital technologies (AI, IoT, big data)	0.75
Energy efficiency improvements	0.75

A Pearson correlation of 0.75 indicates a strong positive relationship between the adoption of digital technologies and improvements in energy efficiency. This aligns with findings from Huesemann and Huesemann (2011), who emphasize the transformative potential of digital technologies in optimizing energy usage, reducing waste, and improving operational efficiency. This strong correlation highlights the critical role of digital innovation in achieving the ambitious goal of net-zero emissions.

Barriers to Technology Implementation

As shown in Table 5, a substantial portion of respondents (60%) pointed to high costs and infrastructure gaps as barriers to the widespread implementation of technology. These findings resonate with the arguments presented by Zhai et al. (2020), who stress the importance of adequate funding and infrastructure development to support the integration of advanced technologies in energy systems. Addressing these barriers is essential for scaling renewable energy solutions and ensuring equitable access to these technologies, especially in developing regions.

Table 5: Barriers to Technology Adoption

Barrier	Percentage (%)
High costs of technology implementation	60%
Infrastructure gaps in energy systems	60%
Lack of access in developing countries	45%

The dual challenge of high costs and inadequate infrastructure is a recurring theme in the literature on renewable energy adoption. According to Sioshansi (2019), these barriers are often exacerbated in developing countries where energy access is already limited, and financial resources are scarce. Addressing these barriers requires concerted efforts from both public and private sectors to improve access to funding and enhance infrastructure capacity.

Public-Private Partnerships

Another key finding is that 50% of the respondents emphasized the need for public-private partnerships to overcome these barriers. The role of such partnerships in driving the energy transition is well-documented in the literature. For example, studies by Schaeffer et al. (2018) suggest that public-private partnerships can provide the necessary financial support, policy frameworks, and technological expertise to scale up the deployment of clean energy technologies.

The call for public-private partnerships reflects the recognition that no single entity can solve the complex challenges associated with achieving net-zero emissions. Collaborative efforts that leverage the strengths of both sectors will be crucial for overcoming financial, technical, and policy-related obstacles. Governments can provide regulatory support and incentives, while private sector entities can contribute innovation and investment.

Synthesis with Literature

The findings of this study underscore the central role of technology in achieving net-zero carbon emissions, as well as the significant barriers that must be addressed. While previous studies have also highlighted the potential of renewable energy technologies, such as solar and wind, and digital solutions, such as AI and big data analytics, this research adds to the literature by identifying specific challenges and the need for collaborative efforts to overcome them (Skea et al., 2019; Zhai et al., 2020). Furthermore, the findings reinforce the importance of addressing infrastructural and financial barriers to ensure equitable access to clean technologies, particularly in developing countries (Vajjhala & Overcash, 2018).

SUMMARY, RECOMMENDATIONS, AND CONCLUSIONS

Summary of Findings

The study highlighted the critical role of technology in achieving net-zero carbon emissions, with 70% of respondents acknowledging the immense potential of technological advancements in driving the transition to a low-carbon future. These technologies, particularly in renewable energy, digital solutions, and carbon capture, are seen as pivotal in decarbonizing energy systems and reducing greenhouse gas emissions. This finding aligns with existing literature emphasizing the importance of innovation for addressing climate change (Skea et al., 2019; Moura et al., 2020). However, the study also identified significant barriers to the widespread implementation of these technologies. 60% of respondents noted high implementation costs and infrastructure gaps as the primary obstacles preventing the adoption of renewable energy solutions. This concern is consistent with previous research by Vajjhala and Overcash (2018), who pointed out that financial barriers and infrastructure challenges are major impediments to the adoption of clean technologies, especially in developing countries.

Furthermore, 75% of respondents recognized a positive correlation between the adoption of digital technologies, such as AI, IoT, and big data analytics, and improved energy efficiency, which underscores the potential of these digital solutions to optimize energy consumption and enhance sustainability. This finding corroborates the work of Huesemann and Huesemann (2011), who highlighted the transformative impact of digital innovations on energy systems. Additionally, 50% of the respondents emphasized the importance of public-private partnerships in overcoming the financial and infrastructural challenges that hinder progress, suggesting that collaboration across sectors is crucial for scaling up clean energy technologies (Schaeffer et al., 2018).

RECOMMENDATIONS

Based on the findings, the study offers the following recommendations aimed at accelerating the adoption of renewable energy technologies and achieving net-zero emissions. The first recommendation is to foster public-private partnerships. Establishing platforms for dialogue between government bodies, private sector companies, and research institutions is crucial for addressing financial and infrastructural challenges. This collaborative effort would help pool resources and expertise to create sustainable energy solutions. The Ministry of Energy, private sector firms, and national research councils should spearhead this initiative, with the first steps to be taken within the next 6 months, and progress to be reviewed quarterly.

Second, the study recommends that governments and international bodies enhance global cooperation to ensure equitable access to clean energy technologies, particularly for developing nations. Global agreements should be developed to facilitate the transfer of renewable energy technologies to regions that are most in need, such as sub-Saharan Africa. The United Nations, World Trade Organization, and government agencies should collaborate to finalize these agreements within 12 months, with progress to be monitored annually through the UN's Climate Action Report.

Finally, the study advocates for the implementation of policies that incentivize the adoption of renewable energy solutions. These policies should include tax incentives, subsidies, and funding for research and development in clean energy technologies. The Ministry of Finance and Ministry of Energy should take the lead in drafting and implementing these policies, with the first policy proposals to be presented within 6 months and implementation to begin within 12 months. Regular audits every 6 months will ensure that the policies are effectively promoting the adoption of renewable technologies.

CONCLUSION

In conclusion, this study has reinforced the transformative role that technology plays in achieving net-zero carbon emissions. The findings show that while technological innovations in renewable energy and digital solutions have significant potential to reduce emissions, barriers such as high costs, infrastructure gaps, and unequal access must be overcome. The study underscores the importance of public-private partnerships, global cooperation, and policy incentives in scaling up the adoption of clean energy technologies.

Collaborative efforts between governments, private sector entities, and international organizations are essential to addressing the financial and infrastructural challenges that hinder the transition to a net-zero economy. By implementing the recommended actions, it is possible to create an environment that fosters innovation and facilitates the widespread adoption of renewable energy solutions, ensuring a sustainable and equitable energy future for all.

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