

Review of Multi-Pillar Evaluation of Mechanical Self-Propulsion Systems for Energy Access in Africa: Applying the STEV Framework

O. J. Alamu^{a*} and A. P. Azodo^b

^aDepartment of Mechanical Engineering, Osun State University, Osogbo, Nigeria

^bDepartment of Mechanical Engineering, Federal University, Wukari, Nigeria

*Corresponding Author: alamuoj@uniosun.edu.ng

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ABSTRACT

The long-standing electricity crisis in Africa due to unstable grids, insufficient infrastructure, and fossil fuel reliance requires novel and sustainable solutions. The paper assesses the prospect of the mechanical self-propulsion systems as alternative energy sources, and proposes the Socio-Technical-Economic Viability (STEV) Framework as a comprehensive assessment tool. The framework is used to critically analyze the technical, economic and social aspects of these systems. Results indicate that, although technically they are feasible, they need improvements in long-lasting materials, energy storage and low-cost maintenance strategies to succeed in resource-limited environments. The cost of high initial expenditures presents a problem economically, yet over time, savings and creative methods of financing make it more viable. Socially, community acceptance, local empowerment, and equitable access come into focus as non-negotiable conditions to successful deployment. The discussion also reveals that supportive policies and regulatory frameworks are critical facilitators of scalability and impact. In general, the paper finds that mechanical self-propulsion systems, assessed in the framework of the STEV Framework, have a great potential to predetermine an even more sustainable and inclusive energy future in Africa.

1. INTRODUCTION

It has been reported that Nigeria can decrease its dependence on refined petroleum product imports by an aggressive use of domestic, renewable energy options (Alamu *et al.*, 2009; Osho, 2025). Africa has a complex electricity problem which is influenced by social, economic, and infrastructural issues. Persistent insufficiencies in energy infrastructure can be solved through the availability of electricity to only 47.67% of the population in the continent in 2018 (Katekar and Deshmukh, 2022). Unplanned settlements, lack of adequate distribution channels and generation capacity impede growth of stable power supply (Quartey, 2021). At the same time, the price of electricity has been skyrocketing by up to 276% in certain areas since 2011, increasing poverty and the disparity between the rich and the poor (Quartey, 2021). The consumption pattern of residential electricity, especially in Nigeria, reflects larger issues in the infrastructure of the continent (Azodo, 2014). It is reported that there are about 1.4 billion individuals lacking electricity access, with the biggest disparities being in rural regions of Sub-Saharan Africa and South Asia (Kaygusuz, 2012).

Although the urban areas are more electrified, there are rural areas with access rates as low as 4% (Ye and Koch, 2023). Such inequalities are impediments to healthcare, education, and economic activities, entrenching poverty and halting sustainable development (Amadi, 2018). The lack of infrastructure, the

fast-growing population, and financial constraints aggravate the crisis of electricity. The financial obstacles prevent investments in modern grids and renewable energy systems, whereas geographic remoteness magnifies the price of electrifying rural areas (Lizunkov et al., 2018). Reliance on fossil fuels is also adding to environmental degradation and putting economies at the mercy of unstable energy markets. The overall effect of the mentioned challenges destabilizes industrialization and small-scale businesses, inhibiting economic growth and innovation (Akinbola, 2017; Azodo and Omokaro, 2018; Halkos and Gkampoura, 2020).

The mitigating measures are integration of renewable energy, decentralized systems and Public-Private Partnerships (PPP). Rural electrification efforts, such as the use of solar mini-grids and community-driven projects, have proven successful, but governance and infrastructure challenges remain (Stritzke and Jain, 2021; Ugwu *et al.*, 2024). Smart grids and PPPs are examples of innovations that prove to be more efficient and reliable in energy use, with the Brooklyn Microgrid being just one example (Uzondu and Lele, 2024). Nonetheless, scalability issues, cost, and regulatory bottlenecks impede a large-scale adoption (Batinge *et al.*, 2019). The increased access to electricity plays a crucial role in attaining SDG 7, which enhances the access to affordable and clean energy. Interconnected goals, such as poverty eradication (SDG 1) and climate action (SDG 13) are also supported by reliable electricity (Awogbemi *et al.*, 2024). The shift to renewable energy not only lowers the emission of greenhouse gases but also ensures the growth of the economy and energy security (Alamu *et al.*, 2009; Moriarty and Honnery, 2021; Henao and Guzman, 2024).

Mechanical self-propulsion systems are innovative technologies that can be used to power off-grid applications (Sei-Bum and Min-Hyun, 2020). As a reaction, new triboelectric-based mechanical self-propulsion systems, fluid dynamics-based self-propulsion, and hybrid energy harvesting systems offer an original solution to energy production (Rana *et al.*, 2022; Wang *et al.*, 2018). Such technologies have the potential to supplement the current systems but the challenges that still remain, including scaling, integration, and optimization, still limit their real-life implementation in the African energy ecosystem (Mirzaliyev *et al.*, 2022). Although research has been conducted on the adoption of renewable energy and traditional energy issues in Africa, research on the assessment of mechanical self-propulsion technologies in the context of a holistic socio-technical and economic context is limited. In particular, there are still unresolved questions about their viability, scalability, and possible socio-economic consequences in different African settings.

To fill this gap, the current review proposes a new framework to examine mechanical self-propulsion systems, which is referred to as the Socio-Technical-Economic Viability (STEV) Framework. Having considered technical performance, economic viability, and social impact, the paper transcends the descriptive summaries of the current technologies, and presents an analysis of the potential of these technologies in providing electricity solutions to Africa. Consistent energy supply is highly associated with economic growth, increased Human Development Index (HDI), and the quality of life (Nowak *et al.*, 2021). Africa today has about one billion people who do not have access to reliable power, which restricts education, health, and agricultural activity (Richard *et al.*, 2023). Current solutions, such as fossil-based and renewable ones, tend to not be as inclusive, reliable, and sustainable as long-term growth requires (Huesemann, 2003; Allal *et al.*, 2024).

Through the analysis of mechanical self-propulsion systems using the STEV Framework, this review is in line with the United Nations Sustainable Development Goals (SDGs), such as SDG 7 (Affordable and Clean Energy), SDG 10 (Reduced Inequalities), and SDG 13 (Climate Action) (Li *et al.*, 2024). By specializing in Africa, it is possible to combine old wisdom with new technological advancements to create context sensitive, sustainable energy solutions. The paper shows how technologies of mechanical self-propulsion, when evaluated in terms of a socio-technical-economic framework, may offer a sustainable and efficient way to overcome the crisis of electricity supply in Africa, fill the gaps in the infrastructure, cost, and environmental footprint.

2. METHODOLOGY

In this paper, a systematic review approach is used to assess the possibilities of mechanical self-propulsion systems to solve the electricity supply crisis in Africa. It involved four different yet related steps; literature review, conceptual framework development, analytical application, and synthesis.

2.1 Methodology Process

2.1.1 Literature review

The literature search involved an extensive review of peer-reviewed journals, conference papers and institutional reports published since 2000 so that the analysis is based on the recent scholarship. The search strategy was based on the keywords such as mechanical self-propulsion, sustainable energy, energy access, and developing nations. The filtering/screening of sources was done to give priority to works which discuss technological innovation and socio-economic aspects of alternative energy systems. This stage defined the contemporary state of research and identified knowledge gaps.

2.1.2 Development of the conceptual framework

Based on the literature reviewed, the STEV Framework was created as an analysis tool. In comparison to single-dimensional measurements, the STEV Framework incorporates three pillars that relate to each other such as technical, economic, and social viability into the comprehension of the mechanical self-propulsion systems in the context of African energy.

2.1.3 Application of the framework

The literature gathered was systematically arranged and evaluated on the three pillars of the STEV Framework:

- i. **Technical Viability:** The research on engineering design, energy conversion efficiency, durability, and connectivity to the current networks was studied.
- ii. **Economic Viability:** Studies that focused on cost structure, investment models, and savings on long-term operations were consulted to assess financial sustainability.
- iii. **Social Viability:** Data related to the acceptance of communities, equity in energy access, empowering of locals, and socio-cultural effects (e.g., on education and healthcare) were analyzed critically.

2.1.4 Comparative analysis and synthesis

The last phase integrated results of the three pillars to have a scale assessment of mechanical self-propulsion systems against conventional and large-scale renewable technologies. This integrative analysis helped understand both the strengths and limitations of the systems as well as come up with the insight on cross cutting challenges, future research requirements and enabling policy actions. With such a multi-step approach, the study provides a high-rigor and conceptually-based basis of the viability of mechanical self-propulsion systems as a solution to sustainable and inclusive access to energy in developing countries.

2.2 Overview of Mechanical Self-propulsion Systems

In energy generation, mechanical self-propulsion systems are those technologies that transform ambient mechanical energy (flow of fluids, vibrations, or human movement) into useful electrical energy. These systems are not reliant on constant external power such as batteries or fuel, as is the case with conventional systems. They are increasingly relevant because they offer decentralized and renewable sources of power which can alleviate the problem of electricity supply in Africa (Mirzaliyev *et al.*, 2022).

2.2.1 Fluid-based systems

These mechanisms harness the energy of flowing fluids like water and air. Micro-hydro turbines can produce electricity using small streams or low-flow water streams, which is especially applicable to the rural population in Africa where a large-scale hydroelectric power plant is not feasible (Kaunda *et al.*,

2012). Likewise, Vortex-Induced Vibration (VIV) generators take advantage of vibrations generated by fluid flow around a structure to generate power, which provides a scalable solution to off-grid applications. Small-scale wind energy harvesters also qualify as such, offering local solutions in situations where wind is sufficient.

2.2.2 Kinetic and motion-based systems

The other group is the technology using human movement or vibrations of the environment as a source of energy. Some examples include kinetic floor tiles that produce electricity when trampled, which can be implemented in areas with large pedestrian flows like train stations or educational institutions. Small but helpful quantities of electricity can also be generated by wearable energy harvesters like shoe-integrated piezoelectric systems to power portable devices. Although each of them is restricted in its production individually, these solutions demonstrate the adaptability of mechanical energy generation in various settings (Rana *et al.*, 2022).

2.2.3 Triboelectric systems and hybrid systems

Triboelectric Nanogenerators (TENGs) are a new generation of self-propulsion systems which transform mechanical movement into electricity via contact electrification and electrostatic induction. TENGs have the potential to utilize the energy of daily mechanical processes, like walking, pressing, or vibrations of the environment (Wang *et al.*, 2021). More efficient systems using hybrid systems with triboelectric effects combined with piezoelectric or electromagnetic systems are even more promising, and have been suggested in decentralized energy collection in resource-constrained environments.

2.2.4 Analytical framework integration

The fluid-based, motion-based and triboelectric/hybrid technologies mentioned above demonstrate the plethora of different methods of ambient mechanical energy utilisation to generate power. Both provide their own distinctive prospects of sustainable, small scale power generation, which is essential in solving the energy access problem in Africa. These systems will then be assessed in the sections that follow in an organized manner using the STEV Framework and hence a systematic evaluation of their applicability, efficiency and scalability is achieved.

2.3 The STEV Framework

It suggests the STEV Framework as a conceptual framework with the purpose of assessing the viability of mechanical self-propulsion technologies in the African context. It is aimed at offering a systematic prism through which the appropriateness of emerging solutions can be evaluated, to be not only technically operational, but also economically and socially viable. The STEV framework allows combining three key dimensions, namely, technical viability, economic viability, and social viability, into one comprehensive assessment system, which is unlike traditional approaches that pay close attention to only a sub-set of the stated (Peterson, 2016; Taghvaei *et al.*, 2023).

2.3.1 Technical viability

Technical viability is concerned with the technical healthiness and practical stability of self-propulsion technologies. Some of the main factors are energy production, which will dictate whether the technology can produce enough and reliable power to serve its purpose (Sabino *et al.*, 2025). Scalability is also important, since solutions should be flexible to varying capacities and contexts, whether it is a single mobility device or a community application (Tale and Rege, 2024). Central to them is also durability and resilience which makes sure that technologies are able to survive local environmental factors like heat, dust and humidity (Gasser, 2008). Lastly, maintenance needs should be sizable regarding technical skills locally and the existing infrastructure, minimizing the chances of system breakdowns and system abandonment (Faludi *et al.*, 2024).

2.3.2 Economic viability

Economic viability stresses upon financial sustainability and affordability throughout the life cycle of the technology. Initial capital expenditure and the long-term operation costs have to be balanced not to strain users or governments (Ojha *et al.*, 2023). Adoption and long-term success can be impacted by financial models, such as subsidies, micro-financing, or cooperative ownership structures (Cortez and Pérez, 2024). Moreover, the potential of such technologies to drive local employment by producing, installing, or servicing them supports their purpose in driving the local economy (Das and Muchhara, 2024). The inclusion of these aspects means that the framework will not make proposed solutions donor-dependent but a driver of sustainable development.

2.3.3 Social viability

Social viability is the measurement of how self-propulsion technologies match with society, its values and practices. Community acceptance is essential as technically and economically valid innovations can fail because of the lack of trust and readiness to accept (Clain *et al.*, 2024). The training needs should be friendly to handle and provide users and technicians with the required skills without putting entry barriers (Adegbite, 2024). Equity of access means that the marginalized groups such as women and rural population will not be left behind in the benefits of innovation (Leong, 2024). The compatibility on the cultural level is also considerable, where technologies should align with the local culture, everyday life, and movement trends to become accepted (Latif, 2020).

2.3.4 Interconnections among the pillars

Although all pillars of the STEV Framework offer individual assessment criteria, they all are interlinked. Technology that is technically superior at prohibitively high costs will not be adopted, nor will a low-cost system, which lacks social acceptance, be adopted. In the same vein, socially adopted solutions that are not technically sound may end up becoming obsolete quickly. The framework therefore puts a focus on balance whereby any proposed technologies must show sufficiency in all the three dimensions before any of them becomes viable. This interconnectedness echoes a wider sustainability framework, like the triple-bottom-line model, that focuses on balance in the technical, economic, and social realms (Peterson, 2016; Yazdandoost, 2021). The STEV framework (Figure 1) shows the three pillars and how they are interrelated. The figure is a visual map of the convergence of technical, economic and social dimensions.

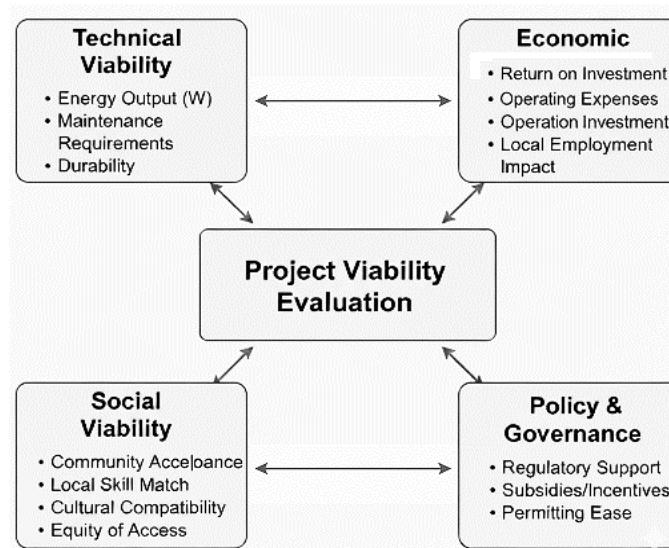


Figure 1: Conceptual Diagram of the STEV Framework for Project Viability Evaluation (Peterson, 2016; Yazdandoost, 2021)

2.4 Technical Viability: Engineering and Design Considerations

Mechanical self-propulsion systems hold promise as a sustainable solution to the electricity crisis in Africa but this depends on their technical viability. In addition to the generation of power, these systems should prove to be durable, adaptable, and maintainable in resource-limited environments. This part critically analyzes the contribution of materials, energy conversion and storage as well as maintenance strategies to technical feasibility (Peterson, 2016; Yazdandoost, 2021).

2.4.1 Innovative materials and design

Innovations in materials and design have increased the resilience of self-propulsion systems and efficiency (Adetunji *et al.*, 2011). The utilization of nanostructured composites and adaptive surfaces can be used as an example, which enhances the resistance to environmental stressors such as heat and dust, prevalent in most parts of Africa. Systems can adjust themselves to maximize energy harvesting by using structural innovations, especially self-orienting wind turbines. The horizontal and vertical axis designs have been demonstrated to enhance efficiency in output in variable wind conditions (Cowap, 2013). These innovations directly cope with the problem of intermittency of renewable energy in the continent.

2.4.2 Energy conversion and storage

Self-propulsion systems rely on the effective energy conversion and storage. The hybrid renewable systems like wind turbines combined with solar panels offer affordable electricity production to off-grid rural areas (Kosonen and Alku, 2013). Nonetheless, renewable intermittency needs scalable storage to smooth supply. Studies indicate that poor storage is one of the primary constraints of long-term feasibility, especially where there is a poor grid network (Lebrouhi *et al.*, 2021). This is one of the barriers that should be overcome in an effort to provide power in Africa.

2.4.3 Durability, maintenance and longevity

Such attributes as durability and maintenance are essential in maintaining self-propulsion systems in Africa. A lack of access to special spares and trained technocrats imply that systems will be modeled to be inexpensively maintained with low-end technologies. The low success rate and low lifetime of operations discourages the trust in new technologies (Lebrouhi *et al.*, 2021). The duration of the system and cost reduction can be achieved by adding predictive maintenance models in the system and designing components with simplified substitute methods (Zaman *et al.*, 2024).

The technical feasibility of self-propulsion systems depends on three main points: (1) resistant materials and design that can withstand extreme conditions, (2) efficient energy conversion and reliable storage, and (3) maintenance solutions that fit in the area with inadequate technical infrastructure. These are the main concerns of the STEV framework that should focus on the abilities of technologies to survive, evolve, and provide reliable power. Unless these barriers are overcome, self-propulsion system promise in alleviating the electricity crisis in Africa will not be fulfilled (Zaman *et al.*, 2024).

3. ECONOMIC VIABILITY: COST, INVESTMENT, AND SUSTAINABILITY

According to Zaman *et al.* (2024), one of the most critical factors in assessing the feasibility of mechanical self-propulsion systems is economic viability, in ascertaining whether this solution can truly help to address the electricity crisis in Africa. On the one hand, these systems are associated with lower operation costs and economic benefits in the long term. On the other hand, they have great obstacles based on high startup expenses, lack of access to capital and frequent maintenance cost. This discussion addresses both the demand and supply sides of the economic equation and sheds light on the ways to achieve a sustainable implementation.

3.1 Cost Savings and Long-Term Value

Mechanical self-propulsion systems have long-term cost benefits in the form of reduced operational and maintenance costs. As an example, resilient components have longer lifespan and less downtime, which lowers the ownership cost (Carmiel *et al.*, 2022; Akinyemi and Alamu, 2009). The systems also supply cheap power to rural areas where traditional grid extensions are frequently economically infeasible, thereby assisting in supplying energy disparities. Moreover, deployment generates local manufacturing, installation, and maintenance jobs and this can trigger the overall economic development (Xiao, 2023). These technologies not only provide a technical answer but also a local development engine by making it possible to produce energy in a decentralized and resilient way.

3.2 Investment Barriers and Financial Constraints

Although these benefits exist, many have not been able to be widely adopted due to the large financial barriers. The most pressing issue is the high upfront cost of procuring and installing mechanical self-propulsion systems, which deters investment in resource-constrained settings (Onwude *et al.*, 2016; Ahmed and Miller, 2022). Moreover, other hinderances include inaccessibility to financing especially in the rural setting where the conventional banking systems are not strong enough, small enterprises and communities are unable to make the required capital investments. Likewise, revenues on continuous maintenance are another significant cost, even when installed, particularly in low-income areas where a repair can cost more than end-users can afford (Ahmed and Miller, 2022). All these contribute to a slower adoption rate, with the potential of the technology remaining untapped.

3.3 Addressing Financial Barriers

As reported in the study conducted by Ahmed and Miller, (2022), to conquer these economic challenges, novel economic policies are needed. Micro-finance programs can give households and small businesses the funds to invest in small steps towards decentralized energy. Another viable opportunity is to use public-private partnership, whereby the government can share risks with the privates and at the same time promote foreign and domestic investments. The initial expenses can be further lowered using international development funds and energy-oriented subsidies, which will enable the adoption to be accessible to underserved groups. These strategies can be used to balance short-term affordability and long-term sustainability by customizing financial models on a local basis (Ahmed and Miller, 2022).

The financial feasibility of mechanical self-propulsion systems lies in their ability to find a balance between long-term advantages and the short-term financial challenges to implementation. Although cost savings, rural electrification and job creation provide a strong argument in favor of investing, the existence of barriers like high initial costs and inadequate financing should be overcome with the help of innovative financial mechanisms. In the framework of STEV, this pillar emphasizes that in order to deploy sustainably, it is not only necessary to have technical feasibility but also affordability and accessibility to local populations to calculate the overall viability of self-propulsion technologies (Ahmed and Miller, 2022).

4. SOCIAL VIABILITY, COMPARATIVE ANALYSIS, POLICY AND REGULATORY FRAMEWORK

The most important pillars of the STEV Framework are discussed in this section including social viability, comparative analysis, policy and regulatory framework.

4.1 Social Viability: Community Impact and Acceptance

One of the most important pillars of the STEV Framework is social viability, which states that the success of energy technologies cannot be determined only by their technical efficiency or economic feasibility but must also be determined by their capacity to meet the local needs, values, and practices. Mechanical self-

propulsion systems are not guaranteed to succeed even when they are cheap and technically viable, unless they are accepted by the community. This section discusses the ways in which these systems can reshape education, healthcare, and local economies and outlines some of the possible obstacles connected with equity, engagement, and cultural processes.

4.1.1 Education and healthcare

Educational and health outcomes in underserved communities can be greatly enhanced through access to reliable electricity. Powered classrooms in schools allow digital learning tools and electronic teaching aids to be used, which have been associated with increased primary school completion rates in marginalized areas (Kelly, 2023). On the same note, powering up of medical facilities using electricity would be able to electrify important medical equipment, enhance service delivery, and decrease avoidable mortality. These not only improve quality of life, but also economic productivity by introducing healthier and better educated populations (UNCTAD, 2023).

4.1.2 Economic empowerment and job creation

In addition to service provision, the decentralized self-propulsion systems raise the economy on the ground. These technologies develop a base of economic growth by supporting the work of small businesses and the industrial performance (Molu *et al.*, 2022; Chakravorty and Pelli, 2022). The jobs are created on various levels: to install the system, engineers and technicians will be required, skilled employees will maintain the systems, and researchers will improve the system design and efficiency (Iakimkin *et al.*, 2018; Early *et al.*, 2011). This wide range of employment helps to empower locals and lessen the reliance on foreign expertise, enhancing community resilience.

4.1.3 Energy equity and community engagement

Among the most disruptive applications of decentralized systems is the fact that they will increase access to cheap electricity, a longstanding problem of energy poverty (Alamu, 2007). Self-propulsion technologies using solar- and biogas-based systems have increased equitable access in underserved communities, elevating the quality of life, advancing gender equity, and empowering the development of local enterprises (Canfield *et al.*, 2024; Henao and Guzman, 2024; Khalid *et al.*, 2023; Miñas *et al.*, 2024). Equally important is the role of community engagement. Communities are empowered to own projects through participatory forms of governance e.g. cooperative energy schemes. Such an inclusive practice not only enhances sustainability but also increases social cohesion (Sanyare *et al.*, 2024; Boostani *et al.*, 2024).

4.1.4 Cultural dynamics and the possible challenges

The social benefits are tremendous but the technological adoption can also bring in risks. The traditional practices can be undermined by Westernization and cultural transformations, and methods have to be developed to retain the local wisdom and identity (Nasution, 2017; Odeyale *et al.*, 2024). In the same way, the automation and new energy infrastructure can render obsolete the traditional jobs, which is why retraining and adaptability programs in the workforce should be emphasized (Şenyapar and Bayındır, 2023). Ultimately, the excessive dependence on foreign technologies can cause the development of the dependency and weaken local autonomy and self-reliance (Pozas, 2015). These issues need to be dealt with through active policies that incorporate social protection in the implementation of technologies.

Social viability in mechanical self-propulsion systems is based on the fact that they will enhance education and healthcare, boost local economies, increase energy equity and encourage inclusive engagement. Simultaneously, the threat of cultural erosion, loss of jobs, and foreign dependence have to be expected and addressed with the help of community-based approaches. In the STEV Framework, this pillar highlights the fact that the only way to achieve long term success is to ensure technology, rather than only making people have electricity, is in line with the social and cultural context of the communities it is supposed to empower (Ahmed and Miller, 2022).

4.2 Comparative Analysis

This section is meant to present a thorough comparison of conventional, renewable and mechanical self-propulsion systems based on the STEV Framework. This analysis presents the trade-offs between existing energy models and new ones by putting together the findings of the technical, economic and social pillars, and indicates the extent in which each type of system fits in the sustainability objectives in developing settings.

4.2.1 Conventional and renewable systems

Traditional systems based on fossil fuels continue to form the backbone to electricity supply in the world because of technical maturity, scalability, and infrastructure. They are well-established economically, in most cases with subsidies and pre-existing supply networks. Nevertheless, their adverse environmental effects are environmental emissions especially greenhouse gases and air pollution, which is an unsustainable long-term model (Rahman *et al.*, 2017; Calanter, 2015; Darkazalli, 1991; Kim *et al.*, 2020).

The situation is reversed in large scale renewable systems like wind and solar power. They are eco-friendly, and their emissions are almost zero in combination with battery or hybrid devices (Phanindra *et al.*, 2024; Wang *et al.*, 2021). But they still have obstacles of economic and technical feasibility. Initial expensive capital, intermittency, and difficulties in connecting decentralized sources to weak grid networks impede large-scale adoption, particularly in developing nations (Sruthy *et al.*, 2023; Tay and Konovessis, 2023).

4.2.2 Mechanical self-propulsion systems

Mechanized self-propulsion comes as a clear and level alternative. They use, technically, the developments in resilient materials and adaptive designs to operate in resource-constrained and variable surroundings (Cowap, 2013; Zaman *et al.*, 2024). They offer lower operational costs over the long term, employment opportunities, and electrifying rural areas, but their implementation is limited due to high initial capital requirements and insufficient financing options (Onwude *et al.*, 2016; Ahmed and Miller, 2022; Xiao, 2023). Their decentralized nature provides them with a special advantage socially. They can address social viability without conventional and renewable systems do, through expanding access to energy, enabling the community to govern, and empowering local (Kelly, 2023; UNCTAD, 2023; Molu *et al.*, 2022; Sanyare *et al.*, 2024).

As stated by Kelly, (2023), the comparison indicates that conventional systems are good in terms of scale and stability but they fall short with respect to sustainability. Renewable systems are also doing very well in the environmental front but they continue to be challenged by their cost and infrastructural suitability in the developing areas. Mechanical self-propulsion systems are somewhere in between: they are not yet free of technical and financial challenges, but offer a socially engaging and ecologically responsible channel to local energy solutions. The following table summarizes these distinctions, offering a side-by-side comparison across the STEV Framework dimensions (Table 1).

4.3 Policy and Regulatory Framework

Mechanical self-propulsion systems are viable in aspects other than their technical, economic, and social aspects. Enabling these systems to flourish in Africa is a precondition to having a supportive policy and regulatory framework. The STEV Framework is used to assess internal viability, whereas policy determines the external environment where such technologies are applied. Weak policies or lack of policies, incomprehensible regulations and lack of institutional support may sabotage adoption, despite technical potential and economic viability. This section outlines the main areas that policy intervention is necessary (Molu *et al.*, 2022; Sanyare *et al.*, 2024).

Table 1: Comparative Overview of Conventional, Renewable, and Mechanical Self-Propulsion Systems

System Type	Cost	Scalability	Environmental Impact	Authors
Conventional Systems	- High operational costs - Fluctuating fossil fuel prices	- Well-established - Easily scalable	- Major contributor to greenhouse gas emissions - Drives global warming and ozone layer depletion	(Rahman <i>et al.</i> , 2017; Calanter, 2015; Darkazalli, 1991; Kim <i>et al.</i> , 2020)
Renewable Systems	- High initial investment - Becoming more affordable over time	- Scalability improving - Integration into larger systems possible	- Substantial reduction in emissions - Battery-powered and hybrid systems show near-zero emissions potential	(Phanindra <i>et al.</i> , 2024; Obuseh <i>et al.</i> , 2023; Wang <i>et al.</i> , 2021; Tay & Konovessis, 2023)
Mechanical Self-Propulsion Systems	- More cost-effective in remote/off-grid areas - High initial costs - Limited investment	- Scalable - Adaptable for rural communities and decentralized energy	- Environmentally friendly - Supports green economy - Ammonia fuel: carbon-free alternative	(Zambrano <i>et al.</i> , 2019; Olabode <i>et al.</i> , 2021; Ofori-Amoah, 2020; Kim <i>et al.</i> , 2020)

4.3.1 Financial incentives and creating markets

Governments have a central role in reducing the financial hurdles that constrain the use of mechanical self-propulsion systems. These systems are expensive to obtain and finances are not readily available to a wide range of communities (Onwude *et al.*, 2016; Ahmed and Miller, 2022). Financial instruments like subsidies, tax exemptions, and special grants can be triggered by policy so as to lower the start-up cost on investors. Governments can support or guarantee micro-financing programs to enable households and small enterprises to implement the use of decentralized energy systems step by step. Also, PPPs and international development funds are capable of assisting in the scale deployment, help to distribute the investment risks and encourage the extended involvement. These actions not only speed up the adoption, but also provide the conditions under which the market can grow sustainably.

4.3.2 Regulatory clarity and standards

According to Molu *et al.* (2022), it is important that clear regulations are in place to promote confidence with emerging technologies. In the absence of enforceable standards, there is a danger of flooding the markets with low quality products that can erode confidence and performance. To achieve safety, reliability, and durability, governments should put in place strong technical standards and certification procedures. The simplified licensing and permitting process is also essential, because bureaucratic processes tend to slow down or discourage the implementation of a project. These issues are further worsened by weak implementation of the current policies, which restrain accountability and hinder development. Governments can achieve this by enhancing regulatory clarity to create a stable and predictable environment that promotes innovation and investment in mechanical self-propulsion technologies (Kelly, 2023).

4.3.3 Local content and capacity building

To be sustainable in the long run, the policy should make adoption to be accompanied by empowerment at local levels. Industrial growth, job creation, and less dependence on imported technologies can be stimulated by local content requirements that promote the local production of its products and their local assembly (Molu *et al.*, 2022; Chakravorty and Pelli, 2022). Complementary vocational training programs can also play a crucial role in providing local technicians with the knowledge and skills to install, use, and

maintain these systems, which will overcome the need to rely on foreign knowledge (Pozas, 2015). Potential job displacement due to automation and modernization can also be reduced with the help of the policies that support the retraining of the workforce (Şenyapar and Bayındır, 2023). Governments can incorporate capacity building into the policy framework to make communities active participants in the technological transitions and not passive beneficiaries.

4.3.4 Policy as an enabler of social equity

Policy also contributes towards equitable access to energy. Social viability advantages of mechanical self-propulsion systems can be magnified through programs giving preference to marginalized populations (women, rural population, and low-income households) (Canfield *et al.*, 2024; Henao and Guzman, 2024). The cooperative energy schemes are inclusive governance structures that entail legal support in order to scale and maintain them. Participatory policy frameworks enable governments to institutionalize community engagement, which means that the deployment of technologies is more in line with local values and cultural contexts (Sanyare *et al.*, 2024).

Favorable policy and regulatory environment is not a fringe benefit but a pillar requirement to the popularization of mechanical self-propulsion systems. Through a mix of financial incentives, regulation clarity, and building local capacity, governments can turn these technologies into solutions that can scale and promote energy access, equity, and sustainability. Devoid of this support, even the most technologically advanced and cost-effective systems are at risk of stagnation. Finally, alignment of policies to the STEV Framework will make technological advancements directly relevant to the Sustainable Development Goals and the overall development agenda in Africa (Molu *et al.*, 2022).

5. CONCLUSION

The power crisis in Africa characterized by poor grids, insufficient infrastructure and reliance on fossil fuels requires innovative and contextually-based solutions. The Socio-Technical-Economic Viability (STEV) Framework has been presented in this paper as a systematic framework to analyze the viability of mechanical self-propulsion systems as a source of sustainable energy. The framework combines technical, economic, and social factors to show that such systems are promising to provide resilient, locally adaptable, and community-driven energy alternatives. Technically, self-propulsion systems are practicable, but they need considerable improvements in materials, energy storage and design durability to withstand the extreme conditions and to enable low-cost maintenance. On the economic side, the high initial costs still pose a limitation but the long-term savings, creative financing strategies and the possibility of creating employment opportunities enhance adoption. On the social front, success is not merely a matter of technology, but must be based on the social needs of community ownership, equal access, and capacity building of the locality to ensure that deployment does not create the same inequalities as those already present.

The lesson that comes out throughout all the pillars of the STEV Framework is that policy and governance are decisive enablers. The scalability and impact of these systems will not be as high without any clear regulatory frameworks, specific incentives, and supportive investments in infrastructure. Policy is the element that bridges the gap between the conceptual viability and the practical implementation. Going forward, mechanical self-propulsion systems are not just an engineering innovation but it is a chance to rethink the future of energy in Africa. With the STEV Framework, such systems can transform into the experimental solutions into the cornerstones of sustainable development, propelling energy security, social empowerment, and economic resiliency. The way is easy: the only solution to the mechanical self-propulsion systems to become a real possibility is a balanced and integrated approach, which will open an era of clean, dependable, and inclusive energy in Africa.

References

- Adegbite, A. O. (2024). Diversity, equity, and inclusion in workforce training: From concept to implementation. *IOSR Journal of Humanities and Social Science*, 29(12), 30-37.
- Adetunji, O. R., Aiyedun, P. O., Alamu, O. J. and Surakat, A. S. (2011). Electrochemical properties of metals in cassava fluid *Journal of Engineering and Technology Research*, 3(10), 292-297
- Ahmed, H., and Miller, E. E. (2022). Human systems integration of agricultural machinery in developing economy countries: Perceptions of adoption. In *INCOSE International Symposium*, 32, 18-28.
- Akinbola, F. (2017). The power sector and its impacts on industrialization of businesses in Nigeria. *Sosyal ve Beşeri Bilimler Dergisi*, 2(1), 38-59.
- Akinyemi, O. O. and Alamu, O. J. (2009). Effect of 0.05M NaCl on corrosion of coated reinforcing steels in concrete. *Pacific Journal of Science and Technology*, 10(1), 462-471.
- Alamu, O. J. (2007). Development and evaluation of palm kernel oil biodiesel fuel. *Pacific Journal of Science and Technology*, 11(2), 90-97.
- Alamu, O. J., Waheed, M. A. and Jekayinfa, S. O. (2009). Determination of optimum temperature for the laboratory preparation of biodiesel from Nigerian palm kernel oil. *Energy Sources, Part A*, 31(13), 1105–1114
- Allal, Z., Noura, H. N., Salman, O., and Chahine, K. (2024). Machine learning solutions for renewable energy systems: Applications, challenges, limitations, and future directions. *Journal of Environmental Management*, 354, 120392.
- Amadi, H. N. (2018). Design and performance evaluation of a dual-axis solar tracking system for rural applications. *Journal of Electrical and Electronic Systems*, 7(4), 275.
- Awogbemi, O., Von Kallon, D. V. and Kumar, K. S. (2024). Contributions of artificial intelligence and digitization in achieving clean and affordable energy. *Intelligent Systems with Applications*, 22, 200389.
- Azodo, A. P. (2014). Electric power supply, main source and backing: A survey of residential utilization features. *International Journal of Research Studies in Management*, 3(2), 87-102.
- Azodo, A. P., Idama, O., Mezue, T. C., and Owoye, F. T. (2018). Evaluation and analysis of environmental noise from petrol fuelled portable power generators used in commercial areas. *Journal of Experimental Research*, 6(1), 8-13.
- Batinge, B., Musango, J. K. and Brent, A. C. (2019). Perpetuating energy poverty: Assessing roadmaps for universal energy access in unmet African electricity markets. *Energy Research and Social Science*, 55, 1-13.
- Boostani, P., Pellegrini-Masini, G. and Klein, J. (2024). The role of community energy schemes in reducing energy poverty and promoting social inclusion: A systematic literature review. *Energies*, 17(13), 3232.
- Calanter, P. (2015). Economic and environmental aspects associated with the technologies for electricity production from conventional sources and measures to mitigate the produced impacts. *Global Economic Observer*, 3(2), 150–160.
- Canfield, D. da C., Siqueira, J. A. C., Nogueira, C. E. C., Santos, R. F., Tokura, L. K., Rossi, A., Zanchet, E. and Orben, J. M. C. (2024). Comparative analysis between distributed generation and centralized electric power system to serve the inhabitants of remote areas of Brazil. *Observatório de la Economía Latinoamericana*, 22(3), e3627.
- Carmiel, Y., Bram, A. I., Atar, N., Bolker, A., Eliaz, N., Moshe, N., Barmoha, S., Bouzaglou, A., Galun, E., Gouzman, I. and Verker, R. (2022). Remote propulsion of miniaturized mechanical devices via infrared-irradiated reversible shape memory polymers. *Advanced Intelligent Systems*, 4(6), 2200006.
- Chakravorty, U. and Pelli, M. (2022). Electrification and development: Empirical evidence on the effect of electricity provision on household welfare. In *Environmental economics in developing countries 1st ed.*, pp. 14. Routledge India.
- Clain, P., Khelladi, I., Rodrigues, C, Biancalani, A., Guerard, G. and Rezaee, V. S. (2024). Increase social acceptability of nuclear fusion, agrivoltaics, and offshore wind through national support programmes. In: *Strengthening European energy policy: governance recommendations from innovative interdisciplinary collaborations*. Cham: Springer Nature Switzerland. p. 101-13.
- Cortez, R.I. and Pérez, I.K. (2024). Assessment of the economic viability of low power wind farms in Mexico. *IEEE Lat Am Trans*, 22(4), 329-38.
- Cowap, S. F. (2013). Self-orienting vertical axis wind turbine (U.S. Patent No. 8410627 B2). U.S. Patent and Trademark Office. <https://patents.google.com/patent/US8410627B2/en>
- Darkazalli, G. (1991). Photovoltaic, utilities, and the environment in the 21st century. In: *Tenth EC Photovoltaic Solar Energy Conference: Proceedings of the International Conference, Lisbon, Portugal, 8–12 April 1991*. Dordrecht: Springer Netherlands; 1991 Jan 1. p. 446–48.

- Das, D. K. and Muchhara, V. (2024) Exploring cost factors in the feasibility study of a hydropower project. *Int J Innov Res Eng Multidiscip Phys Sci.*, 12(4), 1-4.
- Faludi, J., Ritsma, R. and Flipsen, B. (2024). The total cost of ownership score: unifying repair with durability and improving objectivity, completeness, and scalability. In: 2024 Electronics Goes Green 2024+ (EGG); 2024 Jun 18; Berlin, Germany. Piscataway (NJ): IEEE; 2024. p. 1-11.
- Gasser, L. (2008). Function durability over system's life span. In: *INCOSE International Symposium*, 18(1), 681-90.
- Halkos, G. E., and Gkampoura, E. C. (2020). Reviewing Usage, Potentials, and Limitations of Renewable Energy Sources. *Energies*, 13(11), 2906.
- Henao, A., and Guzman, L. (2024). Exploration of alternatives to reduce the gap in access to electricity in rural communities Las Nubes Village Case (Barranquilla, Colombia). *Energies*, 17(1), 256.
- Huesemann, M. H. (2003). The limits of technological solutions to sustainable development. *Clean Technologies and Environmental Policy*, 5(1), 21–34.
- Iakimkin, V., Kirillov, S., Kirillov, A., and Pecht, M. (2018). Basic principles, models, and algorithms for creation of self-maintenance and self-recovery systems for engines, gas turbines, and mechanics. In 2018 Prognostics and System Health Management Conference (PHM-Chongqing) (pp. 270–275). IEEE. <https://doi.org/10.1109/PHM-Chongqing.2018.00053>
- Katekar, V. and Deshmukh, S. (2022). Electrification and energy transition in Sub-Saharan Africa: Status, issues and effects, from a source-to-household perspective. In *Handbook of energy transitions*, 1st ed., pp. 36
- Kaygusuz, K. (2012). Energy for sustainable development: A case of developing countries. *Renewable and Sustainable Energy Reviews*, 16(2), 1116-1126.
- Kelly, A. M., Yimele, B. L. T., Tchieu, N. L. W. and Rutazihana, P. N. (2023). Access to electricity and primary education nexus in central Africa. *Journal of Regional Economics*, 2(1), 26-41.
- Khalid, R., Landini, S., Valasai, G. D., Khalid, F. and Sandwell, P. (2023). Towards equitable and inclusive energy systems for remote off-grid communities: A socio-technical assessment of solar power for village Helario in Tharparkar, Pakistan. *Renewable and Sustainable Energy Transition*, 4, 100067.
- Kim, K., Roh, G., Kim, W., & Chun, K. (2020). A preliminary study on an alternative ship propulsion system fueled by ammonia: Environmental and economic assessments. *Journal of Marine Science and Engineering*, 8(3), 183.
- Kosonen, I., and Alku, A. (2013). Intelligent electric mobility. In 2013 Eighth International Conference and Exhibition on Ecological Vehicles and Renewable Energies (EVER) (pp. 1-7). IEEE. <https://doi.org/10.1109/EVER.2013.6521536>
- Kumar, M. D., Himabindu, D., Vijaya Kumar, Y. N., Mohana, T., Shashank, R. and Rajanna, B. V. (2024). Efficiency enhancement in hybrid renewable energy system using polycrystalline silicon cell. *International Journal of Applied Power Engineering*, 13(3), 679–686.
- Latif, A. S. (2020). The importance of understanding social and cultural norms in delivering quality health care—A personal experience commentary. *Tropical medicine and infectious disease*, 5(1), 22.
- Lebrouhi, B. E., Khattari, Y., Lamrani, B., Maaroufi, M., Zeraoui, Y. and Kousksou, T. (2021). Key challenges for a large-scale development of battery electric vehicles: A comprehensive review. *Journal of Energy Storage*, 44(Part B), 103273. <https://doi.org/10.1016/j.est.2021.103273>
- Leong, W.Y. (2024). TVET for all: fostering social equity through inclusive skills education. In: 2024 International Conference on TVET Excellence & Development (ICTeD); 2024 Dec 16; Piscataway (NJ): IEEE; 2024. p. 284-8.
- Li, N., Agene, D., Gu, L., Osabohien, R., and Jaaffar, A. H. (2024). Promoting clean energy adoption for enhanced food security in Africa. *Frontiers in Sustainable Food Systems*, 8, 1269160.
- Lizunkov, V., Politsinskaya, E., Malushko, E., Kindaev, A., and Minin, M. (2018). Population of the world and regions as the principal energy consumer. *International Journal of Energy Economics and Policy*, 8(3), 250-257.
- Mirzaliev, S., Yusupov, S., Turgunboev, T., Kholikov, A. and Inoyatkhodjaev, J. (2022). Justification of the synergy of innovative intelligent transport systems in local conditions. In *Proceedings of the 6th International Conference on Future Networks & Distributed Systems*, pp. 182-193.
- Molu, R. J. J., Mbasso, W. F., Naoussi, S. R. D., Kenfack, S. T. and Wira, P. (2022). Investigating the dependency between electricity and human development based on metaheuristic optimization. *International Journal of Energy Economics and Policy*, 12(5), 55–60. <https://doi.org/10.32479/ijeeep.13445>
- Moriarty, P. and Honnery, D. (2021). The limits of renewable energy. *AIMS Energy*, 9(4), 812–829.

- Nasution, R. D. (2017). Effect of the development of communication information technology on local cultural existence. *Masyarakat Sudah Mengakui, Menerima, Pengaruh Perkembangan Teknologi Informasi Komunikasi Terhadap Eksistensi Budaya Lokal*, 21(1), 30–42.
- Nowak, M., Rabczun, A., and Łopatka, P. (2021). Impact of electrification on african development-analysis with using grey systems theory. *Energies*, 14(16), 5181. <https://doi.org/10.3390/en14165181>
- Obuseh, E., Eyenubo, J., Alele, J., Okpare, A., and Oghogho, I. (2025). A systematic review of barriers to renewable energy integration and adoption. *Journal of Asian Energy Studies*, 9, 26-45.
- Odeyale, S.O., Alamu, O.J. and Odeyale, E.O. (2014). Performance Evaluation and Selection of Best Mode of Transportation in Lagos State Metropolis. *International Journal for Traffic and Transport Engineering*, 4(1), 76-89
- Ofori-Amoah, B. (2020). Disruptive technologies, sustainable energy generation and storage as forms of green economy. In: Arthur P, Hanson KT, Pupilampu KP, editors. *Disruptive Technologies, Innovation and Development in Africa*. Cham: Springer; 2020. p. 85–113.
- Ojha, K. P., Uprety, S. K., and Acharya, K. R. (2023). Viability Measurement of Hydropower Projects. *Pravaha*, 29(1), 40-47.
- Olabode, O. E., Ajewole, T. O., Okakwu, I. K., Alayande, A. S., & Akinyele, D. O. (2021). Hybrid power systems for off-grid locations: A comprehensive review of design technologies, applications and future trends. *Scientific African*, 13, e00884.
- Onwude, D. I., Abdulstter, R., Gomes, C., and Hashim, N. (2016). Mechanisation of large-scale agricultural fields in developing countries—a review. *Journal of the Science of Food and Agriculture*, 96(12), 3969-3976.
- Osho, G. S. (2025). The geopolitical dynamics of oil and gas: Nigeria’s strategic role, emerging challenges, economic policies and opportunities. *Journal of Energy Technologies and Policy*, 15(1), 121-136.
- Peterson, N. D. (2016). Introduction to the special issue on social sustainability: integration, context, and governance. *Sustainability: Science, Practice and Policy*, 12(1):3-7.
- Phanindra, K., Bavirisetti, K., Balaji, K., Krishna, P. S., & Ganesh, K. M. (2024). Renewable energy technologies: Advances and challenges. *International Journal of Advanced Multidisciplinary Research and Studies*, 4(6), 395-397.
- Pozas, L. M. U. (2015). Los impactos múltiples de las empresas eléctricas globales. El caso de Iberdrola en México. *ANDULI. Revista Andaluza de Ciencias Sociales*, (14), 121-134.
- Quartey, J. D. (2020). Energizing Africa Sustainably: Lessons from Ghana’s Electricity Infrastructure. *International Journal of Publication and Social Studies*, 6(1), 1–17.
- Rahman, M.M., Salehin, S., Ahmed, S.S., and Islam, A.S. (2017). Environmental impact assessment of different renewable energy resources: a recent development. In: *Clean Energy for Sustainable Development*. Academic Press; p. 29–71.
- Rana, S. S., Salauddin, M., Sharifuzzaman, M., Lee, S. H., Shin, Y. D., Song, H., Jeong, S. H., Bhatta, T., Shrestha, K., and Park, J. Y. (2022). Ultrahigh-output triboelectric and electromagnetic hybrid generator for self-powered smart electronics and biomedical applications. *Advanced Energy Materials*, 12(40), 2202238.
- Richard, L., Saincy, N., Le Saux, N., Frey, D., Alvarez-Herault, M.-C., and Raison, B. (2023). A new electrification model to end energy poverty: An example from a novel rural electrification approach in Madagascar. *IEEE Electrification Magazine*, 11(2), 62–73.
- Sabino, L., Asghar, R., Crescimbin, F., and Riganti Fulginei, F. (2025). Evaluation of Technical Aspects of Solar Photovoltaic (PV) Power Installations on Farmland. *Energies*, 18(2), 317.
- Sanyare, F. N., Yakubu, A. W. and Der Bebel, F. (2024). Promoting effective local participation in local decision-making processes: Perspectives from sub-district structures in Karaga District, Ghana. *Ghana Journal of Development Studies*, 21(1), 1-23.
- Sei-Bum, C. and Min-Hyun, K. (2022). Manual wheelchair propulsion aid device using mechanical self-energizing action (U.S. Patent Application No. 17/561,771). Korea Advanced Institute of Science and Technology (KAIST).
- Senyapar, H. N. D. and Bayindir, R. (2023). The negative social impacts of renewable energy: A key consideration for a successful energy transition. 2023 12th International Conference on Renewable Energy Research and Applications (ICRERA), 591-596.
- Sruthy, V., Krishna, K. and Preetha, P.K. (2023). Techno-economic analysis of electrically propelled marine vessels. In: 2023 International Conference on Circuit Power and Computing Technologies (ICCPCT). IEEE; 2023. p. 1600–8.

- Stritzke, S. and Jain, P. (2021). The sustainability of decentralised renewable energy projects in developing countries: Learning lessons from Zambia. *Energies*, 14(13), 3757.
- Taghvaei, V.M., Sharifpour, Y., Akbari, F., Arani, A.A., and Tatar, M. (2023). Integrated sustainability of social, environment and economy: Defining the hypotheses and theories interconnecting the pillars of sustainable development. In: Reference Module in Social Sciences; <https://doi.org/10.1016/B978-0-44-313776-1.00156-2>
- Tale, V. and Rege, P. (2024). A comprehensive study of techno economic viability (TEV) report of various projects. *Int J Sci Res Eng Manag.* 8(10), 1-8.
- Tay, Z.Y. and Konovessis, D. (2023). Sustainable energy propulsion system for sea transport to achieve United Nations sustainable development goals: a review. *Discover Sustainability*, (1), 20. doi: 10.1007/s43621-023-00132-y.
- Ugwu, M. C., Adewusi, A. O. and Nwokolo, N. E. (2024). The Role of Public-Private Partnerships in Building Clean Energy Infrastructure in the United States and Nigeria. *International Journal of Management & Entrepreneurship Research*, 6(4), 1049-1068.
- Uzundu, N. C. and Lele, D. D. (2024). Comprehensive analysis of integrating smart grids with renewable energy sources: Technological advancements, economic impacts, and policy frameworks. *Engineering Science & Technology Journal*, 5(7): 2334-2363.
- Wang, H., Boulougouris, E., Theotokatos, G., Priftis, A., Shi, G. and Zhou, P. (2021). A comparative life cycle assessment study on environmental performances between battery-powered and conventional marine vessels. In: Maritime Technology and Engineering. Volume 1. CRC Press; p. 119–26. doi: 10.1201/9781003216582-13.
- Wang, X. Q., Tan, C. F., Chan, K. H., Lu, X., Zhu, L., Kim, S. W. and Ho, G. W. (2018). In-built thermo-mechanical cooperative feedback mechanism for self-propelled multimodal locomotion and electricity generation. *Nature Communications*, 9(1), 1-10.
- Xiao, R. (2023). Economic benefit, challenges, and perspectives for the application of Autonomous technology in self-driving vehicles. *Highlights in Science, Engineering and Technology*, 38, 456-460.
- Yazdandoost, M.Y. (2021). Multi-scale interlinkages for transformation to sustainability. *J Glob Resour.* 7(2), 47-53.
- Ye, Y., and Koch, S. F. (2023). Towards accessibility or affordability? Multidimensional energy poverty across the South African urban–rural divide. *Energy Research & Social Science*, 97, 103002.
- Zaman, A., Abdelaty, A. and Jamal, M. S. (2024). Limitations and Barriers Affecting the Applications of UAVs in Transportation Infrastructure Systems Assessment. In Construction Research Congress 2024 (pp. 446-455).
- Zambrano, J. C., Michavila, J., Arenas Pinilla, E., Diehl, J. C., and Ertsen, M. W. (2019). Water lifting water: a comprehensive spatiotemporal review on the hydro-powered water pumping technologies. *Water*, 11(8), 1677.