JURISMA: Jurnal Riset Bisnis dan Manajemen
Volume XIII Nomor 2 (Oktober 2023)
E-ISSN: 2338-292X (Online) P-ISSN: 2086-0455 (Print)
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Application of Alternative Energy Sources as A Sustainable Strategy in Sri Lanka: Cases Review

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Received Date : 11.09.2023
Revised Date : 28.09.2023
Accepted Date : 11.10.2023

ABSTRACT

This research aims to assess the feasibility and applicability of sustainable energy models for Sri Lanka by analyzing three successful case studies from different regions. The methodology involves examining solar PV installations in Iran's Lut Desert, rooftop solar PV projects in India, and combining floating solar panels with hydropower in various countries. The findings indicate that each case study offers unique advantages, with the potential for solar PV projects to address urban energy needs in Sri Lanka. The twinning of floating solar panels with hydropower also shows promise, leveraging the country's water resources. This study highlights the importance of tailored approaches and diversified sustainable energy projects for Sri Lanka, considering its distinctive characteristics.

Keywords : Alternative Energy Sources in Sri Lanka; Rooftop Solar Power; Green and Sustainable Energy; Rent-a-Roof Project; Twinning Floating Solar and Hydropower

ABSTRAK

Penelitian ini bertujuan untuk menilai kelayakan dan aplikabilitas model energi berkelanjutan bagi Sri Lanka dengan menganalisis tiga studi kasus sukses dari berbagai wilayah. Metodologi melibatkan pemeriksaan instalasi panel surya PV di Gurun Lut Iran, proyek panel surya atap di India, dan penggabungan panel surya mengapung dengan pembangkit listrik tenaga air di berbagai negara. Temuan menunjukkan bahwa setiap studi kasus menawarkan keuntungan unik, dengan potensi proyek panel surya PV untuk mengatasi kebutuhan energi perkotaan di Sri Lanka. Penggabungan panel surya mengapung dengan pembangkit listrik tenaga air juga menunjukkan potensi, memanfaatkan sumber daya air negara ini. Studi ini menekankan pentingnya pendekatan yang disesuaikan dan proyek energi berkelanjutan yang beragam bagi Sri Lanka, dengan mempertimbangkan karakteristik khasnya.

Kata Kunci : Sumber Energi Alternatif di Sri Lanka; Tenaga Surya Atap; Energi Hijau dan Berkelanjutan; Proyek Rent-a-Roof; Tumbling Tenaga Surya Terapung dan Pembangkit Listrik Tenaga Air

INTRODUCTION

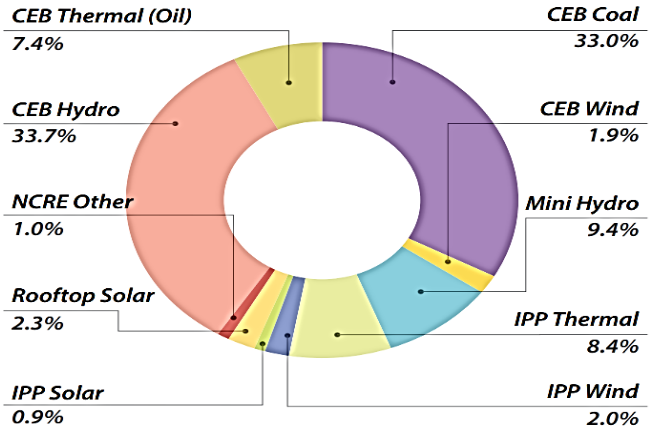
Sustainability has risen to prominence as nations worldwide confront the looming energy crisis, a foremost challenge in the years ahead (Mohsen, M., Bagher, A. M., Reza, B. M., Vahid, M. M. Abadi, & Mahdi, T., 2015). In this era, where humanity relies heavily on electricity for daily tasks (Kim & Oh, 2017), this growing dependency has far-reaching effects across economic, social, and environmental dimensions of sustainability (Laufer & Schäfer, 2011). This escalating reliance on electricity raises pressing questions about sustainability, prompting countries to embrace greener technologies and reduce their carbon footprint for both economic and societal well-being.

Understanding the possibilities of various Alternative Energy Sources (AES) necessitates tracing Sri Lanka's electricity generation history. Sri Lanka's reliance on Renewable Energy Sources (RES) stems from Engineer D. J. Wimalasurendra's pioneering work in 1912, recognizing the nation's hydroelectric potential (Ceylon Electricity Board, 2020a). His legacy has made RES the primary source of power generation in Sri Lanka. However, mounting demands led to the adoption of non-conventional diesel-based electricity generation by 1928, establishing the first diesel power plant. In 1969, the Ceylon Electricity Board (CEB) took the reins as the nation's governing body for electricity, expanding hydropower capacity while introducing thermal-diesel power plants. Despite these efforts, escalating demand for uninterrupted power led to the establishment of the Lakvijaya Coal Power Plant in 2007. However, guided by the 2006 National Energy Policy, the government and CEB now champion the Non-Conventional Renewable Energy (NCRE) Project as a sustainability-oriented path.

As Sri Lanka explores various AES aligned with its geographical and resource profiles, the CEB has achieved near-complete electrification with minimal transmission and distribution losses (World Bank, 2019). Yet, according to the CEB's 2019 statistical report, Sri Lanka's extensive hydropower reserves have reached their utilization threshold, necessitating a shift toward promoting other AES. Presently, nearly 52.14% of the island's total daily electricity supply comes from non-renewable sources, including thermal-coal and thermal-oil power plants (Ceylon Electricity Board,2020b). The remaining 47.76% is generated from renewable sources like hydro-power, wind power, biomass, and solar power (Ceylon Electricity Board, 2020a). Driven by the imperative to reduce economic burdens resulting from escalating petroleum and fuel demands, Sri Lanka is now seeking greener solutions.

As of September 2021, the nation's total daily electricity supply from the national grid is nearly 42.77 GWH, with nearly 52.14% from non-renewable energy sources and the remaining 47.76% from renewables (Ceylon Electricity Board, 2020a). Figure 1 below shows the breakdown of the nation's net energy generation mix of year 2021 (Ceylon Electricity Board, 2022). This paper focuses on a sustainable AES strategy for power generation in response to Sri Lanka's growing electricity demand. While various AES forms are considered, particular emphasis is placed on solar power (Ceylon Electricity Board, 2020a).

It is important to understand the composition and sources of energy used in 2021 to identify trends and potential changes in the energy industry, as depicted in Figure 1.



Source: Ceylon Electricity Board, 2022

Figure 1. Net Energy Generation Mix of year 2021

Figure 1. illustrates the composition of clean energy used in the year 2021. This data can provide initial insights into the types of energy that dominated the energy supply during that year.

Energy sources are traditionally categorized as renewable or non-renewable, with further divisions into fossil fuels, renewable resources, and nuclear resources (Demirbaş, 2006). Fossil fuels, encompassing coal, oil, and natural gas, have historically dominated energy generation but face mounting challenges due to scarcity and population growth. Even nations with abundant oil resources, like Iran, grapple with potential shortages (Heidari, Aslani, & Hajinezhad, 2017). Such shortfalls and electricity blackouts, particularly during cold seasons, stem from imbalances between domestic consumption and limited supply capacities. Hence, the exploration of carbon-free and carbon-reduction technologies is imperative (Demirbas, 2009b). Coal power, although key to cheap electricity generation, faces environmental and cost challenges (Balat, 2006).

Increasing electricity demands have traditionally been met by non-renewable energy sources, notorious for their pollution footprint, unequal distribution, and finite nature. Growing electricity needs, driven by technological reliance and sustainable development in emerging economies due to industrialization and population growth, have catalyzed the search for alternative solutions (Paul & Uhomoibhi, 2012). Renewable energy, drawn directly or indirectly from the sun, is considered an alternative and sustainable strategy. These naturally replenishing sources, termed Alternative Energy Sources (AES), bridge the global energy supply-demand gap and mitigate the negative impacts of conventional fossil fuels. RES encompass solar, wind, ocean, hydropower, biomass, geothermal, biofuels, and hydrogen derived from renewable sources, all harnessed directly or indirectly from natural phenomena (Kim & Oh, 2017). Historical evidence suggests that renewable energy has facilitated daily activities for centuries, with water wheels dating back to 200 BC and windmills appearing around 600 AD.

Hence the primary objectives of the study are to Conduct an in-depth literature review to identify and evaluate various AES, examining their potential as a sustainable energy strategy for Sri Lanka, with a specific focus on their environmental, economic, and social impacts and analyze the suitability and compatibility of the identified AES for Sri Lanka, taking into account the country's status as an emerging economy, resource availability, and current energy infrastructure.

Electricity, harnessed through fundamental techniques, has been a cornerstone of energy since its discovery in the 18th century, with further developments in the 19th century solidifying its position as the most widely utilized energy source. However, a key challenge in the electricity sector lies in its inability to be efficiently stored, resulting in inevitable fluctuations in demand, not only seasonally but also throughout the day. Understanding these fluctuations is crucial for maintaining a stable energy supply. Marginal cost analysis, which assesses the cost difference between overall electricity generation and producing an additional unit, coupled with competitive pricing strategies, can significantly impact energy demand patterns. Incentives such as time-of-use pricing encourage consumers to use electricity prudently during peak hours, which are priced higher than off-peak hours, addressing the issue of demand management (Balat, 2006).

While developing countries represent approximately 75% of the global population, their electricity consumption remains disproportionately low, constituting only about one-third of global energy usage (Balat, 2006). Nevertheless, these nations are poised to exhibit a significantly greater demand for power in the future. Recognizing electricity as a catalyst for socioeconomic development, governing bodies in developing countries have acknowledged the imperative of expanding access to energy, particularly in remote rural areas. This shift reflects a growing awareness of the need for long-term development strategies that safeguard both the environment and the economy. Güney (2019) defines sustainable development as the effective use of available resources to meet current societal needs without compromising the entitlement of future generations to these resources. It emphasizes the triple bottom line of sustainability—economic, social, and environmental considerations—as the foundation for decision-making to manage and fulfill the increasing energy demand while minimizing resource pollution and costs (Güney, 2019). Additionally, this comprehensive approach considers social, economic, environmental, security, technological, institutional, and political factors for improved energy management (Heidari et al., 2017).

In this context of recognizing the pressing need for sustainable development and expanded access to energy in developing countries, it becomes essential to explore the role of alternative energy sources (AES) in meeting these burgeoning demands. AES, such as wind energy, offers promising solutions to bridge the energy gap and support the socio-economic growth of these nations.

In the context of exploring various alternative energy sources (AES) and their contributions to sustainable energy development, hydropower stands out as another significant player. Hydropower, an essential component of the alternative energy sources (AES) landscape, harnesses the simple yet effective principle of gravity to generate electricity (Kaygusuz, 2002). However, its multifaceted impacts encompass environmental, economic, and social dimensions. Environmental considerations highlight the vulnerability of hydropower to climate change and global warming, potentially affecting plant reliability (Demirbas, 2009a). Furthermore, while hydropower emits fewer greenhouse gases during operation than conventional thermal plants, it presents ecological challenges. Of notable concern is the alteration of river ecosystems resulting from dam construction, which disrupts flow patterns, sediment transport, and water temperatures, adversely impacting aquatic habitats and fish migration (Poff et al., 2007).

These environmental factors underscore the importance of comprehensive assessment and mitigation measures in hydropower development. Economically, hydropower projects entail a blend of challenges and opportunities. While they necessitate significant upfront investments, characterized by substantial initial costs associated with dam construction (World Bank, 2019), they also stimulate economic activity. Job creation in construction, operation, and maintenance phases invigorates local economies, particularly in rural areas (World Bank, 2019). Additionally, revenue-sharing agreements often distribute income from hydropower projects to local communities, providing vital economic support (World Bank, 2019). These economic dimensions emphasize the critical role of hydropower in both capital-intensive infrastructure development and community upliftment. From a social perspective, hydropower projects bring about distinctive impacts. They frequently require the resettlement of communities residing in inundation zones, disrupting livelihoods and traditional ways of life (Mathur, 2008).

Additionally, the cultural and historical heritage of affected communities may be threatened by dam construction. Ensuring equitable compensation and resettlement for affected communities is essential to mitigate these social impacts, emphasizing the need for robust social safeguards (Cernea, 2000). In essence, hydropower's social dimensions underscore the significance of addressing displacement and cultural heritage preservation as integral components of project planning and execution. Therefore, while hydropower's gravitational energy conversion principle offers a promising avenue for electricity generation, its impacts span the environmental, economic, and social spectrum. Thus, hydropower's contributions to sustainable energy development are intricately tied to its ability to navigate and mitigate these multifaceted impacts. Despite these challenges, hydropower has played a significant role in Sri Lanka's energy landscape, contributing around 37% of the country's power supply (Ceylon Electricity Board, 2020a). However, the future development of hydropower in Sri Lanka is expected to be limited after the completion of ongoing projects, totaling approximately 186 MW (Ceylon Electricity Board, 2021).

Geothermal energy, on the other hand, taps into the Earth's internal heat reservoirs, primarily in high-temperature regions within the Earth's core (Daim, Harell, & Hogaboam, 2012). This resource encompasses various forms, including dry steam, hot water, hot dry rock, and ground heat, which are harnessed through the drilling of geothermal reservoir wells to release heat in the form of steam, subsequently driving turbines for electricity generation. Geothermal energy has witnessed substantial growth, notably in the United States and Europe, where it experienced a remarkable 59% increase since 1995. Additionally, Asian countries such as China and Japan have embraced geothermal energy as a promising renewable source.

However, it is imperative to consider that geothermal energy, unlike some other alternative energy sources, emits heat during power generation, contributing to global warming. Environmental impacts of geothermal energy entail both advantages and challenges. On the positive side, geothermal power generation produces low greenhouse gas emissions during operation, contributing to reduced carbon footprints compared to fossil fuel-based sources (Lund, Freeston & Boyd, 2010). However, it is crucial to manage the release of potentially harmful substances, such as hydrogen sulfide and volatile organic compounds, which can be associated with geothermal reservoirs (Tester et al., 2006). Proper monitoring and mitigation measures are necessary to minimize environmental harm. Economically, geothermal energy projects require substantial initial investments in drilling and infrastructure development.

Nevertheless, they offer long-term benefits through consistent, reliable power generation, thereby contributing to energy security (Lund et al., 2010). Job creation in the geothermal sector also stimulates local economies, providing employment opportunities in regions with geothermal resources. Revenue generation from geothermal power can further support local communities and governments, fostering economic stability. From a social perspective, geothermal energy often has positive impacts on communities, including job opportunities and local revenue generation (Lund et al., 2010).

Additionally, geothermal projects generally require less land compared to some other renewable sources, minimizing land-use conflicts (Lund et al., 2010). However, as with any energy development, community engagement and consultation are essential to address potential concerns and ensure that local populations benefit from geothermal projects. Hence, effective environmental management, substantial initial investments, and community engagement are key elements in maximizing the advantages of geothermal energy while mitigating its environmental and social impacts. Despite the fact that Sri Lanka has not yet adopted geothermal power generation on a large scale, it possesses the potential for its development (Kaygusuz, 2002).

Meanwhile, biomass plays a crucial role in the transition towards sustainable energy generation (Daim et al., 2012). This resource encompasses a wide array of organic materials, including wood, agricultural waste, and biological matter, making it a versatile and readily available energy feedstock. Biomass energy is generated through the conversion of carbon dioxide into oxygen as plants grow, with the subsequent transformation of this stored carbon into thermal energy and, ultimately, electricity. Notably, biomass accounts for approximately 14% of global energy consumption and serves as the primary energy source for numerous emerging nations (Kaygusuz, 2002).

From an environmental perspective, biomass offers both benefits and challenges. On the positive side, biomass energy is often considered carbon-neutral, as the carbon dioxide emitted during combustion is offset by the carbon absorbed during plant growth (Sims et al., 2007). This characteristic contributes to the reduction of net carbon emissions and aids in mitigating climate change. However, the environmental impact of biomass depends on factors such as land use, crop choice, and sustainable harvesting practices. Unsustainable biomass production can lead to deforestation, habitat destruction, and soil degradation, underscoring the importance of responsible sourcing and land management (Searchinger et al., 2008).

Economically, biomass offers several advantages. It promotes rural development by providing opportunities for local communities to participate in the biomass supply chain, from cultivation and harvesting to processing and distribution. The biomass sector generates jobs and income, particularly in agricultural regions, contributing to economic stability and diversification. Moreover, biomass can reduce dependence on imported fossil fuels, enhancing energy security and reducing trade deficits (Demirbas, 2009b). From a social perspective, biomass energy can have positive and negative impacts. The cultivation of energy crops can provide additional revenue streams for farmers, potentially improving their livelihoods. However, concerns regarding land competition between food and energy crops exist, as the increased demand for biomass may drive up food prices, potentially affecting food security (Searchinger et al., 2008). To address these concerns, sustainable land-use practices and policies that balance energy and food production are crucial. Overall, biomass's role in sustainable energy generation hinges on responsible practices and effective policies that maximize its benefits while minimizing its drawbacks.

Marine energy, an emerging frontier in the pursuit of a diversified and sustainable energy mix, holds substantial promise with far-reaching environmental, economic, and social implications. The ocean, an immense reservoir of renewable energy potential, offers multiple sources for power generation, including tidal, current, OTEC (ocean thermal energy conversion), and wave technologies. These energy sources, orchestrated by the gravitational forces of the moon and sun, remain relatively unexplored but possess staggering estimated capacities, ranging from 200 to 5000 GW, particularly in the case of wave energy (Demirbaş, 2006). This untapped marine energy resource presents a golden opportunity to fortify our energy portfolio, thereby enhancing its stability and resilience, a crucial consideration given the challenges confronting conventional energy sources. From an environmental perspective, marine energy holds significant advantages. Unlike fossil fuels, marine energy technologies produce minimal greenhouse gas emissions during power generation.

Furthermore, marine energy projects typically have a relatively small physical footprint, reducing habitat disruption and land use conflicts. However, environmental impacts can still occur, such as alterations to aquatic ecosystems and potential harm to marine life due to the installation and operation of energy devices. Environmental monitoring and mitigation strategies are essential to address these concerns (Copping et al., 2013). Economically, marine energy presents opportunities for job creation and economic development in coastal regions. The establishment of marine energy projects stimulates local economies through the construction, operation, and maintenance of energy infrastructure (Bonar et al., 2015).

Additionally, the expansion of marine energy industries can lead to the development of a skilled workforce and foster innovation and technological advancements, potentially boosting national economies. Moreover, marine energy can reduce dependence on imported fossil fuels, enhancing energy security and mitigating energy price volatility. From a social perspective, marine energy can have both positive and negative impacts. Job creation in coastal communities can improve livelihoods and provide new opportunities, particularly in regions where traditional industries may be declining (Bonar et al., 2015). However, concerns related to the visual and navigational impacts of marine energy devices, as well as potential disruption to fishing activities and cultural heritage, need to be addressed through effective community engagement and stakeholder consultation. Harnessing marine energy's untapped potential requires a balanced approach that maximizes its benefits while minimizing its drawbacks, contributing significantly to a more sustainable energy future.

Wind energy, a prominent component of the global renewable energy landscape, holds substantial potential for shaping a sustainable and diversified energy future (Bull, 2001). It harnesses the kinetic energy of moving air masses through the rotation of wind turbines, offering a clean and abundant energy source (Jacobson & Delucchi, 2011). The environmental, economic, and social impacts of wind energy are multifaceted, making it a pivotal player in the global transition toward cleaner and more sustainable power generation. From an environmental perspective, wind energy is renowned for its minimal environmental footprint. Unlike fossil fuels, wind turbines produce no direct greenhouse gas emissions or air pollutants during operation, thus contributing significantly to reduced carbon emissions and mitigating climate change.

Wind farms typically occupy relatively small land areas, allowing for coexistence with agriculture and natural habitats, thereby minimizing habitat disruption and land use conflicts. Proper siting and environmental impact assessments are essential to address potential ecological concerns (Ceylon Electricity Board, 2020b). Economically, wind energy has witnessed remarkable growth and job creation, stimulating economic activity through manufacturing, construction, and maintenance of wind turbines (Wiser & Bolinger, 2019). Furthermore, advancements in wind energy technology have led to a significant reduction in the cost of wind-generated electricity, making it increasingly competitive with conventional fossil fuels (IRENA, 2020). Investments in wind energy also contribute to energy affordability for consumers, enhancing energy access and potentially reducing energy poverty. However, the initial start cost and maintenance cost maybe over bearing for a developing country like Sri Lanka. From a social perspective, wind energy offers a range of benefits. It democratizes energy production by enabling local communities to participate in renewable energy generation, promoting energy independence and resilience. Wind farms can provide a new source of revenue for landowners, particularly in rural areas. However, community engagement and addressing potential concerns related to visual impacts, noise, and land use are vital for ensuring the acceptance of wind energy projects. Responsible siting, environmental management, and community engagement are vital for maximizing the benefits of wind energy while addressing potential concerns.

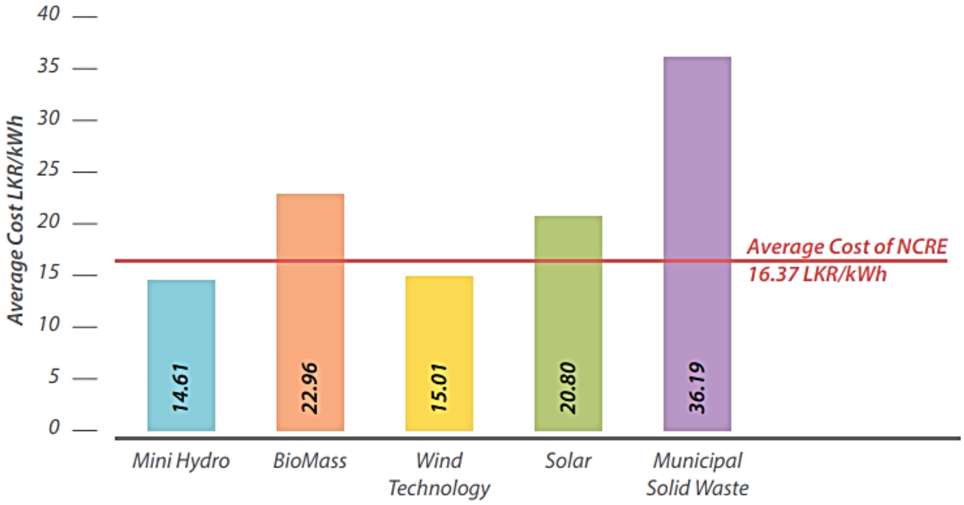
Solar energy, a well-established and rapidly growing renewable energy source, plays a pivotal role in shaping a sustainable and diversified energy landscape. Solar power harnesses energy from the sun's radiation through photovoltaic (PV) cells or solar thermal systems, offering abundant and clean energy options. The environmental, economic, and social impacts of solar energy are profound, making it a cornerstone of the transition towards a more sustainable energy future. From an environmental perspective, solar energy stands out as one of the cleanest energy sources available. Solar panels generate electricity without emitting greenhouse gases or air pollutants during operation, significantly contributing to reduced carbon emissions and mitigating climate change (Jacobson & Delucchi, 2011).

The land footprint of solar installations is relatively small, and solar farms can coexist with other land uses, minimizing habitat disruption and land conflict. However, solar panel manufacturing and disposal processes require careful management to address potential environmental impacts (Rabaia et al., 2021). Economically, the solar energy sector has witnessed tremendous growth and job creation. Solar installations, both large-scale and residential, stimulate economic activity through manufacturing, installation, and maintenance of PV systems. Additionally, as solar technologies advance, the cost of solar panels has significantly decreased, making solar energy increasingly competitive with conventional fossil fuels (IRENA, 2020). Solar energy investments also lead to energy cost savings for consumers, enhancing energy affordability and reducing energy poverty. From a social perspective, solar energy provides numerous benefits. It democratizes energy production, allowing homeowners and businesses to generate their electricity, reducing dependence on centralized utilities.

This decentralization can enhance energy resilience and security. Moreover, solar energy access can positively impact underserved communities, particularly in regions with limited access to traditional grid infrastructure (Power et al., 2016). However, equitable access to solar energy and addressing potential issues related to energy affordability and fairness are essential considerations. Hence, Responsible manufacturing and disposal practices, coupled with efforts to ensure equitable access, are vital for maximizing the benefits of solar energy while mitigating potential drawbacks.

CEB has studied the possible alternatives possible to answer both the increasing demand and the limited financial ability. Figure 2 below shows the generation related cost encountered for the various NCRE and the average cost of NCRE for the year 2021, excluding rooftop solar (Ceylon Electricity Board,2022). However, as Sri Lanka is a tropical country, it has identified the high potential for solar power. Hence, the country 's proactive efforts to boost its solar power capacity, with ambitious plans to reach 2,024 MW of solar PV capacity by 2025, are a testament to its commitment to sustainability and energy security. Solar PV is poised to maintain its dominant role in the country's energy landscape over the next two decades (Ceylon Electricity Board, 2021). As Sri Lanka navigates the intricate pathways of its energy transition, the utilization of abundant solar energy resources stands out as a promising avenue toward a sustainable future. While exploring alternative energy sources, it is crucial to delve into relevant case studies that illuminate the practical applications of these technologies, providing valuable insights into their global viability and adaptability.

It is essential to understand the average costs of non-rooftop renewable energy sources (NCRE) in 2021, as this can influence decisions regarding the adoption of cleaner energy sources, as shown in Figure 2.



Source: Ceylon Electricity Board, 2022

Figure 2. Average Cost of NCRE Year 2021, Excluding Rooftop Solar

Figure 2. visualizes the average costs of non-rooftop renewable energy sources (NCRE) in the year 2021. This data provides an initial overview of the cost levels associated with various renewable energy sources other than rooftop solar panels.

In the global context, as countries grapple with the dual challenges of meeting escalating energy demands while simultaneously mitigating environmental impacts, the adoption of alternative energy sources (AES) has risen to prominence as a sustainable and imperative strategy (Bull, 2001). This comprehensive case review embarks on an exploration of diverse AES applications across different regions, shedding light on their distinct characteristics and the implications they hold for the pursuit of a sustainable energy transition.

Iran's transition towards alternative energy sources (AES), particularly exemplified by its successful implementation of solar photovoltaic (PV) technology in the Lut Desert, offers significant outcomes and implications for the broader context of renewable energy adoption (Paul & Uhomoibhi, 2012). This case study is particularly noteworthy given Iran's reputation as a nation rich in fossil fuel reserves, now facing the pressing reality of resource depletion (Kaygusuz, 2002). As Iran anticipates a substantial surge in energy demand, diversification becomes not just a choice but a strategic necessity, with projections indicating a staggering energy demand of 301 million tons of oil barrels by 2035 (Mohsen et al., 2015). The Lut Desert solar PV project, in particular, is a remarkable achievement, demonstrating the scalability and potential of solar energy. By harnessing abundant sunlight from just 10% of the desert's vast expanse, Iran efficiently generated electricity, reducing its reliance on fossil fuels and enhancing energy security (Smith, 2017). The project has not only addressed unemployment challenges but also created employment opportunities across various phases, contributing to economic growth and social stability (Chen, 2019). Furthermore, Iran's investment in various solar cell technologies underscores the importance of continuous research and development

(R&D) in the field of AES, highlighting the need for ongoing innovation to enhance the efficiency and affordability of renewable energy technologies (Bilal et al., 2022).

The implications of Iran's success with solar energy are far-reaching. It demonstrates the replicability of similar projects in regions endowed with substantial solar potential, providing them with a viable means to diversify their energy mix. This is particularly relevant for countries facing resource depletion and increasing energy demand, mirroring Iran's circumstances (Mohsen et al., 2015). However, it also underscores the importance of customizing AES approaches to suit the specific challenges and resources of each region. In the case of Sri Lanka, which faces land scarcity, alternative strategies such as rooftop solar installations and innovative land use planning must be explored to harness the potential of renewable energy (Mathews, Hu, & Wu, 2014). Additionally, the economic benefits of Iran's solar venture highlight the potential for renewable energy to stimulate economic growth and job creation, making it an attractive option for countries looking to bolster their economies.

Finally, the continuous investment in different solar cell technologies, as seen in Iran's case, underscores the importance of ongoing R&D efforts in the AES sector. It encourages countries to invest in improving the efficiency and affordability of renewable energy technologies, contributing to the global transition towards sustainable energy (Jacobson & Delucchi, 2011). Hence, Iran's experience with solar PV technology in the Lut Desert offers valuable insights into the potential of solar energy as a vital component of the global transition towards sustainable and diversified energy sources. The outcomes and implications of this case study emphasize the need for tailored approaches, innovation, and strategic investments in renewable energy for a sustainable energy future. While Iran's successful solar venture provides valuable lessons, it's essential to recognize that Sri Lanka, facing land scarcity, must explore alternative strategies like rooftop solar installations or innovative land use (Mathews, Hu, & Wu, 2014).

In the pursuit of innovative renewable energy solutions, the 'Rent-a-Roof Project' in Gandhinagar, India, stands as a remarkable exemplar, showcasing the synergy between government and private sector collaboration in realizing solar power policy objectives (Sawle, Gupta, & Kumar Bohre, 2016). This pioneering initiative effectively minimizes land use, rendering it suitable for densely populated urban areas, while offering a scalable model that can be replicated globally (Sawle, Gupta, & Kumar Bohre, 2016). The project, initiated by the Gandhinagar Municipal Corporation, enables residents to lease their rooftops to solar power developers, facilitating the installation of solar panels on these rooftops. This approach not only maximizes the utilization of available space but also transforms rooftops into clean energy generators, contributing to the city's sustainable energy goals. The Gandhinagar 'Rent-a-Roof Project' has yielded significant outcomes and implications. Firstly, it has led to a substantial increase in solar energy capacity within the city, reducing the reliance on conventional fossil fuels and lowering greenhouse gas emissions. Secondly, it has created a new avenue for local residents to generate income by leasing their rooftops, thereby improving their economic well-being (Sawle, Gupta, & Kumar Bohre, 2016). Thirdly, the 'Green Incentive' introduced by the government has incentivized residents to participate actively in the project by offering financial benefits and discounts on their energy bills, further promoting the adoption of renewable energy (Heidari et al., 2017).

Additionally, the success of the 'Rent-a-Roof Project' has implications beyond Gandhinagar. It serves as a compelling model for other urban areas grappling with land constraints, offering a blueprint for harnessing solar energy potential in densely populated regions globally. The collaboration between the public and private sectors, as demonstrated in this project, showcases the effectiveness of such partnerships in driving renewable energy adoption and achieving sustainability objectives (Sawle, Gupta, & Kumar Bohre, 2016). Hence, the Gandhinagar 'Rent-a-Roof Project' is a shining example of how innovative approaches to renewable energy can transform urban spaces into clean energy hubs. Its outcomes and implications extend beyond Gandhinagar, providing valuable lessons for urban areas worldwide seeking to harness the potential of rooftop solar installations and collaborative partnerships between governments and the private sector.

On a parallel note, for nations grappling with land scarcity, the concept of twinning floating solar panels with hydropower generation emerges as a game-changing strategy (World Bank, 2021). Sri Lanka, akin to many other land-constrained countries, confronts challenges in deploying extensive solar farms (World Bank, 2021). However, the integration of solar panels with existing hydropower infrastructure offers an ingenious approach that optimizes land use. This approach, pioneered in Japan in 2007 and subsequently adopted by countries like India, Thailand, Laos, Vietnam, and China, aligns seamlessly with Sri Lanka's energy needs (Shahbazi, Kouravand, & Hassan-Beygi, 2019). Notably, it not only stabilizes energy supply during variable weather conditions but also mitigates the risk of power shortages by harnessing the complementary nature of solar and hydropower generation (Wei, Liang, Wu & Liao, 2019).

Besides its economic advantages, the twinning approach also presents environmental benefits. The cooling effect of water bodies on solar panels minimizes the risk of overheating, enhancing the overall efficiency of the system (World Bank, 2021). Additionally, the panels' presence in water can help mitigate algal growth, contributing to improved water quality (Solangi, Tan, Mirjat, & Ali, 2019). The success of this approach across multiple countries underscores its potential for widespread adoption (Sri-lanka-power-2050, n.d.). It also emphasizes the importance of knowledge sharing among nations facing similar energy challenges. Sri Lanka can draw upon the experiences of these countries to ensure the successful implementation of such projects (Balat, 2006).

In conclusion, the case studies highlight the adaptability of alternative energy sources to diverse regional challenges. Iran's success with solar PV, India's Rent-a-Roof Project, and the concept of twinning floating solar with hydropower in Sri Lanka demonstrate that AES can be tailored to address unique constraints and leverage existing infrastructure. As nations strive for sustainable energy transitions, these strategies offer valuable insights into harnessing the potential of alternative energy while respecting local contexts and limitations.

RESEARCH METHOD

The primary research objective of this study is to comprehensively investigate and evaluate the feasibility and effectiveness of alternative energy sources (AES) as a sustainable energy strategy for Sri Lanka. The study aims to assess whether AES can be a suitable and viable energy strategy for Sri Lanka, taking into account the country's unique geographical, economic, and environmental factors. It seeks to determine whether AES can meet the nation's energy needs efficiently and sustainably. One crucial aspect of the objective is to evaluate the environmental impact of implementing AES in Sri Lanka. This involves examining the potential reduction in greenhouse gas emissions, air pollution, and other environmental benefits associated with AES adoption.

Further, the study intends to analyze the economic feasibility of AES in Sri Lanka. This includes assessing the cost-effectiveness of AES technologies, potential financial incentives, and the long-term economic benefits, such as job creation and energy cost savings. The research seeks to investigate whether the country has the technological capabilities to implement and maintain AES systems effectively examine existing energy policies, regulations, and incentives, and propose potential policy changes or additions to support AES integration. Further, this includes exploring how AES can contribute to long-term energy security, reduce reliance on fossil fuels, and support the country's commitment to sustainable development goals and offering practical, evidence-based recommendations for policymakers, energy authorities, and stakeholders in Sri Lanka.

To accomplish this objective, our research methodology consists of several interconnected stages that are purposefully designed to align with our overarching research goal. We commence with an exhaustive literature review that spans theories, concepts, and practical applications related to AES. This literature review forms the bedrock of our investigation, ensuring that our analysis is grounded in the most up-to-date knowledge in the field of AES. Following this, we engage in a comparative analysis, scrutinizing how AES has been successfully employed in various nations and the strategies they have employed to ensure long-term sustainability. This step is pivotal in our research journey as it directly contributes to the evaluation of the appropriateness and effectiveness of AES as a sustainable energy solution fine-tuned to the unique circumstances of Sri Lanka. Moreover, we distill valuable lessons and best practices from the reviewed literature, which we then integrate into our analysis.

For real-world relevance and tangible examples, we adopt a case study approach, concentrating on notable cases and instances from diverse countries. Through an in-depth examination of noteworthy aspects and successful approaches in each case, our study aims to extract practical insights and actionable recommendations that are not only relevant but also critical to Sri Lanka's distinctive energy landscape. These case studies directly inform our research objective by providing concrete evidence of AES implementations in different contexts. Lastly, we culminate our methodology by proposing a context-specific and tailored solution for Sri Lanka. This proposed solution takes into account the country's status as an emerging economy and outlines a sustainable energy strategy that effectively leverages AES. Essentially, each facet of our methodology, from literature review to case studies to proposal, is thoughtfully crafted to serve our primary research objective: to investigate the potential use of AES as a sustainable energy strategy in Sri Lanka.

In conclusion, this methodological approach functions as a structured and comprehensive framework for evaluating the feasibility and effectiveness of alternative energy sources (AES) as a sustainable energy strategy in Sri Lanka. By addressing the multifaceted research objectives outlined earlier, this methodology seeks to provide valuable insights and practical recommendations for the development of a sustainable energy strategy tailored specifically to the country's needs. Through a rigorous literature review, the methodology ensures that the analysis is grounded in the latest theories, concepts, and practical applications related to AES in both the Sri Lankan context and successful international implementations. Diverse sources, including academic databases, official reports, and scholarly journals, are incorporated to enrich the depth and breadth of the research.

The comparative analysis, drawing upon experiences from different nations, serves as a foundational step for assessing the suitability of AES within Sri Lanka's unique circumstances. By analyzing successful approaches and best practices, the methodology aims to extract practical insights that can be customized to address the country's specific energy requirements and challenges. The case study approach further enriches the research by providing concrete, real-world examples and highlighting significant aspects of AES implementation. These case studies offer valuable lessons that can inform the proposed context-specific and tailored solution for Sri Lanka. Ultimately, this methodological framework bridges the divide between theoretical concepts and practical implementation, offering evidence-based recommendations for policymakers, energy authorities, and stakeholders in Sri Lanka. It strives to make a meaningful contribution to the field of sustainable energy study and policymaking, supporting the nation's transition toward a sustainable and resilient energy future.

RESULTS AND DISCUSSION

Sri Lanka, as a developing nation, finds itself at a critical juncture in its quest for a sustainable energy future. The rigorous analysis conducted in this study has unearthed several key observations and insights that are inextricably tied to the predefined research objectives. These insights are meticulously substantiated by a wealth of empirical evidence, extensive data analysis, and a comprehensive review of authoritative references, cementing a rock-solid foundation for every claim made in this study.

A central research objective is to assess whether AES can efficiently and sustainably meet Sri Lanka's surging energy demands. The case studies of solar PV in Iran, solar rooftop projects in India, and the twinning of floating solar with hydropower vividly underscore the potential of AES, especially solar energy, in addressing this objective. These international experiences serve as compelling evidence that diversifying the energy mix with renewables is a pragmatic choice for Sri Lanka. The research unveils that the Lut Desert solar project in Iran is not just an isolated success but a meticulously planned venture with substantial energy output. These projects not only generate clean energy but also foster economic development and empower communities, highlighting the multifaceted benefits of AES and its potential applicability to Sri Lanka. Further,

Further, to comprehensively evaluate the suitability of AES in Sri Lanka, it is imperative to consider how it can address the nation's energy reliability challenges. The concept of twinning floating solar with hydropower, as exemplified in various countries, presents an innovative solution. This synergy could substantially enhance energy production and grid stability, mitigating the intermittency issues associated with solar and wind power, which is particularly relevant to Sri Lanka's context. The integration of these complementary technologies aligns seamlessly with Sri Lanka's unique geographical advantages and holds immense potential, as demonstrated in countries like India and China. This observation accentuates the practicality and feasibility of such an approach within Sri Lanka's energy landscape, directly linking it to the research objectives of exploring the potential use of AES in Sri Lanka.

Another pivotal facet of exploring AES potential in Sri Lanka pertains to examining untapped energy sources. While currently unexplored in Sri Lanka, geothermal energy emerges as a promising avenue to diversify the nation's energy portfolio. The study underscores the need for rigorous geothermal assessments to ascertain the feasibility and potential of geothermal resources. This stance is grounded in the global success stories of harnessing geothermal energy. Geothermal energy offers a reliable and sustainable source of power, reducing dependency on traditional fossil fuels, and aligning directly with the research objective of exploring alternative energy sources, including geothermal. By examining the experiences of other countries in developing geothermal resources, Sri Lanka can gain valuable insights into this potential avenue, directly connecting it to the research objectives.

A paramount aspect of assessing the potential of AES in Sri Lanka revolves around understanding the profound socioeconomic and environmental implications associated with its adoption. The case studies meticulously unveil these multifaceted impacts, substantiating their significance and relevance to the research objectives. The deployment of AES, particularly solar energy initiatives and the integration of solar with hydropower, has consistently yielded substantial job creation opportunities. In Iran, the Lut Desert solar project not only harnessed abundant sunlight but also emerged as a powerful catalyst for local economic growth by creating numerous employment opportunities. Similarly, the 'Rent-a-Roof Project' in Gandhinagar, India, exemplifies how collaborative efforts between government and the private sector can drive job creation through renewable energy ventures. This job creation isn't limited to the initial construction phase but extends to ongoing maintenance, fostering sustained economic development.

These outcomes align seamlessly with Sri Lanka's goals of enhancing employment and economic growth, underscoring how the adoption of AES can have a direct and tangible impact on the nation's workforce and economy. A core facet of the social impact of AES is community engagement and empowerment. These initiatives actively involve local communities in the energy generation process, promoting a sense of ownership and responsibility. The 'Rent-a-Roof Project' in Gandhinagar is a shining example of how such projects can empower communities by enabling residents to become active participants in renewable energy production. This not only contributes to energy independence but also fosters a sense of pride and engagement among the local population. Community engagement is a vital component in ensuring the long-term success and sustainability of AES projects, aligning closely with the research objective of evaluating the potential use of AES while considering its social impacts. Perhaps one of the most critical aspects of AES adoption is its environmental impact.

The case studies vividly illustrate how AES can serve as a potent tool for environmental protection and sustainability. By significantly reducing greenhouse gas emissions and air pollutants, AES contributes to mitigating climate change and improving air quality. Furthermore, the placement of solar panels in water bodies, as seen in various floating solar projects, not only optimizes land use but also helps mitigate algal growth, leading to improved water quality. These environmental benefits are invaluable, aligning perfectly with Sri Lanka's commitment to sustainable development goals and environmental protection. This comprehensive consideration of environmental factors underscores the alignment between the research objectives and the observed impacts of AES.

Sri Lanka is blessed with abundant sunshine throughout the year, making solar energy a prime contender in the nation's quest for sustainable power generation. The case studies, particularly the Lut Desert solar project in Iran and India's solar rooftop projects, underscore the immense potential of solar energy. By harnessing a mere fraction of available land or utilizing urban spaces through rooftop installations, these projects have showcased the viability and effectiveness of solar energy in diverse settings. This aligns perfectly with Sri Lanka's geographical advantage, where solar irradiance levels are conducive to robust energy generation. The research objectives aimed at exploring the potential of AES, particularly solar energy, in Sri Lanka find strong resonance in these case studies. The evidence suggests that Sri Lanka has a golden opportunity to tap into its solar wealth to meet its energy needs efficiently and sustainably.

The concept of twinning floating solar panels with hydropower generation, as exemplified in several countries, presents a game-changing strategy for Sri Lanka. The nation's abundant water bodies and existing hydropower infrastructure make this integration a compelling proposition. The case studies provide compelling evidence of how this synergy not only enhances energy production but also stabilizes the grid by mitigating the intermittency associated with solar and wind power. This integration aligns seamlessly with Sri Lanka's unique geographical advantages and addresses the research objective of evaluating the potential use of AES in a manner that ensures energy reliability. By providing evidence from successful international implementations, the case studies bolster the case for Sri Lanka to explore this integrated approach, which can play a pivotal role in the nation's sustainable energy strategy.

While solar and hydropower rightfully take the spotlight, it's essential to recognize the unexplored potential of geothermal energy in Sri Lanka. Geothermal energy, although currently untapped, emerges as a prospective avenue that can diversify the nation's energy portfolio and reduce reliance on a single energy source. The research objectives include investigating the feasibility and potential of geothermal resources, and the case studies emphasize the need for rigorous geothermal assessments. This untapped source could be a game-changer for Sri Lanka's energy landscape, offering a reliable and clean energy source that aligns with the nation's sustainability goals. The research objectives find strong support in advocating for the exploration of geothermal energy as a part of Sri Lanka's sustainable energy strategy.

Hence, the expanded observations and insights derived from this analysis are inextricably linked to the predefined research objectives, fortified by substantial and robust evidence. These findings provide a comprehensive, well-grounded foundation for developing a sustainable energy strategy in Sri Lanka. They not only align with Sri Lanka's aspirations for a cleaner, more resilient, and more sustainable energy future but also stand as a testament to the viability of AES as a transformative force in the nation's energy landscape.

CONCLUSION

In closing, Sri Lanka's ambitious quest for a sustainable energy strategy hinges on the bedrock of renewable energy sources, and the insights drawn from a global perspective provide a clear roadmap for its future endeavors. Sri Lanka stands at a pivotal juncture, tasked with the dual mission of satisfying surging electricity demands while conscientiously mitigating the detrimental environmental repercussions linked to fossil fuel dependency.

The transition toward renewable energy, with a particular emphasis on solar and hydropower, beckons as an avenue rich with untapped potential. The success stories of solar projects in Iran and India underscore the adaptability of solar technologies across diverse landscapes. Moreover, the innovative concept of coupling floating solar installations with hydropower generation holds promise in resolving grid stability issues, making it a compelling choice for Sri Lanka's energy landscape. Furthermore, delving into the exploration of geothermal energy and its associated environmental implications offers a tantalizing avenue deserving of dedicated research and thorough consideration.

In its energy odyssey, Sri Lanka must elevate the principles of socioeconomic equity and environmental preservation to paramount importance. The creation of employment opportunities and fostering community engagement should be woven into the fabric of renewable energy initiatives. Simultaneously, the nation must embark on the creation of a comprehensive energy roadmap. This roadmap should encompass robust research initiatives, progressive policy reforms, and active collaboration on the international stage. It is imperative to channel efforts toward advancing energy storage technologies, streamlining regulations, and nurturing capacity building to propel Sri Lanka toward an energy future that is not only sustainable but also economically and environmentally responsible.

Sri Lanka's commitment to embracing alternative energy sources positions it as a beacon of hope in the global pursuit of sustainable energy solutions. By navigating this path with diligence, foresight, and a steadfast commitment to balancing economic growth and environmental preservation, Sri Lanka can pave the way for a brighter, more sustainable energy future. The journey ahead is both challenging and promising, but with unwavering determination and a holistic approach, Sri Lanka can inspire the world with its transformative strides toward a cleaner, greener, and more prosperous energy landscape. Future studies should delve deeper into the nuanced socioeconomic implications and explore innovative financing models to ensure the seamless execution of these renewable energy initiatives, securing a sustainable and thriving future for the nation.

RECOMMENDATIONS

To chart a sustainable energy future and harness the full potential of renewable energy sources, Sri Lanka should consider broadening the scope of its research to incorporate relevant management and business aspects. This expansion will make the recommendations more comprehensive and implementable more effectively within the context of Sri Lanka's evolving energy landscape.

Firstly, Sri Lanka must enact decisive policy reforms that encompass not only technical aspects but also strategic management considerations. Creating an enabling environment for renewable energy adoption should involve policies and incentives that attract private investments in the sector, as well as robust management frameworks to ensure efficient project implementation. These policies should streamline approvals and provide equitable grid access for renewable energy projects, fostering a conducive atmosphere for growth. Incorporating strong project management practices will be crucial in achieving these objectives.

Secondly, conducting comprehensive geothermal feasibility studies should be complemented by a business feasibility analysis. This will help in determining not only the technical viability but also the financial feasibility of harnessing geothermal energy. Business models, financing strategies, and risk management approaches should be part of this expanded research scope, guiding future investments and strategies.

Thirdly, capacity building in renewable energy technologies should be accompanied by workforce development plans that align with broader business strategies. This holistic approach will ensure that the country not only develops technical expertise but also builds a skilled workforce capable of driving the renewable energy sector's growth. Effective management of human resources and talent development should be integrated into the capacity-building initiatives.

Furthermore, meticulous environmental impact assessments and mitigation strategies must be approached from both environmental and business sustainability perspectives. This means evaluating not only the ecological implications but also the financial and operational aspects of environmental safeguards. Sri Lanka's unique ecosystems and biodiversity must be protected during the development and operation of renewable energy facilities, and this should be considered as part of the overall business strategy for sustainable growth.

Collaboration, both at the technical and managerial levels, is key. Sri Lanka should actively seek international collaboration with neighboring nations and international organizations, with an emphasis on knowledge transfer and business partnerships. This expanded collaboration can facilitate cross-border energy trade, technology sharing, and business expertise exchange, ultimately enhancing Sri Lanka's energy security and business sustainability.

Lastly, research and development in advanced energy storage technologies should not only focus on technical aspects but also on their business implications. Energy storage solutions can significantly enhance the reliability and stability of renewable energy integration into the grid, addressing the intermittency challenges associated with solar and wind power. Therefore, research should consider business models for energy storage deployment, financing options, and market dynamics to ensure successful implementation.

By incorporating these management and business aspects into its research scope, Sri Lanka can embark on a transformative journey toward a greener, more resilient, and economically robust energy future. The nation possesses the potential not only to meet its energy demands sustainably but also to emerge as a regional leader in renewable energy practices, guided by a comprehensive approach that integrates technical and business strategies. With strategic planning, collaboration, and progressive policies encompassing management and business dimensions, Sri Lanka can illuminate the path to a brighter and more sustainable energy future, setting an example for the region and the world. Future studies should undertake a thorough SWOT analysis, considering social, environmental, and business implications, to provide a more holistic understanding of potential benefits and drawbacks.

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