International Journal of Inventive Engineering and Sciences (IJIES)
ISSN: 2319-9598 (Online), Volume-11 Issue-9, September 2024

Digitalization and Decarbonization of Sri Lanka's Electric Power System: A Way Forward for Sustainability

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***Abstract:** The global energy landscape is undergoing a transformative shift driven by the dual imperatives of digitalization and decarbonization, essential for creating sustainable and resilient power systems (Lichtenthaler, 2021, [1]). This transformation is particularly critical for developing nations like Sri Lanka, where the integration of smart technologies and renewable energy sources can significantly enhance system efficiency and contribute to a robust response to climate change challenges (Lichtenthaler, 2021, [1]). This paper examines the potential of leveraging advanced digital technologies—such as artificial intelligence, big data analytics, and the Internet of Things—to optimize energy management and facilitate a swift transition toward a low-emission economy in Sri Lanka, while addressing the socio-economic implications of this transition. Furthermore, this study highlights the importance of fostering a circular economy through these technological advancements, emphasizing that innovative solutions can not only improve energy efficiency but also contribute to broader sustainability goals, ensuring equitable access to resources and combating the adverse effects of climate change. Through this lens, the investigation underscores the necessity of a holistic approach that integrates digital transformation with sustainable practices, enabling the decoupling of economic activity from resource depletion and environmental degradation, thereby fostering a resilient energy future for Sri Lanka.*

***Keywords:** In Sri Lanka, Lichtenthaler, Through, Smart Technologies*

I. INTRODUCTION

This article aims to examine how integrating digital technologies and renewable energy sources can transform Sri Lanka's electric power system into a resilient, efficient, and sustainable model. By leveraging the principles of polycentric governance and sustainable management frameworks, the study aims to highlight the benefits of digitalization and decarbonization, address the challenges faced in the transition, and propose actionable strategies to achieve a carbon-neutral future. This involves exploring the roles of smart grids, distributed energy resources, advanced control systems, and policy frameworks in driving this transformation, ultimately contributing to the nation's sustainability goals and economic growth.

Manuscript received on 22 August 2024 | Revised Manuscript received on 14 September 2024 | Manuscript Accepted on 15 September 2024 | Manuscript published on 30 September 2024.
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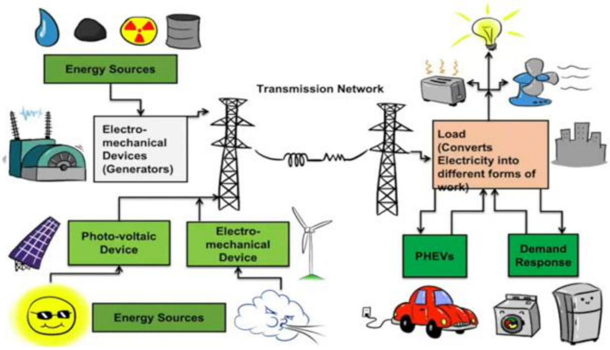

Figure 1: Future Power Systems

II. IMPORTANCE AND UNIQUENESS

The evolution of the energy industry has led to various schools of thought regarding the future of electric energy systems. Some advocate for large, clean nuclear plants and strong grids, while others favor hybrid systems with distributed energy resources (DERs) and active user participation. Another viewpoint suggests self-sufficient, decentralized microgrids. It is not prudent to take a singular position; instead, we emphasize the scientific principles needed to integrate diverse stakeholders into a well-functioning dynamic system. This approach allows for the integration of advanced technologies and coordinated management of variable renewable energy sources (Sinsel et al., 2020, [2]), addressing key challenges such as aging infrastructure, reliability issues, and the need for increased access to clean energy. The integration of specific digital technologies, such as smart grids, advanced metering infrastructure, grid-scale energy storage, and data analytics, holds immense potential for transforming Sri Lanka's power system. By embracing these technologies, Sri Lanka can address its pressing energy challenges, including aging infrastructure, reliability issues, and the need for increased access to clean energy. Smart grids, for instance, can optimize energy distribution, integrate renewable energy sources seamlessly, and improve the overall reliability of the grid (Amin & Wollenberg, 2005, [3][11][12][13][14]). Furthermore, advanced metering infrastructure empowers consumers with real-time data on their energy consumption, enabling them to make informed decisions and actively participate in demand-side management programs. Moreover, grid-scale energy storage solutions, such as battery systems and pumped hydro, can effectively balance the intermittency of renewable energy sources, ensuring a stable and reliable power supply.

A. Theoretical Framework and Sustainability Principles

Elinor Ostrom's principles of polycentric governance and local adaptation (Ostrom, E. ,2010, [4]), are crucial for designing resilient and adaptive energy systems. Her work on sustainable management of social-ecological systems (SES) provides a foundational framework for understanding how complex systems can be managed sustainably. These principles have been applied across various fields, including water management and forestry, and now offer valuable insights for energy systems. Ostrom's concepts suggest that sustainable energy systems should be managed through decentralized, interactive governance structures, aligning resource management with user needs and ecological constraints.

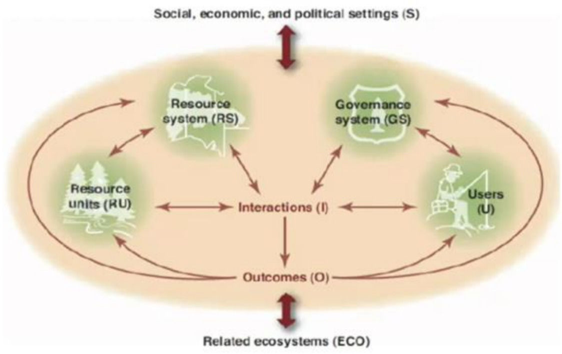

Figure 2: Elinor Ostrom's Principles of Polycentric Governance and Local Adaptation

B. Digitalization in Electric Power Systems

Digitalization, involving the integration of advanced technologies into Sri Lanka's power grid, is crucial for enhancing monitoring, control, and communication capabilities. This transformation towards a smarter grid relies on several key components:

i. *Smart Meters for Energy Efficiency*

Deploying smart meters across Sri Lanka can empower consumers with real-time energy usage data. This enables better management of consumption, facilitates demand-side response programs, and contributes to energy efficiency improvements. Smart meters provide detailed insights into energy patterns, allowing consumers to make informed decisions to reduce their energy consumption and costs.

ii. *Advanced Sensor Networks for Grid Reliability*

Integrating advanced sensor networks across Sri Lanka's grid infrastructure can provide real-time data on grid performance. This data is crucial for identifying potential faults, enabling predictive maintenance, and minimizing outages. By enhancing the reliability of Sri Lanka's electricity supply, these sensor networks play a vital role in maintaining a stable and efficient power system.

iii. *Real-Time Data Analytics for Informed Decision-Making*

Leveraging real-time data analytics is essential for harnessing the full potential of a digitalized grid. By analyzing data from smart meters and sensors, Sri Lanka can optimize energy distribution, predict and prevent outages, and make informed decisions regarding renewable energy integration. Real-time analytics enable dynamic adjustments to power flows, enhancing overall grid efficiency and reliability.

iv. *IoT and Big Data for a Smarter Grid*

The Internet of Things (IoT) and big data are fundamental to transforming Sri Lanka's traditional power grid into a smart grid. Connecting various grid components through IoT and analyzing the resulting data can lead to more efficient grid management, improved reliability, and better integration of renewable energy sources. IoT devices enable seamless communication between grid elements, while big data analytics provide insights for proactive grid management and decision-making (Fang et al., 2012, [5]).

C. Decarburization Strategies

Decarbonization aims to reduce carbon dioxide emissions by adopting low-carbon and renewable energy sources. Integrating renewable energy sources such as wind, solar, and biomass into the power grid can significantly reduce greenhouse gas emissions. Policy frameworks that support renewable energy deployment and grid integration are essential for successful Decarbonisation (IRENA, 2019, [6])

Figure 3: Digitalization of the Energy Systems

D. Hybrid Systems and Distributed Energy Resources (DERs)

Hybrid systems combining centralized and distributed energy resources are emerging as a sustainable solution. DERs include small-scale renewable energy installations, energy storage systems, and active consumer participation in demand response. These systems offer flexibility and resilience, enabling the grid to adapt to variable renewable energy supply and changing demand patterns (Parhizi et al., 2015, [7]).

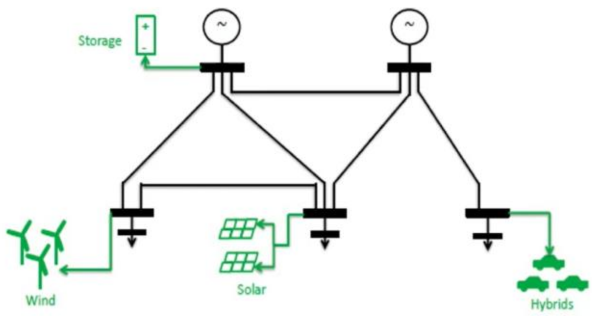

Figure 4: Emerging Distribution Systems- High DER Penetration

Retrieval Number: 100.1/ijies.K997213111024
DOI: 10.35940/ijies.K9972.11090924
Journal Website: www.ijies.org

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP)

III. MICROGRIDS AND DECENTRALIZATION

Microgrids, which allow localized generation and consumption of electricity, enhance grid resilience by reducing dependence on centralized infrastructure. They can operate independently during grid outages, making them a valuable component of a sustainable energy system. The technical, economic, and regulatory challenges of integrating microgrids into the broader power system are well-documented and critical to address (Lasseter, 2002, [8][15])

Figure 5: Distribution Automation, a New Effort

A. The Role of Advanced Control Systems

Advanced control systems are crucial for managing the complexity of modern power grids. These systems use machine learning algorithms and predictive analytics to optimize grid operations and ensure stability. Adaptive control techniques enable real-time adjustments to power flows, enhancing the efficiency and reliability of the grid (Huang et al., 2019, [9]).

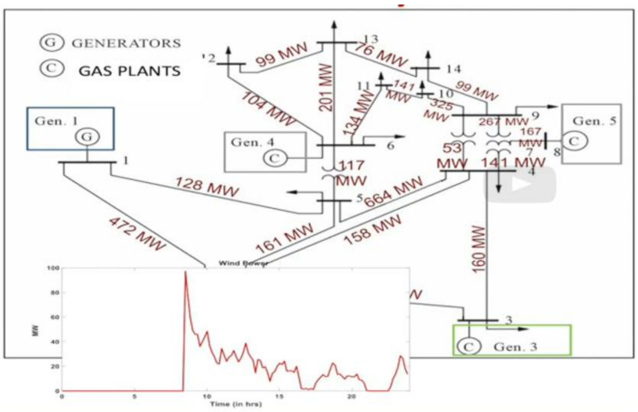

Figure 6: IEEE 14- bus Test Systems

B. Case Studies and Applications

Several case studies illustrate the successful implementation of digitalization and Decarbonisation strategies. For instance, the European Union's efforts to create an integrated energy market have resulted in significant advancements in renewable energy integration and grid management (European Commission, 2018). Similarly, the adoption of smart grid technologies in the United States has led to improved grid reliability and efficiency (DOE, 2015, [10]).

C. Advantages in Sri Lankan Context

Digitalization and decarbonization offer numerous economic, environmental, social, and technological advantages for Sri Lanka's power system. Economically, integrating renewable energy sources such as solar and wind, which are abundant in Sri Lanka, can significantly reduce reliance on expensive fossil fuel imports, leading to substantial long-term cost savings. Increased energy independence is another critical benefit, as generating more electricity domestically from renewable sources reduces the country's dependence on volatile global energy markets, enhancing national energy security. Furthermore, the transition to a digitalized and decarbonized power sector will create new job opportunities in renewable energy, technology development, and grid modernization, contributing to economic growth. Additionally, a commitment to a sustainable and modern power system can attract foreign investment in renewable energy projects and technology partnerships, further bolstering the economy. Environmentally, shifting away from fossil fuels towards renewable energy sources will significantly reduce greenhouse gas emissions, helping Sri Lanka achieve its climate goals and mitigate the impact of climate change. Improved air quality is another important environmental benefit, as decreasing reliance on fossil fuel-based power plants will reduce air pollution, benefiting public health and reducing respiratory illnesses. Moreover, transitioning to a more sustainable power system will help preserve natural resources by reducing the environmental impact associated with fossil fuel extraction and transportation. Socially, a diversified energy mix with a higher share of renewables enhances energy security by reducing reliance on a single energy source. This diversification ensures a more stable and reliable energy supply. Additionally, decentralized renewable energy systems, enabled by digitalization, can expand electricity access to rural and underserved communities, improving energy equity and fostering social development. As renewable energy costs continue to decline, a decarbonized power system will contribute to more affordable electricity prices for consumers, making energy more accessible and reducing the financial burden on households.

IV. CONCLUSION

By leveraging advanced technologies and adopting sustainable management principles, Sri Lanka can create a resilient, efficient, and environmentally friendly energy system. There are tools to conceptualize, model, and control these complex systems, enabling a sustainable future for Sri Lanka's electric power system. The integration of digitalization and Decarbonisation strategies, supported by a unified approach to modeling and control, is essential for achieving these goals. Future research and development efforts should continue to explore innovative approaches to overcome existing challenges and achieve sustainability targets.

DECLARATION STATEMENT

I must verify the accuracy of the following information as the article's author.

- **Conflicts of Interest/ Competing Interests:** Based on my understanding, this article has no conflicts of interest.
- **Funding Support:** This article has not been sponsored or funded by any organization or agency. The independence of this research is a crucial factor in affirming its impartiality, as it has been conducted without any external sway.
- **Ethical Approval and Consent to Participate:** The data provided in this article is exempt from the requirement for ethical approval or participant consent.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Authors Contributions:** The authorship of this article is contributed solely.

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