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1. Introduction

Sri Lanka aims to raise its renewable energy share to 40% by 2030, necessitating Energy Storage Systems (ESS) for effective grid integration and balancing of diverse renewable sources. ESS implementation is crucial for addressing the intermittent nature of renewables like solar and wind, enhancing overall flexibility, and power quality, and reducing peak demand while optimizing green energy utilization. This requires a comprehensive national policy catering to policymakers, consumers, energy storage solution providers, and researchers.

2. Objectives

- To identify the best ESS for uninterrupted power supply to consumers.
- To develop a roadmap for implementing ESS in Sri Lanka.
- To ensure fair and competitive technological implementation of ESS in Sri Lanka.
- To remove barriers in energy regulations to promote ESS in Sri Lanka.
- To maximize the use of local raw materials in developing energy storage technologies.
- To improve the national economy by minimizing power purchases during peak hours at higher costs from third-party energy providers.

Based on an extensive evaluation of various energy storage technologies, four (4) key solutions have been identified as the most suitable options for Sri Lanka which can be implemented over the next six/couple of years. This assessment considered factors such as power and energy densities, lifespan, charge/discharge times and frequencies, technological feasibility, system interconnectivity, capital, operational and maintenance costs, and the availability of raw materials for future ESS production.

The proposed 4 energy storage solutions for Sri Lanka include:

1. **Pumped Hydro Storage**: An efficient and established method for large-scale energy storage.
2. **Battery Technologies**: Focusing on Lithium-ion Batteries and Flow Batteries, which offer high energy densities and flexible applications.
3. **Hydrogen Storage**: A promising and sustainable solution for storing and converting renewable energy.
4. **Double Layer Super Capacitors**: Fast-charging and high-power devices that can support grid stability and power quality.

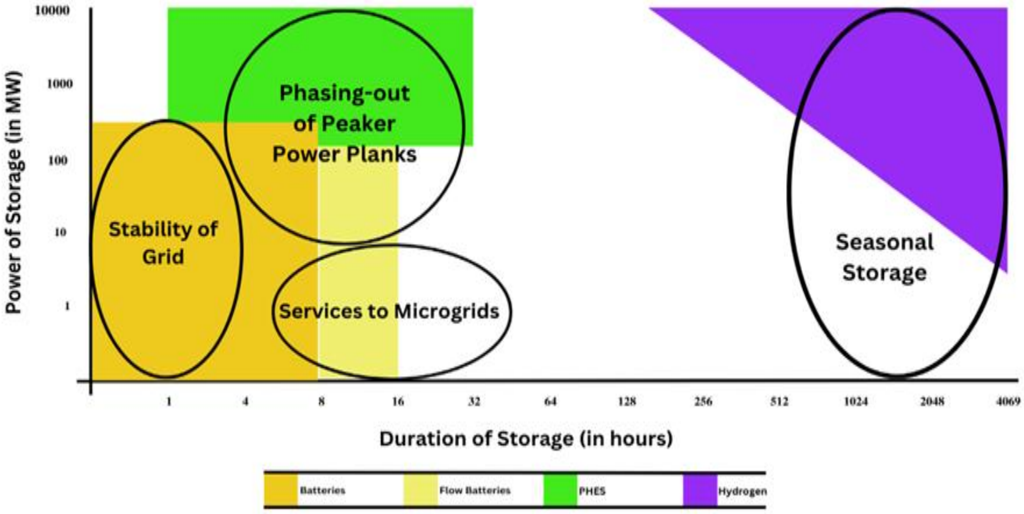

Figure 1: Chart of energy storage systems according to function, technology, power and duration

Figure-1 illustrates the main energy storage technologies (represented by colored rectangles or triangles) in relation to their functions (ellipses), power (y-axis), and duration (x-axis). In Sri Lankan context, addressing grid stability and peak power plant phasing out are crucial for resolving many existing electricity supply issues. The functions of selected storage systems include grid stability, peak power plant phasing out, micro-grid services, integration with intermittent renewables, and seasonal storage. As shown in Figure-1, the proposed ESS solutions in this document offer both short-term and long-term benefits for Sri Lanka's energy needs.

3. Methodology

This document combines four (4) primary components to address the challenges and opportunities in the energy sector of Sri Lanka. The methodology employed in each component is designed to provide a detailed understanding of the respective focus areas and guide the development of actionable recommendations.

1. **Converting existing hydro power plants into pumped hydro-wind-solar PV hybrid systems**: To assess the feasibility of this proposed solution, a systematic approach is adopted, which includes the following steps:
   a. Review of relevant literature to understand the technical aspects of hydro-wind-solar PV hybrid systems and their potential benefits.
   b. Identification of suitable locations for the implementation of hybrid systems based on the availability of hydro power plants, solar irradiance, and wind potential.
   c. Development of an Artificial Intelligence (AI) based model to analyze the technical and economic performance of the proposed systems, considering factors such as power generation, storage capacity, grid stability, and system costs.
   d. Examination of regulatory and policy frameworks to identify potential barriers and opportunities for the implementation of such hybrid systems in Sri Lanka.

2. **Integration of battery energy storage systems (BESS) into the Sri Lanka's energy system**: The analysis of BESS integration is carried out through a multi-level approach, which includes the following steps:
   a. Review of relevant literature and case studies to understand the various benefits and challenges associated with the integration of BESS in the energy grid.
   b. Assessment of the potential for BESS integration at various levels of the grid, including generation, transmission, and distribution, by analyzing the existing energy infrastructure and future energy demands.
   c. Identification of opportunities for BESS applications in specific areas such as rooftop solar PV systems, grid-scale solar power plants, electric vehicles, and microgrids.
   d. Evaluation of the cost-effectiveness and financial viability of BESS integration in the identified areas, considering factors such as capital costs, operational costs, and potential benefits.

3. **Developing local minerals and related materials for rechargeable batteries and double layer super capacitors**: The methodology for this component consists of the following steps:
   a. Review of existing research, development, and commercialization efforts related to local minerals and materials for battery production in Sri Lanka.
   b. Identification and analysis of available mineral resources, such as vein graphite, vein quartz, apatite, iron ores, and mineral sands, that hold potential for use in battery production.
   c. Evaluation of technical challenges associated with the utilization of these minerals, including impurities and inadequate electrochemical activity, and the development of home-grown solutions to address these issues.
   d. Assessment of the economic feasibility of utilizing local minerals and materials in battery production and the potential market opportunities for Sri Lanka, both domestically and internationally.

4. **Hydrogen Storage**: A promising and sustainable solution for converting and storing renewable energy. To thoroughly assess the potential of hydrogen storage in the context of Sri Lanka's energy landscape, the following systematic approach will be employed:
   a. Conduct a comprehensive literature review to understand the technical aspects, advantages, and challenges associated with various hydrogen storage technologies, such as compressed hydrogen, liquid hydrogen, and solid-state hydrogen storage, as well as the role of hydrogen storage in renewable energy integration.
   b. Identify suitable applications and locations for hydrogen storage deployment in Sri Lanka, considering factors such as the availability of renewable energy resources, existing energy infrastructure, and the potential for hydrogen utilization in various sectors such as transportation, industry, and power generation.
   c. Develop a model to analyze the technical, economic, and environmental performance of integrating hydrogen storage into Sri Lanka's energy system. This model will consider factors such as hydrogen production and storage capacity, efficiency, system costs, greenhouse gas emissions, and potential synergies with other energy storage solutions.
   d. Examine regulatory and policy frameworks to identify potential barriers and opportunities for the implementation of hydrogen storage in Sri Lanka, as well as

strategies to promote the adoption of hydrogen storage as a key component of the country's transition to a more sustainable and resilient energy system.

By employing this comprehensive methodology across the four components, the proposal aims to provide valuable insights and actionable recommendations for addressing the challenges and capitalizing on the opportunities in Sri Lanka's energy sector.

4. Results and Analysis

1. Converting existing hydro power plants into pumped hydro-wind-solar PV hybrid systems has the potential to address capacity adequacy, economic efficiency, and grid stability challenges faced by Sri Lanka. By integrating solar PV with existing hydro power plants, the harvested energy during daytime can be utilized to fill the gap during peak hours, while maintaining grid stability. However, integrating solar PV without an energy storage can negatively impact system stability due to a lack of inertia.

2. BESS can provide numerous benefits to the grid at different levels, such as addressing the variability of renewable energy sources, improving grid stability, and reducing the need for peak load power plants. In the Sri Lankan context, several opportunities can be identified, including installing BESS at generation power plants, grid substations, rooftop solar PV systems, grid-scale solar power plants, and integrating them with electric vehicles (EV) and microgrids.

3. Sri Lanka has a variety of mineral resources, including vein graphite, vein quartz, apatite, iron ores, and mineral sands, which can potentially be utilized for battery production. Vein graphite, a rare and valuable form of graphite, has already shown promising results as an anode material for lithium-ion batteries. Additionally, local vein quartz is being developed for use in high-capacity rechargeable batteries, and other minerals also hold potential for battery electrode materials and electrolyte bases.

4. Hydrogen storage presents a promising and sustainable solution for storing and converting renewable energy. As a clean and abundant energy carrier, hydrogen can be produced from various renewable sources, such as solar, wind, and hydropower. This energy can then be stored and utilized to generate electricity through fuel cells or combustion, providing a versatile and efficient means of integrating intermittent renewable energy into the grid. In the context of Sri Lanka, the potential for utilizing hydrogen storage systems can be explored at different scales, including large-scale centralized storage facilities, decentralized storage systems for microgrids, and mobile hydrogen storage solutions for transportation applications. Moreover, hydrogen storage can complement other energy

storage technologies like BESS, providing a diversified and resilient energy storage portfolio.

In summary, the analysis highlights the potential benefits of pumped hydro-wind-solar PV hybrid systems, battery energy storage systems, local mineral development for rechargeable batteries and double-layer supercapacitors, and hydrogen storage as promising and sustainable solutions for converting and storing renewable energy in Sri Lanka. These combined efforts can help the island nation to optimize its energy resources, enhance grid stability, and promote a sustainable and economically viable energy sector.

5. Conclusions

1. The proposed solution of converting existing hydro power plants into pumped hydro-wind-solar PV hybrid systems has the potential to address Sri Lanka's capacity adequacy and economic efficiency challenges while maintaining grid stability. This would enable the country to utilize its abundant sunlight without compromising the grid's stability, thereby ensuring a sustainable and reliable energy future.

2. BESS technology holds great promise for the electrical energy sector in Sri Lanka, enabling enhanced grid stability, heightened reliability, greater utilization of renewable energy sources, and a reduction in reliance on costly and ecologically harmful peak load power plants. The adoption of BESS has the potential to significantly impact the country's economy, promote research and development, and attract foreign investment.

3. Successful development and utilization of local minerals and related materials for rechargeable batteries and double-layer supercapacitors can open new market opportunities for Sri Lanka. The low-cost, longer-duration, and higher-capacity batteries produced using these materials could be competitive in the global market, supporting the national drive for sustainable energy and increasing income through exporting value-added minerals and locally manufactured battery systems.

4. Hydrogen storage represents a promising and sustainable solution for storing and converting renewable energy, complementing the existing energy infrastructure in Sri Lanka. As a flexible, clean, and versatile energy carrier, hydrogen can be used to store excess renewable energy, such as solar and wind power, to provide electricity during periods of low generation. Additionally, hydrogen can be utilized in various sectors, including transportation, industrial applications, and residential energy systems, offering a comprehensive energy solution with minimal environmental impact.

The combination of the above strategies and technological advancements can lead to a more sustainable, resilient, and efficient energy system in Sri Lanka. By adopting innovative energy storage solutions, such as BESS and hydrogen storage, the country can better manage the integration of renewable energy sources and maintain grid stability. Furthermore, the development of local minerals and related materials for rechargeable batteries and double-layer supercapacitors not only contributes to the growth of the domestic battery industry but also strengthens the nation's position in the global market. These efforts, in conjunction with the conversion of existing hydro power plants into pumped hydro-wind-solar PV hybrid systems, can collectively pave the way towards a more sustainable and secure energy future for Sri Lanka.

6. Implications and Recommendations

The Implications and Recommendations section highlights 15 critical issues that need to be addressed in order to advance Sri Lanka's renewable energy, energy storage, and hydrogen storage sectors. These issues encompass various aspects of policy, technology, infrastructure, and capacity building. By tackling these challenges, the country can move closer to achieving a sustainable and resilient energy system. In this section, we provide recommendations and rationales for each identified issue, emphasizing the importance of strategic planning, targeted investment, and collaborative efforts to overcome barriers and accelerate the transition toward a more sustainable energy future.

01	**Issue**	The need for comprehensive techno-economic studies in various fields of energy storage and renewable energy.
	Recommendation	Conduct comprehensive techno-economic studies for the proposed hydro-wind-solar PV hybrid systems, BESS integration, battery material development, and hydrogen storage as a sustainable solution for storing and converting renewable energy.
	Rationale	Thorough evaluations can help identify potential challenges, benefits, and investment opportunities in the development and implementation of these technologies, ensuring optimal resource allocation and informed decision-making.
02	**Issue**	Technical challenges faced by local battery material developers and hydrogen storage researchers.
	Recommendation	Address technical challenges through focused research and development efforts, emphasizing home-grown solutions and collaborations with international experts.
	Rationale	Overcoming technical challenges will enable the development of innovative, cost-effective, and efficient energy storage technologies that can contribute to the country's energy security and sustainability.
03	**Issue**	Lack of support for local battery material developers and hydrogen storage researchers.

	Recommendation	Provide necessary fundings, testing equipment, incentives for innovation, and foster a collaborative environment among academia, industry, and government.
	Rationale	Adequate finance and government support can accelerate the development and commercialization of advanced energy storage technologies, creating a strong foundation for a sustainable energy future in Sri Lanka.
04	**Issue**	Commercialization of inventions in renewable energy, energy storage, and hydrogen storage technology.
	Recommendation	Establish an institutional mechanism to support commercialization efforts, coordinating with potential investors, institutions, and international partners for further development, technology transfer, and market expansion.
	Rationale	Streamlined commercialization processes can facilitate the integration of novel technologies into the market, promoting economic growth and the expansion of the energy sector.
05	**Issue**	Aligning energy development with national priorities and promoting sustainable development.
	Recommendation	Focus on the utilization of locally developed battery-grade materials, hydrogen storage technologies, and renewable energy systems for manufacturing, exporting value-added materials, and increasing income.
	Rationale	Focusing on local resources and technologies can boost the country's economy, create jobs, and contribute to a sustainable energy future.
06	**Issue**	Grid reliance and high electricity bills for consumers.
	Recommendation	Encourage the adoption of rooftop solar PV systems with battery backup and hydrogen storage systems.
	Rationale	Reducing grid reliance and promoting self-sufficient energy generation can lower electricity bills and create a more resilient and sustainable energy infrastructure.
07	**Issue**	Balancing the grid and reducing peak demand.
	Recommendation	Promote the integration of electric vehicles, microgrids, and hydrogen storage systems with BESS and renewable energy sources.

	Rationale	Integrating various energy sources and storage solutions can enhance grid stability, optimize energy distribution, and create a cleaner transportation infrastructure.
08	**Issue**	Need for a roadmap for hydrogen storage technology adoption.
	Recommendation	Develop a roadmap for the widespread adoption of hydrogen storage technologies in conjunction with renewable energy systems.
	Rationale	A well-planned roadmap can guide the development and integration of hydrogen storage technologies, ensuring a smooth transition to a more sustainable energy system.
09	**Issue**	Lack of battery storage and hydrogen storage manufacturing industry in Sri Lanka.
	Recommendation	Explore public-private partnerships to establish a battery storage and hydrogen storage manufacturing industry.
	Rationale	Developing a local manufacturing industry can create employment opportunities and contribute to a more sustainable and equitable energy future.
10	**Issue**	Barriers in energy regulations and policies.
	Recommendation	Review energy regulations and policies to remove barriers, promote the adoption of innovative energy storage solutions, including hydrogen storage systems, and support their integration into the existing energy infrastructure.
	Rationale	Revising regulations and policies can foster a more conducive environment for the development and deployment of advanced energy storage technologies and ensure their seamless integration.
11	**Issue**	Lack of a skilled workforce and knowledge in renewable energy, energy storage technologies, and hydrogen storage systems.
	Recommendation	Invest in capacity building and education programs for researchers, engineers, technicians, and policymakers in the fields of renewable energy, energy storage technologies, and hydrogen storage systems.
	Rationale	Fostering a skilled workforce in the aforementioned fields is essential to drive the nation's transition towards a more sustainable and resilient energy system. By providing targeted education and training programs, Sri Lanka can ensure that its workforce is well-equipped

		to develop, implement, and manage innovative energy solutions that contribute to long-term energy security and sustainability.
12	**Issue**	Limited access to advanced technologies, knowledge sharing, and funding opportunities for the development, deployment, and commercialization of renewable energy, energy storage, and hydrogen storage technologies.
	Recommendation	Leverage international collaborations and partnerships to access advanced technologies, knowledge sharing, and funding opportunities for the development, deployment, and commercialization of renewable energy, energy storage, and hydrogen storage technologies in Sri Lanka.
	Rationale	Engaging in international collaborations and partnerships can help Sri Lanka overcome barriers to technology access, knowledge transfer, and funding. These partnerships can enable the country to learn from best practices, adopt cutting-edge technologies, and secure necessary financial resources to support the widespread adoption of renewable energy, energy storage, and hydrogen storage systems, ultimately accelerating the transition to a more sustainable energy future.
13	**Issue**	Battery waste management
	Recommendation	Sri Lanka needs to establish a comprehensive battery waste management system to handle the waste generated from degraded batteries. The system should include guidelines for the disposal, recycling, buy-back, and secondary use of batteries. The government should work with battery manufacturers to establish a take-back program and promote the recycling of materials used in battery production.
	Rationale	Battery waste is a significant concern globally as the world increasingly adopts battery-based energy storage solutions. Sri Lanka cannot afford to ignore this issue, as it will lead to environmental degradation and health hazards. The establishment of a comprehensive battery waste management system will enable Sri Lanka to mitigate the negative environmental and health impacts of battery waste.

14	**Issue**	Safety issues of large-scale battery packs
	Recommendation	Sri Lanka needs to prioritize safety regulations for large-scale battery packs. The government should establish safety standards, guidelines, and protocols to ensure the safe handling, installation, and operation of large-scale battery packs. The safety regulations should be enforced and periodically reviewed and updated as necessary.
	Rationale	Safety is a critical issue when dealing with large-scale battery packs. Several incidents have occurred globally, leading to concerns over the safety of these systems. Sri Lanka needs to establish safety regulations to protect its citizens, the environment, and infrastructure.
15	**Issue**	Safety of large-scale hydrogen energy storage
	Recommendation	Sri Lanka needs to establish safety regulations for large-scale hydrogen energy storage. The government should develop safety standards, guidelines, and protocols to ensure the safe handling, installation, and operation of hydrogen storage tanks. The safety regulations should be enforced and periodically reviewed and updated as necessary.
	Rationale	Hydrogen energy storage is a promising technology for Sri Lanka's energy transition. However, hydrogen storage tanks are highly pressurized and require safety precautions to prevent accidents. Sri Lanka needs to establish safety regulations to ensure that the deployment of large-scale hydrogen energy storage is safe for its citizens, the environment, and infrastructure.

Table 1: Critical energy issues and recommendations

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