Ministry of Education

NASTEC

National Science and Technology Commission

Technical Report on Renewable Energy, Energy Storage and Green Hydrogen

SCIENCE TECHNOLOGY INNOVATION

SUSTAINABLE DEVELOPMENT

IN THE ERA OF CLIMATE CHANGE

9th SRI LANKA BIENNIAL CONFERENCE ON

SCIENCE & TECHNOLOGY 2023 (BICOST IX)

23rd & 24th March 2023

Waters Edge, Battaramulla

RENEWABLE ENERGY, ENERGY STORAGE AND GREEN HYDROGEN

Ninth Biennial Sri Lanka Conference on Science and Technology

BICOST IX

23 – 24 March 2023

Waters Edge, Battaramulla

NATIONAL SCIENCE AND TECHNOLOGY COMMISSION

ISBN 978-955-8630-31-0

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1.1 Rationale

It is now recognized that indigenous renewable energy sources could fulfil national energy demand aspirations. It is important to evaluate the different renewable energy sources and formulate policies, strategies, and national action plans on the development of these resources. Committed, time bound actions definitely could yield returns to the national economy by developing a resilient net-zero energy system.

Sri Lanka's per capita energy use remains very low, compared to other countries in similar circumstances. The total energy use per capita was 18.14 MJ/person in 2021 and the per capita oil and electricity use were recorded as 214.28 kg and 696.41 kWh per person in 2021. Renewable energy share of the total primary energy supply stood at 48.64% and in power generation mix, renewables constituted a 50% share. Per capita renewable energy capacity in the country stood at 122.4 W per person, the highest rank in the South Asian region.

The renewable energy resource potential of the country is many times the demand in the foreseeable future. Already, 813 MW of solar resource, 247 MW of wind resource, 423 MW of hydro resource and 53 MW of biomass energy resource have been connected to the grid, and based on the resource availability, the country can rapidly and significantly improve the renewable energy supply to enable the society to become a smart society with a per capita energy use comparable with the mature economies, yet without a large carbon footprint.

In terms of renewable energy resource availability, the country has adequate renewable energy resources; solar, wind, and biomass being the most promising sources. Nevertheless, the various constraints associated with different renewable energy sources need to be addressed in order to facilitate their harnessing in meeting the energy needs. For example, both wind and solar resources, being susceptible to weather patterns, introduce challenges related to power system stability in the large-scale absorption of such resources.

The recommendations have a strong bias towards electricity in all three sectors - domestic, institutional and industry – stemming from the fact that in the National Energy Balance the electricity percentage is quite low (approx. 13%). When considering the versatility of this energy medium, a higher per capita availability enables positioning the economy at a completely different position.

1.2 Recommendations for the broader areas of Renewable Energy Systems development

1.2.1 Financing, Tariff and Demand Side Management

1. Develop supportive policy and regulatory frameworks, such as dynamically changing win-win feed-in tariffs, wheeling, tax incentives, green financing (the accepted green financing taxonomy now exists with the CBSL), green bonds and public-private partnerships. This will reduce the cost of renewable energy technologies and encourage local and foreign investment in the sector. Ensure that doing energy business in Sri Lanka is made efficient and effective.
2. Introduce demand side management through time-of-use tariff, designed based on proper studies to effectively shift the peak to allow a reduction of required energy storage capacity. Ensure strong DSM measures in place broadly.
3. Introduce tariff schemes for micro-grid interconnection to the system.
4. Introduce tariff schemes to Waste-to-Energy, Anaerobic Digestion, Geothermal, Off-shore wind, ocean energy etc.

1.2.2 Site Identification and Allocation of Lands

1. Direct and facilitate Sri Lanka Sustainable Energy Authority (SLSEA) to carry out the identification of sites for large-scale renewable energy development through detailed site information surveys.
2. Streamline the land acquisition and permitting processes for renewable energy projects to reduce delays and improve investor confidence.

1.2.3 Renewable Energy Development, Conversion and Services to be an Industry Segment

1. Establish two new dedicated Industrial Estates (IEs) to renewable energy developers, one on the coast and the other in the dry zone. One on the coast can have the suggested research centres (marine energy) associated with that. This will give a stronger voice to the

renewable energy developers.

2. Establish a start-up space in these IEs to support the commercialization of energy research outputs of the university system. The assessment of research taking place in the country shows an impact above the global average, but the absence in the global patent space demonstrates research not moving into the commercialization stage.

1.2.4 Transmission & Distribution Infrastructure Development

1. Direct and facilitate CEB and licensees to develop a comprehensive system integration plan that identifies the technological solutions required to integrate renewable energy sources into the grid.
2. Direct and facilitate PUSCL, CEB and licensees to develop regulations and standards for renewable energy integration ensuring compliance with the international standards.
3. Direct and facilitate CEB and licensees to upgrade the grid infrastructure, including transmission and distribution lines, transformers, and substations, to improve the capacity and stability of the grid, through comprehensive research studies.
4. Direct and facilitate CEB and licensees to implement advanced grid technologies, such as energy storage, microgrids, and smart grid technologies, to improve the stability and reliability of the grid, through comprehensive research studies.

1.2.5 Sustainable Energy Supply for Rural Communities

1. Develop renewable energy based sustainable energy supply systems using small-scale solar, hydro or solar/hydro integrated microgrid systems or off-grid electricity systems in order to ensure the supply of electricity for rural communities and islands.

1.2.6 Enhance Institutes to collaborate to derive synergy

1. Introduce formal collaboration approaches for the institutions of scientific & technological research related to energy, such as SLINTEC, IFS, in order that adequate knowledge sharing and equipment sharing will happen and the energy research work implemented in different institutions would be done in a complementary manner.

1.2.7 Drive energy literacy in the population, drive HC generation and demonstration schemes

1. Considering the strong resource potential demonstrated as well as the need to ensure indigenous resources. Find their due place by driving the need for change (climate change, net zero targets etc.) keeping the populace well informed using practical measures to improve understanding.
2. Streamline the training and capacity building process to develop the workforce requirement of the renewable energy industry locally, as well as to make it a foreign exchange income earning avenue through the export of technical personnel to the international renewable energy industry.

1.3 Renewable Energy Sources

1.3.1 Biofuels

1.3.1.1 Solid, liquid and gaseous biofuels

Biofuels have considerable diversity, and a significant generation potential exists in the country. Energy content of biomass depends on its characteristics, and a standardization procedure is required to maintain the quality of supply. The contribution of biomass in the electricity mixes for the 100% renewable energy target by 2050 has been reported in the current generation plans as 149 MWe in 2025 and 394 MWe in 2050, with around 100 MWe increment per decade. This is far below the potential; however, supply chain issues, and technologies such as pelletizers need to be improved in order to drive scale.

- **Dedicated energy plantations**

Sri Lanka Sustainable Energy Authority (SLSEA) has identified 92,606 ha of land availability for energy plantations, and the estimated power generation potential is 763 MWe. Studies by ADB and JICA have indicated a potential of 2,400 MWe. Gliricidia, Ipil Ipil, Acacia, Bamboo and Eucalyptus have been identified as the dedicated plantation crops for subsequent dendro power generation.

- **Agricultural residues and livestock wastes**

Agricultural residues and livestock wastes are also potential bio energy sources in the country. These resources are underutilized mainly due to not having a proper collection mechanism and very low energy density, and low-grade nature with inconsistent fuel qualities. Agricultural residues are mainly field residues and process-based residues. By considering an energy use factor, a surplus availability factor and a collection factor, the predicted amount of total biodegradable residue generation in 2021 is 12 million tons/yr. The total estimated amount of livestock wastes including cattle, buffalo, goats, and pigs is 23 million tons/yr. Power generation potential from both agricultural residues and livestock wastes is 2,300 MWe.

- **Organic Fraction of MSW**

The per capita waste generation varies between 0.4 and 1.0 kg/d, and the local authorities and urban councils collect the municipal solid waste (MSW) generated. More than 300 open dumping sites are available in the country, and the amount collected varies from 5 tons/d to several hundred tons. The organic fraction of MSW with high moisture (i.e.>60% moisture), should be subjected to biological processes such as anaerobic digestion (AD). When organic wastes are treated anaerobically, biomethane generation potential is 300 m^3 of biogas per one ton of biodegradable organic waste, according to modelling and simulation. With Short term biodegradable waste tonnage assessment of 13514 MT the electricity generation potential is 338 MWe. Then the recyclable materials of MSW should be recovered, and following the recovery of recyclable materials, non-recoverable materials in terms of residue derived fuel (RDF) could be prepared. However, according to the scientific experimental investigations conducted locally, anaerobic digestion mixing different types of organic wastes (anaerobic co-digestion) is the best strategy for mixed wastes available in the country.

In order to realize the benefits from AD technology, high-rate AD systems should be deployed. Sri Lanka has utilized low-rate AD systems, which has unfortunately failed, and resulted in a negative perception over the whole technology. Further, large-scale AD plants are yet to be established, and the current focus is to do it through the local community and institutions with small and medium scale bioreactors.

1.3.1.2 Non-electricity Applications of Biofuels

- **Biomass utilization**

Biomass, i.e., fuel wood and agricultural residues are used as the primary energy source for cooking and also to meet the thermal energy requirements in industries. Steam generation is accomplished by local industries using wood pellets, barks, or residues as feed stocks.

- **Biogas as a domestic cooking fuel**

Biogas technology has been well established in Sri Lanka. However, its usage as a viable cooking fuel to replace imported LPG has not been possible, primarily due to inadequate gas generation in using only the domestic kitchen wastes, and also attributed to the need for further improvements of biogas generators to be more user-friendly to suit the urban households. Overcoming these problems would promote it to be a viable and acceptable source of cooking energy with the same level of attraction as the expensive imported LPG. In order to consider biogas in equal terms with LPG, biogas may need upgrading and containerization so as to offer similar convenience to LPG.

- **Biomethane as transport fuel**

Scandinavian and European countries by and large harness energy and fertilizer from varieties of feed stocks using advanced technologies. They generate biomethane in three different forms, i.e., Biomethane (BM), Compressed Biomethane (CBM) and Liquefied biomethane (LBM). These biofuels are utilized in light-duty and heavy-duty vehicles. For Sri Lanka, the potential for biomethane as a transport fuel has been revalidated at a local university. Purification and upgrading are a must before compression /liquefication at sub ambient temperatures.

- **Bioethanol and biodiesel**

Currently, Sri Lanka cannot meet its sugar demands from the local supply, and it depends on imports. Thus, the generation of bioethanol using sugar cane feed stocks is not economically viable. An alternative option is to generate bioethanol from lignocellulosic substrates, which is called the second-generation biofuels. Biodiesel had been generated using plant oils (i.e., Jatropha, rubber seeds, etc.), and these offer opportunities at certain locations and/ or with limited scale. Jatropha is a potential energy crop.

1.3.1.3 Recommendations for enhancing the usage of Biofuels

1. Generate resource maps to identify the recovery potential of all waste types in Sri Lanka. SLSEA has only completed agro-residues and grown biomass only.
2. Facilitate the expansion of short rotation coppicing renewable energy species as mixed crops with multiple benefits for agriculture and rural economies at farmer level and establish dedicated energy plantations where possible, with the added benefits of the large volume of leaves as a source of fodder and fertilizer.
3. Promote fuel switching to biomass in industries by promoting the supply chain activities for biomass supplies.
4. Promote urgent research to elevate the domestic level biogas generators to the level of the main source of cooking fuel including in urban households.
5. Promote biogas energy systems as a rural energy system.

6. Promote anaerobic digestion technology to local communities in small and medium scales. However, recovery potential is less, and to receive a national level gain, economy of scale is very important.
7. Carry out bio process resource recovery, instead of burning high moisture content (60%) organic material which is not efficient.
8. Evaluate the whole spectrum of available bio energy resources under large-scale projects, without confining to biomass, i.e., wood derived resources.
9. Adopt purification, upgrading, and compression technologies, in order to introduce bio methane as a transport fuel. By learning from developed nations, some of these technologies can be developed locally (equipment can be fabricated locally at low cost).
10. Facilitate the private sector partners to establish waste management technologies under favourable financing policies, government approval processes, and electricity pricing.
11. Develop medium-term and long-term action plans to promote large-scale anaerobic digester developments.
12. Adopt practically viable targets for biomass electricity, recognizing the firm nature and ease of integration to the grid, and the overall potential predicted by the ADB and the SLSEA resource development reports.
13. Develop policies and strategies with the petroleum authorities for rapid fuel switching to bio renewable energies.
14. Identify Bamboo, Ipil Ipil as 4^{th} and 5^{th} Plantation crops of Sri Lanka. Remove the outdated misclassification of bamboo as a tree which places several limitations in use.

1.3.2 Hydro Power

1.3.2.1 Large Scale, Mini, Micro and Pico Hydro power

Hydropower is the most important renewable energy source in Sri Lanka, accounting for approximately 30% ~ 40% of the country's total electricity generation. Today it is among the most cost-effective means of generating electricity and is often the preferred method when and where available. There are over 1,400 MWe of large hydropower projects implemented in Sri Lanka. Except for Kukule Ganga and Upper Kotmale projects, all other hydropower schemes are associated with a reservoir. Even though Sri Lanka's hydropower potential is estimated at approximately 2,500 MWe, the reservoir-based hydropower projects are no longer considered environmentally viable due to the multi-faceted impacts they have on the ecosystems. On the other hand, small hydropower projects are almost always run-of-river (RoR) type where the impact on the waterway is minimum. Therefore, they are considered as environmentally friendly projects. Moreover, economically viable large-scale hydropower projects are no longer available in Sri Lanka. With the introduction of the Standard Power Purchase Agreement (SPPA) for project capacities up to 10 MWe in 1996, the first technology to take off was small hydropower. There are about 1000 MWe of small hydropower projects that have been identified as commercially viable.

1.3.2.2 Recommendations for enhancing the usage of hydropower

1. Diversify hydropower sources by identifying and developing new hydropower projects in other regions of the country to reduce the country's reliance on a single river/several selected rivers for hydropower generation.
2. Commission the 2nd 200 MWe generation option at Victoria after necessary feasibility studies.
3. Upgrade the existing hydropower plants to increase efficiency and reliability of existing hydropower plants, by the installation of new turbines, generators, and control systems, as well as repair and maintenance of existing infrastructure. The modernization of existing hydropower plants can increase their capacity and reduce their downtime, leading to an increase in hydropower generation.
4. Encourage private sector investment in small-scale hydropower and provide support for the development of these projects.
5. Exploit the available pico-hydro potential from irrigation water channels.
6. Enhance the tree cover in the catchment areas of hydro power plants using local species as new tree plantations as well as replacing the existing exogeneous species-based plantations.

1.3.3 Solar Energy

The annual average solar radiation in Sri Lanka ranges from 4.2 to 6.2 kWh/m2/day, depending on the area. This translates to a significant potential for solar energy generation, especially in the Northern, Eastern, and North Central regions of the country, where solar radiation levels are highest and plenty of scrub lands for solar power plants are available. The electricity generation capacity from solar energy at present is around 700 MWe, which is less than 12% of the total installed capacity. The majority of this capacity comes from small-scale rooftop solar installations, while utility-scale solar projects are limited; no large-scale (more than 25 MWe) solar power plants are in operation in Sri Lanka yet.

1.3.3.1 Recommendations for enhancing the usage of solar energy

1. Incentivize the rooftop solar PV projects by offering subsidies, tax credits, or other financial incentives, and promote solar power in government buildings, especially universities, schools, and offices, which operate in daytime.
2. Promote behind the meter storage and suitable feed-in-tariff systems.
3. Promote the development of floating solar projects by providing access to water masses under the control of the government, initially as demonstration projects.
4. Promote agro-voltaics in collaboration with relevant state agencies such as Department of Agriculture, on completion of adequate research on the subject.
5. Facilitate research & development and innovation in the efficiency improvement of solar panels, promoting local manufacturing of inverters, battery management systems & chargers, etc., creating job opportunities and boosting economic growth, and reducing reliance on imported solar products.
6. With high quality Quartz available in the country implement a solar cell production facility.
7. Encourage commercializing the ongoing research on thin-film solar-cell development.

1.3.4 Wind Power

Based on the geographical position of Sri Lanka facing a vast oceanic belt, it has an excellent potential for wind energy resources. With the possibility of acquiring the two monsoons of

South-west and North-east, wind power plants can go for plant factors above 40%, which is a welcoming range for wind power generation. Therein, the effect of the South-west monsoon is more significant, and the Northern and North-western belts are the areas mainly identified so far for wind power development. The Mannar 100 MWe wind power plant operated by the CEB runs with a 44% plant factor, which is testimony to the high plant factor in the particular region. Through the records, it is also proven that wind power projects have excellent economic viability, which needs to essentially be used for the economic boost of the country.

Wind energy costs have been declining rapidly in recent years and are becoming increasingly competitive. In the present experience in Sri Lanka, the levelized cost of onshore wind energy is around USD 0.04-0.06 per kWh. According to the World Bank report, the proposed site in the North-east of the Gulf of Mannar, the levelized cost of offshore wind energy is around USD 0.07-0.08 per kWh. However, the cost of wind energy can vary widely depending on the local conditions and policy frameworks.

1.3.4.1 Recommendations for enhancing the usage of wind power

1. Direct and facilitate SLSEA to carry out a wind measuring campaign at appropriate heights considering the latest context, and to carry out drone surveys, which will subsequently support the environmental impact assessment process.
2. Include the necessary technical requirements to make stringent the Grid code for promoting developers to go for wind turbines with latest technologies in the process of updating the Grid code being carried out by the CEB.
3. Direct and facilitate SLSEA and CEB to implement positive possibilities arising out of current studies on off-shore wind power development.
4. Explore the potential of micro-wind conversion devices (eg Vertical Axis wind turbines)

1.3.5 Geothermal Energy

A sufficient amount of information collected through geophysical, geochemical, remote sensing, and geological investigations is available. They provide a positive outlook for power generation using a number of geothermal resources. Drilling and direct measurements are necessary to confirm the parameters essential in power generation. Necessary equipment to drill the test holes to collect vital parameters such as geothermal gradient, flow rates, fracture patterns, etc. are available. Most of the human resources essential for evaluating the geothermal power generation potential are also available. Binary cycle plant is the appropriate technology, which can lead to a high energy yield with a capacity factor expected to 90%-95%, which can be considered excellent compared to other renewable energy power plants and have minimum environmental impact. High quality equipment and components will assure uninterrupted energy generation, and it can be added to the grid as a base load plant.

1.3.5.1 Recommendations for initiating the usage of geothermal energy

1. Direct and facilitate SLSEA to evaluate the geothermal potential in collaboration with research institutes such as NIFS and GSMB.
2. Provide funds to the active researchers to drill the test drill holes or grant necessary permission and offer a purchase agreement with attractive tariff for private investors to conduct tests and to commission the power plants.
3. Include geothermal energy in the CEB Long Term Power Generation Plan
4. To start with a 2 MWe pilot binary cycle geothermal power plant, going up to 10 MWe or more at the first site, depending on the energy potential at each site. It is estimated that at least 6 sites may have 20-100 MWe power generation potential in a commercially viable manner.

1.3.6 Marine energy

1.3.6.1 Wave Energy

Using data from over 18 years, a comprehensive wave energy resource mapping is available as a geo-referenced digital database for Sri Lanka. The maximum annual significant wave heights of 1.5-2.0 m prevail from the south coast, followed by southeast and southwest regions. The average significant wave height ranges from 1.0-1.5 m for the west and east coasts, and the lowest values under 1 m are present in the northern region. Significant wave height values develop up to 2.5 m in the southern region during the southwest monsoon period. The mean annual omnidirectional wave power of the south coast has the highest range of 12-16 kW/m while the lowest range of 1-5 kW/m can be found in the north, northwest and east regions. The west coast has a 5-6 kW/m wave power range. The monthly variation of omnidirectional wave power shows that the maximum range of 20-25 kW/m can be obtained on the south coast during the southwest monsoon period. The estimated plant factor of 50% for the southern region is impressive as an intermittent renewable energy source.

1.3.6.2 Ocean Thermal Energy Conversion (OTEC)

Ocean thermal energy got attention first in 1979 by the "OTEC Thermal Energy Report for Sri Lanka, by the US Department of Energy" and, accordingly, off the coast of Trincomalee has substantial temperature differences at feasible depth year around to develop OTEC plant. A conceptual design for 100 MWe class OTEC plant in 1998 for Trincomalee is available.

1.3.6.3 Recommendations for initiating the usage of Marine Energy

1. Promote Ocean Thermal Energy Conversion (OTEC).
2. Further refine the wave energy resource assessment & characterization that has been carried out by SLSEA.
3. Establish an Ocean Energy Test Centre (OETC).
4. Establish a marine renewable energy research fund and a dedicated research institution.
5. Investigate ocean currents, salinity gradient and marine bio energies.

1.4 Research Directions for Renewable Energies

1.4.1 Proposal for Research and Development Related to Solar Energy

Research findings have revealed new and innovative ways to increase the efficiency of solar energy generation. The use of perovskite solar cells have the potential to significantly increase the efficiency of solar panels. Perovskite solar cells are a new type of solar cell that uses a hybrid organic-inorganic lead or tin halide-based material as the light-harvesting layer. These solar cells have the potential to achieve efficiencies over 30%. Another development is the adoption of bifacial solar panels for ground-mounted solar plants. Studies have shown that bifacial solar panels can generate up to 30% more energy compared to traditional solar panels, especially in environments with high reflectivity, such as sandy areas.

The integration of artificial intelligence (AI) algorithms in the field of solar energy generation is growing rapidly. Researchers have found that AI algorithms can be used to predict solar energy generation based on various factors such as weather patterns, location, and solar panel efficiency. This can help optimize solar energy production in Sri Lanka by enhancing dispatch ability, reducing energy waste, and maximizing energy output. For example, a study conducted by researchers at the University of California, Berkeley, found that AI algorithms could increase energy output by up to 10% in a solar plant in California.

The use of solar energy in combination with other renewable energy sources such as wind energy and hydropower are always possibilities. The concept of agro-voltaic where agricultural crops are planted below the solar panels may find attraction in Sri Lanka and would to some extent reduce the issue of land availability.

1.4.2 Proposal for an Ocean Energy Test Centre (OETC)

An Ocean Energy Test Centre (OETC) primarily tests ocean energy prototypes. A simple kind of OECT only provides a location for developers to test under controlled conditions. Such a facility could be initiated with minimum investment by only providing a location and grid access (energy evacuation system) at a cost. The test centre can be expanded to include a range of testing facilities, such as wave tanks and laboratory facilities, considering the success of such a facility.

1.4.3 Proposal for a Marine Renewable Energy Research Fund and a Dedicated Research Institution

Many developed countries continue to fund universities and other research institutions or SMEs to develop new marine renewable energy systems to solve future energy crises, competing technologies with conventional renewable energy sources such as solar and wind. Such initiatives lead to the development of intellectual property and also develop the human and other capacities of such nations to become leaders in next-generation marine renewable energy exploitation.

1.5 Grid Integration Aspects Related to Renewable Energy Development of Renewable Energy Sources

Electricity is a secondary source of energy, which can be made green with renewable energy resources. Also, to achieve higher energy security in electricity generation, diversification is needed giving less dependence on imported energy resources. The government of Sri Lanka has set an ambitious target of achieving a 70% share of renewable energy in the national grid by 2030. Grid stability, system reliability, and enhanced renewable energy integration is a much-discussed subject and the following addresses this specific area with recommendations.

Table 1: Challenges and solutions for integration of renewable energy resources into the grid

Challenges	Solutions
1. The current infrastructure and resources face multiple challenges in effectively managing the following:	
a) Wheeling renewable energy generated from widely dispersed sources to locations with high demand.	• Development of a comprehensive system integration plan can help to identify the technological solutions required to integrate renewable energy sources into the grid. This plan can include advanced grid technologies, such as energy storage, microgrids and smart grid systems, as well as the development of new grid infrastructure. • Upgrading the grid infrastructure, including transmission and distribution lines, transformers, and substations, can improve the capacity and stability of the grid. • Implement advanced technologies such as grid-connected battery storage and dynamic demand response systems that can help to optimize the existing grid capacity. • Microgrids and distributed generation systems can also help to relieve congestion and improve the resilience of the grid by allowing for localized energy production and consumption.

b) Coping with the irregular and uncertain output of renewable energy sources while meeting a consistent level of demand.	• The integration of energy storage systems, such as batteries can help to smooth out the intermittency of renewable energy sources. • Energy storage systems both the batteries and pump storage systems (dedicated reservoirs or modified existing reservoir systems) can store excess electricity generated during periods of high production and release it during periods of low production. • Cross-border electricity network interconnection, either HVDC or HVAC would allow energy management with variability in renewable energy generation and system demand. • Development of new energy management systems using optimal economic dispatch with renewable energy sources and use of advanced forecasting techniques can be used to manage the supply and demand of electricity. • The use of real-time monitoring and control systems can help to maintain grid stability by providing real-time data on the status of the grid. • Electric vehicles can effectively be used as battery energy storage for peak shifting purpose (charge during low-demand periods and discharge during peak-demand period)
c) Ensuring the overall stability and reliability of the entire system.	• Advanced technologies such as micro grids, and demand response systems can be used to improve the stability and reliability of the grid. • The system inertia can be effectively be supported, thus the system stability will be improved if cross-border HVAC interconnections are used. • Battery energy storage system controls can be designed to provide virtual inertia to the system. • Adaptive load-shedding scheme can be introduced with real-time monitoring to maintain system stability during contingencies. • The deployment of smart grid technologies can help to manage active and reactive power by providing real-time data

	on the status of the grid. Advanced monitoring and control systems can help to optimize the consumption of active and reactive power and maintain stable frequency and voltage levels in the grid. • Reactive power compensation devices, such as static VAR compensators (SVCs), can be used to regulate voltage levels in the grid. These devices can absorb and release reactive power to maintain stable voltage levels, and can be deployed at key locations in the grid to manage reactive power.
d) Ensuring the economic viability of the various components of the existing system	• The implementation of appropriate policy and regulatory frameworks, such as feed-in tariffs, tax incentives, and public-private partnerships, can help to reduce the cost of renewable energy technologies and encourage investment in the sector. • The use of innovative financing mechanisms, such as green bonds can provide alternative funding sources for renewable energy projects. • Streamlining the land acquisition and permitting processes for renewable energy projects can reduce delays and improve investor confidence. This can be achieved through the establishment of clear guidelines and streamlined procedures for land acquisition and permitting. • Private investment can also be encouraged by offering favourable tax policies and other incentives to renewable energy companies. • Simplifying the grid connection process and establishing clear interconnection standards can streamline the process and reduce delays. • Implementation of a centralized platform for grid connection applications can help to improve transparency and accountability. • Introduce tariff schemes for micro grid interconnection to the system.

	• Introduction of demand side management through time-of-use tariff to effectively shift the peak would allow a reduction of required energy storage capacity. • Reduction of energy consumption by encouraging energy-efficient equipment (energy-efficient lighting, air conditioning, refrigeration, etc.) usage. This would effectively reduce the required capacities of renewable energy sources and energy storage.
e) An anticipated highly complex environment that requires a non-traditional set of skills to operate within.	• Developing and implementing clear and consistent policies and regulations for renewable energy, including feed-in tariffs, net metering, etc. can provide a stable and predictable environment for renewable energy investment. • Developing regulations and standards for renewable energy integration, and ensuring compliance with international standards must be mandatory. • Establishing an independent regulatory body can help to ensure the effective implementation and enforcement of regulations. • Building institutional capacity is essential to manage the integration of renewable energy sources into the power grid. This includes training and capacity building for grid operators and regulatory bodies to manage the variability and uncertainty of renewable energy sources. • Development of training programs, workshops, and seminars for grid operators and regulatory bodies to enhance their skills and knowledge in managing renewable energy sources is needed.
2. The adequacy of the current vertically integrated corporate structure or the proposed deregulated structure and regulatory framework to facilitate the integration of a renewable energy grid.	
	• Encouraging market and technological competition.

	• Providing a well-balanced system that empowers both consumers and producers to benefit from the new energy paradigm.

1.5.1 Recommendations for increased integration of renewable energy to the grid

1. Invest in upgrading the electricity grid to handle larger amounts of intermittent renewable energy.
2. Deploy grid integration technologies, such as micro grids, and smart grids with advanced systems like demand-side management technologies, and reactive power management technologies, to help maintain the stability and reliability of the grid while integrating large amounts of renewable energy, through comprehensive grid studies.
3. Encourage energy storage solutions, such as batteries and pump hydro and hydrogen energy storage, to help stabilize the electricity grid and increase the renewable energy absorption.
4. Establish partnerships with neighbouring countries to allow for grid interconnection and the exchange of power between grids.

Carry out institutional capacity building and conduct joint research and development on grid integration, with the universities.

Section 02

Energy Storage

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2.1 Rationale

Sri Lanka aims to raise its renewable energy share to 70% by 2030, necessitating Energy Storage Systems (ESS) for effective grid integration and balancing of diverse renewable sources and maintaining stability in the electric power grid. ESS implementation is crucial for addressing the intermittent nature of renewables like solar and wind, enhancing overall flexibility, power quality, and reducing peak demand while optimizing green energy utilization. Despite achieving key milestones of 100% electrification in 2016, reduction in network losses to less than 9% in 2018 and 50% of grid energy from renewable sources in 2021, Sri Lanka has not been able to meet the capacity adequacy and economic efficiency in electricity generation. Table 1 shows the indicative generating capacity of 2022-2023, which clearly shows a gap of 200 MWe during January –April in the night time. These gaps are usually filled by emergency power purchasing at much higher rates obtained by burning fossil fuels, further depleting the foreign currency as well as harming the environment by emitting greenhouse gases.

2.2 Objectives

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

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. **Electric Double Layer Capacitors (EDLCs)**: Fast-charging and high-power devices that can support grid stability and power quality.

The functions of selected storage systems include grid stability, peak power plant phasing out, micro-grid services, integration with intermittent renewables, and seasonal storage. The proposed ESS solutions offer both short-term and long-term benefits for Sri Lanka's energy needs. The time period for this proposal is over 10 years.

The methodology that led to the recommendations are summarized below;

Table 2: Recommendations for proposed energy storage solutions

Pumped Hydro Storage	**Battery Technologies**	**EDLCs**	**Hydrogen**
• Identification of suitable locations for the implementation of the above hybrid systems based on the availability of hydro power plants, solar irradiance, and wind potential. • Development of an Artificial Intelligence (AI) based techno-economic model to analyze performance of the proposed systems, considering factors such as power generation, storage capacity, grid stability, and system costs. • Examination of regulatory and policy frameworks	• Assessment of the potential for BESS integration at the generation and distribution levels of the grid, by analyzing the existing energy infrastructure and future energy demands. • Identification of opportunities for BESS applications in specific areas such as rooftop solar PV systems, grid-scale solar power plants, electric vehicles, and microgrids. • Techno-economic Evaluation of BESS integration in the identified areas, considering factors such as	• 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. • 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.	• Identify suitable applications and locations for hydrogen 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. • Develop a model to analyze the technical, economic, and environmental performance of integrating

to identify potential barriers and opportunities for the implementation of such hybrid systems in Sri Lanka.	capital costs, operational costs, and potential benefits.	• 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.	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.

Table 3: Issues with energy storage

01	**Issue**	Need of short-term energy storage solution
	Recommendation	Focus on establishing pump hydro-wind-solar PV hybrid systems as a reliable, low-cost short-term solution for energy storage.
	Rationale	Pump hydro can provide immediate benefits to the energy sector by utilizing existing infrastructure, offering cost-effective energy storage, and supporting grid reliability in the short term by enhancing grid stability and balancing energy supply and demand.
02	**Issue**	Need of medium-term energy storage solution utilizing local resources
	Recommendation	Develop and integrate lithium-ion batteries, flow batteries and EDLCS using locally available minerals such as vein graphite, vein quartz, apatite, iron ores, and mineral sands that hold potential for use in battery and EDLCS production. This includes grid integration and load balancing to enhance the overall efficiency and reliability of the energy system.

	Rationale	Utilizing local resources for energy storage can reduce dependency on imported materials, create employment opportunities, and contribute to a more sustainable and self-reliant energy future. Furthermore, batteries and EDLCS can provide medium-term energy storage solutions while supporting load balancing while promoting self-sufficient energy generation which lower the electricity bills and create a more resilient and sustainable energy infrastructure.
03	**Issue**	Need of a long-term sustainable energy storage solution
	Recommendation	Invest in hydrogen storage technologies as a green, long-term solution for energy storage, and develop a roadmap for their widespread adoption in conjunction with renewable energy systems.
	Rationale	Hydrogen storage offers a sustainable, long-term solution for energy storage with a high energy density, supporting the transition to a low-carbon economy and aligning with global sustainability goals.
04	**Issue**	Overcoming policy barriers and addressing environmental concerns
	Recommendation	Review and revise existing policies and regulations to remove barriers to the development and implementation of energy storage technologies. Address environmental concerns by establishing guidelines for waste management, safety regulations, and promoting the sustainable use of natural resources.
	Rationale	Removing policy barriers can create a conducive environment for the growth of energy storage technologies, while addressing environmental concerns can ensure the responsible and sustainable development of the energy sector. This integrated approach can support the Sri Lanka's transition to a secure, sustainable, and resilient energy system.

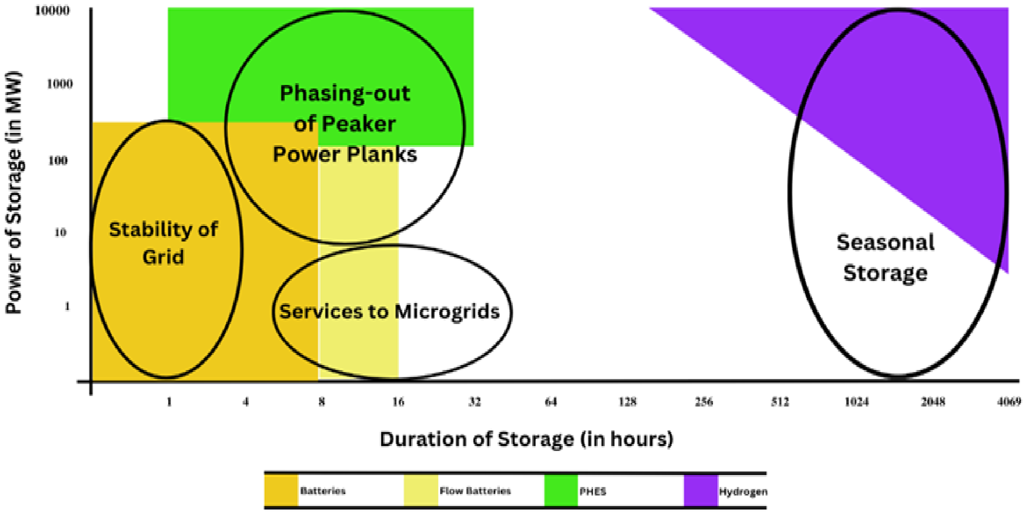

Figure 1: Chart of energy storage systems according to function, technology, power and duration

2.3 Recommendations

1. Converting existing hydro power plants into pumped hydro 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 using the PV system can be utilized to operate the pumped hydro system. Wind power also can be used in the same way.

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 micro grids as Vehicle to Grid (V2G) and Grid to Vehicle (G2V) systems.
3. Sri Lanka has a variety of mineral resources, including vein graphite, vein quartz, apatite, iron ores, and mineral sands, activated carbon (AC) and hard carbon (HC) which can potentially be utilized for battery/EDLCs production. Vein graphite, a rare and valuable form of graphite, has already shown promising results as an anode material for lithium-ion batteries. In Addition, 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. Locally produced high quality ACs and HCs can also be used to develop EDLCs and Lithium-Ion Capacitors.

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 and wind. 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 micro grids, 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.

Section 03

Green Hydrogen

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3.1 Rationale

Green Hydrogen is a net-zero alternative that can meet the energy needs of the modern world while helping to meet climate action goals. Green hydrogen has multiple applications, including serving as an energy storage solution for modern grids and connecting hard-to-decarbonize sectors such as steel, chemicals, long-haul transport, shipping, and aviation with renewable energy. Its untapped potential makes it an exceptional concept and the basis for the Hydrogen Economy. Although the potential is promising; there are some key challenges Sri Lanka in the direction of Green Hydrogen. Economic feasibility, lack of knowledge transfer potential and safety issues demand proper recommendations from scientific and engineering community in Sri Lanka.

3.2 Applications

3.2.1 Include Green Hydrogen to the National Energy Plan

The review of the Green Hydrogen potential suggests the introduction to Green Hydrogen to start from renewable energy sources that could be scaled to produce more than the conventional demand which effectively means harnessing the resources to the full.

While enriching the national power sector with higher capacities of renewable energy sources even beyond the saturation limits, the intermittencies, and extra capacities of these sources such as solar and wind energy will provide opportunities to generate energy vectors while stabilizing the grid such as hydrogen or more specifically *Green Hydrogen*. Grid scale battery systems also will support the power grid in the same manner but the high infrastructure cost, high lifecycle cost of such systems and limitations of battery systems to power sector, the relative benefits of green Hydrogen gain a high score in comparative evaluations. ***Therefore, the combination of renewables and green Hydrogen will offer a high potential in uplifting the national economy through a sustainable path.*** This situation is developing in the Northern Province.

Additionally, Green Hydrogen contributes to connecting sectors that are difficult to connect with renewable energy, such as steel, chemicals, long-haul transport, shipping, and aviation. Grid connected green hydrogen generation will provide a grid stabilization option while generating hydrogen (as green hydrogen) will provide multiple opportunities to utilize the generated hydrogen in modes such as;

- ❖ Reconverting to power through gas turbine systems or fuel cell systems and feeding to the grid in power deficiencies,
- ❖ Use green hydrogen as a transport fuel (either through IC engine applications or Fuel cell technology based electric vehicle systems,
- ❖ Use of hydrogen to enhance the thermal capacity of Biogas or natural gas applications,
- ❖ Manufacturing green ammonia and use of liquefied green ammonia as a fuel in marine vessels,
- ❖ Manufacturing green fertilizer (green ammonia and urea etc.),

- ❖ Green methanol production,
- ❖ Use as a carbon capturing agent to produce methane.

3.2.2 Green Hydrogen in Manufacturing in captive form as the first venture

Green energy produced using solar PV, wind or biomass in the industry premises shall be converted into green hydrogen by using an electrolyser and feed the green hydrogen straight to either boiler furnace or kiln where there shall not be complex energy storage infrastructure such as battery storage or hydrogen storage. Economical use of green hydrogen in the industry as a source of energy would depend on the cost to produce a kilocalorie of energy from green hydrogen. The current international price indication of green hydrogen is US$ 6.0 per kg (generation cost). The current gray hydrogen price is approximately 2.0 dollars per kg. It is expected that green hydrogen price will come down to 2 dollars per kg by around 2030 or early 2030s. By the time green hydrogen price reaches this value of 2 dollars per kg, green hydrogen would be able to economically use in industrial applications such as boilers, furnaces, kilns etc.

3.2.3 Green Hydrogen in Transport – Mass Transport first

The public transportation share is highly affected by private vehicle ownership that contributes to high economic impacts with other externalities such as traffic congestions, accidents, and higher emissions by inefficient use of fuel consumption that has increase the imports of petroleum products which is nearly 20% of the total imports of Sri Lanka at stable economic conditions. Therefore, it is mandatory to review the present inefficiencies and the required future planning for an efficient transportation supply setup for Sri Lanka to reduce the energy cost and to contribute for direct economic benefits to SL economy.

At present green hydrogen is most suitable for mass transportation than the individual transportation modes. Hence, the available public transportation and the future potential shall be to encourage for Railways and Bus Transportation to use the green hydrogen as the alternative fuelling source even though they consume only 18% of the total petroleum fuel as of now.

3.2.4 Upgrade Safety and Health and Industrial Standards to accommodate Green Hydrogen

Sri Lanka uses Hydrogen today in industry in a limited manner but there is no specific industry standards existing to support an economic changeover. The management of Hydrogen as a Hazardous Material should be supported by the legal system of Sri Lanka. It is emphasized that appropriate regulations are established to manage licensing, permitting and monitoring of the safe use of Green Hydrogen in Sri Lanka. Sri Lanka can form alliances or partnerships with International Parties and Research Organizations with the required competence and experience in managing the Safety aspects of Hydrogen (e.g.HySafe).

3.3 Recommendations for the Green Hydrogen Generation

Two options are offered for green hydrogen generation process;

1. Dedicated self-utilized green hydrogen generation systems
2. Dedicated bulk green hydrogen generation systems

3.3.1 Dedicated self-utilized green hydrogen generation systems

These are mainly designed to generate hydrogen at their own sites and for captive use of the gas for their own operational requirements such as powering furnaces, kilns, boilers, district heating / cooling systems etc. However, in these systems flexibility required to be maintained subjected to the economic feasibility of the use of renewable power source directly to fulfil the thermal energy requirement (using directly either resistance or induction heating technologies). Selection of mode of operation will be a flexible SMART technology based rather than a fixed. Heating operations are required to dual fuel (direct electrical or hydrogen combustion) which will required to designed according to process requirement and stability of the thermal energy need which will be highly process specific. If required these systems will be connected with national grid for the mutual benefits preferably with the focus on organizations thermal energy requirement.

3.3.2 Dedicated bulk Green Hydrogen generation systems

Dedicated green hydrogen generation systems will be totally grid independent and large-scale renewable facilities such as dedicated solar PV systems (ground mounted or floating systems etc.) or Wind farms (both onshore and off-shore) will be adapted to this option. Land resource limitation will be one of the major barriers to this option. This source will be one of the major components in the national green Hydrogen supply chain network.

Overall green Hydrogen supply chains and value chains will require very effective regulatory mechanism, proposed to be a main requirement in the country.

3.4 Green Hydrogen Research

While R&D is significant in the international area over Green Hydrogen Sri Lanka too should embark on applied research and development to provide knowledge, skill enhancement as well as resilience to the National Green Hydrogen strategy.

3.4.1 Photo catalytic water splitting

Photo catalytic water splitting is a promising approach to green hydrogen production that uses sunlight to drive the electrolysis reaction. This method involves using a photo catalyst, such as titanium dioxide or tungsten oxide, to absorb sunlight and create electron-hole pairs that can drive the electrolysis of water into hydrogen and oxygen. While still in the early stages of development, photo catalytic water splitting has the potential to provide a low-cost and sustainable method of green hydrogen production.

3.4.2 Bio methane (Biogas) Steam Methane Reforming

Bio methane steam methane reforming is another promising approach to green hydrogen production that involves using methane derived from biomass or bio waste as a feedstock for steam methane reforming. This method produces hydrogen while also reducing greenhouse gas emissions by capturing and utilizing methane that would otherwise be released into the atmosphere. Bio methane steam methane reforming is a promising approach to green hydrogen production that is already being used in several commercial applications.

3.4.3 Sea Water Electrolysis

Sea water electrolysis is a promising approach to green hydrogen production that involves using seawater as a feedstock for electrolysis. This method has the potential to provide a sustainable and cost-effective source of hydrogen in regions where freshwater resources are limited. While still in the early stages of development, sea water electrolysis has the potential to provide a significant source of green hydrogen in coastal regions.

3.4.4 Catalysis and Electrodes using indigenous sources

Graphene-based catalysts and electrodes are also being studied as a potential way to improve the efficiency and cost-effectiveness of green hydrogen production. Graphene is a two-dimensional material that has unique electrical and mechanical properties that make it an attractive material for use in catalysts and electrodes. Researchers are exploring the use of graphene-based catalysts and electrodes to improve the efficiency and stability of electrolysis and other green hydrogen production methods.

3.4.5 Microbial hydrogen research

This area of study is more research based but has the potential to succeed with biowaste and AD research. Methane from AD processes offers a route to Hydrogen.

3.5 Hydrogen Energy Research Centre

In the future, it is likely that research in green hydrogen production will continue to focus on improving the efficiency and cost-effectiveness of existing methods, as well as exploring new and innovative approaches to green hydrogen production. A central facility which is connected to all other state-of-the-art research facilities in Sri Lanka with workgroups consist of members from diversified background will certainly catalyse the journey towards successful implementation of this technology in Sri Lanka.

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