RENEWABLE ENERGY

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1. Introduction

Modern Energy has become an essential component of the day-to-day lives of all the people and the economies of the entire world. It is recognized as the SDG No 7: Access to affordable and clean energy. As such, it has taken a broader perspective than the mere sources and processes of supply of such energies but requires the consideration of such other aspects as energy security impinging on national security, environment, global warming, economy & balance of payments, social equity and the potential of entire spectrum of energy from development of resources to ultimate usage to be a contributor to the national development goals.

In Sri Lanka's context, it is now recognized that indigenous sources of energy, which are fortunately all renewable, could fulfil all these criteria. Therefore, it is important to evaluate the different renewable energy sources and formulate policies, strategies, and action plans on the development of these resources.

In the present context of the depressed economy as well as the international commitments made by Sri Lanka, the policies, goals, and prevailing status need to be viewed in the development of policies and strategies to be congruent with the above criteria, which are essential from a national point of view, and recommendation be made to accept or amend the existing policies, or propose new policies, as well as the strategies need to be identified to implement such updated policies.

In terms of renewable energy resource availability, the country has adequate renewable energy resources; solar, wind, and biomass being the most promising sources. Nevertheless, it is required to address the various constraints associated with different renewable energy sources in order to facilitate their harnessing in meeting 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.

2. Objective

The main objective of this report is to conduct a critical review of different renewable energy resources available in the country and providing recommendations on addressing the constraints of each renewable energy source, in consideration of harnessing them through optimal techno-economic approaches for future applications – primarily electricity in meeting the renewable energy development targets, and in fulfilling the overall energy needs of Sri Lanka.

3. Status of Renewable Energy Resources in Sri Lanka

The current programmers on renewable energy are being carried out with a target of realizing the policy directives of the government, and the major renewable energy sources used are hydro, biomass, solar and wind, which are the proven renewable energy sources available in the country. In addition to that, there are emerging renewable energy sources – ocean energy and geothermal energy. An overview of the use of different energy sources and the possibilities for future development are presented below.

3.1 Bio Renewable Energy (Bio Fuel)

Biofuels are derived from biomass, which is broadly defined as plants, animals and microorganism derived materials. Biomass resources available on renewable basis can be identified as dedicated energy crops and trees, agricultural residues (field residues), wood wastes & process residues, organic fraction of MSW, industrial wastes, livestock waste (pig, cattle, poultry manure), aquatic plants (water hyacinth, Salvinia), primary sludge from sewage treatment, etc. When biomass is transformed by using thermochemical and biochemical processes into intermediate products in solid, liquid and gaseous states, they are called "Biofuels." Wood and residues in its raw form can be used as biofuel. Bioethanol, biodiesel, biogas, producer gas, biohydrogen, charcoal are some examples for biofuels.

3.1.1 Bioenergy Resource Availability and Generation Potential

According to the National Energy Policy & Strategies of Sri Lanka 2019 [1], renewable energy sources introduced must be sustainable and reliable. Different resources available in the country are given below.

- **Dedicated energy plantations**

Sri Lanka Sustainable Energy Authority (SLSEA) has already identified 92,606 ha of land availability for energy plantations, and the estimated power generation potential is 763 MW [2]. Studies by ADB and JICA have indicated a potential of 2,400 MW.

- **Agricultural residues**

Broadly classified as field residues and process-based residues, and by considering energy use factor, surplus availability factor and collection factor, the predicted amount of total biodegradable residue generation in 2021 is 12 million tons/yr.

- **Livestock wastes**

Poultry waste makes the highest contribution, and the total estimated amount including cattle, buffalo, goats, and pigs is 23 million tons/yr. Poultry farms have been largely established in Puttalam and Kurunagala districts. Power generation potential from both livestock and agricultural residue is 2,300 MW.

3.1.2 Organic Fraction of MSW

Local authorities and urban councils in Sri Lanka collect the MSW generated and the per capita generation varies between 0.4 and 1.0 kg/d. More than 300 open dumping sites are available in the country, and the amount collected varies from 5 tons/d to several hundred tons. Some of the authorities have successfully implemented source separation with the objective of promoting technologies. If these organic fractions are treated anaerobically, according to modeling and simulation, biomethane generation potential is 300 m3 of biogas per one ton of biodegradable organic waste [3].

3.1.3 Rationale for Energy Generation and Utilization

- **Biomass utilization**

Biomass i.e. fuel wood and agricultural residues are used as the primary energy source for cooking and also to meet thermal energy requirements in industries. Steam generation is accomplished by local industries using wood pellets, barks, or residues as feed stocks and the main issue faced by industries when adopting biomass as a thermal energy source is the lack of a reliable supply of biomass and pretreatment requirement.

Gliricidia, Ipil Ipil, Acacia, Bamboo and Eucalyptus have been identified as the dedicated plantation crops for subsequent dendro power generation in the country. Energy content of biomass depends on its characteristics, and a standardization procedure is required to maintain the quality of supply.

The main reason for underutilization of agricultural residues is, not having a proper collection mechanism and very low energy density, and low-grade nature with inconsistent fuel qualities. The contribution of biomass in the electricity mix for the 100% renewable energy target by 2050 has been reported in the current generation plans as 149 MW in 2025 and 394 MW in 2050 with around 100 MW increment per decade. This is far below the potential reported above.

- **Waste management and Bioenergy**

Sri Lanka is blessed with multiple types of waste with ample energy generation potential. Major contributor for wastes is the municipal solid waste, generated in alarming quantities and openly dumped within 320 open dumping sites scattered over the entire country. Following the recovery of recyclable materials, non-recoverable materials, in terms of RDF should be subjected to combustion or incineration. However, organic fraction with high moisture (i.e. more than with 60% moisture), should be subjected to biological processes such as anaerobic digestion.

According to the National Waste Management Policy published in 2020 [4], circular economy principles are promoted and technology development for waste recycling and resource recovery shall be promoted with appropriate partnerships covering the entire life cycle. Current global trend is to apply large-scale anaerobic digestion technology for triple benefits as waste management, energy generation (heat, electricity and transport), and high-quality fertilizer production. According to the scientific experimental investigations conducted locally [5], anaerobic co-digestion is the best strategy applicable for mixed wastes available in the country.

- **Bio Gas as a domestic cooking fuel**

Bio Gas technology has been well established in Sri Lanka. However, its usage as a viable cooking fuel to replace imported LPG has not been possible due to inadequate gas generation using only the domestic wastes from the kitchen and the need for further improvements of the Bio Gas generator 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.

- **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. Potential for biomethane as a transport fuel has been revalidated at local university [6]. Purification and upgrading are a must before liquefication at sub ambient temperatures. 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.

- **Green electricity and thermal energy**

With the principle of combined heat and power, thermal energy as hot water and electricity can be simultaneously generated.

- **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. Alternative option is to generate bioethanol from lignocellulosic substrates, which is called the second-generation biofuels.

3.2 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 MW 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 MW, 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.

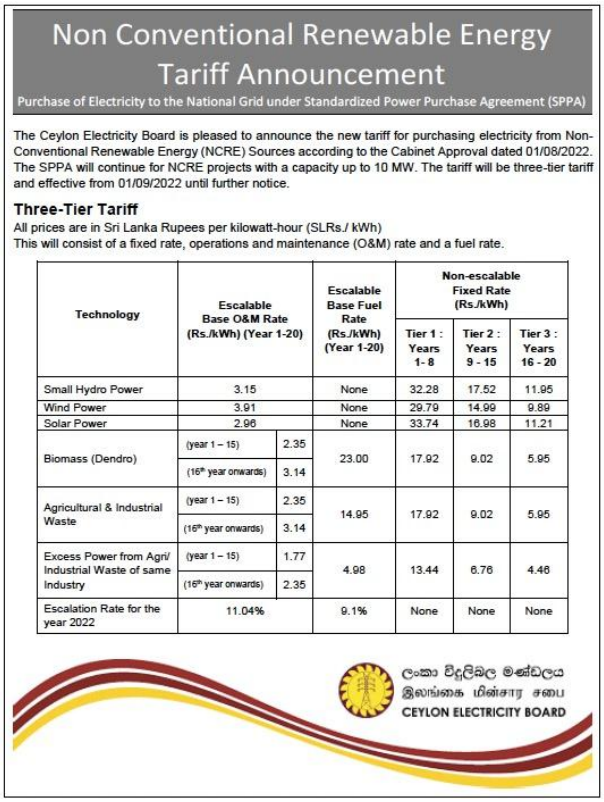
3.2.1 Small Hydropower Development in Sri Lanka

With the introduction of the Standard Power Purchase Agreement (SPPA) for project capacities up to 10 MW in 1996, the first technology to take off was small hydropower. Many projects were developed by private investors, and initially the project allocation was done by the CEB on a first come first served basis. Until 2007, the tariff offered was based on avoided cost basis. This tariff was further improved by offering a higher tariff for the energy supplied during the dry season. Table 1 shows the avoided cost offered up to 2014. This tariff was sufficient to make these projects commercially viable and the Sri Lankan banks gradually started to consider the SPPA as a bankable document and projects got loans up to debt-equity ratios of 80/20%.

Year	Dry Season (Rs,/kWh)	Wet Season (Rs./kWh)
1996	2.90	2.90
1997	3.38	2.89
1998	3.51	3.14
1999	3.22	2.74
2000	3.11	2.76
2001	4.20	4.00
2002	5.13	4.91
2003	6.06	5.85
2004	5.70	4.95
2005	6.05	5.30
2006	6.73	5.82
2007	7.64	6.94
2008	9.65	8.94
2009	11.17	10.59
2010	11.94	11.09
2011	11.19	10.23
2012	10.44	9.49
2013	12.31	11.61
2014	15.90	14.87

Figure 1: Avoided cost offered for hydropower

In 2007, a major tariff revision was introduced to renewable projects by offering cost-based, technology-specific tariffs. This further increased the viability of small hydropower projects. This tariff was initially available as a three-tier or a flat tariff. However, the flat tariff option is not available now. Figure 1 shows the latest tariff announcement for projects under the SPPA.



Non Conventional Renewable Energy Tariff Announcement

Purchase of Electricity to the National Grid under Standardized Power Purchase Agreement (SPPA)

The Ceylon Electricity Board is pleased to announce the new tariff for purchasing electricity from Non-Conventional Renewable Energy (NCRE) Sources according to the Cabinet Approval dated 01/08/2022. The SPPA will continue for NCRE projects with a capacity up to 10 MW. The tariff will be three-tier tariff and effective from 01/09/2022 until further notice.

Three-Tier Tariff

All prices are in Sri Lanka Rupees per kilowatt-hour (SLRs./ kWh)
This will consist of a fixed rate, operations and maintenance (O&M) rate and a fuel rate.

Technology	Escalable Base O&M Rate (Rs./kWh) (Year 1-20)		Escalable Base Fuel Rate (Rs./kWh) (Year 1-20)	Non-escalable Fixed Rate (Rs./kWh)		
				Tier 1 : Years 1-8	Tier 2 : Years 9 - 15	Tier 3 : Years 16 - 20
Small Hydro Power	3.15		None	32.28	17.52	11.95
Wind Power	3.91		None	29.79	14.99	9.89
Solar Power	2.96		None	33.74	16.98	11.21
Biomass (Dendro)	(year 1 – 15)	2.35	23.00	17.92	9.02	5.95
	(16th year onwards)	3.14				
Agricultural & Industrial Waste	(year 1 – 15)	2.35	14.95	17.92	9.02	5.95
	(16th year onwards)	3.14				
Excess Power from Agri/ Industrial Waste of same Industry	(year 1 – 15)	1.77	4.98	13.44	6.76	4.46
	(16th year onwards)	2.35				
Escalation Rate for the year 2022	11.04%		9.1%	None	None	None

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இலங்கை மின்சார சபை
CEYLON ELECTRICITY BOARD

Figure 2: Latest tariff announcement for projects under SPPA

Due to these positive steps, many projects were connected to the national grid and by 21/06/2022, there were 213 projects with a total capacity of 426.4 MW successfully grid-connected and in operation. As can be seen in Figure 2, small-hydro projects dominated over wind, solar and other technologies in total capacity added to the network.

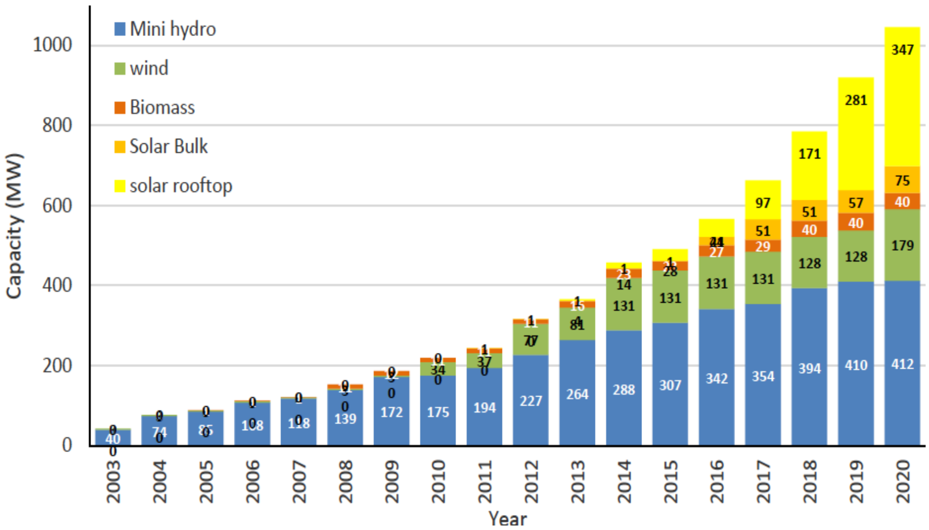

Figure 3: Projects implemented on the SPPA up to 2020

3.2.2 Need for Considering Hydro Power in Future Expansion Plans

As per the CEB's Long Term Generation Expansion Plan 2022-2041, the expected project development under SPPA is shown in Figure 3.

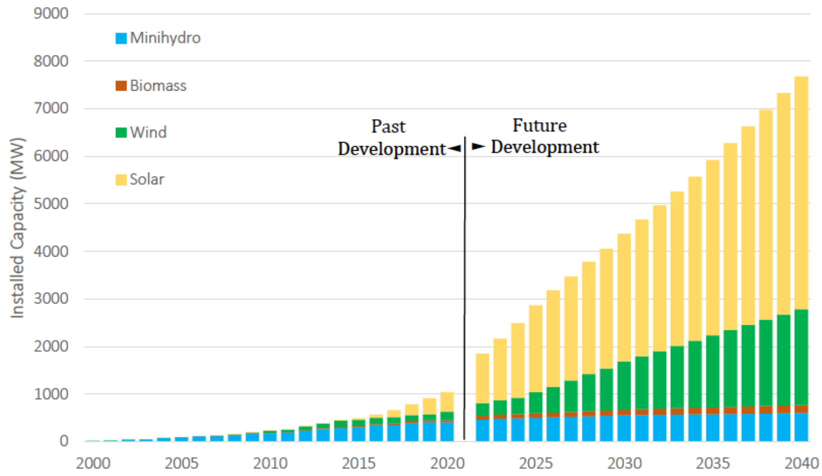

Figure 4: Past and projected development of renewable energy projects in Sri Lanka

As per Figure 3, future renewable energy additions are mainly expected from solar and wind projects. The hydropower sector is being saturated.

Large as well as small hydro opportunities are being dwindled in Sri Lanka. However, there are about 200 MW of small hydropower projects that have been identified (this number will further increase) as commercially viable. For the following reasons, these projects have not been developed or stopped after the initial project development work.

- Limitations in grid connection capacities
- Difficulties in acquiring land
- Public protests for various reasons
- Foreign currency crisis
- Difficulties in project financing due to very high exchange rates
- Accessibility and maintenance issues due to remote locations in hilly terrain
- Increased climate variability leading to frequent, extended dry periods and low flows.

3.3 Solar Energy

Sri Lanka has a great potential for solar energy generation, given its location in the tropical belt with abundant sunshine throughout the year. With the advancement of photovoltaic technology, solar energy has become a competitive and sustainable source of electricity. The government has recognized the importance of solar energy and has implemented policies and initiatives to promote its use. However, there is still much to be done to fully utilize the potential.

3.3.1 Solar Resource Potential

Sri Lanka has a relatively high average annual solar radiation compared to many other countries. The country has ample sunshine throughout the year, with only a few rainy days per month. This makes it an ideal location for solar energy generation. 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.

However, currently, solar energy accounts for only a small fraction of Sri Lanka's total energy mix in electricity generation. The country's total installed capacity of solar energy is around 700 MW, 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 MW) solar power plants are in operation in Sri Lanka.

To increase solar energy generation, it is necessary to identify suitable sites for solar power plants and develop the necessary infrastructure for solar power generation and transmission. SLSEA has identified several sites across the country with high solar energy potential, and it is essential to prioritize these sites for the development of solar power plants.

3.3.2 Challenges and Opportunities

Despite its great potential, there are several challenges that need to be addressed for further development of solar energy in Sri Lanka. Some of these challenges are:

1. Lack of Grid Integration Possibility: One of the biggest challenges for solar energy in Sri Lanka is the lack of grid integration possibility. The country's electricity grid is not equipped to handle large amounts of intermittent renewable energy, which can lead to instability and grid failures.
2. Cost of Storage Solutions: Even though storage solutions can address the intermittency issues, high capacity batteries are expensive at present.
3. Limited Investment: Investment in solar energy projects in Sri Lanka is limited due to several factors, including the high initial cost of solar PV systems, lack of financing options, and regulatory barriers.
4. Land Constraints: As Sri Lanka is a small island nation with limited land resources, finding suitable lands for large-scale solar projects can be a challenge.

Despite these challenges, there are several opportunities for the development of solar energy in Sri Lanka. These include:

1. Prosumer concept: The government has implemented schemes allowing consumers to produce energy and supply excess to the grid (prosumers). This has made solar energy more economically viable for consumers and increase the adoption of solar energy.
2. Innovative Financing Models: Innovative financing models, such as green bonds, tax breaks and subsidies can provide funding for solar energy projects and attract private investors.
3. Rooftop Solar Potential: Sri Lanka has a high potential for rooftop solar installations, which can help reduce the demand for energy from the grid and ease the burden on the electricity system. This offers an immediate potential for substantial addition to the national grid without making a burden on the government and leveraging relatively small investments by the consumers themselves. Nearly 50,000 such installations have proven its financial and technical viability.
4. Floating Solar Option: Floating solar installations will be an option to overcome land constraints, considering the large extent of such water surfaces.
5. Local Manufacturing Possibility: Sri Lanka can get the maximum benefits from solar power by promoting local manufacturing.

3.3.3 Recent Research Findings

Research findings have revealed new and innovative ways to increase the efficiency of solar energy generation. One such finding is the use of perovskite solar cells, which 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%, which is significantly higher than the efficiency of traditional silicon-based solar cells.

Recent research indicates that the adoption of bifacial solar panels for ground-mounted solar plants can significantly improve energy generation. 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. A recent study by the National Renewable Energy Laboratory in the United States found that bifacial panels can offer even greater energy gains when combined with tracking systems that follow the sun's path throughout the day.

In addition, 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.

Several studies have explored the use of solar energy in combination with other renewable energy sources such as wind energy and hydropower. Further, the concept of agro-voltaics 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. The integration of multiple renewable energy sources, energy storage solutions, etc. can increase the reliability and stability of the power grid, making it possible to meet the country's growing energy demands sustainably. The reducing cost of batteries will overcome the problem of intermittency and the diurnal nature of solar energy with behind the meter battery storage, playing a major role in solar power development. Converting solar energy to a firm source of energy will enable the fast development of this resource.

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 southwest and northeast, 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 MW 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.

As a low-income country, we should go for low-cost generation sources with less foreign cost involvement. There are possibilities to increase local contribution to wind power developments. The cost of wind energy generation varies depending on the type of technology used and the location. In general, 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.

3.4.1 Interventions Related to Wind Power Development

The following sections provide details related to different aspects of wind power development.

❖ **Identification of project sites**

The SLSEA has established the district-wise wind power development capacities, considering the developable lands. There, flat terrains as well as mountain terrains of the country have feasible lands. Considering the logistical difficulties, it is expected to exclude the mountain terrains. Also, the latest land use pattern could be taken from the DS offices of specific areas to avoid any problems related to land selection.

As far as the areas where wind power plant development has been carried out so far are concerned, it has been based on the wind resource measurements carried out using wind measuring masts of 80 m height. The district-wise feasible wind power development capacities in the flat terrains are given in Table 2. In wind turbine technology developments, tower heights can be above 120 m, and then new sites can be identified in the districts like Anuradhapura.

Table 1: District-wise wind power potentials

District	**Capacity (MW)**		
	(10–25 MW sites)	(25-100 MW sites)	(More than 100 MW sites)
Anuradhapura	835	1,951	831
Hambantota	64	129	156
Jaffna	139	273	402
Kilinochchi	103	240	411
Kurunegala	207	29	
Mannar	300	648	544
Puttalam	62	87	123
Vavunia	56	62	163

- **Identification of transmission infrastructure enhancement requirements**

After the identification of each project development site in an exact manner, transmission infrastructure development needs should be assessed, i.e. the requirement of new transmission infrastructure for each site in terms of line voltage, its capacity, and line length.

- **Prioritizing the prospective sites**

Once a long list of sites is prepared along with the transmission infrastructure development needs, it is needed to prioritize the sites with the least constraints for the sites as well as with the comparatively lesser transmission infrastructure needs.

- **Making stringent the Grid Code of the CEB**

The latest state-of-the-art wind turbines have in-built features for reducing the dynamic impacts on power systems by way of making the rotational parts of the turbine a flywheel. It will be required to go for turbines with this type of improved technology so that the large-scale capacity addition from wind will make less impact on the power system. In order to push the developers to introduce the latest improved technologies, it is required to make stringent the Grid Code of the CEB, where this could be tightened with fault ride through capability, limitations on power quality at the grid connection point, further any simple stability criteria such as supporting to the grid voltage.

- **Studies & other technological interventions**

Offshore wind power as a new wind power technology

Sri Lanka has a high potential for offshore wind power as well; probably a comparatively larger potential than on-shore wind. In techno-financial aspects, capital investment for offshore wind is comparatively higher; however, the plant factor is higher than for on-shore wind. Nevertheless, as offshore wind is a novel area of wind power development for Sri Lanka, it will be required to carry out detailed studies on offshore wind power development with substantial stakeholder involvement and overall economic assessments.

Research on small-scale wind turbines

Hitherto wind power has been developed and addressed on MW scale, which requires high investment and may depend on foreign investment for making a significant impact. However, technologies have now developed small-scale wind power. This brings it down to the level accessible and investable by consumers, and it is at a scale possible to be manufactured locally.

3.5 Geothermal Energy

Geothermal power is the most stable renewable energy source in the world; it is totally weather independent and stable. Therefore, it can be used as a base load power source. Other strong points of geothermal energy are the high capacity factor, low maintenance cost, very low land requirement, low noise pollution, little or no air pollution and long plant life.

3.5.1 Past Interventions in Geothermal Energy

Although research work on geothermal studies goes back to 1963, most of the early research work was focused on the origin of the geothermal systems and little attention was given to the geothermal energy potential. Recent studies conducted by the National Institute of Fundamental Studies (NIFS), University of Peradeniya, University of Moratuwa and a few other institutes shed some light on the power generating potential, and direct use of geothermal energy. In understanding the economic potential of using geothermal energy in Sri Lanka, heat source and reservoir are vital to be located in depths, reachable economically.

3.5.2 Geothermal Potential in Sri Lanka

Sri Lanka is yet to utilize its geothermal resources for power generation, despite having strong evidence from a considerable number of studies proving its potential. Sri Lanka has seven major hot springs with outflow temperatures ranging between 35-72 °C and possible reservoir temperatures ranging between 140-150 °C. Hence, they are categorized as low enthalpy geothermal systems.

Recent studies carried out by NIFS and other researchers using modern geophysical and geochemical techniques revealed that the heat sources of Nelumwewa, Mahapelessa, Kanniya, and Kapurella hot springs are situated at depths which can be considered as suitable for economical drilling. Therefore, these sites can be earmarked as suitable locations for geothermal power plants supplying electricity.

The other hot springs, which may not be suitable for electricity generation, due to the high cost of drilling, can be used for direct heat utilization such as, drying of agricultural products (fish, rice, etc.), steaming in sugar production from canes, direct use of heated water as recreation and medicinal applications.

3.5.3 Current Status Related to Geothermal Energy Development

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 in the country. 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. If funding can be provided, the drilling operations can be started.

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.

3.5.4 Benefits of Geothermal Energy to the Country

Sri Lanka can obtain diverse benefits through the development of geothermal energy, as follows:

- Most of the thermal springs are located in rural areas of the country. Initiating geothermal plants could develop the infrastructure of those areas enhancing the living conditions of the communities.
- The exploration programme headed by experts could be used to train university students eventually producing a number of postgraduate degrees.
- Individuals who are willing to invest in local projects can obtain energy at a lower cost.
- It will help enhance the tourism industry by providing access to natural hot water spa facility.

3.6 Ocean Thermal Energy (OTEC)

Ocean Thermal Energy (OTEC) systems use the ocean's natural thermal gradient to drive a power-producing cycle. As long as the temperature between the warm surface water and the cold deep water differs by about 20 °C, an OTEC system can produce significant power. 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 [19]. Later, several studies were done by Kamal Tennakoon et al. for the same location and proposed a conceptual design for 100 MW class OTEC in 1998 [20]. OTEC is a versatile resource due to its potential benefits, such as baseload electricity, desalinated water for industrial, agricultural, and residential uses, and deep-sea water for on-shore and near-shore mariculture operations, the potential to provide air-conditioning for buildings and moderate-temperature refrigeration and so on. Therefore, OTEC needs further and more focused attention.

3.7 Wave Energy

The Government of Sri Lanka has recognized the importance of assessing wave energy resources in Sri Lanka, and SLSEA concluded wave energy resource assessment and characterization in 2020 [21].

3.7.1 Wave Resource Assessment and Characterization

The following pathway outlines the steps required to develop a detailed analysis of Sri Lankan wave energy resources based on the available resource assessment. Such analysis provides valuable information to guide the development of wave energy projects in Sri Lanka and help the country to harness the resources in a sustainable and economically viable manner.

- **Data collection**

Refinement of wave models is needed to predict more accurate wave data with high resolutions. Once the key parameters and characteristics are identified for a selected location at sea through low-resolution wave models, the next step is to collect actual data to tune the computer models. This may involve the installation of wave buoys, current meters, and other monitoring equipment to collect data on the wave and current conditions at various locations along the coast.

- **Data analysis**

The above data should be analyzed to determine the wave energy resource potential at various locations along the coastline. The analysis should be based on IEC standards and consider factors such as energy yield, resource density, and capacity factor.

- **Site characterization**

The next step is characterizing the wave energy resource and other site-specific parameters. It may involve a detailed assessment of the local wave climate, bathymetry, and other factors that may impact the wave energy resource potential at a given location.

- **Technological assessment**

Once the wave energy resource potential is characterized, the next step is to assess the technical feasibility of harnessing this resource. It may involve an assessment of the various wave energy technologies available, such as point absorbers, oscillating water columns, and attenuators, among others, along with grid connectivity.

- **Economic analysis**

The final step is to conduct an economic analysis of the wave energy resource potential, considering factors such as the cost of installing and maintaining wave energy devices, the revenue potential from energy sales, and any incentives or subsidies available to support the development of wave energy projects.

3.7.2 Wave Energy Resource Potential

The characterized wave resource parameters of mean significant wave height, mean energy period and mean omnidirectional wave power of the Sri Lankan wave energy resource is presented in Figure 4 using 18 years of data. Moreover, time series for all of these outputs, including monthly, seasonal and annual variations, have been stored in a geo-referenced digital database, which will be essential for future research in this field.

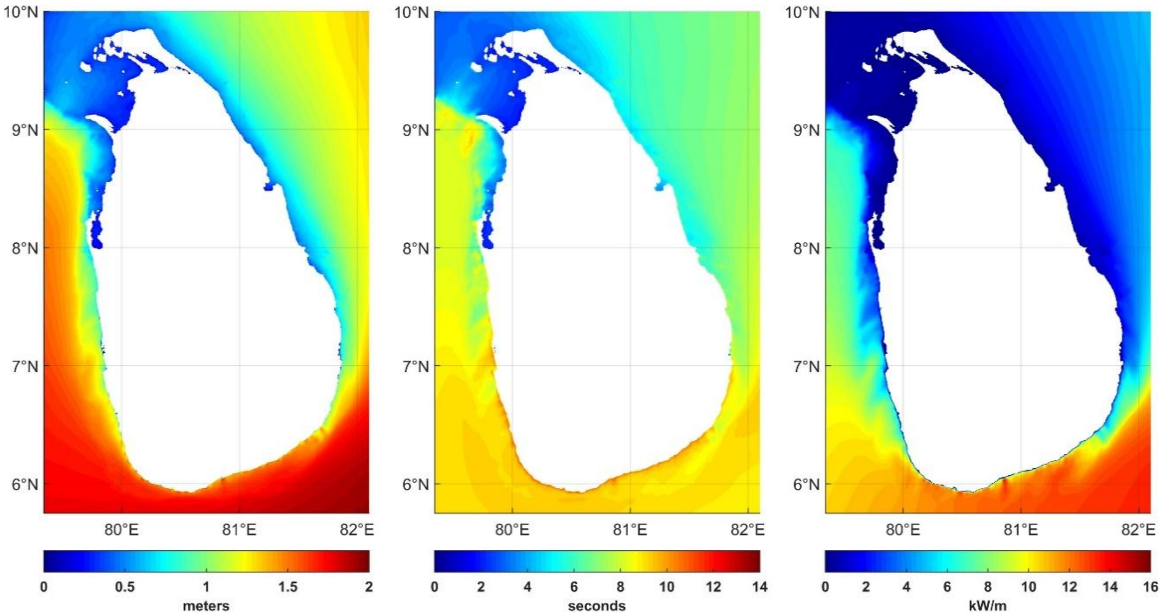

Figure 5: Annual mean variations of significant wave height, mean energy period and omnidirectional wave power (2001-2018)

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. It is also important to highlight that significant wave height values develop up to 2.5 m in the southern region during the southwest monsoon period (May-September). The mean annual omnidirectional wave power of the south coast has consisted of the highest range of 12-16 kW/m while the lowest range of 1-5 kW/m values can be found in the north, northwest and east regions of the country. 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 regional information shows the mean annual energy period has the highest range of 9-12 s at the south, southwest and west coast regions. Table 3 indicates regional theoretical wave power; the southern sea is more energetic than other regions. Also, further analysis revealed that the plant factor in the southern region would be around 50%, which is impressive as an intermittent renewable energy source.

Table 2: Theoretical wave energy resource potential of each province

No.	Province	Theoretical wave resource potential (TWh/year)
1	Northern province	2.65
2	Eastern province	4.35
3	Southern province	26.30
4	Western province	8.75
5	Northwestern province	5.25

3.7.3 Proposal for an Ocean Energy Test Centre (OETC)

An Ocean Energy Test Centre (OETC) primarily tests ocean energy prototypes [22]. 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. Then, a range of tests could be performed, such as wave energy extraction efficiency, device survivability, and performance. The centre can also provide support services to developers, such as engineering design support, fabrication services, and access to specialized testing equipment. Thus, it will help to reduce the entry barriers for new developers and encourage innovation in the sector. This also provides inward investments and the transfer of technologies. Additional details of such a test centre idea are found in work by Matt Folley et al. [21]. By following this pathway, Sri Lanka can establish a world-class ocean energy test centre that will help to accelerate the deployment of marine energy technologies, create new economic opportunities, and promote sustainability in the sector.

3.7.4 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. However, Sri Lanka does not have a proper plan with milestones, allowing the local researchers to collaborate and engage in research & development activities to develop local technology aiming to scale up for commercialization gradually. For this to happen, a suitable funding scheme on ocean renewable energy research or broadly on renewable energy research should be established, which may be through the support of the government or the stakeholders such as SLSEA, CEB, LECO or the investors.

Also, a proper research & development institution should be formed which will oversee and manage the research work on marine renewable energy by coordinating with local and international researchers and interest parties. With that, a proper research roadmap with nationally set milestones could be established, rather than what individual researchers or universities do in their interests under minimum or no funding, mainly without a holistic perspective. This kind of institution could be gradually formed based on Ocean Energy Test Centre.

3.8 Other Marine Renewable Energy

As far as other marine renewable energy sources are concerned, since Sri Lanka is placed close to the equator, the tidal range is considerably small, and hence, the tidal energy potential in Sri Lanka is negligible. Other technologies such as ocean currents, salinity gradient and marine bio energies are yet to be exploited and are worth investigating.

4. Grid Integration Aspects Related to Renewable Energy Development

Despite the existing policies and initiatives to support renewable energy integration, Sri Lanka still faces several challenges. The integration of renewable energy sources into the grid requires complex and advanced technological solutions as briefly discussed in Table 4.

Table 3: 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	• 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

meeting a consistent level of demand.	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.

5. Recommendations

Recommendations to be considered by policy makers to overcome the difficulties in renewable energy development and make a conducive environment for the development of renewable energy projects are given below.

❖ **Financing**

- Develop supportive policy and regulatory frameworks, such as feed-in tariffs, wheeling, tax incentives, green financing, green bonds, and public-private partnerships, to reduce the cost of renewable energy technologies and encourage investment in the sector.
- Implement an effective time-of-use tariff through proper studies for residential consumers as well.
- Introduce demand side management through time-of-use tariff to effectively shift the peak to allow a reduction of required energy storage capacity.
- Introduce tariff schemes for micro-grid interconnection to the system.

❖ **Site Identification and Allocation of Lands**

- Direct and facilitate SLSEA to carry out the identification of sites for large-scale renewable energy development through detailed site information surveys.
- Streamline the land acquisition and permitting processes for renewable energy projects to reduce delays and improve investor confidence.

❖ **Transmission**

- Consider expanding the CEB grids where more renewable energy opportunities exist (eg. Rathnapura grid substation for hydro power).
- Consider setting up collector substations under the existing 220 kV and 132 kV transmission lines.
- Direct and facilitate CEB to establish the transmission infrastructure requirements for the identified large-scale renewable energy development sites.

❖ **Capacity Building and R&D**

- Carry out institutional capacity building and conduct joint research & development with the universities.
- Establish suitable approaches to move for new technologies, such as hydrogen and storage to support and enhance the renewable energy absorption and to shift the transport sector towards green energy

❖ **Stakeholder Engagement**

- Establish a mechanism for creating awareness of the value of renewable energy, to win over the support of all stakeholders to abide by the recommendations and strive to achieve the targets set as of benefit to themselves.
- Establish high-level committees headed by the Divisional Secretaries to solve land issues faced by the developers, in renewable energy abundant areas.
- Direct and facilitate SLSEA and CEB to carry out the initial project development work for the prioritized renewable energy development sites, in collaboration with the relevant stakeholders.
- Increase public awareness and education on the benefits of renewable energy and the importance of energy conservation.

❖ **Technological Interventions**

- Consider the possibility of developing pumped storage technology that can store excess energy generated during peak periods and release it during periods of high demand, which help address the issues associated with the diurnal power generation patterns of renewable energy sources and increase the reliability of the electricity grid.

❖ **Preserving the benefits to the public**

- Make sure to establish appropriate techno-economic and legal conditions in connection to the implementation and operational aspects of renewable energy power plants developed through foreign investments, for preserving the benefits of renewable energy for the country, in connection to the relevant situations such as:
  - (i) Any new business models proposed by the government for developing renewable energy projects through foreign investments

(ii) In case it is decided to establish the proposed Indo-Sri Lanka grid interconnection, which will act as a power evacuation option for large-scale renewable energy plants.

In addition to the general interventions proposed above, specific actions are proposed under each energy source in the following sections. In that regard, recommendations are made for getting rid of the different constraints and the speeding up of the project development process in connection to the proven energy sources, whereas resource assessment, pilot/demonstration projects, etc. are proposed for the emerging renewable energy sources.

5.1 Recommendations on Bio energy

- Generate resource maps to identify the recovery potential of all waste types in Sri Lanka.
- 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.
- Promote fuel switching to biomass in industries by promoting the supply chain activities for biomass supplies.
- Promote urgent research to elevate the domestic level bio gas generators to the level of the main source of cooking fuel including in urban households.
- 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.
- Carry out bio process resource recovery, instead of burning high moisture content (60%) organic material.
- Evaluate the whole spectrum of available bio energy resources under large-scale projects, without confining to biomass, i.e. wood derived resources.
- Adopt purification, upgrading and compression technologies, in order to introduce biomethane 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).

- Facilitate the private sector partners to establish waste management technologies under favourable financing policies, government approval processes and electricity pricing.
- Develop medium-term and long-term action plans to promote large-scale anaerobic digestor developments.
- 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.
- Develop policies and strategies with the petroleum authorities for rapid fuel switching to bio renewable energies.

5.2 Recommendations on Hydro Power

- 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.
- Upgrade the existing hydropower plants to increase the efficiency and reliability of existing hydropower plants, by the installation of new turbines, generators, and control systems, as well as the 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.
- Develop small-scale hydropower with less than 10 MW capacity, which can be developed in remote areas that are not connected to the national grid. Developing small-scale hydropower can help increase the share of renewable energy in rural areas and provide electricity to communities that currently do not have access to electricity.
- Encourage private sector investment in small-scale hydropower and provide support for the development of these projects.
- Develop and implement clear and consistent policies & regulations for renewable energy, including feed-in tariffs, net metering, etc.

5.3 Recommendations on Solar Power

- 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.
- Promote behind the meter storage and suitable feed in tariff systems.
- Promote the development of floating solar projects by providing access to water masses under the control of the government, initially as demonstration projects.
- Promote agro-voltaics in collaboration with relevant state agencies such as Department of Agriculture, on completion of adequate research on the subject.
- 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. This can contribute to the development of a thriving domestic solar industry, making Sri Lanka a leader in solar product manufacturing in the region.
- Train solar technicians and provide license to them.
- Raise public awareness about the benefits of solar energy and encourage consumers to adopt solar energy, through education and outreach programs.

5.4 Recommendations on Wind Power

- 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.
- Direct and facilitate CEB to make stringent the Grid Code for promoting developers to go for wind turbines with the latest technologies.
- Direct and facilitate SLSEA and CEB to carry out studies on off-shore wind power development.

5.5 Recommendations on Geothermal Energy

- Start with a 2 MW pilot binary cycle geothermal power plant, going up to 10 MW or more at the first site, depending on the energy potential at each site.

5.6 Recommendations on Marine Renewable Energy

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

5.7 Recommendations on Grid Integration

- Develop a comprehensive system integration plan that identifies the technological solutions required to integrate renewable energy sources into the grid.
- Develop regulations and standards for renewable energy integration ensuring compliance with the international standards.
- 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.
- Implement advanced grid technologies, such as energy storage, micro-grids, and smart grid technologies, to improve the stability and reliability of the grid, through comprehensive research studies.
- Deploy advanced systems, such as 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 research studies.
- Encourage energy storage solutions, such as batteries and pump hydro, to help stabilize the electricity grid and increase the renewable energy absorption.

- Invest in upgrading the electricity grid to handle larger amounts of intermittent renewable energy.
- 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.

6. Conclusion

Sri Lanka has a great potential for renewable energy generation, but there are several challenges need to be addressed for its further development. By implementing the recommended measures, Sri Lanka can increase its renewable energy capacity. Converting intermittent energy sources to firm power through appropriate storage systems will enable fast development of the particular resources.

Sri Lanka's grid integration of renewable energy sources presents a range of technical and regulatory challenges. However, these challenges can be addressed through a combination of advanced technological solutions and supportive policy and regulatory frameworks. The 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 and smart grid systems, as well as the development of new grid infrastructure. The deployment of advanced systems, such as cross-border interconnection, battery and pump-storage systems, demand-side management technologies, and reactive power management technologies, can help to maintain the stability and reliability of the grid while integrating large amounts of renewable energy. Developing regulations and standards for renewable energy integration and ensuring compliance with international standards must be given priority for the reliable operation of power system with high renewable penetration. Additionally, supportive 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 renewable energy.

Investment in renewable energy is a highly sought-after venture at the international level. However, to make that happen it is required to create projects less risky so that those projects will be investor-ready. For that, it will be required to do the process of obtaining lands, project pre-feasibility, and feasibility studies and obtaining the environmental clearances through direct involvement of the government. Even making available the past project development reports, their timelines, and reports on lessons learned from those projects. Further on, clearly defined steps are required for implementing large-scale renewable energy projects and predicted timelines are required for each step. For approvals, required reports and their formats could be made available to speed up those projects while making much easier administration to the developers while strengthening the technical side to implement solid projects as fast as possible.

Sri Lanka has a greater potential for ocean wave energy, particularly on the southern coast, while OTEC has considerable potential at the off coast of Trincomalee. Other potential resources such as salinity gradient, ocean current and ocean bioenergy are yet to be investigated. Except for tidal energy, the other ocean renewable energy harnessing technologies are mostly under the pre-commercial or prototype stage, and hence immediate energy production would not be competitive compared to solar and wind. Therefore, Sri Lanka has other opportunities to become the technology leader in the region by engaging in more research and development while engaging in supporting services enhancing the capacities in the ocean energy sector. As such, concepts like Ocean Energy Test Center and funding for research and development would be beneficial.

In overall perspective, Sri Lanka inherited with a vast potential of renewable energy, and in need of economic development options, should take serious consideration on renewable energy development for meeting energy needs of the country, providing a vast support to the macro-economic development of the country.

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