10-31-2022

Energy efficient smart port development, implementing renewable energy in a port: a case study in Port of Colombo, Sri Lanka

Darshana Sampath Kumara Habakkala Watawala Kankanange

WORLD MARITIME UNIVERSITY
Malmö, Sweden

ENERGY EFFICIENT SMART PORT DEVELOPMENT, IMPLEMENTING RENEWABLE ENERGY IN A PORT

A case study in the Port of Colombo, Sri Lanka

By

DARSHANA SAMPATH KUMARA

A dissertation submitted to the World Maritime University in partial fulfilment of the requirements for the award of the degree of

MASTER OF SCIENCE
in
MARITIME AFFAIRS

(MARITIME ENERGY MANAGEMENT)

2022

Declaration

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views and are not necessarily endorsed by the University.

Signature :

Date : **20.09.2022**

Supervised by: **Professor Alessandro Schönborn (Ph.D.)**

Supervisor's affiliation**: Assistant Professor of Maritime Energy Management Specialization at the World Maritime University**

Acknowledgments

First, I would be grateful to express my sincere gratitude to Dr. Yohei Sasakawa, the Chairman of the Nippon Foundation (Japan) for giving me a great fellowship and to World Maritime University (WMU).

Secondly, I place on record my immense gratitude to my supervisor, Professor Alessandro Schoenborn for the guidance and clear direction from beginning to end excellently and genuinely. Highly appreciated his way of guidance and support. Also, the Head of our Maritime Energy Management (MEM) Specialization Professor Aykut Olcer, of encouraging and motivating. Besides, I want to thank Professor Fabio Ballini for his quality lectures, which have helped to deepen my professional knowledge. I would like to thank Research Assistant at WMU, Captain Seyedvahid Vakili for sharing his knowledge of my research.

I would like to mention here the Managing Director of SLPA and Chief Operation Officer of SAGT for the given information and data of the Port of Colombo, Sri Lanka. My sincere appreciation goes to the higher Management of Ceylon Shipping Corporation Limited for their significant encouragement.
My sincere appreciation wants to give Dr. Matthias Schilf from IMS Nord, Germany, for sharing his expert knowledge, especially in wind farm installation projects. Then I would specially thank Mr. Arthur Van Vossel, Quality assurance & Energy manager in Port of Antwerp for his impression gave me and for expressing his practical knowledge about the smart port concept.

I am deeply indebted to my love for my wife Mrs.Himali Deepika to take care of my kids (Sandew, Randira, and Sandisi) and parents while I was far away from home. Without her perseverance throughout the period, it becomes too much difficult to concentrate my mind.

Last but not least, I would extend to all my friends in Sri Lanka and Sweden for everything they shared to ease up my homesickness.

Abstract

Title of Dissertation**: Energy Efficient Smart Port development, implementing Renewable Energy in a Port. A Case Study in Port of Colombo, Sri Lanka.**

Degree: **Master of Science**

Energy requirement in a port consists of fossil fuels and generated Electricity from a national or a common grid. They are distributed to terminals, Yard operational machineries, storage facilities, several feeder vessels, and buildings. This dissertation's main research questions are: Where does electricity come from? How does it affect the environment? What options exist to improve this situation? This research is making feasibilities with economic, and environmental aspects by introducing renewable energies to address those questions for a smart port.

The unique Energy baseline of a port needs to be identified from the current energy consumption of the Port of Colombo. Most of the ports have taken measures to reduce fossil fuel energy generated and the trend toward renewable Energy sources. This research emphasizes cost-benefit analysis for Wind, Solar, and Solar Aided Power Generation (SAPG) as major cases targeting the Port of Colombo Sri Lanka with the aid of information from the NASA database.

According to the findings of this study, the most suitable system was identified that the Solar Photovoltaic (PV) system offered due to the efficient constant solar irradiation to Sri Lanka as it is located near the Equator. For solar, the Levelized Cost of Energy (LCOE) was 0.01774 $/kWh with 8 years payback period for the project. Understanding Electricity generated cost as comparatively lower level in Sri Lanka, the sensitivity analysis showed if a 300% increase in electricity generated price, all of the mentioned major cases become positive NPV.

Furthermore, the study indicates that Ports are challenged by energy, environmental and economic perspectives increasing pressure on the global supply chain with the impact on their sustainability. High-performing, implementation of smart technologies with better management and continuation of continual improvements by introducing renewable energy sources to mitigate the environmental impact will be indicated in this research based on the port of Colombo, conducting comparatively discussion with globally sustainable smart ports.

KEYWORDS: Renewable Energy, Cost-Benefit Analysis, Wind, Solar, SAPG, LCOE, PB, NPV, Smart Technologies

Table of Contents

List of Tables

To be continued

List of Figures

List of Abbreviations

CAPEX	- Capital Expenditure
CICT	- Colombo International Container Terminal
DECOM	- Decommissioning Cost
EATM	- Economic Attractiveness Technological Maturity
EE	- Energy Efficiency
ESS	- Energy Saving Systems
IEA	- International Energy Agency
IMO	- International Maritime Organization
IRENA	- International Renewable Energy Agency
ISO	- International Organization for Standardization
LCOE	- Levelized Cost of Energy
LED	- Light Emitting Diodes
MASS	- Maritime Autonomous Surface Ship
NASA	- National Aeronautics and Space Administration
NPV	- Net Present Value
nZEP	- Nearly Zero Emission Port
OPEX	- Operational Expenditure
RES	- Renewable Energy Systems
SAGT	- South Asian Gateway Terminal
SAPG	- Solar Aided Power Generation
SEMS	- Smart Energy Management Systems
SLPA	- Sri Lanka Ports Auth

Chapter 1

INTRODUCTION

1.1 Background of study

Over the years, ports have already proven to be synonymous with ongoing innovation and agility, strenthening shipping operations and countryside connections, reconsidering the areas affecting the environment and social effects, maximizing their economic strength, and making the greatest use of available space. The function of ports is already changing. According to the ESPO Green Guide 2021, the maritime service providers of the past are no longer found in ports. They serve as smart hubs for leisure and tourism, multimodal transport and logistics, as well as hubs for sustainable business and clean renewable energy. In an attempt to minimize greenhouse gas (GHG) emissions, many people have started to test integrated electricity systems.

Moreover, port operations are connected to numerous emission-producing sources both directly and indirectly. These emission sources include port administration vehicles, power plants that supply of electricity to tenant buildings and administration offices, electrified and fuel-powered cargo-handling machinery, ships, harbour crafts, trucks, and rail locomotives, among others. Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), as well as other pollutants of concern such oxides of nitrogen (NOx), particulate matter (PM), and sulphur oxides (SOx), are produced by these sources. However, the International Maritime Organization (IMO) formed its own viewpoint in April 2018 as part of an effort commonly to minimize GHG emissions caused by international shipping (IMO, 2018). Therein, challenging goals for the whole marine industry were set. The following will be accomplished in accordance with the stated basic strategy (IMO, 2018).

- To lower global shipping's average CO_2 emissions per transport job by at least 40% by 2030 while seeking a 70% reduction by 2050 as compared to 2008.
- The vision calls for a point on a pathway of CO_2 emission reduction coherent with the Paris Agreement temperature objectives to highlight the peak of GHG emissions from international shipping as soon as possible and to reduce the total annual GHG emissions by at least 50% by 2050 compared to 2008 while pursuing efforts towards phasing them out.

Therefore, Positive renewable energy and cutting-edge technologies must be created to realize these objectives, and significant adjustments in governmental policies and practices must be made. Numerous of these are allegedly being looked into globally to get the shipping industry to help slow down global warming. The organization provided 44 abatement methods in the final report of the Fourth IMO GHG Study 2020 regarding the reduction of GHG emissions from ships (MEPC 75/7/15,IMO, 2020). Ther e are 4 exemptions for renewable energy sources, such as solar panels and wind turbines, among the 44 technologies.

Government bodies and other international organizations are also pushing to clear strategies and concrete actions toward efficient and clean transport with proper mechanisms. To optimize the implementation of renewable technologies proper mechanism is very important. The **electricity consumption** in the routine operation of port and tenant facilities, electrified cargo handling machinery (such as electric wharf cranes, rail-mounted gantries, rubber-tired gantries, etc.), shore powering of vessels (Cold Ironing), tenant industrial facilities, and reefer plugs all contribute to the consumption of electricity at the ports. Despite tEven thoughied freight handling equipment is often considered to be a mobile source, because of their electrification, the emissions from their activities are assessed based on purchased electricity ("9 Carbon footprint Port", 2010).

In order to cut costs and improve environmental performance, it is important to ensure that the port operates in an energy-efficient and mainly emission-free manner. An essential part of the port's overall "energy sustainability plan" is the Action Plan for Sustainable and Low Carbon Port of Colombo, which provides thorough and useful information on how to reduce the environmental impactsthe of port opcost-effectively. Both energy efficiency and the usage of renewable energy sources have gained importance for the port business globally. As the Port of Colombo, Sri Lanka is located in a strategic and unique place in the world 60% of trade passes through, it ranks in the top 25 ports in the world having the highest container handling capacity port in South Asia. Therefore, the energy demand of the port is to be handled in a holistic manner.

In order to compile a thorough overview of the port's structural equipment and infrastructure conditions, gather data on energy consumption, and record the operational procedures on the terminals, this research is conducted generally, including an on-site terminal inspection. Finally, focus on determining how much energy can be saved through the optimization of **wind, solar energy and effective energy storage system**, and **how this will impact the port's sustainable environment** as it strives to become the ISO 50001: 2018 accredited first port in South Asia.

1.2 Problem statement

In 2021, the Electricity consumption of the port was **95,422.00 MWh** and total fuel oil consumption was **17,495 MT** including all pilot operations, agency operations of husbandry work, and assumed fuel consumed during the total time at the berth of vessels according to the direct data obtained from SLPA. This became a challenging circumstance. The world smart concept is to reduce the energy and increase the efficiency of ports with **new renewable sources** in order to make **socio-economic benefits** by controlling GHG emissions.

Identification of the areas for the energy consumed and addressing those key areas are hard to focus. According to the IRENA, 2021 report, Electricity generates from renewable is 52% (With Hydro, Wind, Solar and Bioenergy) in Sri Lanka. Since the port of **Colombo doesn't have any renewable source**, the total power demand has to be taken from the grid-supplied. That is 48% of electricity generates from fossil fuels. Therefore, this research represents how much energy can produce from wind and solar installation in the port premises to utilize the energy from renewable energy and also from the **energy storage mechanism**. **What are the methods and how much emissions can be reduced by optimizing the energy by RE Sources?** This research is being elaborated on the answer to this problem.

1.3 Aim

Even the Port of Colombo is one of the busiest ports in the world and is ranked among the first 25 ports, but it is not a smart port as well as there is no smart port in the South Asian region. The general goal of this study is to determine the whether it is feasible to establish an energy-efficiency plan management system with renewable energy to the Port premises with a **cost-benefit analysis.** In addition, how can the energy consumption be reduced, and how can the amount of GHG be reduced lowering the operational cost of heading the smart port concept of the port of Colombo.

1.4 Objectives

The following objectives are aimed at realizing the main goal of this research. The SLPA has managed no. of tug boats, Pilot boats, supply boats, Bunker Barges, and Firefighting boats for the vessel assisting and husbandry work. All these vessels are driven by MGO. Huge Electricity is consumed from the port as handling the massive number of containers. Therefore, in this research, convenient renewable energy sources are willing to implement with proper cost-benefit analysis. Following mentioned main objectives with addressing the specific sustainable topics.

i. Identify the total energy demand of SLPA by the actual data using practical assumptions from the primary and secondary data.
ii. Identify the total existing figure of the GHG emission per annum of Port premises using the same practice of above no. i.
iii. Identify the best alternative renewable energy Sources, Practices and develop an optimized way in order to address the above ii.

1.5 Research Questions

i. What is the existing baseline of the port energy consumption?

ii. What are the current GHG emissions from energy consumption at the Port of Colombo?

iii. How could current energy needs be met by low-carbon energy sources (e.g. renewable energy)?

iv. How does introducing REs affect the cost of electricity?

v. What are the technical and operational measures to improve/optimize the current energy consumption of SLPA?

vi. How can evaluate Socio-Economic activities to reduce GHG emissions by a cost-benefit analysis for renewable energy sources?

1.6 Methodology

In order to achieve the aim of this research, the materials were gathered through relevant literature, especially Renewable Energy generation. A **quantitative approach was used for this research, in combination with a qualitative critical analysis**. Calculations were used to develop and evaluate the feasibility analysis of the implementation of an optimized /utilize Energy Management System (EnMS). Used NASA database for collecting the historical data for wind and Solar for the location in Colombo. The primary data for the energy demand have been obtained from SLPA officials and the website. Journal articles, relevant publications and books, and official web pages of organizations, institutions, Port equipment manufacturing companies, and other relevant companies. The approach and outline have been created according to the most suitable similar studies from particular universities and it was directed for a better approach. Annual reports and roadmaps of the following mentioned organizations were considered to establish the correlation to the port of Colombo.

- Port of Antwerp, Belgium
- Port of Rotterdam & Amsterdam, Netherland
- Port of Oslo, Norway
- Port of Oakland, New York, New Jersey, Houston, Long Beach, USA
- Port of Helsinki, Finland

1.7 Research Limitations

- The Fuel Consumption at the waiting time at the anchorage or Out Port Limit (OPL) and manuring from anchorage to berth and berth to high seas and better alternative fuels for the vessel propulsions have not considered in this research.
- For a smart port, issues to be observed for Operational, Environmental, Energy and safety perspectives. In this research focuses only the commodity of **Energy management** of the Port with **REs**.
- This dissertation is partially related to the greener concept, but totally related to the smarter concept in energy perspective.
- Port infrastructure and berthing operation, loading, unloading, hinterland connectivity, in port energy utilization are the boundaries.
- All the costings and functions of Wind and solar REs are related to the market prices as of September 2022.
- New Port City constructing functions of Colombo were not included but its indirect influence was considered.
- Fuel oil consumption was investigated only for generators and with the stage of slow steaming operation until berthing of the vessel by Main propulsion will not be considered.
- Investigations of research are narrowed into only one commercial port, - Port of Colombo, Sri Lanka.

1.8 Dissertation Structure

Chapter 1 : Highlighted the Aim, Objectives, Research Questions, Data Collection process, and limitations of the research.

Chapter 2 : This chapter will describe the extensive literature review IMO regulations and policies of the Smart port concept, and GHG reduction process. Secondly, port energy optimization using REs will be described. Then planning of energy from the social, environmental, and economic ways will be described.

Chapter 3 : This chapter presents the methodology of data collection and baseline of energy demand and theoretical procedures for measuring RE for the Port.

Chapter 4 : This chapter is implementing the calculation, observations, and analysis.

Chapter 5 : This chapter will be described the advantages and benefits of the smarter energy management concept and critical sensitivity discussion.

Chapter 6 : Final chapter will be concluded this research and presenting for the recommendations and further research.

Chapter 2

LITERATURE REVIEW

2.1 Chapter overview

This chapter reviews some prior studies and literature undertaking in relation to energy-efficient port management systems in ports for Economic, Social and Environmental ways. The measures, regulations and policies with attached benefits will be focused on in order to conduct a smarter port concept. This further refers to the findings of the benefits of reducing GHG emissions and rules. The usage of renewable energy in smart ports and energy-efficient optimization planning is the basement and it will be discussed in the literature.

Utilizing energy-efficient equipment, having good operational procedures, lean management, and improved port processes, using renewable energy sources to generate electricity, establishing port energy management strategies and their objectives/targets, having top management commitment, and a combination of these can all help ports become more energy efficient (Ölçer et al., 2017).

2.2 Heading Smart Port Concept

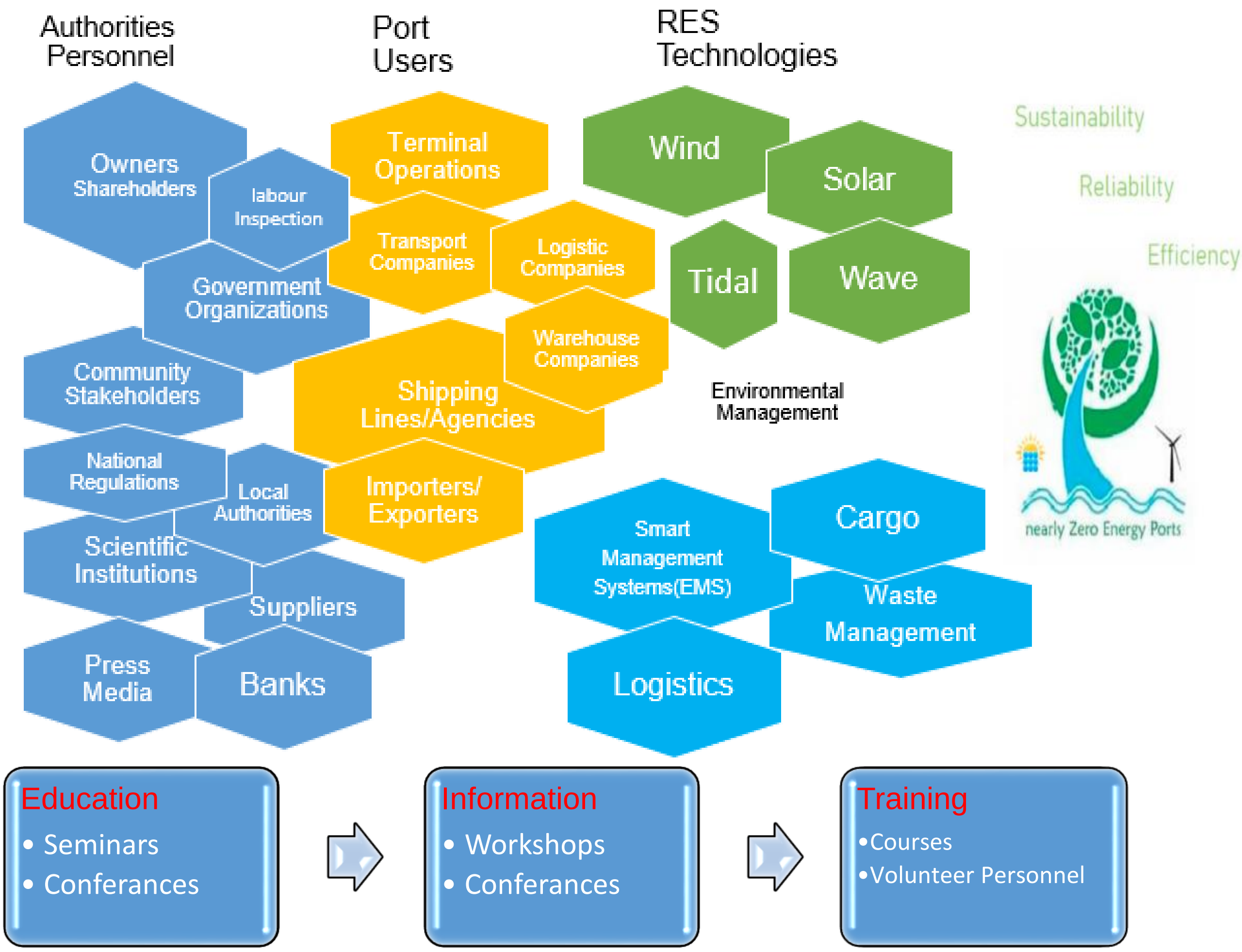
Ports are owned, managed, and maintained by a variety of administration types and stakeholders with varying sizes, geological environments, and activities and interests, all of which have an impact on the decisions they make. Some central public ports operate using a combination of public and private custody, including all regulatory and landlord duties. They are occasionally fully privatized, with all governing and operational duties transferred from the public sector, with the aim of boosting income with the least amount of capital expenditure. In order to move toward a more sustainable future, many authorities put into practice a variety of tactics and actions, including adjustments to their urban environments, energy usage, and climatic perspectives (Sdoukopoulos et al., 2019; Yang & Ge, 2020; García-Olivares et al., 2018). Ports are inextricably linked to social, economic, and environmental problems since they are comprised of complex systems that operate on both internal and external elements. The ports' geographical location, actual size, number of passengers, number of ships, ownership, stakeholders, and decision-makers define and apply their distinct management strategies and business plans. Because of the complicated operations and the need to consider numerous points of view, ports have steadily attracted academic interest. Characteristic examples include the evaluation of the significance of changing their operations in order to be more sustainable, the sustainability of their logistics, the assessment of their operations' sustainable potential, the environmental effects of shipping operations, the investigation of the potential for implementing REs for green energy production, and the effectiveness of the installation of SEMS into their infrastructures in order to improve their EE (Parise et al., 2016; Wilmsmeie et al., 2014; Lopez et al., 2017).

Implementing monitoring and real-time reporting systems is the first and most important step for any industry seeking to lower its GHG emissions and combat climate change. These technologies create a trustworthy, long-lasting database that provides a wide range of capabilities. Such systems have already been established by a number of authorities in various sectors, including ports in the EU and other countries. Their public image and EE both reaped substantial advantages (Kang & Kim, 2017). Ports all around the world are beginning to pay more attention to EE as their administrations become more aware of and appreciative of the potential for genuine energy savings (Denktas & Karatas, 2012). Buildings and lighting fixtures add to the energy use in ports, which raises GHG emissions. Additionally, most ports use outdated heating/cooling equipment and indoor/outdoor lighting systems; however, some ports have begun to upgrade these systems by adding light-emitting diode (LED) lights (Van et al., 2017).

By efficiently reducing air pollution emissions and noise from ships in ports, shore-side electrical supply (**Cold Ironing**) can improve the environment and human health. As a result, the engine room environment is calm during port visits, workers onboard are subjected to less noise and pollution on deck, and stevedores are exposed to less ship emission. Shutting down the vessel's auxiliaries typically results in a large reduction in the overall noise produced by the vessel; however, this depends on the specifics of each individual vessel. A high-voltage shore-side supply of energy at berth is seen by all of the participating operators who have been contacted as a very welcome development. Ships connected to shore-side energy incur much reduced external costs for air pollution emissions when they are in port, according to the appraisal of these costs. The external expenses for onboard generation of energy were found to be between 15 and 75 times higher than those for shore-side electrical connection, depending on the fuel (HFO or MGO) and the type of maritime service evaluated (Jivén, 2004).

In order to advance the nearly Zero Energy Ports (nZEP) concept, there is an urgent need for an informational and thorough endeavour to combine the current technology and approaches. It is a bold undertaking that port authorities should think about if they want to maximize their contribution to sustainability; it entails using the available tools and technologies to provide the best results (Sifakis et al., 2019a). Ports are primarily attempting to move towards sustainability by utilizing clever strategies and technologies like on-shore power supply or cold-ironing, which enables ships at the dock to shut down their fossil-fuel engines relying on electricity for their mandatory operations; this results in significant energy savings. It can be put to use for various purposes including powering e-vehicles or port container terminals (PCT), managing cargo, or using RE sources. By being tailored to the cold-ironing technology, where the local port grid depends on REs, micro-grids could further advance ports' efforts toward sustainability. It is often used globally compared to other technologies, and its implications on EE as a whole are exceptional (Lopez et al., 2017). Ports all over the world are already using smart and micro-grids for their operations, which has substantial positive effects on the economy and the environment. the best synthesis and assemblage of the approaches and technology already in use to create the broader notion of nZEP (Figure 01).

Figure 1: Port-related parties, available REs, and “greenable” operations



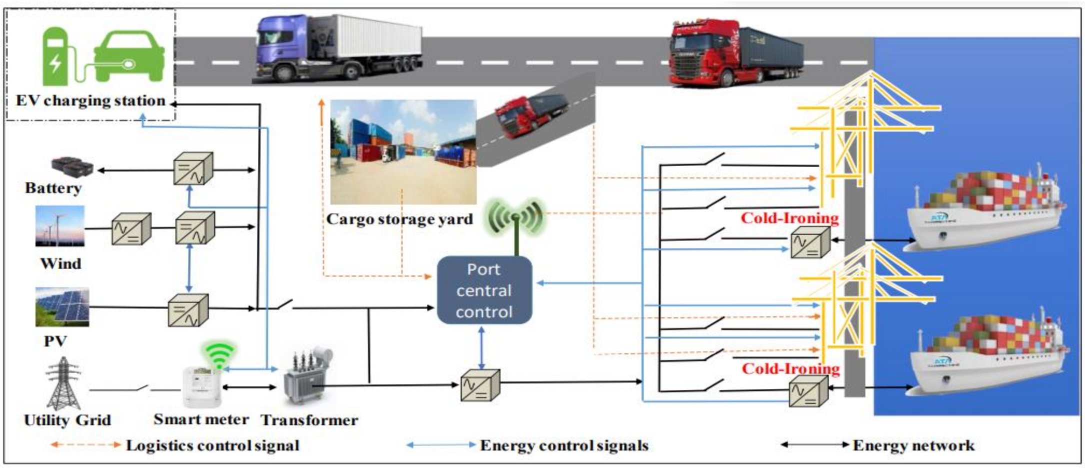
Source : Adapted from Sifakis & Tsoutsos (2021). Planning zero-emissions ports through the nearly zero energy port concept.

Reducing the speed of ships when they approach ports can be essential for cutting emissions associated with ships as an easy-to-implement but effective solution (Zis et al., 2014). To enhance the dependability of their services, port authorities have begun adopting different power sources for the energy-hungry equipment in ports, namely electricity. It has been determined that electrifying cargo handling equipment and trucks with batteries might result in energy and GHG reductions of between 60 and 70 percent (Dhupia et al., 2011; Yang & Chang, 2013).

Explaining the smart grid is an electric power system that uses various cutting-edge technologies, such as communications networks, to efficiently control and manage the generation and distribution of electricity. According to the European Regulatory Group for Electricity and Gas, a smart grid is an electricity network that can efficiently incorporate all connected users' behaviour and actions (Yoldaş, 2017). There are five main features to distinguish the smart port, they are as follows (Yau, 2020).

- "Use of technologies such as data center, communications, networking, and automation"
- "Cluster management, such as shipping companies and their stakeholders, expanded worldwide"
- "The use of smart technologies leads to increase energy efficiency and reduce GHG emissions"
- "Development of hub infrastructures to raise partnership among various global ports"
- "Smart port services, such as vessel and container management"

Figure 2:The topology of the seaport microgrid



Source : "Toward Future Green Maritime Transportation: An Overview of Seaport Microgrids and All-Electric Ships," IEEE Trans. Veh. Technol., vol. 69, no. 1, pp. 207–219, 2020(Fang et al., 2020).

The carbon dioxide emissions from the Noatum Container Terminal Valencia (henceforth NCTV) in the Port of Valencia, Spain were calculated with a specific focus on the terminal emissions, measuring the energy utilized and the CO_2 emissions of the equipment used for and during terminal operations. Given the significance of this container terminal within the network of Spanish ports, NCTV offers a berthing line of 1780 meters, 93 hectares of yard space for container storage, and 7 extra meters for container services. The port is equipped with 1020 reefer container plugs and has 19 Ship-to-Shore (STS) cranes, 56 Rubber Tyred Gantry (RTG) cranes for handling yard containers, 4 reach stackers, 23 trucks, and 66-yard tractors (Green Cranes, 2014). Reefer containers and ship-to-shore cranes are the two primary consumers of electricity, accounting for 47.87 and 33.90 percent, respectively, of NCTV's total electrical usage. It should be noted that while the electrical consumption of offices and lighting changes less, the electrical consumption of both is greatly influenced by the volume of container traffic as given in below table 01 with the tons of CO_2 emitted from the diesel used for types of machinery (Martínez et al., 2019).

Table 1: NCTV CO_2 Emissions in 2011

	Type of Consumer Centre	2011			
		kWh	CO_2 Tonnes	kg CO_2/TEU	kWh/TEU
Electrical Consumption	**STS Cranes**	6 510 256	2180.935	1.14	3.40
	Yard Lightning	2 438 803	816.999	0.43	1.27
	Offices	1 061 346	355.551	0.19	0.55
	Container Reefers	9 193 395	3070.787	1.60	4.81
	TOTAL	**19 203 800**	**6424.272**	**3.36**	**10.03**
	2011 **Type of Consumer Centre**	**TOEs**	**CO_2 Tonnes**	**kg CO_2/TEU**	**Litres/TEU**
Diesel Fuel Consumption	**RTGs**	3266.7	9996.102	5.20	0.0017
	Yard Tractors	1684.6	5154.876	2.68	0.0009
	Reach Stackers	163.9	501.534	0.26	0.0001
	Empty Forklifts	52.8	161.568	0.08	0.0000
	TOTAL	**5168.0**	**15 814.080**	**8.22**	**0.0027**
	TOTAL (electrical + diesel)		**22 238.352**	**11.58**	

Source: Energy efficiency and CO_2 emissions of port container terminal equipment: Evidence from the Port of Valencia. (2019)

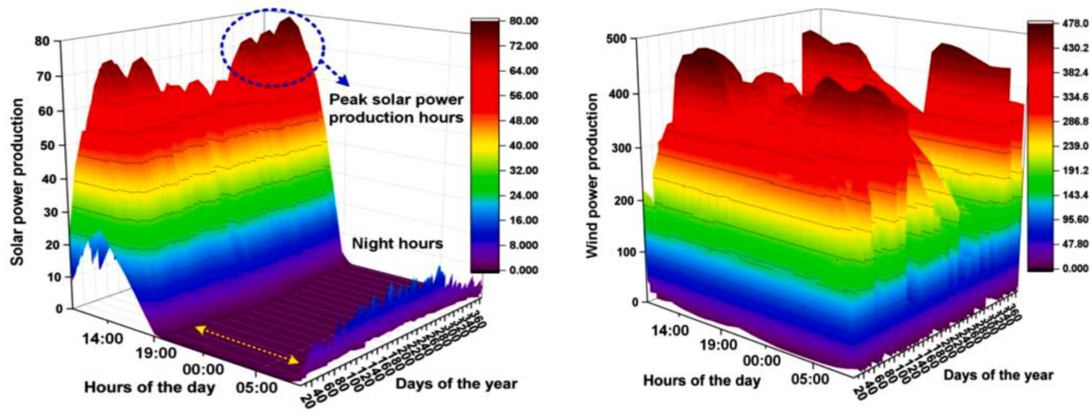
GHG emissions in many ports are based on detailed inventories in various ports across various nations. For instance, emissions were estimated to be 280,558 tonnes

CO_2 per year in the port of Chennai, India, and 331,390 tonnes GHG per year in the port of Barcelona (2008 inventory). 548,075 (CO_2) tonnes in five major UK ports in 2008; 6172 (CO_2) tonnes in the Port of Limassol, Cyprus; 580,128 (CO_2) tonnes in the Port of Shenzhen (2013); and 15,814 (CO_2) tonnes in the Port of Valencia in 2011. Generally, port plans incorporate designs for eco-friendly and sustainable port environmental and energy management systems, as well as CO_2 emission reduction in expansion projects (e.g., port of Rotterdam expansion project Maasvlakte II) The technical and operational improvements, however, can be included into upcoming port designs. For example, in the ports of Amsterdam, Rotterdam, Antwerp, and Hamburg, ports may have plans to integrate with their cities for the production of renewable energy, carbon capture, Energy storage, and utilization, circular economy and recycling, waste management, and recovery and reuse of heat and steam from industrial activities (Alamoush et al., 2022).

2.3 Implementing RE sources in port premises

Reduced environmental impact and access to renewable energy are made possible by sustainable port construction and policies. RES installations, particularly given the growing demand for geothermal, wind, solar, tidal, and wave energy. Rooftop PVs are the most desired choice because they can generate a lot of energy and make use of unused space. In addition, a number of research studies highlight the use of wind resources near port regions or elsewhere. Because ports that are interested in placing wind turbines (WTs), either onshore or offshore, need large spaces, there appear to be limited, which results in a limited level of knowledge and skill in the technology. Despite being more energy-efficient than PVs and other RES, this technology is less favoured because of its high initial investment costs and poor social acceptance (Fossile et al., 2020). Special contracts with the wind farm developers governing the energy purchase protocol and the power grid must be negotiated for offshore WTs. Despite the fact that there is virtually always energy generation, even when the wind speed is low, it has been demonstrated that this technology can increase the efficiency of smart grids when combined with ESS (Sifakis & Tsoutsos, 2020).

Figure 3 *:* Wind and Solar power (kW) data Treads Hourly and Daily Basis

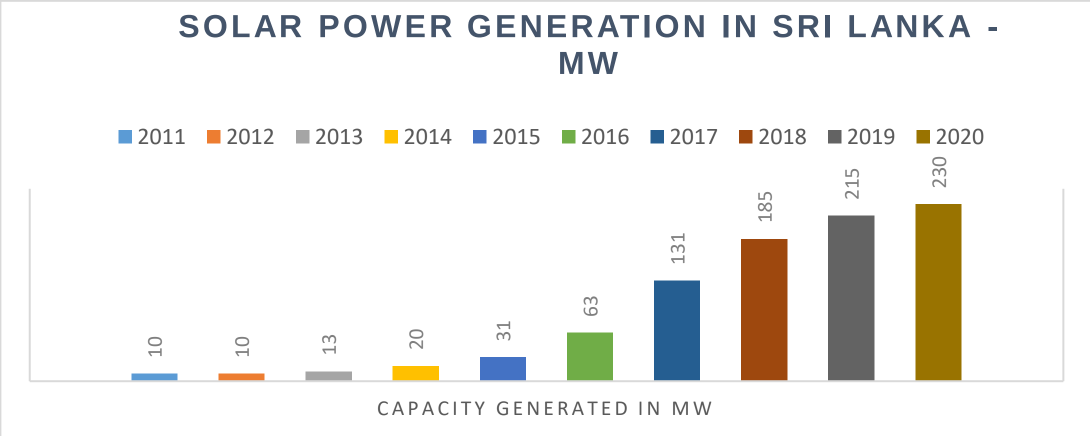


Source: Ahmad et al, 2021) Forecasting high penetration of solar and wind power in the smart grid environment using robust ensemble learning approach for large-dimensional data. *Sustainable Cities and Society*, *75*, 103269.

The above figure 3, the data for the solar comes from Huanghe Hydropower Golmud Solar Park in China and Wind data comes from the Longyuan Wind farm, located in China. The solar energy production runs from 7:00 am to 5:00 pm. 80 kW was the most solar energy that could be generated throughout the day. As can be observed, there is no solar energy production between the hours of 6:00pm to 6:00am. Throughout the year, the average producing power ratio fluctuates between 24 kW to 60 kW. The initial and final quarters of the year have higher solar power generation than the other quarters. From January to May, wind energy output is substantially higher than it is throughout the balance of the year. Wind energy generation is also high in November. 478 kW was the most wind energy that could be generated. In addition, it changes during the day. To illustrate the renewable energy data intervals, the day runs from 9:00 a.m. to 8:00 a.m. (Ahmad et al., 2021).

According to IRENA (2021), Figure 4, mentioned the solar power generation in Sri Lanka.

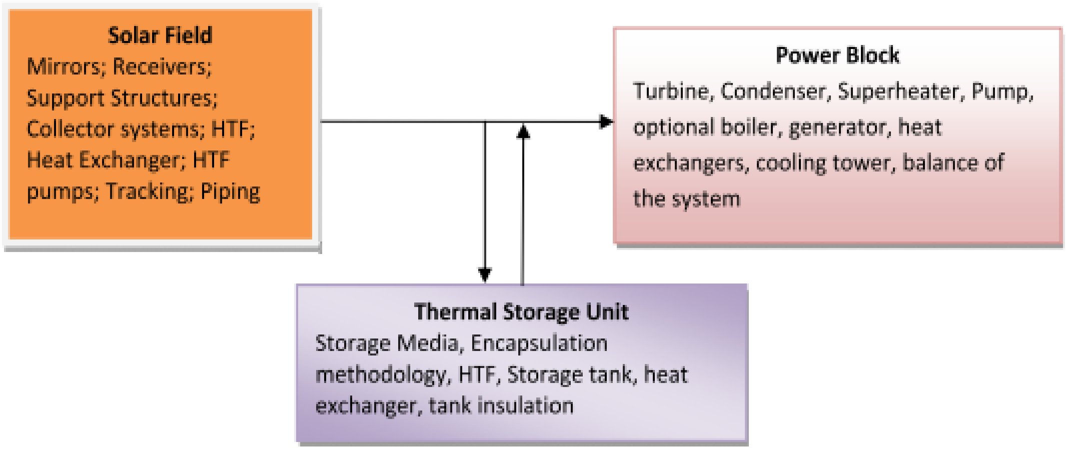
Figure 4: Solar Power Generation from 2011 to 2020 in Sri Lanka



Source: Adopted from IRENA,2021- Renewable Energy statistics

Solar Thermal Storage: Concentrating solar thermal power, or CSP as it is more generally known, stands out from other renewable energy sources because, despite being variable like solar photovoltaics and wind, it is very dispatchable due to its simple coupling with thermal energy storage (TES) and conventional fuels. TES is superior than mechanical or chemical storage systems in a number of ways. When comparing to certain other storage technologies, TES often offers lower initial costs and extremely high operating efficiency. Figure 5 illustrates the levels of components TES (Kuravi et al., 2013).

Fi*gure 5*: Main parts of a CSP plant and their components.



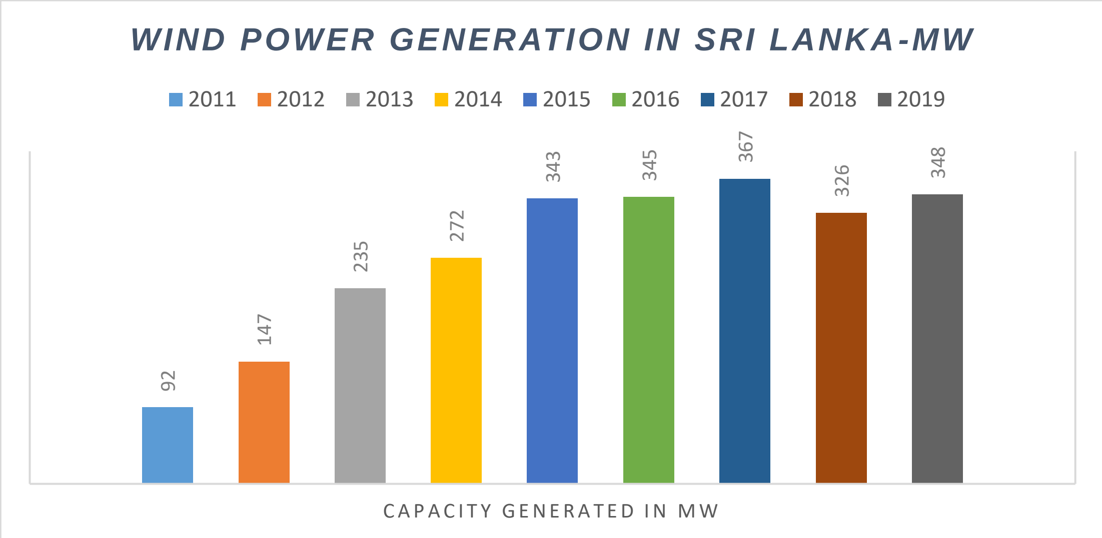
Source: Thermal energy storage technologies and systems for concentrating solar power plants. *Progress in Energy and Combustion Science*, *39*(4), 285-319.

Wind Power: The seven NREL classes, measured at a height of 100m, are illustrated with potential wind power density (W/m2). In comparison to the global distribution of wind resources, the bar chart displays how the nation's land area is distributed among each of these categories (IREANA, 2021).

The use of wind energy can reduce reliance on fossil fuels because it is widely available everywhere (Nelson & Starcher, 2018). Recent advancements in wind energy production and dropping unit costs make this renewable energy source a potential substitute for other energy sources. Although offshore wind farms have a high energy density, up until now most wind energy has been produced onshore. In terms of output capacity, this may potentially be compared to conventional power plants. In comparison to onshore surfaces, impediments that generate turbulence to the wind on the sea surface are less disruptive. Thus, the production of wind energy is used more frequently (Kazak, 2017).

For wind generation, the trend of declining costs is still present. LCOE for onshore and offshore wind declined by 13% and 9%, respectively, notwithstanding the effects of COVID-19(IRENA, 2021). The following mentioned in Figure 5, the wind power generation in Sri Lanka from 2011 to 2019. Due to less efficiency and high rental cost in Hambantota wind farmed has removed in 2018.

Figure 5: Wind Power Generation from 2011 to 2020 in Sri Lanka



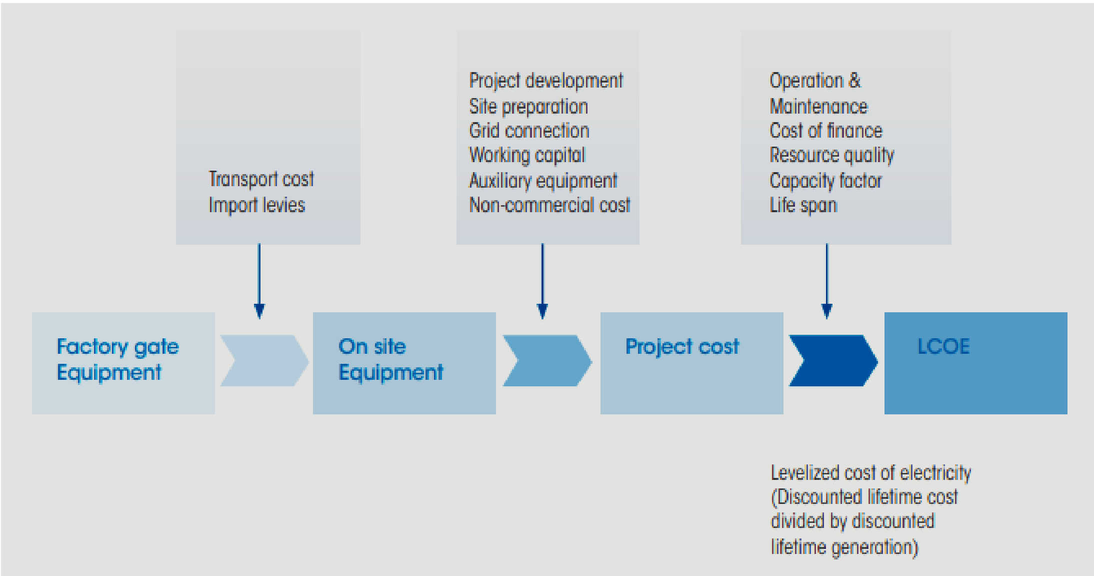
Source: Adopted from IRENA, 2021- Renewable Energy statistics

64% to 84% of the total installed costs for wind turbines on land are made up of grid connection fees, building fees, and other expenses. The cost of offshore wind farms is higher, ranging from USD 4000 to USD 4500/kW, with the cost of the wind turbines making up between 44% and 50% of the whole cost. Operating and maintenance expenses (O & M) can make up 11% to 30% of the LCOE for an onshore wind plant. In the largest wind markets, O&M expenses for onshore wind farms range from USD 0.01/kWh and USD 0.025/kWh on average. Due to the challenges given by the offshore environment, the O&M expenses of offshore wind farms are greater and can range from USD 0.027/kWh and USD 0.048/kWh. Onshore wind farms have the opportunity to cut costs toward best practice levels, while offshore wind farms should experience cost reduction over time but will always have higher costs than onshore (IRENA, 2012).

Currently, the most affordable methods of producing new electricity come from renewable energy sources. The cost of energy for a total of 162 GW, or 62% of the new renewable power production capacity added globally in 2020, was lower than the cost of the lowest source of new fossil fuel-fired capacity. A total of 644 GW of renewable power generation capacity has been added since 2010 with predicted costs that are less expensive than the least expensive fossil fuel-fired option (IRENA, 2021).

Based on the renewable energy source, capital and operational expenses, and the efficiency/performance of the technology, the LCOE of renewable energy technologies vary by technology, nation, and project. This analysis's methodology is based on a straightforward discounted cash flow (DCF) analysis (IRENA, 2012).

Figure 6: Renewable Power Generation Cost Indicators and Boundaries

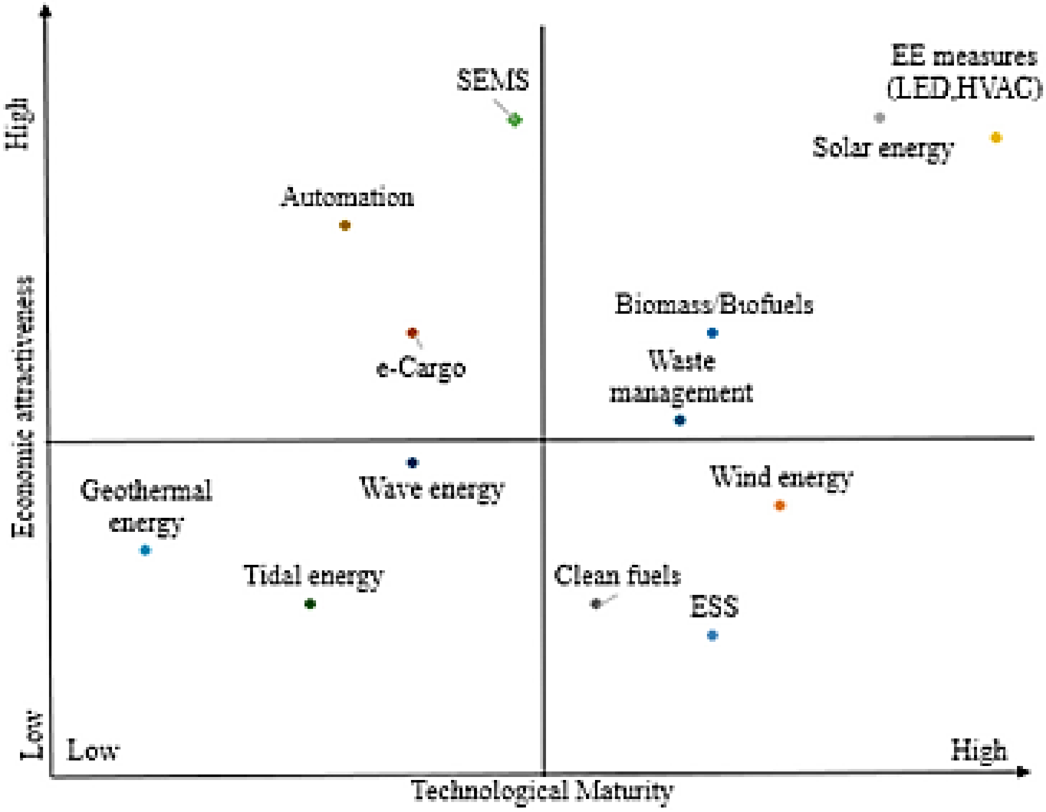


Source: IRENA Report, 2012

Tidal and wave energy are the two most popular methods of using ocean resources. However, even if they can be projected at some point, they both currently share several significant drawbacks, including the extremely high cost and low reliability of such machinery (Hiranandani, 2014). Although both of these technologies are developing, they are still in their infancy and are not favored by the port authorities; there is insufficient literature on the subject (Nikolaos, 2020).

Following Figure 7 mentioned the Economic Attractiveness and Technological Maturity diagram considering both parameters.

Figure 7: EATM diagram of the Renewable Energy technologies and techniques



Source: Sifakis, & Tsoutsos (2021). Planning zero-emissions ports through the nearly zero energy port concept.

According to IRENA (International Renewable Energy Agency), 2021 report total world renewable energy generation Capacity 2,802,004 MW in the year 2020. Furthermore, 2,352 MW Capacity was generated from renewable energy in Sri Lanka. In order to achieve sustainable development, energy access, energy security, and low-carbon economic growth and prosperity, IRENA advocates for the widespread adoption and sustainable use of all renewable energy sources, including bioenergy, geothermal, hydropower, ocean, solar, and wind energy (Arvydas et al., 2021). In spite of global uncertainty, according to new data from the IRENA, renewable energy grew in 2021.

According to the Renewable Capacity Statistics (2021) study, hydropower generated 1.23 TW of the total global renewable energy capacity. Together, solar and wind-generated 88 percent of the new renewable energy capacity. With a 19 percent increase, solar took the lead, and wind saw a 13 percent increase. With 849 GW compared to 825 GW, solar capacity outperformed wind in total.

Making sure the industry's growth paradigm is sustainable, just, and socially responsible while relying on a clear and realistic economic offer is essential to wind energy's role as a protagonist of the energy transition, a significant change in how the world produces and consumes energy (Joyce Lee, 2022).

Salem & Seddiek (2016) demonstrate that there are a few variables that could influence whether using the solar system as a power source is appropriate for maritime applications.

1. Availability of high solar radiation,
2. Existence of an adequate area exposed to the sun,
3. Availability of a suitable grid-connected PV solar power system,
4. Techno-economic selection of available solar panels,
5. Scientific preparation of the system layout.

The ports of Hamburg, Zeebrugge, Rotterdam, Venice, and Kitayjush have successfully integrated wind energy, and Genoa plans to do the same in the near future to save a significant quantity of CO_2. Similar to this, the offices at the port of Hamburg use solar energy to heat their water (Bjerkan & Seter, 2019).

2.4. Renewable Energy for GHG mitigation measures and regulations

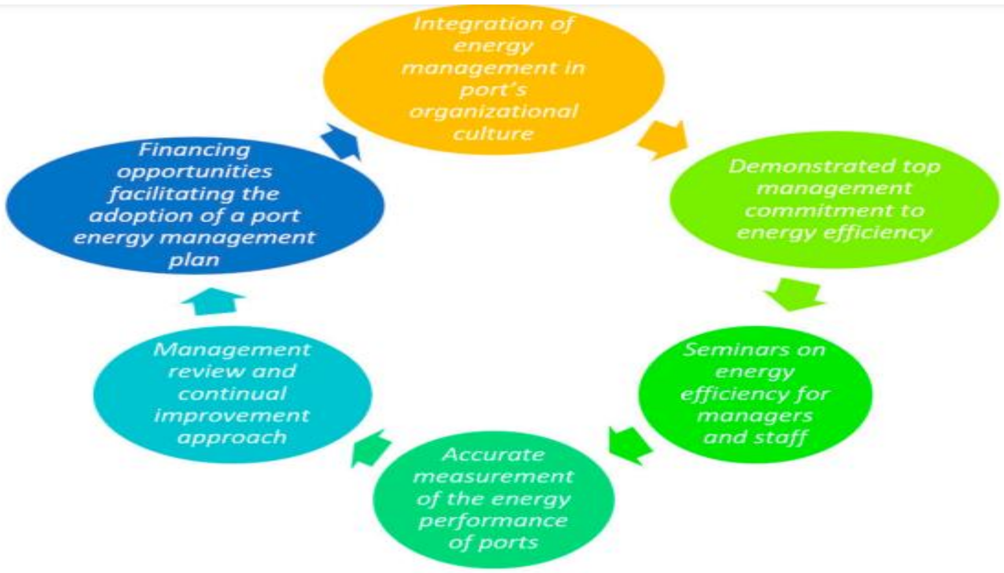
The backbone of world trade is maritime transport, which carries out nearly half of all trade worldwide. Because of this, the energy demand for maritime shipping, including ports, increased by an average of 2.6 percent year between 2016 and 2019. (UNCTAD, 2019). This rising energy demand has an impact on energy prices, greenhouse gas (GHG) emissions, and other pollutants. According to the 4th International Maritime Organization (IMO) GHG assessment, the shipping industry's share of air emissions increased from 2.76 percent in 2012 to 2.89 percent in 2018 and is expected to rise even further (IMO, 2020). Controlling the energy demand or boosting commerce would be very helpful to lower transportation costs because greater energy costs are also a significant burden for the ports. Similar to this, the creation of green ports reduces the emissions of hazardous gases and boosts productivity (Acciaro et al., 2014). Energy efficiency is, in every sense, a strategy for using less energy to produce the same amount of useful power. The fundamental goal of port authorities is to validate and adopt policies, technological solutions, and the incorporation of renewable energy (REs) sources in order to achieve large energy savings (Iris & Lam, 2019).

Important environmental concerns that the ports must address include CO2 emissions, air pollution, noise, shipping congestion, and garbage (Blackman, 2020). Because of the maritime sector, CO2, nitrogen oxides (NOx), and sulfur oxides (SOx) are produced at rates of 2.2%, 15.2%, and 6.2%, respectively (Siemens, 2017). It is crucial to put environmental controls in place and manage the external consequences of port operations in order to combat the problem of global climate change and promote the image of green ports. Many ports throughout the world are making significant efforts to combat the negative effects of GHG emissions (Tichavska & Tovar, 2015). The Port of Shanghai and Tianjin have revised their legislation to require the installation of OPS at all new terminals as a result (Siemens, 2017). Similar measures are being taken by the ports of **Hamburg, Helsinki, and Antwerp** to lessen their negative effects on the environment (HPA, 2021). For instance, the city of Hamburg has chosen to cut CO_2 emissions by increasing renewable energy sources and gradually phasing out coal energy sources. In addition, the port of Helsinki has made a commitment to become completely carbon-free by implementing the Carbon neutral Helsinki Action Plan 2035, which places a strong emphasis on energy efficiency and renewable sources of power (Port of Helsinki,2020). Moreover, the port has also made the decision to reduce energy use by updating the heating system, installing LED lighting, and installing a solar system in the port area until 2035(Port of Helsinki, 2020). Another sizable port in Germany, **Niedersachsen** Port, adopts environmental protection measures on issues including greenhouse gas (GHG) emissions, air pollution, and energy. It handles 30 million tonnes of cargo annually. Regarding this, the amount of direct greenhouse gas emissions has decreased by an additional 25% since 2017 and all outdoor lighting in Ports-operated areas has been upgraded to LEDs (Niedersachsen Port, 2019).

Similar to this, the port of Singapore has provided 25% charge reductions for vessels utilizing alternative technology to lower GHG emissions. Nearly 70 million USD have been invested by Singapore's port authority in greening the nation's ports and related technology. The European ports set a 2025 deadline for the adoption of OPS and provided 20–50% subsidies for OPS's success (Sdoukopoulos, 2019).

2.5. Implementing Environmental Management Systems (EMS) for ISO 50001

Figure 8: Guidelines and best practices for the implementation of a port energy management plan.



Source: Christodoulou & Cullinane, (2019) Identifying the Main Opportunities and Challenges from the Implementation of a Port Energy Management System: A SWOT/PESTLE Analysis. *Sustainability*

Individual ports might make improvements and best practices that the port industry, its organizations, and the states where ports are located could embrace are included in the guidelines for the effective deployment of a port energy management system in Figure 8. Ports are required to create an energy management strategy in accordance with the ISO 50001 energy management standard, taking a number of criteria into account. From the beginning the energy management goals, regulations and standards need to be set Internationally, Nationally and regionally. After the port energy strategy has been created, information on the energy requirements as well as viable solutions for enhancing the port's energy efficiency should be obtained. Measures to improve energy efficiency should be chosen based on their ability to lower CO_2 emissions, their affordability, their viability, the availability of funding sources, and other factors (Boile et al., 2016).

According to Figure 8, The Change of organization that a port energy efficiency management plan entails and potential resistance from the management and staff present the biggest obstacles to its successful implementation. This could be avoided by increasing management and staff participation in and engagement in the implementation of the port energy management plan as well as their ongoing training on energy efficiency issues. Only if the senior management of the port proves its commitment to the reduction of energy usage by including energy management in its strategic policy and conveying this priority to the management and personnel can energy management be successfully integrated into a port's culture. The duties of a company's top management are spelled out in detail in the ISO 50001 standard. These standard states that top management is in charge of determining the scope of the energy management system's applicability, developing and maintaining the company's energy policy, designating an energy officer, providing the necessary technical, staffing, and financial resources, ensuring internal communication, defining the strategic energy objectives, ensuring meaningful energy performance indicators, and carrying out management reviews (Jafarzadeh, 2014). Moreover, the successful adoption of a port energy management plan and the acceptance of energy management as a part of the organizational culture of the port depending on the port management and staff, who will implement the port's energy efficiency measures, being aware of the port's energy policy, as well as being continuously trained and actively involved in energy conservation. In order for variations from the initial energy goals to be obvious and examined by the port management, the success of the various energy efficiency measures should be evaluated through an accurate performance monitoring system that contains quantitative and measurable data. Only regular management reviews will allow ports to continuously increase their energy efficiency. New energy objectives could be developed aiming for larger reductions in the port's energy usage based on the outcomes from the deployment of the energy efficiency measures and their comparison with the necessary energy objectives.

These findings, which are comparable to those attained by implementing SEEMP in boats, show that successful energy management planning should incorporate more stringent criteria, such as those outlined in the ISO 50001 standard. The creation and development of ports' energy management plans should have financial support, such as funding from various international or regional organizations. These suggestions are among the potential remedies for reducing the organizational and financial constraints that contribute to the energy efficiency gap in shipping (Fenton, 2017).

Chapter 3

THEORETICAL FRAMEWORK AND METHODOLOGY

3.1 Overview of the Chapter

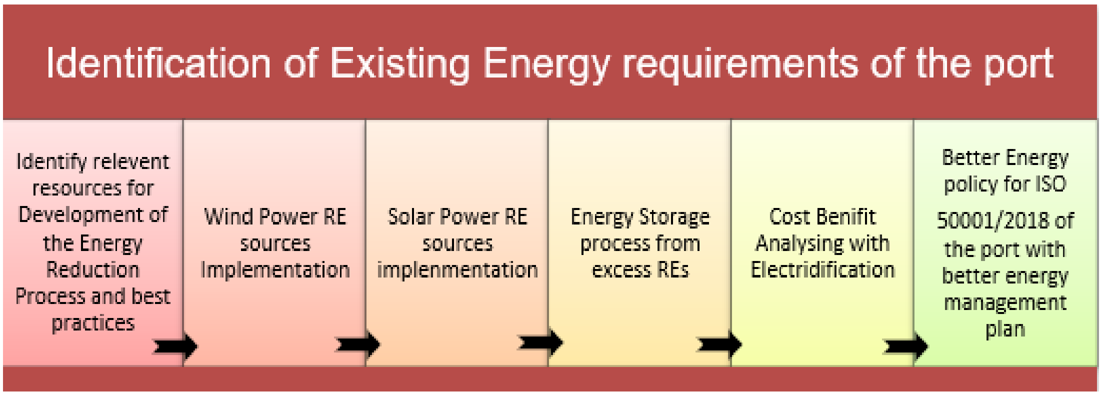
In order to achieve the aim and objectives of answering research questions itemized in chapter 01, a productive data collection method and theoretical criteria were considered. The qualitative primary will be gathered directly from SLPA Colombo Statics, Electrical, Mechanical, Marine, and operational divisions and secondary data will be from the official websites of SLPA, SAGT and CICT. More secondary data was obtained from the internet, books, previous dissertations, annual reports journal publications and international organizations such as IRENA, IEA and IMO. The cost-benefit analysis has been carried out in order to measure the Economic, Environment and Social advantages. The output of Wind, Solar renewable energies and their energy storage system, Cold Ironing, LED Lighting have been indicated to optimize the Energy of the port premises. In this research, altogether six measures have been discussed, with an investigation of three major renewable energy measures (see 1, 2, 3 below) and three energy-efficiency/electrification measures (see 4, 5, 6 below):

1. Total 18 nos. of offshore wind farms Levelized cost of Energy sensitivities (LCOE)-Python wind speed optimization has been applied
2. Total area of 200,000m^2 Solar PV panels with battery storage and converters for AC Power LCOE analysis.
3. Solar Aided Power Generation (SAPG) and Thermal Energy Storage System LCOE analysis.
4. Process of Cold Ironing and environmental benefit.
5. Yard Lighting System Cost-benefit analysis

6. Electrification of Logistic machineries

The implemented methodology is visualised in Figure 9 below, each and every method was conducted with the smart port concept in Port of Colombo, Sri Lanka.

Figure 9: Port Energy management process



Source : Developed by Author

3.2 Energy Baseline of the Port of Colombo.

According to the limitations mentioned in chapter 01, all the energy consumed in port premises was addressed. Total Electricity consumed and total diesel consumed are identified of the port premises in order to calculate the amount of fuel(diesel) and CO_2 reductions after electrification of logistic machineries in the port.

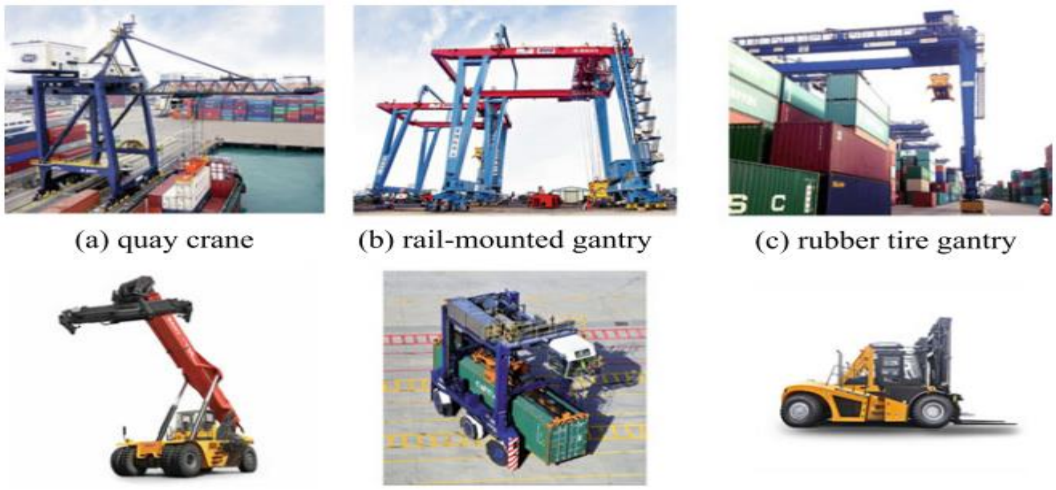
<u>**Metric**</u>	<u>**Baseline**</u>
Total Electricity demand per year	XXX kWh/Year
Cost of the Electricity per year	USD xxx /year
Carbon Factor of Sri Lanka	XXX kg/kWh
Total Diesel oil Consumption	XXX Ltrs/Year
Renewable Energy % in the Port	XXX %
Optimum Capacity from Wind farm	XXX
Optimum Energy from Solar Plant	XXX
Total No of CO_2 MT Can Reduce	XXX MT

3.3 Electrification of Port Cranes and logistic machines

According to the Port Diesel consumption of the Port Cranes and logistic machineries, it has been addressed the subject study to overcome the consumption of diesel. In order to supply the berthed ships with necessary logistical services, ports must use a variety of tools. In the following Figure 09, the key pieces of equipment are depicted as quay crane (QC), rail-mounted gantry crane (RMG), rubber-tire gantry crane (RTG), reach stacker (RC), straddle carrier (SC), and lift trunk (LT). For loading and unloading goods or containers from the ship side, employ QC. The key distinction between RMG and RTG, which are both used to stack containers in the stockyard, is that the former moves along a rail while the latter does so on rubber tires. Reaching a container in the stockyard requires the usage of RS. Within the stockyard, the containers are moved using SC and LT. Conventionally, the aforementioned machinery is nearly entirely manually operated. However, in recent years, highly automated port machinery, like automated RTG, RMG, LT, and SC, has started to be used to increase productivity and decrease labor requirements. Additionally, those devices' energy sources have expanded in variety (Fang & Wang, (2021).

Diesel and LNG are two fuel types that are frequently used in port-side operations and may power a variety of port-side machinery. In addition to what was stated above, electricity is the most universal energy source and can operate all of the major port-side equipment. It is also the most energy-efficient, controllable, and practical energy source. Electrification has made large ports into an unstoppable trend in both shore-side operation and yard-side operation mentioned in table 02(Fang et al., 2019).

Figure 10: Main Port side Logistic equipment



(a) quay crane (b) rail-mounted gantry (c) rubber tire gantry
(d) reach stacker (e) straddle carrier (f) lift truck

Source : S. Fang and H. Wang, (2021) Optimization-Based Energy Management for Multi-energy Maritime Grids,

Table 2: Energy sources of different port-side equipment

	QC	RMG	RTG	RS	SC	LT
Diesel	Yes	No	Yes	Yes	Yes	Yes
Electricity	Yes	Yes	Yes	Yes	Yes	Yes
LNG	No	No	Yes	Yes	Yes	No

Source: Two-step multi-objective management of hybrid energy storage system in all-electric ship microgrids. IEEE Trans (2019)

Energy savings = Existing Energy consumed – Fuel Saving after modification/ Electrification --------(1)

3.4 Wind Power Optimization in Port premises

The kinetic energy of the wind can be turned into electrical energy via a wind turbine. As given in equation (2), is necessary to determine the electrical Power(P) output from a wind turbine (Justus et al., 1978).

P (turbine) = 0.5 x ρ x A x v^3 x Cp ---------- (2)

where A is the cross-sectional area (swept area) of the wind turbine rotor (m^2), v is the wind speed (m/s), ρ is the air density (kg/m^3) and Cp power coefficient.

The energy (E) of a wind turbine is as follows,

E (turbine) = P turbine x time --------- (3)

By creating a computational script by Python Programming language for the geographical location of Colombo, Sri Lanka for 3 years (2019,2020 & 2021) wind speed(m/s) data the average wind power was calculated. The LCOE for 25 years life cycle was created (mentioned below) accordingly.

A good wind power evaluation program necessitates the execution of numerous tasks, including preliminary wind analysis, site selection, installation, and accurate collection of current wind flow patterns (Ttrevor, 2016).

3.5 Solar Power Optimization

In this research, the solar optimized solar power generation was discussed with the Solar Irradiation in the geographical area in Colombo Sri Lanka creating a computational script by Python Programming language years 2019,2020, and 2021. The workable space of **25,000 m^2** has been considered for the installation of PV panels including on the roofs of administrative buildings, on top of the controller cabins of the Gantry Cranes, and identified unutilized areas of the Port.

The calculation for electrical energy production is as follows in equation (4). E = energy (kWh), A = total photovoltaic (PV) area (m^2), r = photovoltaic panel yield (percent), H = yearly average solar radiation (kW/m^2), and PR = coefficient of performance, or coefficient of losses.

$E = A \times r \times H \times PR$ -------(4)

$P_{mp} = \eta_{pv} \times G_B \times A$ -------(5)

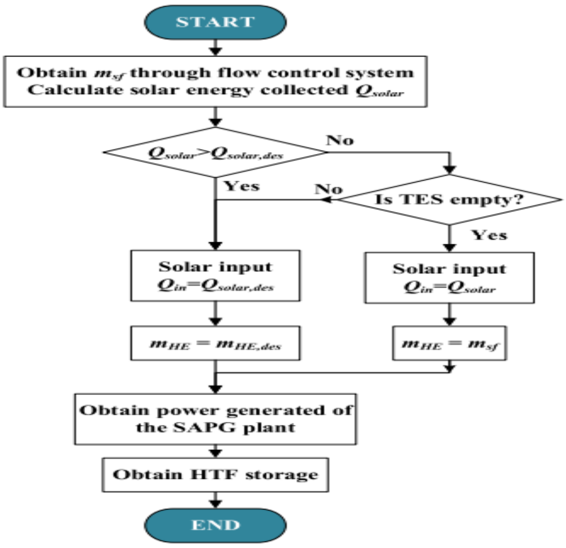
Furthermore, equation (5) can be used to determine the maximum power produced by a solar panel (Alizadeh et al., 2020).

Where, η_{pv} = Solar Cell's Efficiency, A= Module's Surface Area, P_{mp} = Solar cell's maximum power and G_{B} =. Global horizontal solar irradiance.

3.6 Solar Aided Power generation and Thermal Energy Storage system

Due to their dependability and affordability, photovoltaic (PV) and wind power are becoming increasingly popular as large-scale energy sources worldwide. On the other hand, the amount of electricity produced by solar or wind power might vary greatly over time. Therefore, it is necessary to maintain a constant supply of electricity and store any excess generated by balancing instantaneous electrical generation and consumption (Stringer et al., 2020).

Figure 11: Logical Flow of Excess Power storage



Source: On the use of thermal energy storage in solar-aided power generation systems. *Applied Energy*,

The following formula can be used to compute the LCOE ($/kWh) in order to analyze the SAPG plant's economic impact (Huang et al,2022)

$$LCOE = \frac{(C_{capital} \cdot A_F) + C_{O\&M}}{P_{solar,annual}}$$ -------------(10)

where $P_{solar,\ annual}$ (kWh) represents the amount of electricity produced annually from solar energy, $C_{capital}$ ($) represents the increased total capital cost after solar heat is added to the SAPG system, and $C_{O\&M}$ ($) represents the amount spent annually on operating and maintaining the solar field, and A_F represents the annuity factor, which is defined as follows.

$$A_F = \frac{r(r+1)^D}{(r+1)^D - 1}$$ ----------------(11)

r= Discount rate

D= Lifetime

3.7 Economic Evaluation Criteria

Following Economic calculation to find LOCE, NPV, for wind farm installation, Solar PV panels installation, Electrifications of Logistic machinery, Cold Ironing, and Proper lighting System.

The Levelized cost of energy method and the breakdown of the life cycle cost structure serve as the basis for the cost assessment technique. Three components make up the life cycle cost evaluation: CAPEX, OPEX, and DECOM (Levitt et al., 2011).

Predevelopment and permitting, production and purchasing, installation and commissioning, operation and maintenance, and decommissioning and disposal are all phases. The broad definition of life cycle costs or cost of economic viability (ECv) is given in equation (6) (Castro & Diaz, 2016).

$EC_V = \sum C_{CAPEX} + C_{OPEX} + C_{DECOM}$ ------(6)

The Levelized Cost of Energy is calculated by summing the costs incurred throughout a wind farm's lifetime with the total amount of power generated during that time. It is defined as the present value of produced energy in equation (7).

LCOE = Sum of cost over the lifetime / Sum of Electrical Energy Produced over the lifetime

$$\text{LCOE} = \frac{\sum_n \frac{C_n}{(1+r)^n}}{\sum_n \frac{E_n}{(1+r)^n}} \quad \text{--------(7)}$$

The net present value (NPV) of costs was calculated using a discounted cash-flow analysis in Equation 8(Raturi,2016).

$$NPV_C = \frac{\sum C_{CAPEX} + C_{OPEX} + C_{DECOM}}{(1+r)^n} \quad \text{-------(8)}$$

To account for the impact of the inflation rate as shown in the Equation in this study, the discount rate was changed in equation (9) Trailers

$$r = \frac{1+i}{1+e_a} - 1 \quad \text{------(9)}$$

where e_a is the inflation rate and *i* is the discount rate.

Chapter 4

ANALYSIS AND OBSERVATIONS FOR SMART PORT RENEWABLE ENERGY COST BENEFIT SCENARIOS

4.1. Port of Colombo, Sri Lanka

The Colombo Port Sri Lanka is the country's busiest shipping harbour and situated in the west part of the island, makes the nation a super-strategic maritime hub. The island nation of seven ports managed by Sri Lanka Ports Authority (SLPA) which is strategically located in the Indian Ocean, closer to one of the busiest maritime channels on the globe. Shipping lines from all over the world come to the port because of its unique location. Colombo Port is a marine center for South Asia that is expanding rapidly as the number one port in the region. Through the Colombo Port, cargo arriving from and towards Europe, East and South Asia, the Persian Gulf, and East Africa is conveniently and effectively connected. A container port is exactly what the Colombo Port mostly does. According to Drewry marine research, the Port of Colombo was placed 11th in the third quarter of 2018 for the Global Container Port Connectivity Index score, moving up two spots from the third quarter of 2017(Drewry Report, 2021). It handled roughly 7 million TEUs out of 7.25 million capacities in 2018.

Figure 12: Port of Colombo, Sri Lanka,

Source: Google map and www.slpa.lk

Table 3: Specification & World Ranking of Port of Colombo

Description	**Details**
UN/Locode	LK CMB
Geographical Location	LA:6.95349979 LO:79.8464996
Total Land Area	4.8 km2
Quality Standard	ISO 9001/2015
No. of terminals	06
Available Berths	51
Main Channel	Depth 20m, width 570m
Ranking	No.01 in South Asia/Indian Sub-Continent
	No.03 among ports in Indian Ocean Rim
	No.22 among 370 Ports Globally

Source: www.slpa.lk

The SLPA has transformed the ports and maritime sector, making the key drivers of the national economy and consolidating Sri Lanka's position among other leading maritime nations. In order to accelerate the country's port sector development and boost container volumes, SLPA has created a three-year development plan. These changes aim to elevate Colombo to the rank of Asia's maritime hub.

4.1.1 Terminal Information and Energy consumption

JCT- Jaya container terminal

This is the only state-owned terminal and it has been performing to the highest standards for over three decades and achieved ISO 9001/2015 certificates.
Main berth Length-1292m, Alongside depth- 12-15m, Area- 45.5ha, TEU capacity-53,990

ECT- East Container Terminal
Quay length- 450m, Depth -18m, Area-26 ha.

SAGT – South Asian Gateway Terminal

The first public-private partnership container terminal (PPP) in Sri Lanka, South Asia Gateway Terminals (SAGT), started operating in 1999, establishing the Port of Colombo as the premier gateway center for international trade to South Asia. As a preeminent international container port, we continue to offer the worldwide container shipping industry a competitive best-in-class service by utilizing a committed workforce.
Quay Length-940m, Depth-15m, Area-32ha, No. of berths-3

CICT- Colombo International Container Terminal

CICT is the deepest terminal in South Asia capable of handling the largest vessels afloat. It is committed to carry out operations in a responsible manner by protecting the environment. It's all RTGs have converted to electric. This resulted in an overall 40% reduction in Carbon emission in CICT. CICT has introduced best global practices in terminal operations. Area is 58 ha, Depth-18m

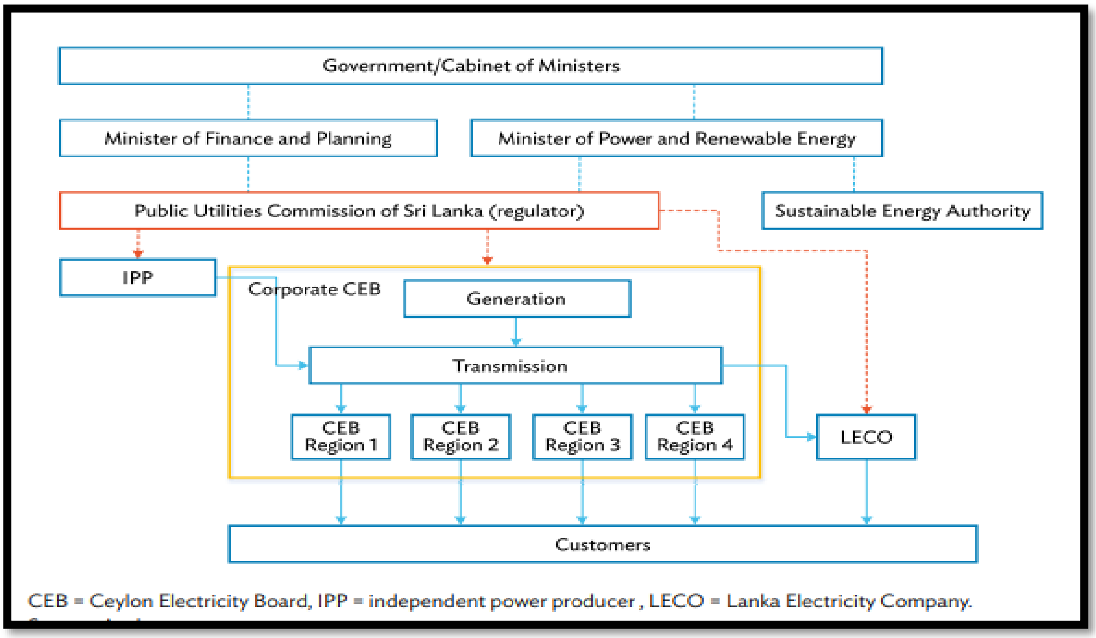
Table 4: Machineries of All terminals

Machine	JCT & ECT	SAGT	CICT	TOTAL	Electrical / Diesel
Quayside cranes	21	12	14	47	Electrical
Rail Mounted Cranes	4			4	Electrical
Rubber tired Container Transfer Cranes (RTG)	62	37	46	145	Diesel
Terminal Tractors & Tailers	141	83	82	306	Diesel
Reach Stackers	06	00	02	08	Diesel

4.2 Performance of the Power Generation and Energy Mix in Sri Lanka

The existing Electricity Industry Structure of Sri Lanka is shown in Figure 14. From 1969 to 1983, CEB served as the nation's monopolistic, vertically integrated electricity utility, handling all operations from generation to retail supply with the exception of distribution within some cities. While distribution outside of urban areas was still being expanded and run by CEB, distribution within some cities and towns was handled by the respective city and town councils. Sri Lanka established a state-owned firm (LECO) for the distribution of electricity in several towns and rural areas as part of the power sector reforms in 1983.The private sector has been able to generate electricity as independent power producers (IPPs) and small power producers since 1996 (Sri Lanka Energy Sector Assessment Strategy and Road Map, 2019)

Figure 13: Functionally Power Sector Monopoly of Sri Lanka

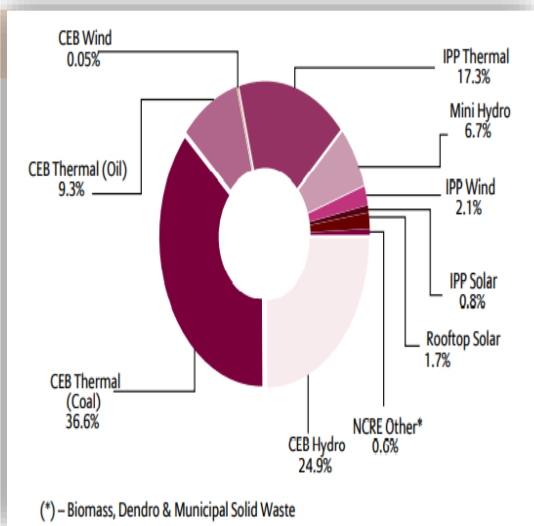


Source: Energy Sector Assessment Strategy and Roadmap of Sri Lanka-Asian Development Bank, (2019). https://www.adb.org

2020 could see a net rise in energy generation of 15,714 GWh. The whole Energy mix in Sri Lanka in 2020 can be illustrated as follows in table 5.

Table 5: Sri Lanka Energy Mix

Total energy generation of 15,714 GWh		Percentage
Hydro Power	3,913 GWh	24.90%
Thermal Coal Power	5,751 GWh	36.60%
Thermal Oil Power	1,461 GWh	9.30%
IPP Thermal Power	2,719 GWh	17.30%
Mini Hydro Power	1,053 GWh	6.70%
Wind Power	330 GWh	2.10%
IPP and Rooftop Solar Power	393 GWh	2.50%
Non-Conventional Renewable Power	94 GWh	0.60%



Source: CEB Annual Report 2020

Therefore, The Electricity Generation in Sri Lanka in 2020,

- Renewable Energy 36.8%
- Non-Renewable Energy 63.2%

4.2.1 Grid Emission Factor (GEF)

A new emission called the "Average Emission Factor (AEF)" was used for starting in 2016 to report the carbon footprint of power users. This emission factor has been computed by dividing the nation's total annual electricity consumption by the total emissions from the power sector. If a specific intervention is undertaken, such as adding a renewable energy project to the grid or adding an energy-saving project to the grid, the GEF shows how much CO_2 will be avoided. The GEF also indicates the annual CO_2 emissions from a power system. The Methodological Tool 07, named "Tool to Calculate the Emission Factor for an Electricity System," was used to calculate the Grid Emission Factor for 2017 and given in below table no 07(UNFCCC, Methodological tool to calculate the emission factor for an electricity system.2013).

Table 6: Average Emission Factor in different years of Sri Lanka

	2005	2010	2014	2015	2016	2017
Emission Factor of Sri Lanka power Generation (tCO_2/kWh)	0.3451	0.3158	0.5077	0.4753	0.5684	0.5845

Source : (*UNFCCC, Methodological tool to calculate the emission factor for an electricity system.*2013)

The **average generation cost** for one unit was 21.21 LKR/kWh in 2020 but they are selling at 16.72 LKR/kWh, according to the CEB annual report 2020.

4.3 Calculation of the Energy Baseline of Port of Colombo

Total Electricity consumed in 2021 in SLPA -95,422MWh

Diesel consumed in 2021 in SLPA including pilot boats and other supply boats -17,495MT/ (year 2021)

Carbon Factor of Sri Lanka - 0.5845 tCO2/ kWh*
*(Sri Lanka Energy balance, 2017)

Total CO_2 emission for Electricity Generation -55,774,159 tCO2/Year
Emission factor for Diesel -3.206 tCo2/t-Fuel**

**(IMO MEPC.1_Circ.684, Page 08)

Total CO_2 emission for Diesel consumption	- 56,088.97t CO2/Year
Therefore, CO_2 Emission per one year	- **55,830,247.97 MT**

The Baseline of Energy SLPA in 2021

Electricity Consumption JCT, ECT, UCT, SAGT & CICT	- 95,422 MWh
Diesel Consumption (Approx.)	- 17,495 MT
TEUs Handled	- 7.25 million of TEUs
No. of Employees	- 9,852
CO_2/TEU	- 7.7007MT/TEU
CO_2/Employee	-5,666.89
MT/Employee/year	
Unit Price for Electricity Generation	**-0.0592 USD/kWh**
(CEB annual report 2020)	
Total Cost for the electricity	**-5,653,353.69 USD**
Total price for the Diesel for Logistic machinery	**-24,392,403.75 USD**

(On 16.08.2022 Price per MT of Diesel is USD1,394.25
(https://www.oilmonster.com/bunker-fuel-prices/south-asia/colombo/58)

4.4 Renewable Energy Alternative Scenarios

In order to address the above-mentioned Energy baseline, three major RE implementation scenarios have been conducted. 1. Offshore wind farm installation 2. Solar Photovoltaic panel Installation and 3. Thermal Energy Storage System for the Solar in the Port Premises.

In order to decentralize the power generation sector and create a sustainable power supply, the energy transition, which is a crucial modification to the current production system, plays a part on a worldwide scale (Hentschel et al., 2018). Energy for port operations could be generated from a variety of sources, including clean fuels and renewable energy sources. It could also be connected to the utility grid. At times, the port area may produce energy. The incorporation of renewable energy sources, such as photovoltaic and wind power, presents grid management challenges in contrast to conventional energy sources because of the erratic power supply. Meanwhile, it is expanding more quickly due to its favourable environmental effects and economic viability (Nnachi et al., 2013).

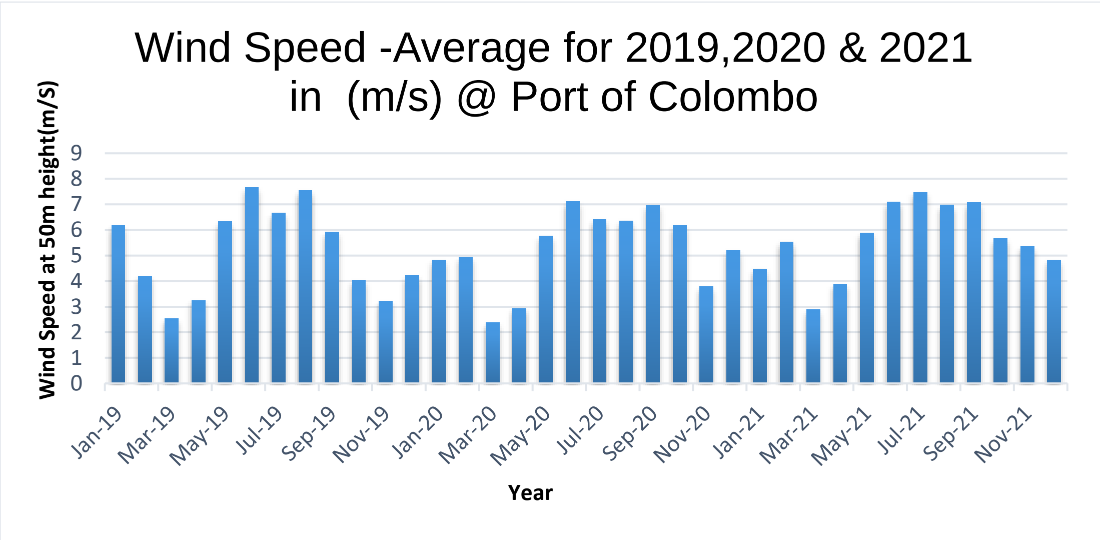
4.4.1 Offshore Wind Power implementation study

Step 01.

According to the Location of Port of Colombo (Location: Latitude 6.9412 N, Longitude 79.8118 E) using the National Aeronautics and Space Administration (NASA) through its satellite system and data providing regarding Wild Speed of Port of Colombo has been generated for the previous three years (2019,2020 and 2021) data (Annexure 01).

Wind Speed at 50m height was considered and taken the average wind speed of particular month. Following mentioned Figure 16, wind speeds for three separate above years.

Figure 15: Wind speed at 50m Height in 2019,2020,2021 in Port of Colombo.



Source: Adopted from https://power.larc.nasa.gov/data-access-viewer, by Author

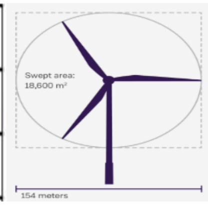
Step 02

The three-year average speed of the Wind (Annexure 01) - 5.596 m/s

As mentioned in Chapter 3, - 3.4 in equation 02, the wind power ($P_{turbine}$) generation of the particular month was calculated. The Selected offshore wind farm profile (SWT-7.0-154) is given below.

Table 7: Specification of Selected Windfarm profile

Wind Turbine Model	Specification							
	Rated Power	Cust in Speed(m/s)	Cut off Speed(m/s)	Rated Speed (m/s)	Rotor Dia(m)	Swept Area(m2)	No of Blades	Grid Freequency
SWT-7.0-154	7 MW	3	25	13	154	18600	3	50 Hz



Source : Siemens Gamesa renewable energy, https://www.siemensgamesa.com/en-int/products-and-services/offshore/wind-turbine-swt-7-0-154

Swept Area of the selected windfarm(A) - 18,600m^2

The air density– (ρ) - 1.225kg/m^3

The power coefficient. - Cp - 40% (Assumed)

Therefore,

$P_{turbine} = 0.5 \times \rho \times A \times v^3 \times Cp$

$P_{turbine}$ Average - $0.5 \times 1.225 \times 18000 \times 5.327^3 \times 0.4$

- 690,070.81 W

Actual Energy Per Year - 6,045,020,274.61 Wh

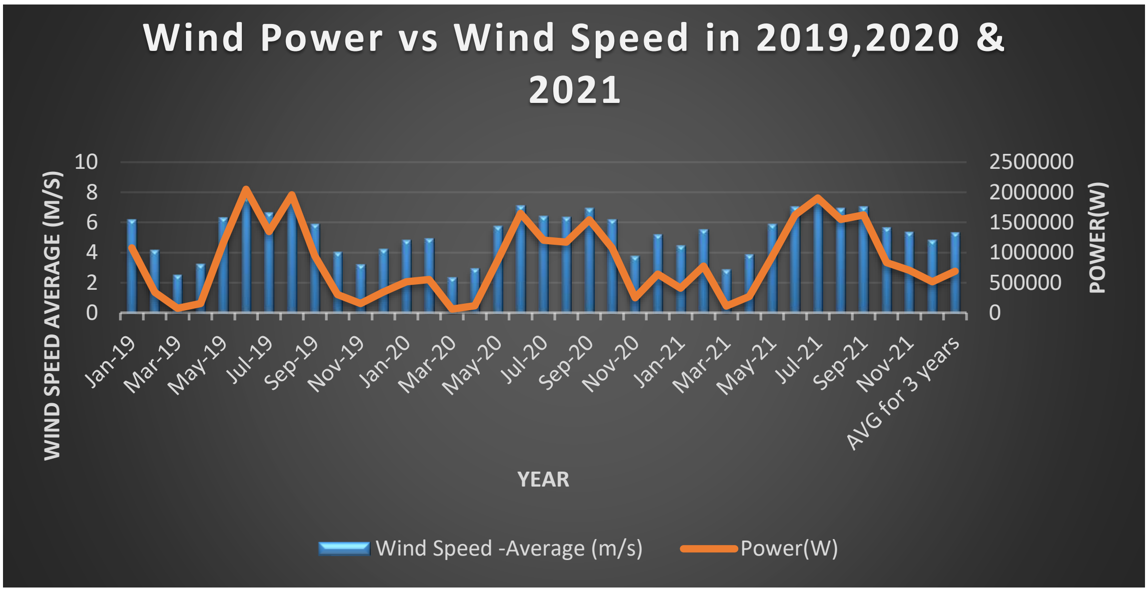
- **6,045.02 MWh**

Capacity Factor - Average Delivered Power/ Theoretical Maximum Power

- 690,070.80/7,000,000

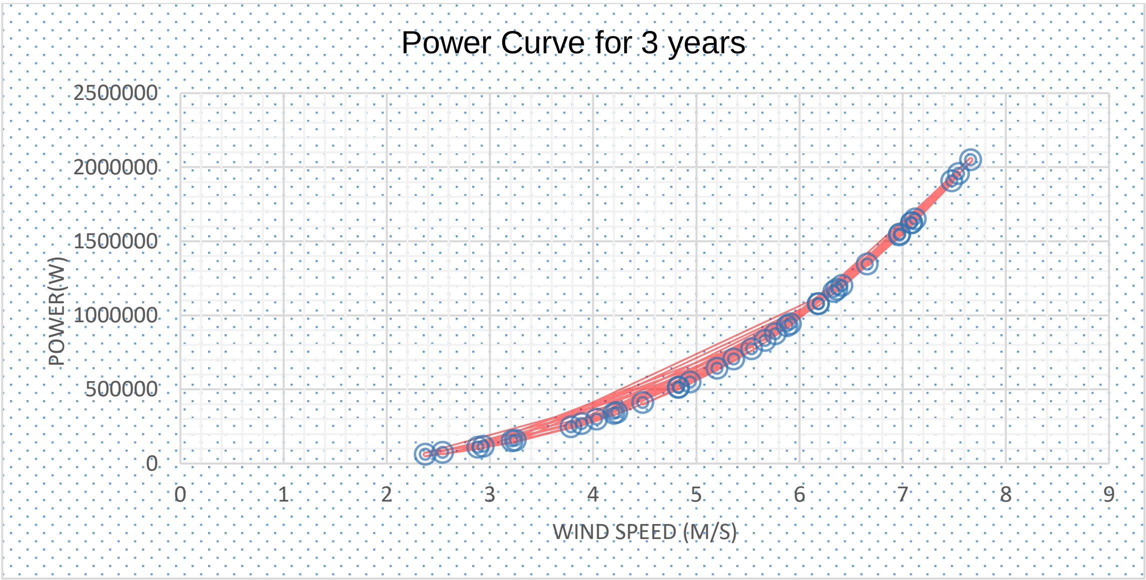
- **9.86%**

Figure 14: 2019, 2020, 2021 Wind Power Vs wind speed in Colombo, Sri Lanka



Source: Author

Figure 15: Wind Power Curve for 2019, 2020, 2021 in Colombo, Sri Lanka



Source : Author

Step 03

Due to some maintenance work and periodical repairs, the power generated by wind farms is assumed to be 90% at the port of Colombo offshore.

Therefore, as per the following table 8,

No of Wind farms required - Port Energy requirement per year/ Actual Energy Generated per Unit

- 95,422/6,045.02
- 17.54
- **18 Nos of wind turbines**

The Total energy Generated - 18 x 6,045,020.27kWh/unit

- **108,810,364.94 kWh**

Table 8: *No of Wind Turbines for the Port required annual demand*

Wind Project 1	**Size**	**Unit**	
Wind turbine	7	MW	
Actual Energy Generated after Losses	6,045.02	MWh/year	Actual
Availability	90.00%		Practical
Actual Energy Availability	5440.518247	MWh/Year	
Port Energy requirement per year	95,422.00	MWh/year	
No of Wind turbines required	17.54	**18**	Nos.
Total Power Generated in end of first year		**108,810,364.94**	kWh

Source: Author

Step 04

According to Alsubal, (2021), the total cost of the project has been categorized into three main parts; CAPEX, OPEX and DECOM and illustrated in table 9.

Table 9: Project Cost for the Wind farm

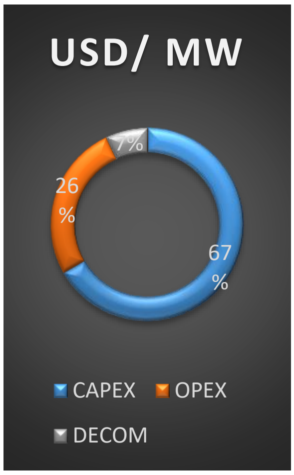
Phase	Cost Element	Cost per MW in (USD/MW)	Contribution to whole lifecycle cost %
CAPEX	**P&C**		
	Project Management	90,000.00	2.50%
	Legal Authorizing	7,901.00	0.22%
	Surveys	30,066.00	0.83%
	Engineering Activities	2,400.00	0.07%
	Contingencies	251,565.00	6.97%
	TOTAL P&C	**381,932.00**	10.59%
	P&A		
	Manufacturing and Procurements of the support structures	1,006,940.00	27.92%
	Wind Turbines	500,000.00	13.86%
	Power Transmission Systems	190,599.00	5.28%
	monitoring systems	5,873.00	0.16%
	TOTAL P & A	1,703,412.00	47.23%
	I&C		
	Cost for Local Authority	34,960.00	0.97%
	support structures and electrical systems	234,281.00	6.50%
	Commissioning Cost	570.00	0.02%
	Insurance Cost	49,504.00	1.37%
	TOTAL I & A	319,315.00	8.85%
	TOTAL CAPEX Cost	**2,404,659.00**	66.67%
OPEX	**O&M**		
	Rent of seabed	23,370.00	0.65%
	Insurance Against collision damages and design faults	87,305.00	2.42%
	Transmission Charges	430,350.00	11.93%
	Direct maintenance costs and indirect maintenance costs	60,325.00	1.67%
	Corrective Maintenance	188,100.00	5.22%
	Component and Proactive Maintenance	160,550.00	4.45%
	TOTAL OPEX	**950,000.00**	26.34%
DECOM	**D&D**		0.00%
	Port Charges	49,639.00	1.38%
	Removal Cost	236,850.00	6.57%
	Waste Management Cost	-43,045.00	-1.19%
	post decommissioning monitoring activities costs	8,589.00	0.24%
	TOTAL D&D	**252,033.00**	6.99%
	TOTAL Project Cost	**3,606,692.00**	100.00%

Source : Adopted by "Life Cycle Cost Assessment of Offshore Wind Farm: Kudat Malaysia Case. Sustainability 2021", 13, 7943. https://doi.org/10.3390/su13147943 by Author

Following mentioned the summary in the table 10, The one-time Capital Expenditure and Expenditure for Decommissioning cost (DECOM) after the lifetime of wind farms and 25 years of operational and maintenance cost.

Table 10: Summary of the wind Project Cost

Phase	USD/ MW	USD for 126 MW	USD for 25 years
CAPEX	2,404,659.00	302,987,034.00	302,987,034.00
OPEX	950,000.00	119,700,000.00	2,992,500,000.00
DECOM	252,033.00	31,756,158.00	31,756,158.00
Total	3,606,692.00	454,443,192.00	3,327,243,192.00



Source : Author

The Levelized Cost of Energy of the offshore wind farms (LCOE)

$$LCOE = \frac{\text{Sum of cost over the lifetime}}{\text{Sum of Electrical Energy produced over lifetime}}$$

Total CAPEX over 25 years -USD 302,987,034.00

OPEX of the first year -USD 119,700,000.00

Total OPEX for the 25-year lifetime with an annually 1% increase has been mentioned in Annex 02, - USD 3,380,710,980.00

One-time Decommissioning Cost - USD 31,756,158.00

In table 10, mentioned the first-year end generated energy from 18 wind turbines and 0.5% annual degradation mentioned in Annex 02.

First year-end Energy Generated -108,810,365 kWh

For 25 years generated energy - 2,563,131,670 kWh

Therefore LCOE **-** (USD 302,987,034.00+ USD 3,380,710,980.00 + USD 31,756,158.00)/ 2,563,131,670 kWh

- **USD 1.44958 /kWh**

Step 05

Net present value of the wind project (NPVc),

$$NPV_C = \frac{\sum C_{CAPEX} + C_{OPEX} + C_{DECOM}}{(1+r)^n}$$

The interest rate of the foreign loan was considered 5 % and the no. of years is 25 years.

As Illustrated in Annex 03.**1% increase in the Operational cost was considered and the annual cost of electricity for the exciting national grid has been taken as the income for the creation of the cash flow**. Therefore, the value was USD 5,653,353.69. The 3% of the annual increase in the price was taken as an assumption. Therefore,

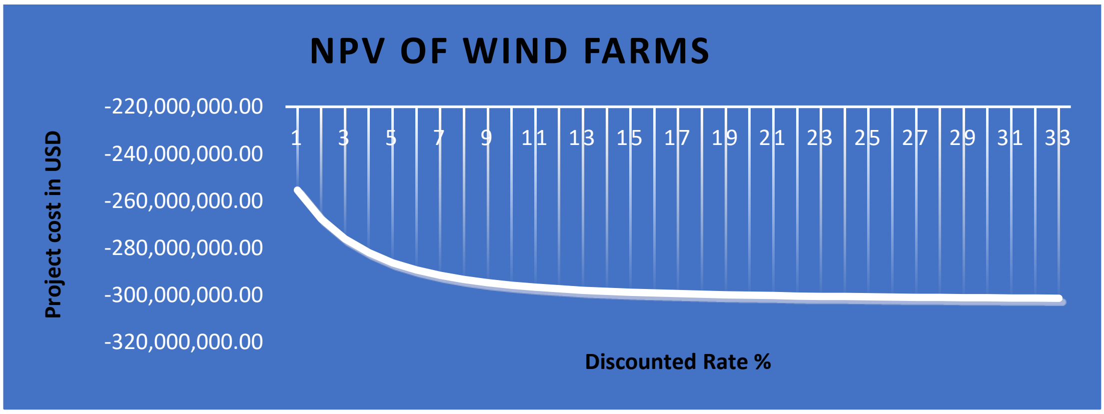
NPV - USD -255,417,004.00

IRR - (-10%)

Payback Period - 312 + years

Therefore, the installation of the 18nos. of wind farms represented negative financial feedback for this project. Following figure 20, is representing the negative feedback of the project.

Figure 16: NPV Curve of 18 nos. of wind farms



Source: Author

4.4.2 Solar Photovoltaic panel implementation Study

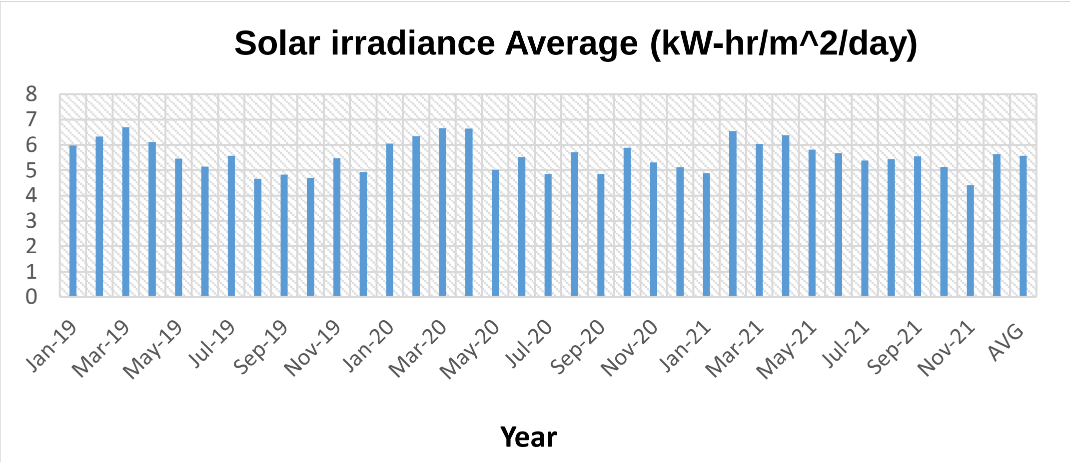
The procedure of 4.4.1 has been implemented for this too. Used the NASA MERA 2 Native Resolution Daily data in order to obtain the Solar irradiance (kW-hr/Sq meter /day) energy in the location of Colombo, Sri Lanka area at the all-sky surface category.

A variation of NASA's Goddard Earth Observing System (GEOS) Data Assimilation System is called MERRA-2. Daily processing of the GEOS 5.12.4 data by the POWER project team results in low latency products that are typically ready within 2 days of real-time and are appended to the end of the MERRA-2 daily time series. Every few months, the MERRA-2 values in the resulting daily time series are routinely updated (Bosilovich et al., 2016).

Step 01

Year 2019, 2020 and 2021, Solar irradiance (in kW-hr/m^2/day) energy was gathered by obtaining the average monthly figures (Annex 04) and it has been mentioned in below figure 21.

Figure 17: Solar Irradiance in Port of Colombo 2019, 2020 & 2021



Source : Adopted from https://power.larc.nasa.gov/data-access-viewer, by Author

Step 02

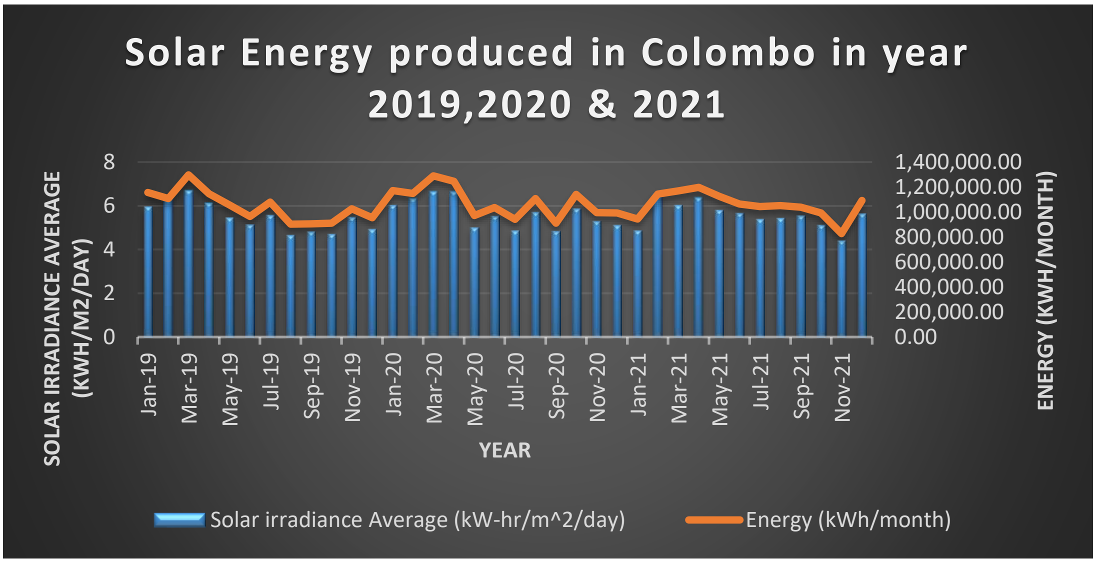
In mentioned periods of three years the Solar energy generated has been created below-mentioned equation. $P_{El\ solar}$ (Generated power of a given area).

$$P_{El.Solar} = \phi \cdot \eta \cdot A$$

In this power equation, ϕ, the solar irradiance mentioned in kW-hr/m^2/day, the equation emphasized the Energy of a given Space(A), here considered 25,000 m^2 for the calculation process.

η = 0.25 considered the efficiency of the solar cell. The calculated values are mentioned in Annexure 04 and illustrated below Figure 22.

Figure 18 : The Solar Energy produced in 2019, 2020 and 2021 in Port of Colombo



Source : Author

Step 03

The Total Energy generated in year 2021 - 12,694,322.75 kWh/ (25,000m^2 area)

Identified Port Energy Consumption in 2021 - 95,422,000.00 kWh

Total No of area 25,000m^2 units - 7.72 units

Therefore, total Area need - 187,922.59 m^2

Approx. - 200,000.00 m^2

Total Energy generated - 101,554,581.97 kWh/year

*Area of 5kW generated panel - 32m^2

Step 04

Table 11: The market Price of a specimen Solar panel

System Size	Estimated Costs	Number of Panels	Roof Space	Annual Electricity Bill Savings	Savings after 25 Years with SEG
3kW panel system	£5,000 - £6,000	12	22 m²	£160	£5,993
4kW panel system	£6,000 - £8,000	16	29 m²	£270	£9,240
5kW panel system	£8,000 - £9,000	20	32 m²	£320	£11,088
6kW panel system	£9,000 - £11,000	24	43 m²	£430	£14,533

Source : Green match power panels UK.https://www.greenmatch.co.uk/blog/2014/08/what-is-the-installation-cost-for-solar-panels

Required 5kW panels - $200{,}000m^2/32m^2$

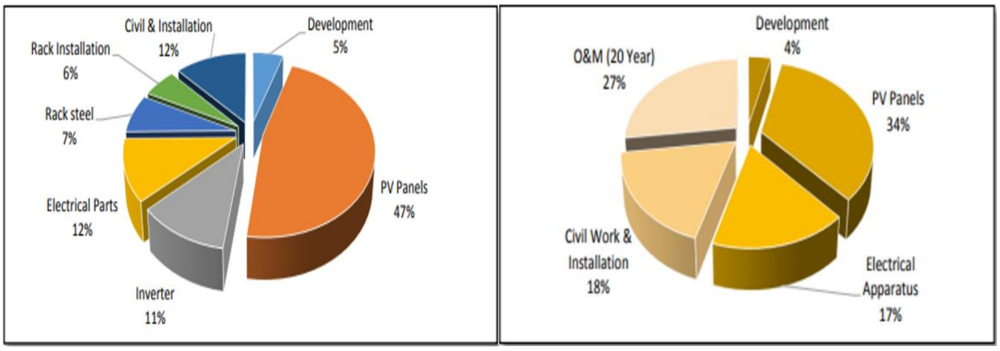
-6,250 nos.

Total Power of the plant -31,250 kW

-31.25 MW

According to Wang et al., (2011) the capital cost for per one watt was USD 1.184. According to Rumman et al., (2017), all the categories of the project cost has mentioned in the following figure 23.

Figure 19: Categories of cost for Solar plant in detail



Source : Life Cycle Costing of PV Generation System by Rumman et al., 2017

Accordingly, CAPEX and OPEX have been created and given in table 12. The decommissioning cost was not evaluated in this project.

Table 12: CAPEX and OPEX finding for the PV Project

Phase	Description	Percentage	$ per W	$ For 31.25MW for 25 years lifetime
CAPEX	PV panel	34%		
	Inverter			
	Electrical Parts	17%		
	Rack Steel			
	Rack Installation			
	Civil Installation	18%		
	Development	4%	1.184	37,000,000.00
OPEX	Maintenance	27.00%	0.44	13,684,931.51
The whole cost for 31.25MW	**50,684,931.51**			

Source: Author

CAPEX per MW - USD 1,184,000.00

OPEX per MW/Year - USD 437,917.81

LCOE for the 25 years lifetime Capex cost from the first year assumed a 1% increase and Energy generation degradation by 0.5% per year was assumed and mentioned in annexure 05.

LCOE : Total Lifetime cost/Sum of Electricity produced over the lifetime

: USD 423,506,251.00/2,392,214,798.31 kWh

: 0.1774 $/kWh

Step 05

Net present value of the 31.25MW Solar project (NPVc),

$$NPV_C = \frac{\sum C_{CAPEX} + C_{OPEX} + C_{DECOM}}{(1+r)^n}$$

The interest rate of the foreign loan was considered 5 % and the no. of years is 25 years.

As illustrated in Annex 06.**1% increase in the Operational cost was considered and the annual cost of electricity for the exciting national grid has been taken as the income for the creation of the cash flow. Therefore, the value was USD 5,653,353.69.** The 3% of the annual increase in the price was taken as an assumption.

Therefore,

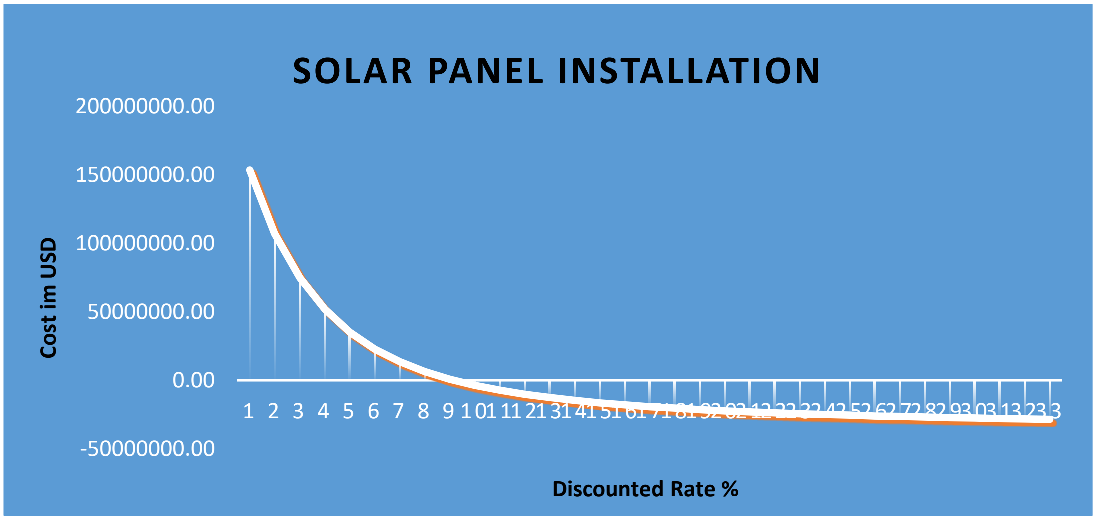
NPV - USD 62,392,330.48

IRR - 16%

Payback Period - 08 years

Following figure 24 illustrated the positive feedback of the project as NPV has a Positive value and 16% IRR is more than the 5% interest rate of the initial capital investment.

Figure 20: The economic positive feedback of PV installation in Colombo



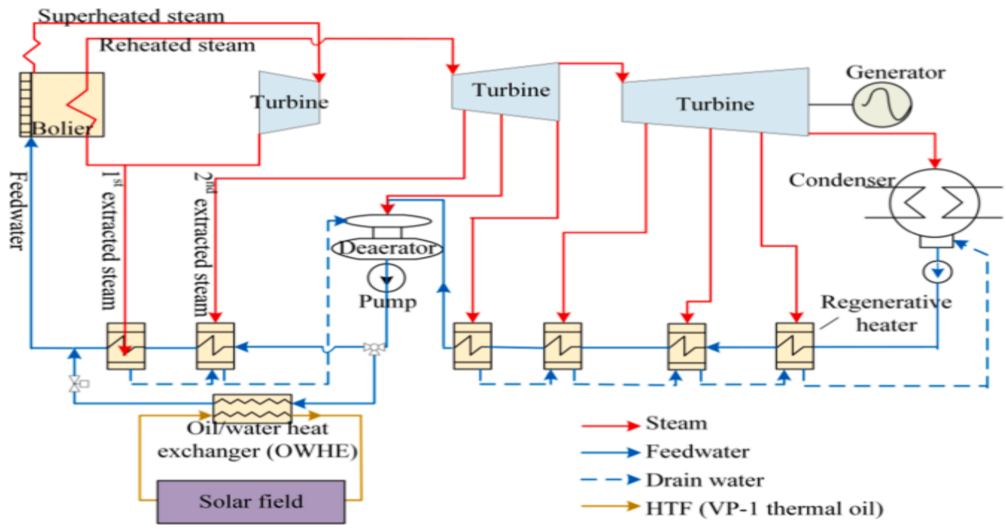
Source : Author

4.4.3 Thermal Energy Storage System

By using the power block for longer periods of time, thermal energy storage for concentrating solar thermal power (CSP) plants can assist overcome the intermittent nature of the solar resource and lower the Levelized cost of energy (LCOE). In general, sensible heat, latent heat, and thermochemical reactions can all be used to store heat (Kuravi et al., 2012).

Following figure 03 shows the typical plant for the installation to cater to energy requirements in the port of Colombo.

Figure 21: Schematic diagram of a typical SAPG plant to be integrated



Source : On the use of thermal energy storage in solar-aided power generation systems. *Applied Energy*,

Table 13 :TES and SAPG 31.5MW plant Cost

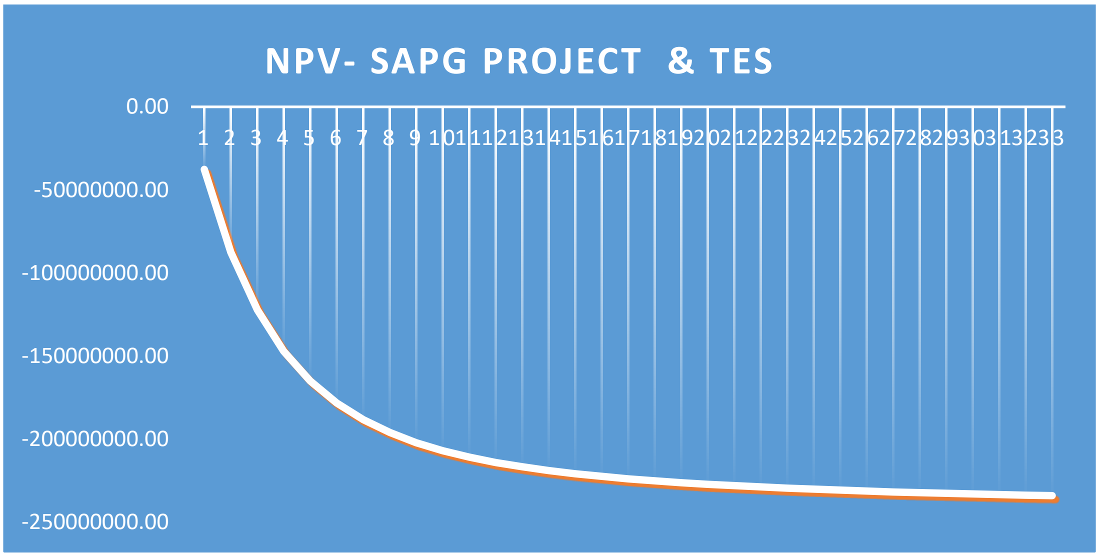
Thermal Energy Storage System (TES) -Port of Colombo	
Solar Aided Power Generation (SAPG)- 31.5MW capacity	
Direct cost	**USD**
Components of SAPG Plant	242,000,000.00
Boiler System	
Burner	
Drum	
Evaporation Heater:Water Wall	
Heater	
Superheater	
Reheater	
Economizer	
Air Preheater	
Turbine Subsystem	
Turbine Stage	
Condenser	
Regenerative Heaters	
Deaerator	
Solar Field System	
Solar Collectr Unit	
Oil /Water Heat Exchanger	
No. of TES 500 Units (TES)	989,100.00
Total Direct cost	**242,989,100.00**
Indirect cost from the direct cost	
Contingency -10%	24,298,910.00
Engineers, Construction & Procue-15%	36,448,365.00
Project, land , Management -3.5%	8,504,618.50
Total CAPEX	**312,240,993.50**
Operation and maintanace -1.7%	4,130,814.70
Total OPEX	**4,130,814.70**
Power Generation(kWh)/year	275,940,000.00
CAPEX for MW	9,912,412.49
OPEX per MW/year	0.13

Source : Adopted from “On the use of thermal energy storage in solar-aided power generation systems. *Applied Energy*, *310*, 118532” by Author.

As the total lifetime of the project is 30 years, LCOE has been mentioned in Annexure 07 and LCOE was **0.04811 USD/kWh**.0.5% of annual degradation for the power generation and a 1% increase for the Operational cost have been considered.

As per the attached Annexure 07 for the NPV and IRR calculation, the 5% interest rate and 3% increase of income have been considered. As the huge CAPEX and having less income against the cost the NPV value was a negative value and figure 26 represented the same.

Figure 22 : NPV Negative value representing - SAPG plant implementation



Source : Author

4.5 Implementation of energy-efficient LED Mast Lighting System of Port premises

According to the existing sodium mast lighting of SLPA following mentioned table 14,the cost-benefit analysis of implementing LED Mast Light for the port premises.

Table 14 :LED Mast lighting implementation cost benefit analysis by Author

LED Mast Light sub-Research		**UNIT**	**References**
Energy Consumption Per Hour of LED	150	Wh	1
Price of LED mast Light	1000	USD	2
The lifetime of LED bulb	50,000	hrs	1
Lifetime (years)	11.4155		1
Operational Hours	12	hrs	
No of Masts	50		2
No of Bulbs per mast	16		2
No of LED light needed	800		
Emission Factor of Sri Lanka	0.5845	Kg CO2/kWh	Sri Lanka Energy balance, 2017
Price of kWh of Electricity in Sri Lanka	0.0592	USD	Annual Report CEB 2020
Sodium Bulbs	800		2
Energy Consumption Per Hour of Sodium	1000	Wh	2
Energy Saving Per Hour of implementing LED	680	kWhr	
Energy saving per year	2,978,400	kWhr	
Cost for the savings of energy	40.256	USD / Hr	Energy Saving per hour *Cost of Electricity
The Lifetime Saving	1,212,800	USD	
Total Savings per year	106,241	USD	
Reduction of CO2 Per year	1,740.87	t CO2/Year	
Return on Investment	4.53717	USD/ year	

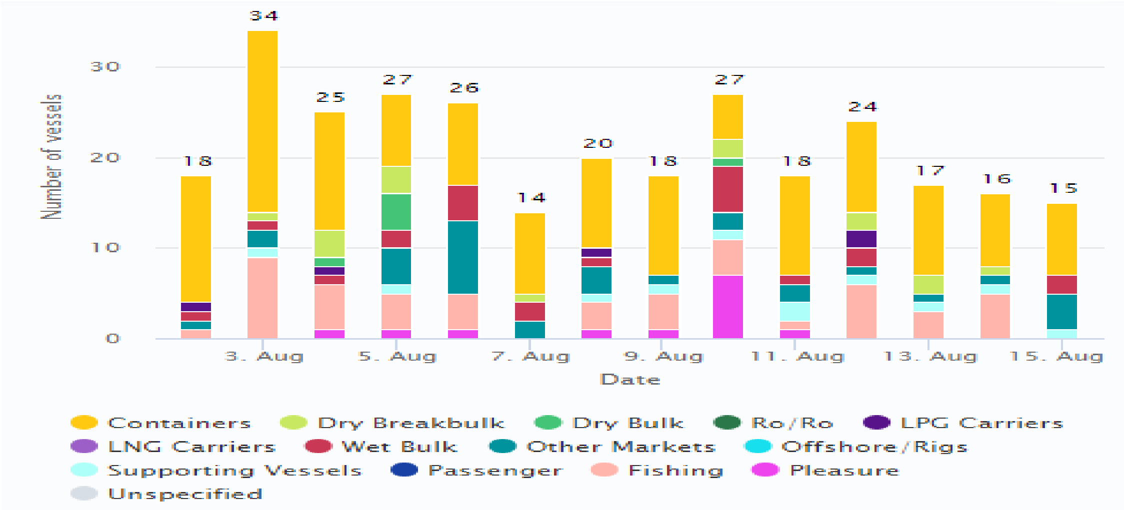
References

1. Van Duin, J. H. R., Geerlings, H., Froese, J., & Negenborn, R. R. (2017). Towards a method for benchmarking energy consumption at terminals: In search of performance improvement in yard lighting. *International Journal of Transport Development and Integration*, *1*(2), 212-224.
2. www.slpa.lk & direct data

Source : Author

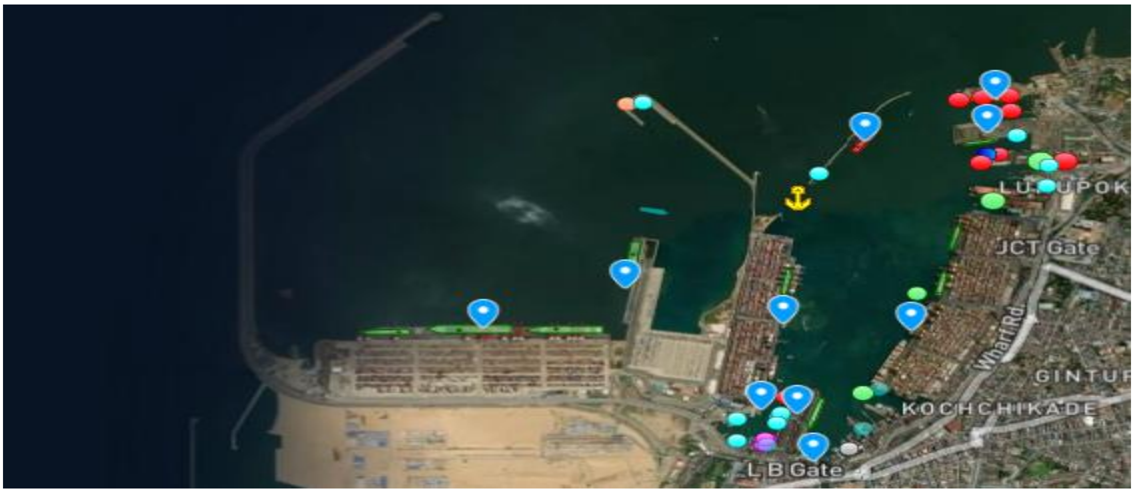
4.6 Cold Ironing process in port of Colombo

Figure 23 : Vessel Arrival to Port of Colombo from 02nd August to 15th August 2022



Source : Adopted from https://www.marinetraffic.com/en/ais/details/ports/1272?name=COLOMBO&country=Sri-Lanka#Summary

Figure 24: Live map of arrived vessel berthing in port of Colombo at 0800hrs on 16.08.2022



Source : Adopted from https://www.marinetraffic.com/en/ais/details/ports/1272name=COLOMBO

According to the above Figure 23 & 24, the average vessel arrival to port of Colombo was created following table 15, considering the vessel berthing time and fuel oil consumption by the Auxiliary engines half working load.

Table 15 : Vessels' Berthing time and Fuel oil consumption from 02.08.2022 to 15.08.2022 in the port of Colombo

Vessel Arrival Port of Colombo from 02.08.2022 to 15.08.2022						
Type of vessel	No of vessels	%	AVG Berthing time per vessel (hrs)	Total Berthing time(hrs)	Fuel Consumed Per Hour from all Auxiliary engines (1/2 Load)-MT/Hr	Total fuel Consumption(MT)
Container	91	46.67 %	12.5	1,137.5	1.5	1,706.25
Dry Break Bulk	8	4.10%	336	2,688	0.208	559.104
Dry Bulk	1	0.51%	336	336	0.208	69.888
LPG Carrier	3	1.54%	48	144	0.2059	29.6496
Wet Bulk	17	8.72%	8	136	0.1025	13.94
Other Markets	25	12.82 %	8	200	0.005	1
Supporting Vessels	9	4.62%	6	54	0.005	0.27
Fishing Vessel	30	15.38 %	4	120	0.001	0.12
Pleasure	11	5.64%	5	55	0.004	0.22
Passenger	0	0.00%	0	0	2	0
Total Vessels	195	100%	763.5	4,870.5	4.2394	2,380.4416

Source: Author

Accordingly, 2,380.4416 MT of Fuel oil has been consumed during the vessel berthing stage of total 4,870.5 hrs for two weeks' time. Assuming all auxiliary engines consume Marine Diesel oils the Total CO_2 emissions would be 7,631.695 MT (Carbon Factor of MDO = 3.206 tCO2/t Fuel according to IMO MEPC1/Cir 684).

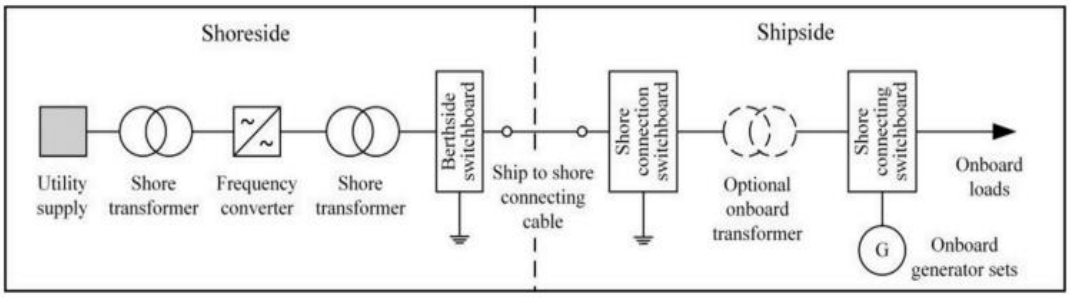
Therefore, annual Fuel Consumption during the berth = 61,891.48 MT

Total CO_2 Emission during the year = 198,424.09 MT

Fuel Price / MT in Colombo = USD 1,394.25 on 16.08.2022 o(https://www.oilmonster.com/bunker-fuel-prices/south-asia/colombo/58)

Total Fuel Cost Per year = USD 86,292,195.99

Figure 25 : The general requirements of OPS system



Source : A method for determining the allocation strategy of on-shore power supply from a green container terminal perspective (2019)

Figure 29 has mentioned the components of the cold ironing process. According to the Jiven, (2004), the following mentions the cost of the installing cold ironing process. One unit consists with three feeding points for 350 m in length (Normal Length for VLCC Container carrier).

The input power is considered herewith the power generated by the solar thermal plant (50Hz). Therefore, as the Ships have 60Hz input frequency, it is to be converted by the frequency converter.

Component	**Unit Cost (USD)**	**Total Cost (USD)**
Frequency Transformer with converter	400,000.00	400,000.00
Flexible Cable (10KV)	22.25/m	11,125.00 for 500m
Onboard Transformers	55,000.00	55,000.00
Total Onboard installation	100,000.00	100,000.00
Total Cost		**556,125.00**

Assuming that installing 51 units as the port has 51 berthing facilities the total cost will be USD 2,811,375.00 at the worst-case scenario. The benefit even in the first year **USD 83,480,820.99**

Chapter 5

FINDINGS AND SENSITIVITY ANALYSIS

5.1 Overview of the Smart port Concept

Ports are the multimodal crossroads of regional supply networks on a global scale. They operate in a setting of intricate infrastructure, commercial activity, and rules. Ports are under increasing pressure to operate at their best in terms of economic, environmental, energy, and operational difficulties that have an impact on their sustainability as a result of the need for maritime transportation in the global economy (Molavi et al., 2020).

Considering many of the findings of research articles and methodologies of existing smart ports in the world, the overall view of the smart port issues to be addressed.

Figure 26: Findings the consisting to be addressed in a smart port

Source : Author

According to the research limitations mentioned in chapter 1, **only the energy concept** mentioned in figure 30 relevant to Smart port concept has been followed in this research.

According to the baseline of the energy per year in port of Colombo **95,422 MWh** has been consumed for electricity and the cost for the electricity **USD 5,653,353.69**. The CO_2 emission for the consumed electricity was **55,774,159 MT**. The total Diesel Consumption was **17,495.00 MT**/year 2021 for supply boats, pilot boats, RTG and folk lifts. The total amount of produced CO_2 from Diesel was **56,088.97 MT/year**.
For the Cold Ironing process, the total cost for installing charging points for the 51 berths fixing 3 units for each berth in the port of Colombo was USD **2,811,375.00**. The cost for **61,891.48 MT** of MDO consumption with a half load of normally 3 engines during the berth will be USD **86,292.195.99.** The CO_2 emission of **198,242.09 MT**

can be saved by introducing cold ironing if the electricity is supplied only from RE sources.

Considering the retrofit of LED inverter type lighting system instead of High-Pressure Sodium Lamps (HPS) the total cost can save is **USD 106,241.00** and for the 50,000hrs lifetime saving cost is **USD 1,212,800.00.** The total CO_2 emission prevention would be **1,740.87** per year and for the lifetime of **19,872.901 MT.**
The following summary is mentioned in table 16, the economic and environmental effects of the above scenarios and Figure 27 & 28 illustrated them.

Table 16: Economic and Environmental Scenario for one year period in Port of Colombo

SN	Details of the Scenario	Cost /year USD	CO_2 Production MT/Year
1	Electricity Consumption year in Port of Colombo	5,653,353.69	55,774,159.00
2	*Saving after Electrification of Logistic machineries and supply boats	24,392,403.75	56,088.97
3	Saving Cold Ironing sub-research for 51 Units for all berths	2,811,375.00	198,424.09
4	LED Bulb retrofit sub research	106,241.00	1,740.87
*	Considered only the fuel-saving cost for the Diesel. Did not consider the retrofit cost for the modifications of engines or replacing new machineries		

Source: Author

Figure 27 : The cost for several Scenarios in Port of Colombo per year

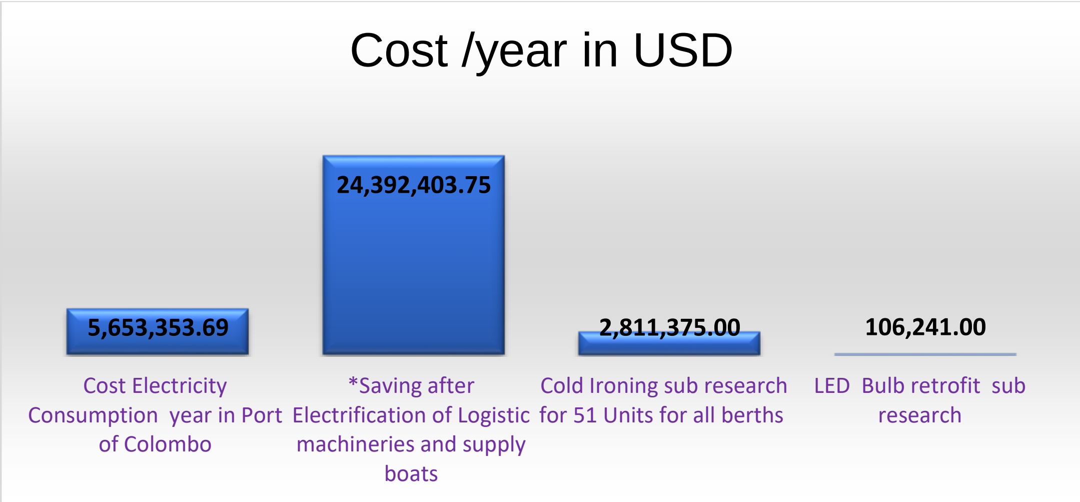
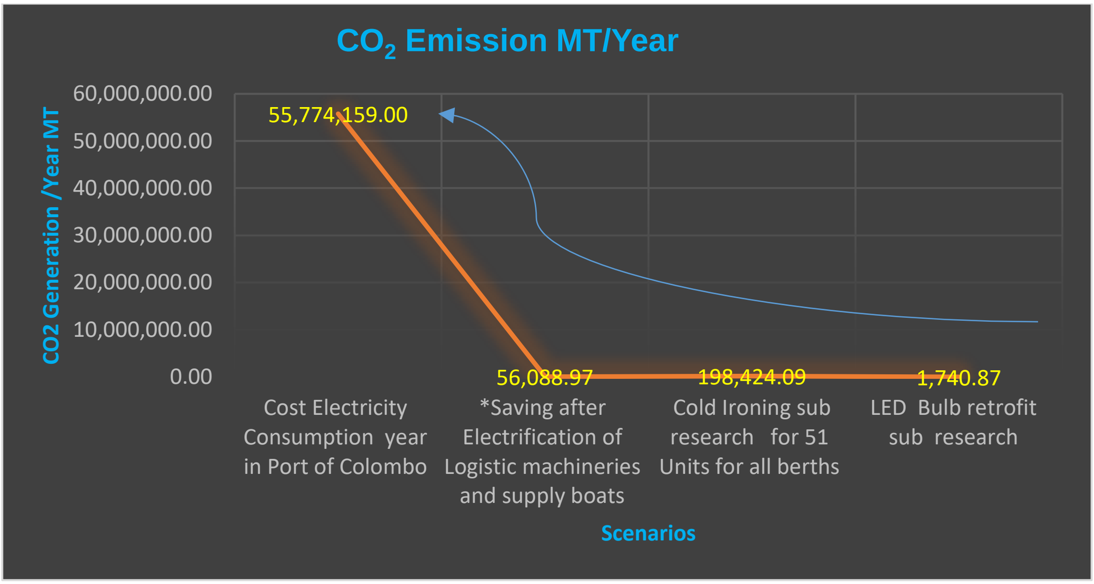


Figure 28 : The effect on the environment from different Scenarios in Port of Colombo per year



Source : Author

Among the 4 scenarios mentioned in graph 2, the CO_2 emission from the electricity consumed was huge compared with the other three scenarios. The management of SLPA should focus on the electrification of logistic machineries as the total high amount of diesel consumed. The cost can be saved for fuel, by electrification of Logistic machines is 431% greater than the one-year electricity cost. The total project for the cost of Cold ironing was around half amount of the cost of the electricity cost of the port. Stockholders, Shipping companies, and ship owners are being informed as the high amount of diesel consumption while berthing. That was USD 86,292,195.99 for 61,891.48 MT of diesel during the year.

5.2 Sensitivity analysis of three major cases

According to figure 28, the main CO_2 emitting scenario is the electricity consumption from the grid. Therefore, the ultimate solution is to generate more electricity using REs. The aim and objectives of this research are to find alternative RE technologies to establish energy efficient management system to address this huge energy utilization in the Port premises from the main grid.

In this research 3 major cost-benefit analysis cases have been emphasized; **Wind Energy, Solar energy, and Thermal Storage by Solar aided power generation** as the huge CO_2 emission for the electricity mentioned in the above figure 27. Following mentioned in Table No 17 the major finding of that RE implementation in the port premises.

Table 17: The summary of 3 Major RE cost-benefit analyses

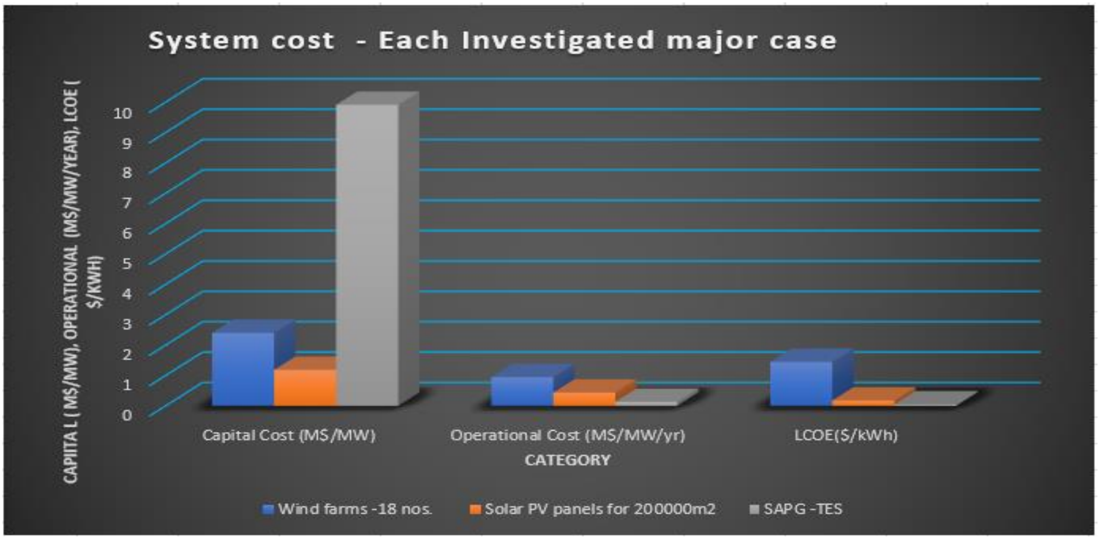
Description	**Wind farms -18 nos.**	**Solar PV panels 200,000m^2**	**SAPG -TES**
Capital Cost (M$/MW)	2.404	1.184	9.912
Operational Cost (M$/MW/yr)	0.95	0.437	0.131
LCOE($/kWh)	1.449	0.1774	0.04811
NPV ($)	-255,417,004.00	62,392,330.48	-135,637,465.31
IRR %	-	16%	-
Discounted Payback period- years	N/A	8	N/A

Source : Author

Solar PV panels implementation research has Positive NPV (USD **+**62,392,330.48) and IRR (16%) also greater than the assumed discount rate (5%) and 8 years

Payback period, the project is better for proceed. The above major cases have been mentioned in below Figure 29.

Figure 29 : System Cost – Each investigated major cases



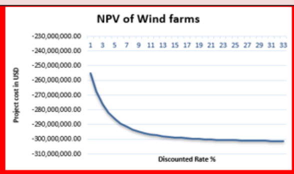
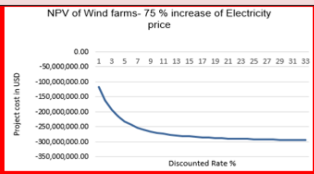
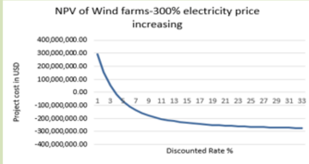
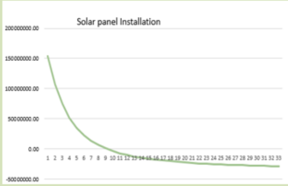
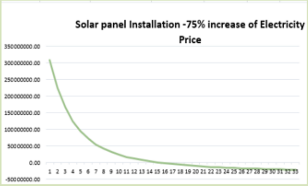
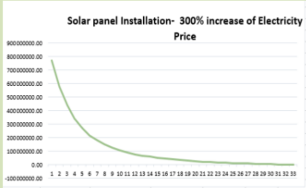
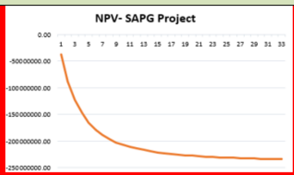
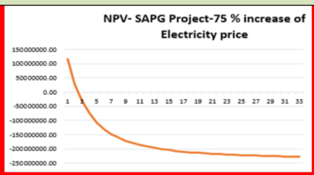
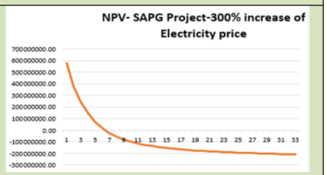
Source: Author

In order to calculate the NPV, the cash flow has been created with the difference between the income from the electricity (existing cost as income of selling the RE power units) and the operational cost. As the cost of generating power of Sri Lanka was USD 0.0592 per kWh it has been compared with the global electricity generation cost and found the generation price of Sri Lanka is comparatively very low.

Germany and Denmark more than 500%, UK, Belgium more than 400%, Australia, Italy, Japan, Rwanda, Ireland, Spain, Venezuela and United Kingdom more than 300%, USA, Brazil, Israel, Chile, Singapore, South Africa, Poland, France, New Zealand, Kenya more than 200%, higher than Sri Lanka.

Therefore, the following mention in figure 30 the Changing of NPV of the above three cases against with the 75% increasing and 300% increasing in the price of electricity generation in Sri Lanka.

Figure 30: The sensitivity analysis of 3 major cases

Case	Existing Price	75% increase	300% increase
Wind farms	 NPV=(USD-279,308,234.31) PB =313 + years	 NPV = (USD -205,772,440.93) PB = 82+ years	 NPV = USD 14,834,939.75 PB =23 years
Solar PV	 NPV = USD 62,392,330.48 PB = 8 tears	 NPV =USD 143,313,355.87 PB = 4 years	 NPV = USD 386,076,430.80 PB = 1.7 years
TES and SAPG	 NPV = (USD -135,637,455.31) PB =63+ years+	 NPV = (- USD 54,716,440.22) PB =40+years	 NPV= USD 188,046,635.01 PB= 12 years

Positive **Negative**

Source : Author

Accordingly, if the electricity price will increase 300% in Sri Lanka, All the NPVs in three cases become positive. There is a possibility to increase the electricity of Sri Lanka when compared with other developing Countries. Then it makes sense of installing the wind Power station Project and Thermal Storage Plant to generate RE to the Port. Solar PV already become positive NPV and there will be a battery backup system to cater to the demand in the Night-time. Since the PV panel has 25 years of working life, this will be a very good deal according to the economic and ecological perspective.

5.3 Excess electricity requirement after the RE initiatives

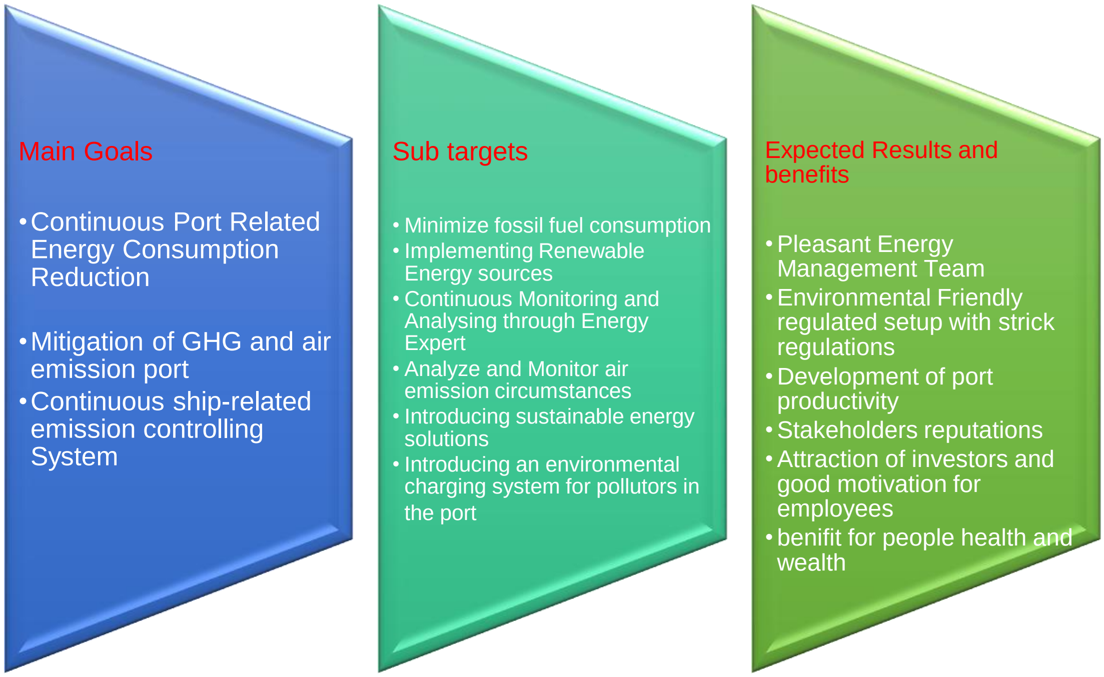
The electricity requirement for the Cold Ironing is depending on the Auxiliary engine capacities of the vessels and the time staying alongside the berth. For the Shippers' side the lifecycle cost and the maintenance cost for A/Es can be reduce long term it is an advantage. For the electrified logistic machineries, in order to charge their batteries or direct current using for the fixed RTGs need charging points and it takes several hours for charging. Therefore, the excising total Electricity requirement (95,422 MWh/year) will be increasing due to the mentioned initiatives.

5.4 ISO 50001:2018 certification for Port of Colombo for a smart port Planning Concept

By adhering to the ISO 50001:2018 guidelines, organizations can lessen their vulnerabilities and inefficiencies by generating less waste energy, using less energy than necessary, and avoiding potential liabilities. As a result, an effective Energy Management plan can be implemented to lessen the environmental impact. Thought and knowledge are necessary for this energy journey to continue. Before beginning, this journey must be completely planned and laid out. If not, money and time will be wasted, and the goals won't ever be reached.

The strategic planning phase, which is the first step in the development of the Green Port Action Plan, primarily aims at creating a broad vision for energy sustainability and a set of objectives addressing sustainability-related challenges. The goal of the Green Action Plan is to help the Port of Colombo increase its level of energy sustainability while minimizing costs. It is also crucial to remember that energy sustainability factors encompass both the use of renewable energy, which is addressed in this study, as well as energy efficiency measures, including the use of ecologically friendly port technologies. Following figure 31 has mentioned the prisized energy management goals and benefit by implementing proper energy management plan within a smart port premisses.

Figure 31: Smart Port Goals and benefits from Proper Energy Sustainable Plan



Source: Author

Chapter 6

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

According to the analysis the potential implementation of REs green initiatives of port of Colombo Sri Lanka, the most convenient and the economical best RE was Solar PV panel installation. The solar irradiation in port of Colombo indicates in an efficient way throughout the year as Sri Lanka is located in the equator. The required area (200,000 m^2) can be fulfilled using the roofs of administrative buildings, Warehouse, Vehicle parking, and top area of control cabins of Shore to Ship Cranes (STS). The same green concept regionally applied in Cochin Port in India (CPT). CPT has already commissioned a 250 kWp and 1500 kWp floating solar project also be commissioned this year (2022). Also, CPT is in line with green goal for achieving 60% solar power by 2030 according to the website of Cochin(www.cochinport.gov.in). CPT Electricity requirement is nearly 40% comparing with the total energy requirement of Port of Colombo.

In this research mention about the 7 MW wind farm turbine profile. According to the “Haliade-X wind turbine technical Specifications” now, in the market more efficient; 14 MW capacity 220m rotor 107m long blades, 38,000m^2 swept area are available. Data collected from the NASA database presented the selected Colombo area is not a proper area for the Wind, according to the wind power curve (Figure 15) since the wind speed was not even fulfil the cut off speed (25m/s) at any single month for the wind turbine, the maximum speed was below 8 m/s. Also, for the rated speed (13m/s) could not be achieved. Therefore, wind turbine installation project cannot perform in Colombo area as well as even the economic prospective. The CAPEX cost for thermal energy storage system is overpriced as of that the whole project cost with all LCOE has been increased.

In this research it has been emphasised three major RE cases and 3 sub cases and their economic and environmental prospective. Controlling and proper monitoring platform is important to make sure for the energy consumed in the port premisses. The port energy consumption shifting towards the renewable energy is directly proportional to reduction of CO_2 emission and purchasing fossil fuel for the electricity generation. In order to monitoring and development of utilization of energy, the **centralized competent personal** to be recruited to maintain and achieve the goals of energy reduction and maximize the efficiency. He/she should possess the accessing authority to each and every department and overall decision-making authority.

As Sri Lanka is one of the developing countries, project funding mechanism is very challengeable. Comparing SLPA, with sustainable ports and smart ports in the world, those are located in developed countries and also huge passenger ferry vessels are being handled these ports. These vessels need comparatively high demand(>15MW) for Cold ironing process at the berth. Port of Colombo is not a famous port for passenger ferry vessels and it is container port. For these container carriers need comparatively less amount of electricity(<7MW) during the berth than ferry vessels. As the cables are heavy, small crane has to be used while hoisting to the vessel and therefore positioning and disconnection cables takes considerable time for the cold ironing. These high electrical voltages and currents are handled close to the water surface and it may hazardous unless getting safety precautions.

In addition to the findings and limitations, I this research in hlostic view regarding the barriers of implementation of projects in Sri Lanka following governing observation can be described.The SLPA is fully government organization, the governing mechanism of the port is under a political appointed Chairman and Board of Directors. Some corporate level decisions are taken according to the agendas of this corporate management team. The accuracy of making decisions and time consuming for the new projects in Sri Lanka and it is totally different with private owned ports. Political corruption in high level is directly influenced when implementation of renewable energy in Sri Lanka. Therefore final destions to be implemented from technically and economocally expert committee instead of politicaly appointed personals in Sri Lanka.

Additionally,handling materials and documents onboard vessels at the anchorage from shore, with feeder boats and it consumes huge diesel when it runs several trips. Using Drones machines instead of boats can reduce considerable amount of diesel and future MASS vessel automation requirements and underwater inspections, the drone technology can be used. Also planting trees in port premisses can reduce CO_2 emission by absorbing them and it creates pleasant environment to reduce speed of busy environment.

6.2 Limitation and Recommendation for further Research

.

- As Sri Lanka is still developing country the funding mechanism for this type of implementations from various international like EU funding, World Bank, and regional organizations like Asian Development Bank with low interest rate need to be received as funding is a unique resource.
- The researcher believed the reliability and accuracy of collected data from NASA data base, but any identified location wind and solar data can be created by developing Python programing language or any other method is open for the next researcher.
- In Port of Colombo, as not having an energy policy and developed energy measuring system, suggest to implement a unique policy and energy team for the goodwill of the all the ports in the world as the whole saving cost is huge, according to the findings of this research. That should be accordance with ISO 50001 standard method consists with strategic energy objectives, has already implemented in Port of Rotterdam and Antwerp.
- Documented meaningful energy performance indicators conducting energy management reviews periodically, ensuring unique communication with inter departments.

Regarding the study's findings, those that pertain to the use of renewable energy in port premisses to meet energy needs are crucial and can inform studies that deal with energy implementation and efficiency optimization. In this regard, additional study is advised to build on and utilize these findings.

REFERENCES

Abu-Rumman, A. K., Muslih, I., & Barghash, M. (2017). Life cycle costing of PV generation system. *Journal of applied research on industrial engineering*, *4*(4), 252-258.

Acciaro, M., Vanelslander, T., Sys, C., Ferrari, C., Roumboutsos, A., Giuliano, G., ... & Kapros, S. (2014). Environmental sustainability in seaports: a framework for successful innovation. *Maritime Policy & Management*, *41*(5), 480-500.

Ahmad, T., Manzoor, S., & Zhang, D. (2021). Forecasting high penetration of solar and wind power in the smart grid environment using robust ensemble learning approach for large-dimensional data. *Sustainable Cities and Society*, *75*, 103269.

Alamoush, A. S., Ölçer, A. I., & Ballini, F. (2022). Port greenhouse gas emission reduction: Port and public authorities' implementation schemes. *Research in Transportation Business & Management*, *43*, 100708.

Alsubal, S., Alaloul, W. S., Shawn, E. L., Liew, M. S., Palaniappan, P., & Musarat, M. A. (2021). Life Cycle Cost Assessment of Offshore Wind Farm: Kudat Malaysia Case. *Sustainability*, *13*(14), 7943.

Arvydas Lebedys, Dennis Akande, Nazik Elhassan, Gerardo Escamilla, Adrian Whiteman and Iana Arkhipov. (2021). Renewable energy statistics 2021. https://irena.org/publications/2021/Aug/Renewable-energy-statistics-2021

Bjerkan, K. Y., & Seter, H. (2019). Reviewing tools and technologies for sustainable ports: Does research enable decision making in ports?. *Transportation Research Part D: Transport and Environment*, *72*, 243-260.

Boile, M., Theofanis, S., Sdoukopoulos, E., & Plytas, N. (2016). Developing a port energy management plan: Issues, challenges, and prospects. *Transportation Research Record*, *2549*(1), 19-28.

Iris, Ç., & Lam, J. S. L. (2019). A review of energy efficiency in ports: Operational strategies, technologies and energy management systems. *Renewable and Sustainable Energy Reviews*, *112*, 170-182.

Christodoulou, A., & Cullinane, K. (2019). Identifying the Main Opportunities and Challenges from the Implementation of a Port Energy Management System: A SWOT/PESTLE Analysis. *Sustainability, 11*(21), 6046. 10.3390/su11216046.

Denktas-Sakar, G., & Karatas-Cetin, C. (2012). Port sustainability and stakeholder management in supply chains: A framework on resource dependence theory. *The Asian Journal of Shipping and Logistics*, *28*(3), 301-319.

Dhupia, J. S., Adnanes, A. K., Lee, K. M., & Kennedy, L. (2011). Electrification of port and port operations. *Proceedings of MTEC2011*, 1-6.

Dirmeyer, P. A., Wu, J., Norton, H. E., Dorigo, W. A., Quiring, S. M., Ford, T. W., ... & Lawrence, D. M. (2016). Confronting weather and climate models with observational data from soil moisture networks over the United States. *Journal of Hydrometeorology*, *17*(4), 1049-1067.

Douaioui, K., Fri, M., & Mabrouki, C. (2018). Smart port: Design and perspectives. In *2018 4th International Conference on Logistics Operations Management (GOL)* (pp. 1-6). IEEE.

Doudounakis, M., & Kanellos, F. D. (2015). Active power management in 'green'ports. In *European Conference on Shipping, Intermodalism and Ports (ECONSHIP)*.

Drewry Maritime research Container market Annual Review and Forcast, (2021). https://www.drewry.co.uk/maritime-research-products/maritime-research-products/container-market-annual-review-and-forecast-202122

Emeis, S. (2018). Wind Energy Meteorology: Atmospheric Physics for Wind Power Generation; Springer: Berlin/Heidelberg, Germany
energy sources cooperatives' initiatives? Energies 13, 1136. https://doi.org/10.3390/en13051136.

ESPO Green Guide (2021). A Manual for European Ports Towards a green Future,https://www.espo.be/media/ESPO%20Green%20Guide%202021%20-%20FINAL.pdf.

Fahdi, S., ELKHECHAFI, M., & HACHIMI, H. (2019). Green port in blue ocean: optimization of energy in Asian ports. In *2019 5th International Conference on Optimization and Applications (ICOA)* (pp. 1-4). IEEE.

Fang, S., Xu, Y., Li, Z., Zhao, T., & Wang, H. (2019). Two-step multi-objective management of hybrid energy storage system in all-electric ship microgrids. *IEEE Transactions on Vehicular Technology*, *68*(4), 3361-3373.

Fang, S., & Wang, H. (2021). Introduction to the Multi-energy Maritime Grids. In *Optimization-Based Energy Management for Multi-energy Maritime Grids* (pp. 1-29). Springer, Singapore.

Fenton, P. (2017). The role of port cities and transnational municipal networks in efforts to reduce greenhouse gas emissions on land and at sea from shipping–An assessment of the World Ports Climate Initiative. *Marine Policy*, *75*, 271-277.

Fossile, D. K., Frej, E. A., da Costa, S. E. G., de Lima, E. P., & de Almeida, A. T. (2020). Selecting the most viable renewable energy source for Brazilian ports using the FITradeoff method. *Journal of Cleaner Production*, *260*, 121107.

García-Olivares, A., Sole, J., Osychenko, O., (2018). Transportation in a 100% renewable energy system. Energy Convers. Manag. 158, 266e285. https://doi.org/10.1016/ j.enconman. 2017.12.053.

Green Cranes, (2014), Green Technologies and Eco-Efficient Alternatives for Cranes and operations at Port Container Terminal (GREENCRANES). European Commission.

Hentschel, M., Ketter, W., Collins, J., (2018). Renewable energy cooperatives: facilitating the energy transition at the Port of Rotterdam. Energy Pol. 121, 61e69. https://doi.org/10.1016/j.enpol.2018.06.014

Hiranandani, V., (2014). Sustainable development in seaports: a multi-case study.WMU J Marit Aff 13, 127e172. https://doi.org/10.1007/s13437-013-0040-y.

HPA, (2021).“Port of Hamburg New climate plan and climate protection law for Hamburg.” https://www.hafen-hamburg.de/en/news/new climate-plan-and-climate-protection-law-for-Hamburg (accessed Apr. 07, 2021).

Huang, C., Madonski, R., Zhang, Q., Yan, Y., Zhang, N., & Yang, Y. (2022). On the use of thermal energy storage in solar-aided power generation systems. *Applied Energy*, *310*, 118532.

IEA (2019), "Offshore Wind Outlook 2019", IEA, Paris https://www.iea.org/reports/offshore-wind outlook-2019.

IMO, “Fourth Greenhouse Gas Study 2020.” https://www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO Greenhouse-Gas-Study-2020.aspx (accessed Apr. 07, 2021).

International Standerd Organizatio(2018). ISO 50001:2018. Energy Management Systems-requirements with Guidance for use. https://www.iso.org

IRENA, (2021). Renewable Power Generation Costs in 2020. International Renewable Energy Agency, Abu Dhabi.

IRENA, (2012). International Renewable Energy Agency. https://www.irena.org.

IRENA, (2021). Renewable Energy Statistics. International Renewable Energy Agency https://www.irena.org/Statistics/Download-Data.

Jafarzadeh, S., & Utne, I. B. (2014). A framework to bridge the energy efficiency gap in shipping. *Energy*, *69*, 603-612.

James Blackman,(2020). "Smart ports: seven practical challenges for port authorities and terminal operators-Article." https://www.apucis.com/enGB/reports/article/F6710C98-9F77- 11BB-18F0-248F9D1F8956?PageSpeed=noscript (accessed Aug. 28, 2020).

Jivén, K. (2004). Shore-side electricity for ships in ports: case studies with estimates of internal and external costs, prepared for the North Sea Commission.

Joyce Lee, F. Z. (2022). Global wind report 2022. https://gwec.net/global-wind-report-2022/ttps://gwec.net/global-wind-report-2022/.

Kang, D., Kim, S., (2017). Conceptual model development of sustainability practices: the case of port operations for collaboration and governance. Sustainability 9, 2333. https://doi.org/10.3390/su9122333.

Kazak, J., Van Hoof, J., & Szewranski, S. (2017). Challenges in the wind turbines location process in Central Europe–The use of spatial decision support systems. *Renewable and Sustainable Energy Reviews*, *76*, 425-433.

Kuravi, S., Goswami, Y., Stefanakos, E. K., Ram, M., Jotshi, C., Pendyala, S., ... & Krakow, B. (2012). Thermal energy storage for concentrating solar power plants. *Technology & Innovation*, *14*(2), 81-91.

Kuravi, S., Trahan, J., Goswami, D. Y., Rahman, M. M., & Stefanakos, E. K. (2013). Thermal energy storage technologies and systems for concentrating solar power plants. *Progress in Energy and Combustion Science*, *39*(4), 285-319.

López-Aparicio, S., Tønnesen, D., Thanh, T. N., & Neilson, H. (2017). Shipping emissions in a Nordic port: Assessment of mitigation strategies. *Transportation Research Part D: Transport and Environment*, *53*, 205-216.

Martínez-Moya, J., Vazquez-Paja, B., & Maldonado, J. A. G. (2019). Energy efficiency and CO2 emissions of port container terminal equipment: Evidence from the Port of Valencia. *Energy Policy*, *131*, 312-319.

Matthias Beer. (2022). *Energy Transition in the Port: an Economic Success Story.* https://marketing.hamburg.de/energy-transition-in-hamburgs-port.html.

Molavi, A., Lim, G. J., & Race, B. (2020). A framework for building a smart port and smart port index. *International Journal of Sustainable Transportation, 14*(9), 686-700. 10.1080/15568318.2019.1610919.

Nadeeshani, M., Ramachandra, T., Gunatilake, S., & Zainudeen, N. (2021). The carbon footprint of green roofing: A case study from Sri Lankan construction industry. *Sustainability*, *13*(12), 6745.

Nelson, V.; Starcher, K.(2018) Wind Energy: Renewable Energy and the Environment; CRC Press: Boca Raton, FL, USA,

Niedersachsen Port, (2019). Sustainability Report. https://www.nports.de/media/Unternehmen/Nachhaltigkeit/NPorts_Sustainability_Report_2019.pdf.

Nnachi, A. F., Ehlers, P. J., Richards, C. G., & Nicolae, D. V. (2013). Double-port interface for small scale renewable sources integration. In *2013 IEEE International Conference on Industrial Technology (ICIT)* (pp. 503-508). IEEE.

Ölçer, A. I., Kitada, M., Dalaklis, D., & Ballini, F. (Eds.). (2018). *Trends and challenges in maritime energy management* (Vol. 6). Heidelberg: Springer.

Parise, G., Parise, L., Martirano, L., Ben Chavdarian, P., Su, Chun-Lien, Ferrante, A., (2016). Wise port and business energy management : port facilities, electrical power distribution. IEEE Trans. Ind. Appl. 52, 18e24. https://doi.org/10.1109/ TIA.2015.2461176.

Parrado, C., Girard, A., Simon, F., & Fuentealba, E. (2016). 2050 LCOE (Levelized Cost of Energy) projection for a hybrid PV (photovoltaic)-CSP (concentrated solar power) plant in the Atacama Desert, Chile. *Energy*, *94*, 422-430.

Peng, Y., Li, X., Wang, W., Wei, Z., Bing, X., & Song, X. (2019). A method for determining the allocation strategy of on-shore power supply from a green container terminal perspective. *Ocean & Coastal Management*, *167*, 158-175.

Port of Helsinki,(2020). “Carbon-neutral Port of Helsinki 2035 Manifestation.” https://www(*Port of helsinki .* w.portofhelsinki.fi/en/port helsinki/sustainable-port-operations/carbon-neutral-port-helsinki 2035-manifestation. Accessed on 28th August 2020.

Sadiq, M., Ali, S. W., Terriche, Y., Mutarraf, M. U., Hassan, M. A., Hamid, K., ... & Guerrero, J. M. (2021). Future greener seaports: A review of new infrastructure, challenges, and energy efficiency measures. *IEEE Access*, *9*, 75568-75587.

Salem A, Seddiek I, (2016). Techno-economic approach to solar energy systems onboard marine vehicles. Pol Marit Res. 23:64–71.

Sdoukopoulos, E., Boile, M., Tromaras, A., Anastasiadis, N., (2019.) Energy efficiency in European ports: state-of-practice and insights on the way forward. Sustainability 11, 4952. https://doi.org/10.3390/su11184952

Siemens,(2017). "Smart Ports; Competitive Cities Global Center of Competence Cities-Urban Development," .

Sifakis, N., & Tsoutsos, T. (2021). Planning zero-emissions ports through the nearly zero energy port concept. Journal of Cleaner Production, 286, 125448.

Sifakis, N., Tsoutsos, T., (2020a). Nearly zero energy ports: a necessity or a green upgrade? IOP Conf. Ser. Earth Environ. Sci. 410, 012037 https://doi.org/10.1088/1755-1315/410/1/012037.

Sri Lanka energy sector assessment strategy, and road map, (2019). https://www.adb.org/sites/default/files/institutional-document/547381/sri-lanka-energy-assessment-strategy-road-map.pdf

Sri Lanka Sustainable Energy Authority. Sri Lanka Energy Balance, (2017)—An Analysis of Energy Sector Performance; Sri Lanka Sustainable Energy Authority: Colombo, Sri Lanka.

Tichavska, M., & Tovar, B, (2015). Environmental cost and eco-efficiency from vessel emissions in Las Palmas Port. *Transportation Research Part E: Logistics and Transportation Review*, *83*, 126-140.

Trevor, (2016). Wind Energy Engineering. A Handbook for Onshore and Offshore Wind Turbines. http: doi.org/10.1016/B978-0-120809451-8.0006-0.

UNCTAD, "Review of Maritime Transport (2019)." https://unctad.org/web flyer/review-maritime-transport-2019 (accessed Dec. 25, 2020).
under climate change at the Kaohsiung port. Transport Pol. 97, 232e244.

UNFCCC, Methodological tool Tool to calculate the emission factor for an electricity system. (2013). https://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-07-v4.0.pdf.

Vakili, S., Schönborn, A., & Ölçer, A. I. (2022). Techno-economic feasibility of photovoltaic, wind and hybrid electrification systems for stand-alone and grid-connected shipyard electrification in Italy. *Journal of Cleaner Production*, 132945.

Van Duin, J. H. R., Geerlings, H., Froese, J., & Negenborn, R. R. (2017). Towards a method for benchmarking energy consumption at terminals: In search of performance improvement in yard lighting. *International Journal of Transport Development and Integration*, *1*(2), 212-224.

Wang, X., Kurdgelashvili, L., Byrne, J., & Barnett, A. (2011). The value of module efficiency in lowering the Levelized cost of energy of photovoltaic systems. Renewable and Sustainable Energy Reviews, 15(9), 4248-4254.

Wilmsmeier, G., Zotz, A.-K., Froese, J., Meyer, A., (2014). Energy Consumption and Efficiency: Emerging Challenges from Reefer Trade in South American Container Terminals.

Wind energy market intelligence. (2022). https://www.thewindpower.net/store_continent_en.php?id_zone=1000.

Yau, K. L. A., Peng, S., Qadir, J., Low, Y. C., & Ling, M. H. (2020). Towards smart port infrastructures: Enhancing port activities using information and communications technology. *IEEE Access*, *8*, 83387-83404.

Yang, Y.-C., Ge, Y.-E., (2020). Adaptation strategies for port infrastructure and facilities

Yoldaş, Y., Önen, A., Muyeen, S. M., Vasilakos, A. V., & Alan, I. (2017). Enhancing smart grid with microgrids: Challenges and opportunities. *Renewable and Sustainable Energy Reviews*, *72*, 205-214.

Zis, T., North, R.J., Angeloudis, P., Ochieng, W.Y., Harrison Bell, M.G., (2014). Evaluation of cold ironing and speed reduction policies to reduce ship emissions near and at ports. Marit. Econ. Logist. 16, 371e398. https://doi.org/10.1057/mel.2014.6.

Appendices

Annexure 01 Port of Colombo Wind speed and Power table for 2019 to 2021

Year	Wind Speed -Average (m/s)	Power(W)
Jan-19	6.182258065	1078268.883
Feb-19	4.201785714	338522.3783
Mar-19	2.542903226	75036.95141
Apr-19	3.245666667	156026.1632
May-19	6.334193548	1159737.424
Jun-19	7.659	2050226.731
Jul-19	6.657096774	1346295.189
Aug-19	7.54	1956139.04
Sep-19	5.912666667	943269.6706
Oct-19	4.035483871	299897.2826
Nov-19	3.214333333	151550.8648
Dec-19	4.23	345387.6346
Jan-20	4.82516129	512650.2672
Feb-20	4.939655172	550016.3264
Mar-20	2.374193548	61070.8612
Apr-20	2.936333333	115531.8556
May-20	5.765806452	874713.5666
Jun-20	7.123333333	1649436.061
Jul-20	6.410967742	1202420.738
Aug-20	6.362258065	1175220.953
Sep-20	6.966666667	1542981.707
Oct-20	6.184193548	1079281.923
Nov-20	3.785666667	247578.4253
Dec-20	5.202903226	642721.647
Jan-21	4.481935484	410849.2373
Feb-21	5.537857143	775016.4629
Mar-21	2.88483871	109559.5636
Apr-21	3.89	268617.6139
May-21	5.882	928668.5615
Jun-21	7.087666667	1624783.636
Jul-21	7.476129032	1906847.879
Aug-21	6.97483871	1548417.926
Sep-21	7.085666667	1623408.578
Oct-21	5.667419355	830695.2555
Nov-21	5.364333333	704422.0673
Dec-21	4.830322581	514297.1148
AVG for 3 years	5.327653739	690070.8076

Annexure 02 LCOE calculator for the 18 wind turbines for 25 years lifetime.

Year	Production (kWh)	Direct Purchase Cost ($)	Decommissioning and Disposal	O&M Cost ($)
0		$ 302,987,034	$ 31,756,158	
1	108,810,365			$ 119,700,000
2	108,266,313			$ 120,897,000
3	107,724,982			$ 122,105,970
4	107,186,357			$ 123,327,030
5	106,650,425			$ 124,560,300
6	106,117,173			$ 125,805,903
7	105,586,587			$ 127,063,962
8	105,058,654			$ 128,334,602
9	104,533,361			$ 129,617,948
10	104,010,694			$ 130,914,127
11	103,490,640			$ 132,223,268
12	102,973,187			$ 133,545,501
13	102,458,321			$ 134,880,956
14	101,946,030			$ 136,229,766
15	101,436,300			$ 137,592,063
16	100,929,118			$ 138,967,984
17	100,424,472			$ 140,357,664
18	99,922,350			$ 141,761,240
19	99,422,738			$ 143,178,853

20	98,925,625			$ 144,610,641
21	98,430,996			$ 146,056,748
22	97,938,842			$ 147,517,315
23	97,449,147			$ 148,992,488
24	96,961,902			$ 150,482,413
25	96,477,092			$ 151,987,237
Total	2,563,131,670	**$ 302,987,034**	**$ 31,756,158**	$ 3,380,710,980

Annexure 03 NPV, IRR and Payback time calculation of eighteen Windfarms (126MW)

For Eighteen offshore Wind farms							
	per 126MW	126	MW				5%
Year	Net Cost	Net Income	Cash Flow	CCF	DCF	CDCF	Dis Rate
0	-302987034	0	-302,987,034.00	-302,987,034.00	-302,987,034.00	-302,987,034.00	1
1	-4,788,000.00	5,653,353.69	865,353.69	-302,121,680.31	824,146.37	-302,162,887.63	1.05
2	-4,835,880.00	5,822,954.30	987,074.30	-301,134,606.01	895,305.49	-301,267,582.14	1.1025
3	-4,884,238.80	5,939,413.39	1,055,174.59	-300,079,431.42	911,499.48	-300,356,082.66	1.157625
4	-4,933,081.19	6,058,201.65	1,125,120.47	-298,954,310.96	925,639.39	-299,430,443.27	1.21550625
5	-4,982,412.00	6,179,365.69	1,196,953.69	-297,757,357.27	937,844.53	-298,492,598.73	1.276281563
6	-5,032,236.12	6,302,953.00	1,270,716.88	-296,486,640.39	948,228.50	-297,544,370.23	1.340095641
7	-5,082,558.48	6,429,012.06	1,346,453.58	-295,140,186.81	956,899.42	-296,587,470.81	1.407100423
8	-5,133,384.07	6,557,592.30	1,424,208.24	-293,715,978.57	963,960.19	-295,623,510.62	1.477455444
9	-5,184,717.91	6,688,744.15	1,504,026.24	-292,211,952.33	969,508.73	-294,654,001.89	1.551328216
10	-5,236,565.09	6,822,519.03	1,585,953.95	-290,625,998.38	973,638.15	-293,680,363.74	1.628894627
11	-5,288,930.74	6,958,969.41	1,670,038.68	-288,955,959.71	976,437.03	-292,703,926.72	1.710339358
12	-5,341,820.04	7,098,148.80	1,756,328.76	-287,199,630.95	977,989.57	-291,725,937.15	1.795856326
13	-5,395,238.24	7,240,111.78	1,844,873.53	-285,354,757.42	978,375.82	-290,747,561.32	1.885649142
14	-5,449,190.63	7,384,914.01	1,935,723.39	-283,419,034.03	977,671.85	-289,769,889.48	1.979931599
15	-5,503,682.53	7,532,612.29	2,028,929.76	-281,390,104.27	975,949.91	-288,793,939.57	2.078928179
16	-5,558,719.36	7,683,264.54	2,124,545.18	-279,265,559.09	973,278.63	-287,820,660.94	2.182874588
17	-5,614,306.55	7,836,929.83	2,222,623.28	-277,042,935.82	969,723.17	-286,850,937.77	2.292018318
18	-5,670,449.62	7,993,668.43	2,323,218.81	-274,719,717.01	965,345.40	-285,885,592.37	2.406619234
19	-5,727,154.11	8,153,541.79	2,426,387.68	-272,293,329.33	960,204.00	-284,925,388.37	2.526950195
20	-5,784,425.65	8,316,612.63	2,532,186.98	-269,761,142.35	954,354.64	-283,971,033.73	2.653297705
21	-5,842,269.91	8,482,944.88	2,640,674.97	-267,120,467.38	947,850.12	-283,023,183.61	2.78596259
22	-5,900,692.61	8,652,603.78	2,751,911.17	-264,368,556.21	940,740.48	-282,082,443.14	2.92526072
23	-5,959,699.54	8,825,655.86	2,865,956.32	-261,502,599.89	933,073.14	-281,149,370.00	3.071523756
24	-6,019,296.53	9,002,168.97	2,982,872.44	-258,519,727.45	924,893.02	-280,224,476.97	3.225099944
25	-6,079,489.50	9,182,212.35	3,102,722.86	-255,417,004.60	916,242.66	-279,308,234.31	3.386354941
Discounted Payback period(DDP)		312.81					
NPV @r=0		-255,417,004.60					
NPV@r=5%		-279,308,234.31					
IRR		-10%					

Annexure 04 Solar Energy generation for 2019,2020 & 2021

Year	Solar irradiance Average (kW-hr/m^2/day)	Energy (kWh/month)
Jan-19	5.97483871	1,157,625.00
Feb-19	6.331785714	1,108,062.50
Mar-19	6.697741935	1,297,687.50
Apr-19	6.116333333	1,146,812.50
May-19	5.456774194	1,057,250.00
Jun-19	5.145333333	964,750.00
Jul-19	5.578709677	1,080,875.00
Aug-19	4.664516129	903,750.00
Sep-19	4.828666667	905,375.00
Oct-19	4.705483871	911,687.50
Nov-19	5.471666667	1,025,937.50
Dec-19	4.932258065	955,625.00
Jan-20	6.051612903	1,172,500.00
Feb-20	6.337241379	1,148,625.00
Mar-20	6.651935484	1,288,812.50
Apr-20	6.642333333	1,245,437.50
May-20	5.014516129	971,562.50
Jun-20	5.528	1,036,500.00
Jul-20	4.85483871	940,625.00
Aug-20	5.716129032	1,107,500.00
Sep-20	4.852666667	909,875.00
Oct-20	5.889354839	1,141,062.50
Nov-20	5.302333333	994,187.50
Dec-20	5.120967742	992,187.50
Jan-21	4.87516129	944,562.50
Feb-21	6.540357143	1,144,562.50
Mar-21	6.03516129	1,169,312.50
Apr-21	6.384	1,197,000.00
May-21	5.813278689	1,126,322.75
Jun-21	5.679	1,064,812.50
Jul-21	5.388064516	1,043,937.50
Aug-21	5.429032258	1,051,875.00
Sep-21	5.546666667	1,040,000.00
Oct-21	5.125806452	993,125.00
Nov-21	4.412666667	827,375.00
Dec-21	5.633225806	1,091,437.50
AVG Irradiance	5.57	
	Total Power generated 2021(kWh)	12,694,322.75

Annexure 05 LCOE cost for PV panel installation

LCOE Calculator			
Year	Production (kWh)	Direct Purchase Cost ($)	O&M Cost ($)
0		37,000,000	1% increase/year
1	101,554,581.97		13,684,931.51
2	101,046,809.06		13,821,780.82
3	100,541,575.01		13,959,998.63
4	100,038,867.14		14,099,598.62
5	99,538,672.80		14,240,594.60
6	99,040,979.44		14,383,000.55
7	98,545,774.54		14,526,830.55
8	98,053,045.67		14,672,098.86
9	97,562,780.44		14,818,819.85
10	97,074,966.54		14,967,008.05
11	96,589,591.70		15,116,678.13
12	96,106,643.75		15,267,844.91
13	95,626,110.53		15,420,523.36
14	95,147,979.97		15,574,728.59
15	94,672,240.07		15,730,475.88
16	94,198,878.87		15,887,780.64
17	93,727,884.48		16,046,658.44
18	93,259,245.06		16,207,125.03
19	92,792,948.83		16,369,196.28
20	92,328,984.09		16,532,888.24
21	91,867,339.17		16,698,217.12
22	91,408,002.47		16,865,199.29
23	90,950,962.46		17,033,851.29
24	90,496,207.65		17,204,189.80
25	90,043,726.61		17,376,231.70
Total	2,392,214,798.31	37,000,000.00	386,506,250.72

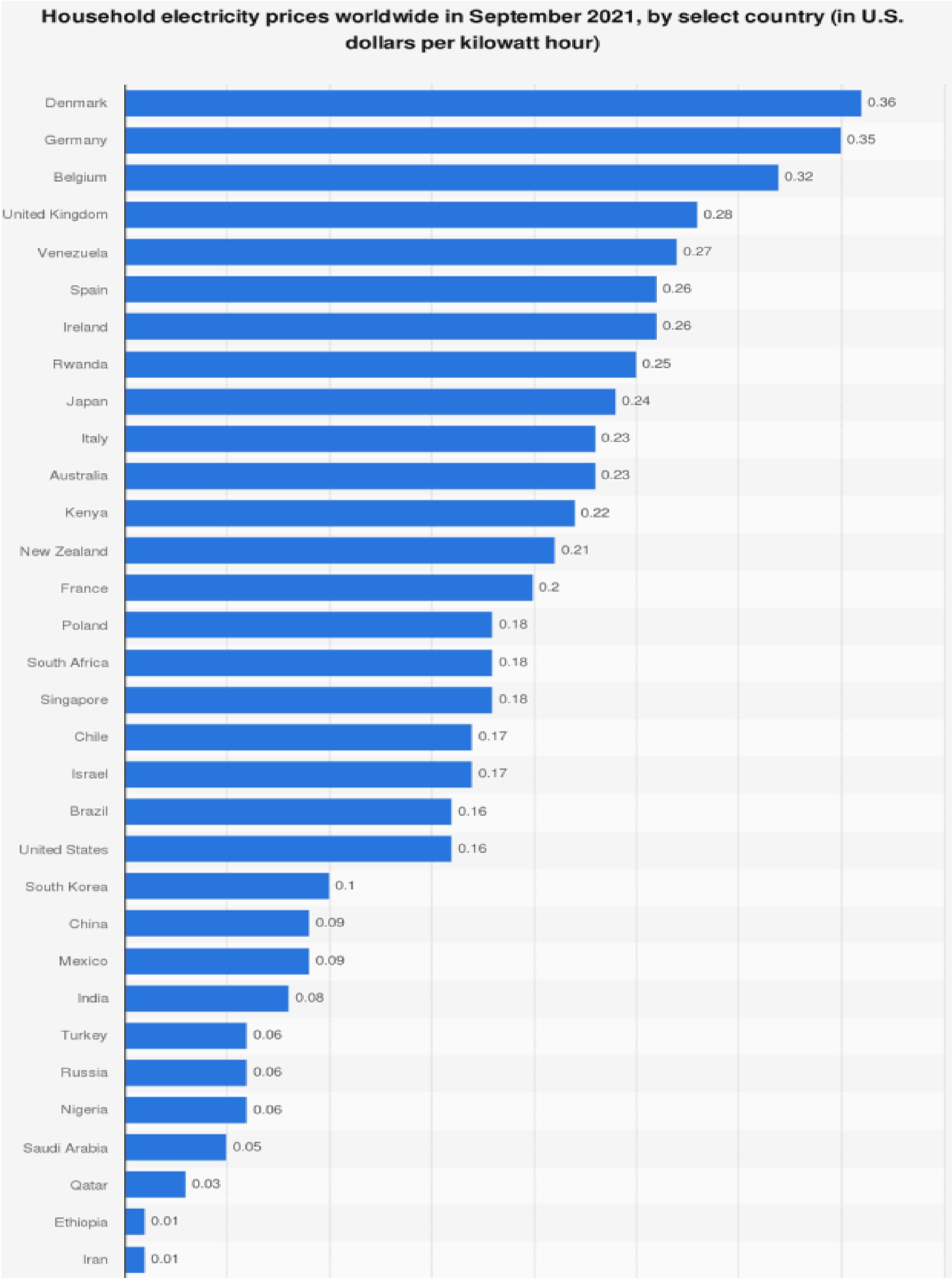
Annexure 06 NPV, IRR, PB calculation for the PV panel installation

Year	Net Cost	Net Income	Cash Flow	CCF	DCF	CDCF	Dis Rate
0	-37000000.00	0.00	-37,000,000.00	-37,000,000.00	-37,000,000.00	-37,000,000.00	1.0000
1	-547397.26	5,653,353.69	5,105,956.43	-31,894,043.57	4,862,815.65	-32,137,184.35	1.0500
2	-552,871.23	5,822,954.30	5,270,083.07	-26,623,960.50	4,780,120.70	-27,357,063.66	1.1025
3	-558,399.94	5,997,642.93	5,439,242.98	-21,184,717.52	4,698,622.60	-22,658,441.06	1.1576
4	-563,983.94	6,177,572.22	5,613,588.27	-15,571,129.24	4,618,312.96	-18,040,128.09	1.2155
5	-569,623.78	6,362,899.38	5,793,275.60	-9,777,853.64	4,539,183.02	-13,500,945.07	1.2763
6	-575,320.02	6,553,786.37	5,978,466.34	-3,799,387.30	4,461,223.63	-9,039,721.44	1.3401
7	-581,073.22	6,750,399.96	6,169,326.73	2,369,939.44	4,384,425.33	-4,655,296.11	1.4071
8	-586,883.95	6,952,911.96	6,366,028.00	8,735,967.44	4,308,778.33	-346,517.78	1.4775
9	-592,752.79	7,161,499.31	6,568,746.52	15,304,713.96	4,234,272.58	3,887,754.80	1.5513
10	-598,680.32	7,376,344.29	6,777,663.97	22,082,377.93	4,160,897.74	8,048,652.54	1.6289
11	-604,667.12	7,597,634.62	6,992,967.50	29,075,345.43	4,088,643.27	12,137,295.81	1.7103
12	-610,713.80	7,825,563.66	7,214,849.86	36,290,195.29	4,017,498.37	16,154,794.18	1.7959
13	-616,820.93	8,060,330.57	7,443,509.64	43,733,704.93	3,947,452.08	20,102,246.26	1.8856
14	-622,989.14	8,302,140.49	7,679,151.34	51,412,856.27	3,878,493.25	23,980,739.51	1.9799
15	-629,219.03	8,551,204.70	7,921,985.67	59,334,841.94	3,810,610.56	27,791,350.07	2.0789
16	-635,511.23	8,807,740.84	8,172,229.62	67,507,071.56	3,743,792.55	31,535,142.62	2.1829
17	-641,866.34	9,071,973.07	8,430,106.73	75,937,178.29	3,678,027.64	35,213,170.26	2.2920
18	-648,285.00	9,344,132.26	8,695,847.26	84,633,025.55	3,613,304.15	38,826,474.41	2.4066
19	-654,767.85	9,624,456.23	8,969,688.38	93,602,713.93	3,549,610.28	42,376,084.68	2.5270
20	-661,315.53	9,913,189.92	9,251,874.39	102,854,588.31	3,486,934.15	45,863,018.84	2.6533
21	-667,928.68	10,210,585.61	9,542,656.93	112,397,245.24	3,425,263.84	49,288,282.68	2.7860
22	-674,607.97	10,516,903.18	9,842,295.21	122,239,540.45	3,364,587.35	52,652,870.03	2.9253
23	-681,354.05	10,832,410.28	10,151,056.23	132,390,596.68	3,304,892.63	55,957,762.66	3.0715
24	-688,167.59	11,157,382.59	10,469,214.99	142,859,811.67	3,246,167.62	59,203,930.27	3.2251
25	-695,049.27	11,492,104.06	10,797,054.80	153,656,866.47	3,188,400.21	62,392,330.48	3.3864
Discounted Payback period(DDP)			8.081836436	Years			
NPV @r=0			153,656,866.47				
NPV@r=5%			62,392,330.48				
IRR			16%				

Annexure 07 LCOE of SAPG Plant

LCOE Calculator for the SAPG plant			
Year	Production (kWh)	Direct Purchase Cost ($)	O&M Cost ($)
0		312,240,994	1%
1	275,940,000.00		16,814.70
2	274560300		16,982.85
3	273187498.5		17,152.68
4	271821561		17,324.20
5	270462453.2		17,497.44
6	269110140.9		17,672.42
7	267764590.2		17,849.14
8	266425767.3		18,027.63
9	265093638.4		18,207.91
10	263768170.3		18,389.99
11	262449329.4		18,573.89
12	261137082.8		18,759.63
13	259831397.3		18,947.22
14	258532240.4		19,136.70
15	257239579.2		19,328.06
16	255953381.3		19,521.34
17	254673614.3		19,716.56
18	253400246.3		19,913.72
19	252133245		20,112.86
20	250872578.8		20,313.99
21	249618215.9		20,517.13
22	248370124.8		20,722.30
23	247128274.2		20,929.52
24	245892632.9		21,138.82
25	244663169.7		21,350.21
Total	6,500,029,232.14	312,240,994	474,900.93

Annexure 08 Cost of Electricity USD/kWh



Annexure 09 Plant wise generation cost of Electricity in Sri Lanka

Plant Wise Cost

JUNE 2022

	Plant	Fuel Type	Unit Cost (LKR/kWh)
Renewables	Large Hydro	Hydro	4.85
	CEB/IPP Mini Hydro	Hydro	15.4
	Solar	Solar	19.9
	Wind	Wind	12.11
	Biomass Power	Biomas	38.31
CBE Thermal	Norachcholai (810 MW)	Coal	33.22
	Sapugaskanda A (70 MW)	Furnace Oil	105.55
	Sapugaskanda B (63 MW)	Furnace Oil	94.82
	Uthuru Janani (25 MW)	Furnace Oil	100.21
	Barge (60 MW)	Furnace Oil	88.69
	Kelanitissa CCGT	Naptha/Auto Diesel	86.57
	Westcoast power (270 MW)	Low Sulphur Furnace Oil	103.59
	KPS(GT7) (115 MW)	Auto Diesel	166.78
	KPS(GT)	Naptha/Auto Diesel	227.92
	Diesel Generators- Thulhiriya (10 MW)	Auto Diesel	114.72
	Diesel Generators - Matugama (20 MW)	Auto Diesel	115.96
	Diesel Generators- Kolonnawa (20 MW)	Auto Diesel	117.52
Private Power Plants (IPP)	Sojitz (163 MW)	Auto Diesel	90.03
	Ace Matara	Heavy Fuel	107.95
	Ace Embilipitiya (72 MW)	Heavy Fuel	101.16
	Asia power (50 MW)	Furnace Oil	104.00 *)

*Assumed cost

ශ්‍රී ලංකා මහජන උපයෝගිතා කොමිෂන් සභාව
இலங்கை பொதுப்பயன்பாடுகள் ஆணைக்குழு
Public Utilities Commission of Sri Lanka