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Integration of a hybrid microgrid system using renewable energy sources: a case study of Lagos Port Nigeria

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INTEGRATION OF A HYBRID MICROGRID SYSTEM USING RENEWABLE ENERGY SOURCES: A CASE STUDY OF LAGOS PORT NIGERIA

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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): **20th September 2022**

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World Maritime University

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Abstract

Title of Dissertation: **Integration of a Hybrid Microgrid System Using Renewable Energy Sources: A Case Study of Lagos Port Nigeria.**

Degree: **Master of Science**

The expansion and increasing uptake of renewable energy for electricity generation has been shown to be crucial for the green transition towards decarbonization goals, energy security, reliability, and sustainability. Distributed energy resources (DERs) using renewable energy are widely implemented in land-based facilities, but there are very few applications in seaport and harbour facilities due to the complex nature of energy demand from varying vessel traffic, sizes, seasons, and port operations.

This study examines the economic, environmental, and societal implications for integrating a smart hybrid microgrid system using renewable energy sources that include solar, wind, and energy storage system using battery to transition the Lagos port complex from complete dependence on the existing poor and erratic supply from the main grid and high-emission diesel generators to a clean, economical, stable, and reliable power supply.

The study utilizes the hybrid optimization of multiple energy resources software (HOMER) to size and model the energy resource components using typical data specific to the location, optimizing the model design to identify the least cost intensive combination, while identifying sensitive parameters.

From the optimization results, categorized feasible combinations are further filtered to identify conflicting alternatives, using a multi-attribute decision making technique TOPSIS to filter designs and rank based on minimised cost, minimised emissions and system resilience during peak demand periods or failures. The societal impact is also discussed, as it will affect the residents of the surrounding area as well as promote economic growth in the nation.

KEYWORDS: Energy Efficiency, Ports, Microgrid, HOMER, renewable energy, Optimization, TOPSIS.

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List of Abbreviations

AC	Alternating current
DC	Direct current
EE	Energy Efficiency
RE	Renewable Energy
IEA	International Energy Agency
GW	Gigawatt
IRENA	International Renewable Energy Agency
HOMER	Hybrid optimization of multiple energy resources
NPC	Net present cost
IRR	Internal rate of return
LCOE	Levelized cost of electricity
EnMS	Energy Management systems
ESPO	European Sea Ports organisation
ROI	Return on Investment
ESS	Energy Storage Systems
NESP	Nigerian Energy Support Programme
NREEEP	National Renewable Energy and Energy Efficiency Policy
NREAP	National Renewable Energy Action Plan
SCADA	Supervisory Control and Data Acquisition
SEU	Significant energy users
VPP	Virtual Power Plant
PCC	Point of common coupling
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
MTCC	Maritime technology corporation centre

Chapter 1 INTRODUCTION

Energy efficiency and sustainable power generation in seaports are becoming critical issues that must be addressed in the wake of increasing and volatile oil prices, stricter environmental regulations, and public pressure from local and environmental pressure groups for the decarbonization of energy systems (Alamoush et al., 2020; Acciaro et al., 2014; Bakar et al., 2022). With an increasing growth in seaborne trade and shipping said to account for 80% by volume and 70% by value of the global world trade (UNCTAD, 2019), the seaport, as a gateway for global trade for her hinterland's economic growth, is compelled to adopt strategies to comply with the rising need for sustainable shipping through renewable power generation (Alzahrani et al., 2021; Alamoush et al., 2022). In addition, considering the recent increase in vessel efficiency for speed and gigantism, the port energy demands to handle more cargo in a shorter time are inevitably greater. Also, because of the increasing need to provide extra services such as cold ironing and electrification of port machinery and car fleet (Fang et al., 2020), the port is experiencing an increase in its energy consumption and an equivalent rise in emissions from its dominant use of fossil fuel (Spengler & Wilmsmeier, 2019).

Many ports rely heavily on fossil fuels for power generation, contributing approximately 3% of total global carbon emissions (Alzahrani et al., 2021; Alamoush et al., 2020) as well as introducing other types of pollution into surrounding areas, such as air, noise and water pollution. The most polluted cities in the world, as described by Alzahrani et al., (2021), are coastal cities, while about 60,000 deaths a year are attributed to emissions from seaports and ships.

To achieve sustainable shipping and mitigate the negative effects of the dominant use of fossil fuels, such as global warming, ocean acidification, sea level rise, and associated health challenges, amongst other things, the energy industry must seek to transition to the use of cleaner alternative fuels and available renewable energy (RE) sources amongst other mitigation measures for its growing energy demands.

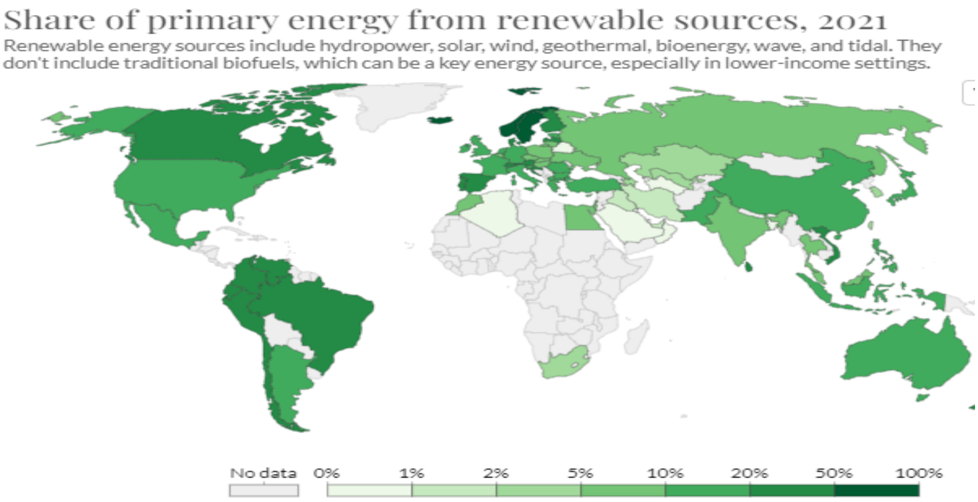


Figure 1. Share of world primary energy from renewables (Ritchie & Roser, 2020)

Even as the regions of Europe, Asia, and the Americas, as shown in Figure 1, are progressing in the uptake of renewable energy, little to no uptake is seen in the African regions as compared to the rest of the world. This is despite evidence for economic, societal, and environmental benefits supported by applications and studies such as by Molavi et al., (2020) and Wang et al., (2019) that theoretically supports the claimed benefits from the use of renewable energy sources. A review of existing literature on the design, sizing, and management of microgrids in port areas conducted by Roy et al., (2020) reveals that the articles are primarily from the United States, Italy, China, Denmark, Germany, Taiwan, Finland, Greece, and Spain.

Developing countries such as Nigeria are lacking sufficient region-specific studies for the implementation of renewable energy for their power generation sector and supporting policies from the government. This study aims to contribute to the body of knowledge for the integration of renewable energy sources in Nigeria, specifically for use in the Lagos Port to address the current deficit in electricity generation while contributing to global decarbonization goals, increasing energy security, and promoting the port operations as a competing port in international shipping.

Chapter 1.1 BACKGROUND

The Port of Lagos shown in Figure 2, also known as Apapa Quays, is the oldest and largest port in Nigeria (NPA, 2018). It is located in Lagos state, Nigeria's commercial capital, and services the hinterlands of landlocked neighbouring countries of Niger and Chad. The port is located at latitude 06°25.7N and longitude 003°20.53E, features infrastructure such as 21 berths with a 3.9 million TEU container handling capacity and a 2,537-meter-long quay (NPA, 2018). The port governance model is that of a landlord port where the Port Authority owns the land and water within the port limits. It is responsible for nautical and harbour operations, enacting, monitoring and enforcing port regulations and bye-laws, while cargo handling, stevedoring, warehousing and other commercial activities and the development and maintenance of superstructures are leased and given under concession to private companies for a given period.

Figure 2 Apapa port Lagos source: (INTELS, 2022)

The port complex is heavily dependent on energy, requiring tens of megawatts for most of its operations and activities, which include cargo handling, storage, buildings, lighting, tools, heating, machinery, and communication systems (Canepa et al., 2018). Inadequate or insufficient power supply will thus not only affect the continuity of operations and the efficiency of port services but will also have a negative impact on the economy of a country like Nigeria, limiting her chances of realizing her blue economy potential.

As rightly identified by Jamoh., (2018), Nigeria will need to expand her maritime assets in order to secure economic growth and diversification in the light of volatile crude oil prices, on which the country's economy is largely dependent.

Chapter 1.2 PROBLEM STATEMENT

The shift towards adopting alternative clean energy for seaports is crucial for the sustainability of maritime transport and power generation at large. Countries are moving towards a more sustainable energy supply in an attempt to preserve the diminishing natural reserves and to reduce the negative effects of externalities such as global warming through the emission of greenhouse gases. The Lagos port is a key and essential sector of the Nigerian economy. As the country aspires to further develop her economy, increase trade and become a hub for the African region, (indicated by the mission statement of her maritime administration) "to be the leading maritime administration in Africa promoting best practices," her energy demand is expected to increase.

Current power generation for port use is predominantly from localized diesel generators and supplemented by the national grid which is not stable and often collapses. In the last nine years, more than 200 grid failures of Nigeria's national energy system have been recorded, resulting in severe blackouts affecting the Lagos port, leading to huge economic and social costs affecting businesses and health (Emodi & Diemuodeke, 2022).

This study is targeted to inform policymakers and relevant stakeholders of the potential for utilizing renewable energy sources such as solar and wind energy with their economic, environmental, and societal benefits for port operations, inhabitants, and the country's economy while also addressing the energy production gap in a sustainable way and supporting Nigeria's energy transition plan to achieve net-zero emissions by 2060 (Sustainable energy for all, 2022).

According to IEA Executive Director Fatih Birol, Africa accounts for only 1% of global solar electricity capacity despite accounting for 40% of global solar radiation. Therefore, to close the gap, this study provides an extensive study on renewable energy potentials within the region, modelling a hybrid microgrid system for the Lagos port using HOMER pro software, providing a cost-efficient design combination with estimated initial and operating costs, CO_2, NOx, and SOx emission values, and further analysing the possible societal benefits the project if implemented will have for the region and her inhabitants.

Chapter 1.3 RESEARCH AIM AND OBJECTIVES

Given the poor uptake in utilizing abundant renewable energy sources in Nigeria for power generation, this study aims to carry out a detailed feasibility study to confirm the hypothesis that the integration of renewable energy in a hybrid microgrid system for electricity generation in the port of Lagos, capable of operating in both islanded and grid connected mode, will provide a clean and reliable energy source for port operations while contributing to global decarbonization goals and ensuring energy security for the region, boosting its operations and services.

To do this, the following objectives have been determined:

1. To identify the significant energy users and estimate the immediate and near future energy load/demand volume and profiles in the Lagos port.
2. To investigate the viability of utilizing available RE technologies identified as the best suited for the location.
3. To establish an optimal energy component mix in a hybrid microgrid system that is economically favourable with the least negative impact on the environment and society.

4. To determine the financial benefits in the form of Net present cost (NPC) and Internal rate of return (IRR) on investment for the implementation of the proposed design.

Chapter 1.4 RESEARCH QUESTIONS

1. What are the significant energy consumers in the port and what is the current and near-future energy load profile for port operations?
2. What are the feasible renewable energy sources and technologies such as solar, wind, and geothermal energy for the port location?
3. What is the optimal energy component sizing and combination with minimum investment cost and maximized environmental and social benefits for the port authority and its stakeholders?
4. How much savings in electricity bills is attainable with the implementation of the proposed microgrid system and if the project is able to recover investment cost and when?

Chapter 1.5 SCOPE AND LIMITATION

This study addresses maritime decarbonization goals, energy security and reliability through renewable energy uptake in Nigeria and particularly in the port of Lagos. As far as the researcher is aware, this is the first attempt to provide technical recommendations and a proposed design to implement a microgrid system for the port of Lagos. The future should count much more on renewable energy as this implements UN sustainable development goal number 7, which talks addresses renewable energy, and goal number 9, which addresses sustainable production and consumption.

Due to the maturity of technology, reduced cost, and available data for implementing solar and wind energy amongst other renewable energy sources after hydro power (see figure 3), this research scope is limited to focusing only on the potentials of these two sources, following a similar application for the port of Aalborg, Denmark (Bakar et al., 2021).

The author also acknowledges other resource limitations such as researcher experience, and time to complete the research.

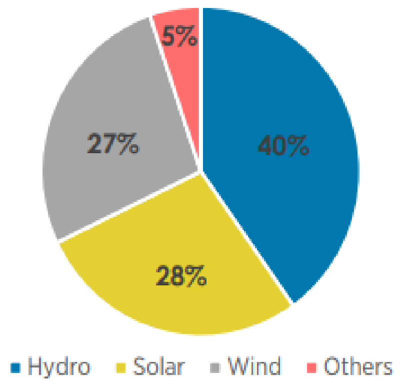


Figure 3. Share of Renewable energy in the world. (Source: IRENA renewable energy highlights 2021)

Chapter 1.6 RESEARCH OUTLINE

To achieve the objectives for this study, the dissertation is structured into six chapters (presented in figure 4).

Chapter one introduces the context of the study, highlighting what the dissertation is about, why it is relevant and identifying the scope and limitations of the research.

Chapter two covers an extensive literature review of existing knowledge on port energy needs and greening measures, answering research questions on port energy users and the RE resource potentials. It also introduces the concept of microgrid systems with its benefits.

Chapter three describes the methodology and theoretical framework adopted with justification to its selection including data collection process.

Chapter four conducts a case study in Lagos port with sizing of the microgrid components, optimizing the design based on a single objective then further filtering using multi-attribute criteria, while defining sensitive parameters.

Chapter five presents the results and discussion as it compares to conclusions from existing knowledge and answers whether the results were in accordance with researchers' preconceived hypothesis.

Chapter six concludes the research making recommendations for further research areas and policy needs.

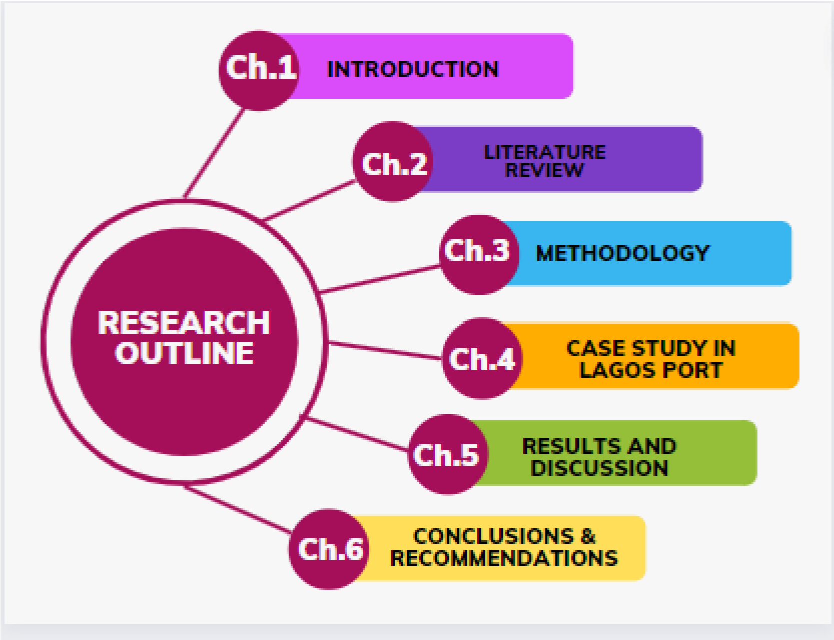


Figure 4. Research outline

Chapter 2 LITERATURE REVIEW

Chapter 2.1 INTRODUCTION

The seaport is described as a gateway for global trade, connecting the sea and land for complex marine activities, and acting as a catalyst for the economic development of countries (Alzahrani et al., 2021; Ahamad et al., 2021; Bakar et al., 2021). The port has been playing an essential role in facilitating imports and exports since the industrial revolution (Alzahrani et al., 2021). It also functions as a social caretaker for employees and the communities, such as in Europe, where more than 110,000 workers were employed by port operators for cargo loading and unloading and other port services (Van Hooydonk., 2014). Most of the developed cities around the world are port cities, and it is no wonder development begins in the port area (Alzahrani et al., 2021).

With a continuous increase in seaborne trade, where in 2019, over 11 billion tonnes of cargo were recorded to have been carried by ships of 1000 GT and above, accounting for 4,362,737 port calls all around the world (Alamoush, 2021). Required energy demands for shipping including ports is predicted to grow by an annual average rate of 3.4 per cent between the years 2019–2024 (UNCTAD, 2019a).

The port is expanding and therefore the need to become more efficient and dependable in its operations. Also, with the expansion of port activities, concerns for energy efficiency and continuity of supply in are gaining recognition where instruments such as ISO 50001 EnMS, ESPO PERS, and the World Port Sustainability Program by IAPH are being employed for port energy efficiency (Ballini, 2022).

Renewable energy adoption is shown to be a key instrument towards green port transitioning to manage growing concerns over energy crises, negative environmental impacts and economic issues (Bakar et al., 2022; Sadiq et al., 2021).

This literature review chapter aims to explore the typical present and future energy needs of the port, the available renewable energy options already implemented in ports, and the way in which these options can function together for power generation.

Chapter 2.2 PORT OPERATIONS AND ENERGY USERS

A seaport is a critical sector that connects the sea and land and provides for the transfer of goods and people from ship to shore (Bakar et al., 2021). Seaports have become more specialized following trends with the development of specialized vessels, giving rise to specialized ports and terminals such as container terminals, general-cargo terminals, liquid-cargo terminals, RORO and passenger vessel terminals. Each specialized terminal is unique in the mode of operation and its energy load differs accordingly. Seaports are generally located close to urban areas and function as an entrance point for imports of raw materials for a city's infrastructural development. These activities inevitably make the port become a highly concentrated energy demand and supply hub (Acciaro et al., 2014).

The port now serves more than just cargo transfers and is linked to the entire logistics supply chain (Ballini, 2022). Competitiveness, profits, pollution reduction, efficiency, and carbon emission trading are crucial energy-related factors for any port authority (Canepa et al., 2020). Due to the massive growth in maritime logistics, an equivalent large energy volume for supply is required to maintain optimal operation of sea trade, bringing about the need to close the current gap between energy generation and demand in ports (Bakar et al., 2021).

For example, Container throughput in 2020 for Nigeria is estimated at 1,528,520 TEU, while an estimated 3,833 ports call were made in Nigerian ports in 2020 as shown in figure 5. These numbers continue to increase from previous years (UNCTADstat,2022).

PORT CALLS AND PERFORMANCE

Port calls, time spent in ports, vessel age and size in 2020[9]

	Number of arrivals	Median time in port (days)	Avg age of vessels	Avg size (GT) of vessels	Avg cargo carrying capacity (DWT) per vessel	Avg container carrying capacity (TEU) per container ship	Maximum size (GT) of vessels
All ships	3 833	3.59	14	32 838	36 286	3 758	149 367
Liquid bulk carriers	1 361	3.38	16	20 677	32 579	..	56 291
Liquefied petroleum gas carriers	190	2.10	11	20 204	23 647	..	48 425
Liquefied natural gas carriers	303	1.37	10	107 540	85 501	..	149 367
Dry bulk carriers	519	6.83	12	28 936	49 867	..	107 374
Dry breakbulk carriers	455	4.82	19	9 532	12 252	..	71 543
Roll-on/ roll-off ships	242	..	13	49 536	21 494	..	76 420
Container ships	763	3.83	13	39 268	..	3 758	95 205
Passenger ships	..	..	..	..	..	..	..

Port liner shipping connectivity index - Top 5 ports in 2020[11]

Maximum 2006=100 for China, Hong Kong SAR

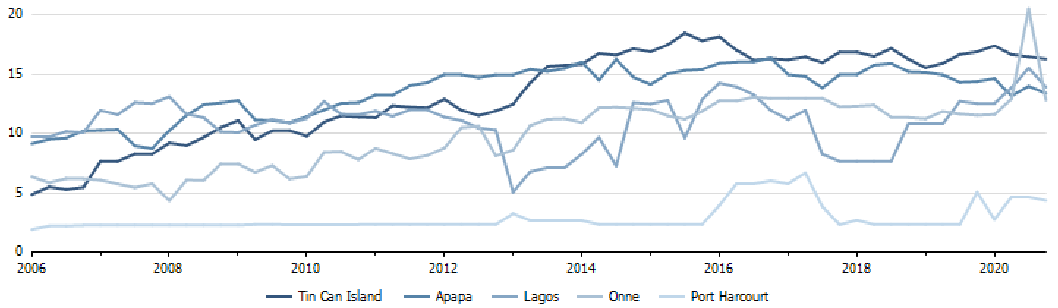


Figure 5. port calls and performance in Nigeria 2020 (source: UNCTADstat, 2022)

Considering the need to handle such large amounts of cargo and ensure a shorter vessel turnaround time, ports are now utilizing machinery, automation, and the internet of things for their processes, reducing human interaction and increasing productivity. These machines are powered by electricity or fuel. Examples of equipment used in ports in a container terminal include Rubber Tyre Gantry, Rail Mounted Gantry, trucks, conveyors, and cranes.

With recent adoption of cutting-edge technologies like cold ironing, electrification of port machinery, alternative fuels, and use of renewable energy installations, there is a need to focus on energy issues in the port areas (Acciaro et al., 2014; Rolan et al., 2019). But to begin any form of energy planning, it is necessary that the significant energy users (SEU's) be identified and also taking into account how different operations in port will vary the load profile (Bakar et al., 2021). Typical energy consumers in a port facility are shown in Table 1.

Table 1. Energy source for equipment in a container terminal (Inspired by Spengler & Wilmsmeier, 2019)

ENERGY CONSUMERS TYPICAL OF A CONTAINER TERMINAL				
	Diesel	Petrol	Natural gas	electricity
Ship to shore cranes	X			X
Mobile cranes	X			X
Rail mounted gantry cranes	X			X
Rubber tyred gantry cranes	X			X
Reach stackers	X			X
Straddle carriers	X			X
Tractor-trailer units	X		X	X
Generators	X		X	
Buildings				X
Lighting				X
Reefer containers		X	X	X
Other port vehicles	X	X	X	X

An analysis on the energy efficiency in a container terminal by (Spengler & Wilmsmeier, 2019) shows that only about 32% of the energy consumed is electricity, the bulk amount is represented by diesel fuel.

Chapter 2.3 ENERGY SOURCES AND GENERATION

Energy is defined as the ability to do work and is essential for almost all of life's processes, even for plant and animal existence.

Energy exists in forms such as thermal, electrical, chemical, and mechanical energy. For port operations, energy is utilized in the form of electrical energy for lighting, buildings, and equipment, as well as charging of electric vehicles while Chemical energy in the form of fuel is used for powering machinery, and heating.

Energy for industrial power generation can be broadly categorized into three:

1. Fossil fuel energy
2. Nuclear energy

3. Renewable energy

Chapter 2.3.1 FOSSIL FUEL ENERGY

Fossil fuels include coal, petroleum, and natural gas. It is a form of energy that has been forming over millions of years from the decomposition of microorganisms and plants buried in the seabed. It is the most used form of energy today due to its relatively lower cost of extraction and ability to store and use it as needed. The fuel is burned in a combustion process to generate useful work; this combustion process is followed by the emission of an exhaust gas containing harmful gases.

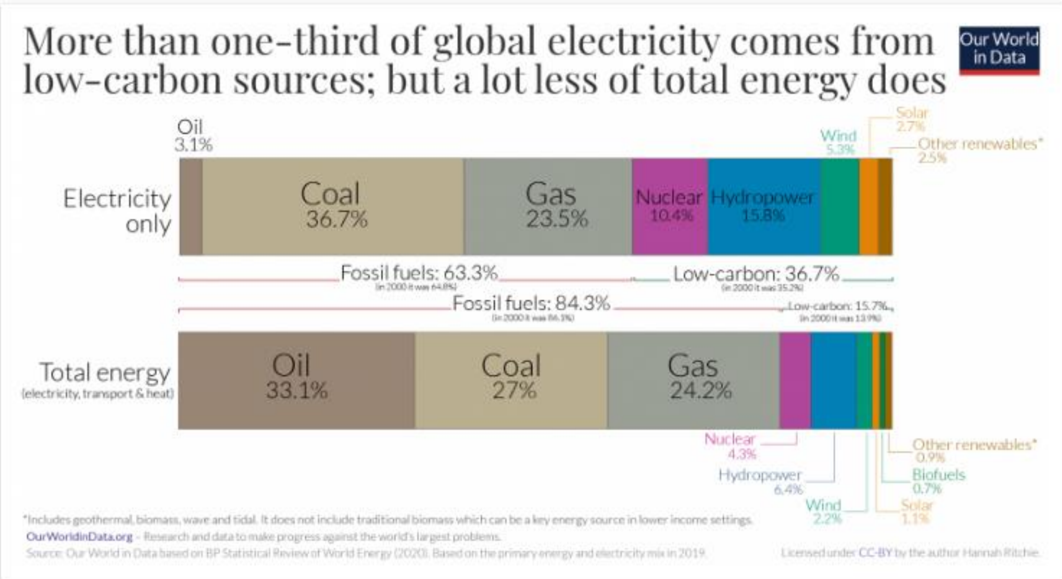


Figure 6. World statistics on energy mix (Source: Ritchie et al., 2020)

As shown from figure 5, fossil fuel is the dominant energy source today, with about 63.3% of electricity generated, while renewable energy sources represent only about 26.3%. 84.3% of total energy is from fossil fuels alone.

Chapter 2.3.2 NUCLEAR ENERGY

This is a form of energy that utilizes nuclear reactors in the process of nuclear fission to generate steam by using a thermodynamic cycle to convert heat into work. It is a cleaner form of energy with high energy density as it does not undergo a combustion process. It has benefits such as being predictable with a low cost of operation, except for disadvantages from the adverse effects of accidents introducing radioactive waste, which has long-term negative effects on inhabitants. Such accidents include the Three-mile Island nuclear power plant in 1979, the Chernobyl nuclear power plant accident in 1986 and most recently the Fukushima accident in 2011 (Cherp & Jewell, 2011).

Chapter 2.3.3 RENEWABLE ENERGY

Renewable energy is energy derived from sources that replenish themselves faster than their rate of consumption. These energy sources are abundant in nature and utilizing them has benefits that include energy security for even remote locations; free access to energy; economic and social benefits; global warming reduction; and reducing environmental and health impacts (Owusu & Asumadu-Sarkodie, 2016).

These energy sources are predicted to play a key part in the future shift from centralized to distributed generation, which is closely related to the smart grid concept (Roy et al., 2020). The high initial costs associated with the use of renewable energy are soon becoming a thing of the past as increasing uptake of RE in various energy sectors has led to a reduction in installation costs for solar and wind technologies in particular (IRENA.,2021). RE sources provide for a cleaner form of energy even though utilizing them will require a complex method for sizing, design and control due to un-even distribution and not very predictable as their availability changes with the seasons (Owusu & Asumadu-Sarkodie, 2016). Examples of renewable energy sources are: hydro-electric, solar, wind, geothermal, biomass and ocean energy.

Chapter 2.3.3.1 SOLAR ENERGY

Solar energy is energy derived from the sun and is usually generated using two main technologies: solar photovoltaic and concentrated heat fluid cycle. Solar efficiency using photovoltaic panels is estimated to be about 24%, while the use of concentrated solar power in combination with a heat engine will have an efficiency of about 60% (Schönborn, 2022).

Photovoltaic technology is the most commonly used today and works by the use of semiconductor silicon crystal panels doped with boron (p-type silicon) or phosphorus (n-type silicon). When light from the sun strikes the electrons from the silicon panel, causing a movement of electrons, an electric field is generated, and with the use of an inverter, the DC current is converted to AC current as support to base load demand.

In ports, solar panels can be installed on wide flat surfaces or on rooftops of buildings, storage areas, and warehouses. Table 2 shows existing ports with solar PV technology and their capacities.

Table 2 Ports with installed solar PV technology (adapted from Roy et al., 2020)

PORT	CAPACITY	INSTALLATION SITE
Stockholm royal seaport (Sweden)	548kw PV	rooftop
Rotterdam (Netherlands)	3.5 MW PV	rooftop
Amsterdam (Netherlands)	4 MW PV	
Antwerp (Belgium)	56 MW PV	
Gothenburg (Sweden)	PV	
Port of Los Angeles (USA)	1 MW PV	
Auckland (New Zealand)	PV	
San Diego (USA)	700Kw PV	Administrative building rooftop
Long beach (USA)	300kW PV	Carport

Chapter 2.3.3.2 WIND ENERGY

Wind energy is energy that is derived from the force of wind speed, maximized at an optimum angle of attack, generating a lift force which causes the rotation of the turbine blades or rotational parts to produce useful work. It is one of the oldest sources of energy utilized by humans in vessel propulsion using sails. Wind energy is abundant and available worldwide. It is free with zero-emission from the energy source itself (Allwright, 2022). Wind energy power generation is already implemented in the ports of Rotterdam, Amsterdam, Antwerp, and Kitakyushu in Japan. Offshore wind power represents 3% of the EU power demand with a total offshore wind capacity of 26.4 GW (Windeurope, 2021).

Technologies for utilizing wind for power generation include onshore and offshore wind turbines, wind sails, flettner rotors, and kites.

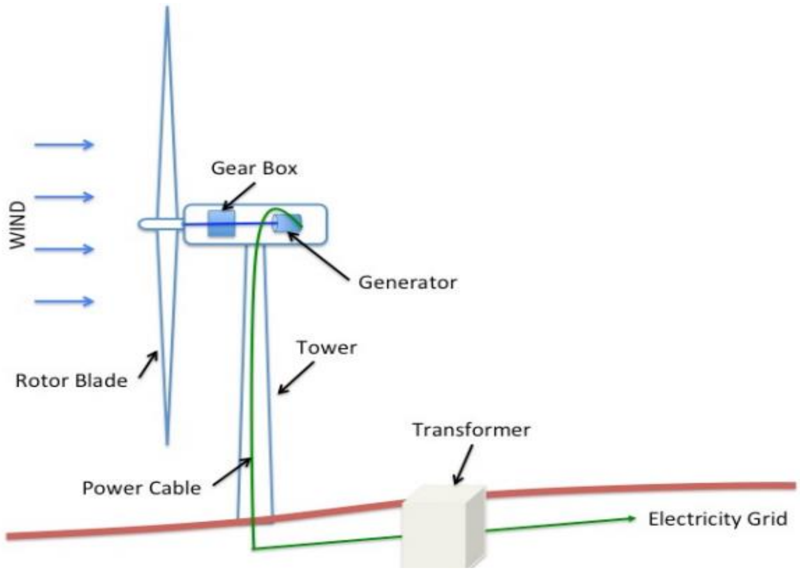


Figure 7. Wind turbine components (source: A. Olcer, course note EGY 112)

Figure 7 shows the key components of a horizontal onshore wind turbine. The wind turbine achieves rotation when a moving fluid (wind) cuts across the aerofoiled shaped turbine blades. A gearbox is used to boost the rotational speed from a low-speed main shaft to a high-speed shaft connected with an electrical generator. The alternator is connected to the utility grid via conversion circuits that convert the AC it produces to DC and then back to AC synchronized with the grid frequency. Then voltage is properly raised by a step-up transformer before supplying the grid. Blades are always positioned at the optimum pitch angle in relation to the relative wind direction for high efficiency. Onshore wind turbines' global cumulative capacity increased more than fourfold during the 2010 to 2021 period, from 178 GW to 769 GW (IRENA, 2022).

Chapter 2.3.3.4 OCEAN ENERGY

Ocean energy is energy derived from the oceans through elements such as tidal currents, waves, ocean currents, salinity gradients, etc. Despite the fact that studies on the use of tidal generators are being conducted in the ports of Aviles, Ribadeo, and close to New Jersey in the United States (Almoush et al., 2020; Ramoset al., 2014), and tide differentials are being studied in Dover, the United Kingdom, and the Port of Digby in Nova Scotia (Acciaro et al., 2014), the technology is not as widely used as much as hydro, wind and solar. Due to seasonal volatility and random variability of wave scales and strengths, wave energy used in Port Kembla, Australia, or Mutriku, the Basque Country, is disadvantageous (Acciaro et al., 2014).

Chapter 2.3.3.4 Geothermal energy

This is a form of renewable energy that utilizes the earth's layers of temperature difference stored in the earth's interior as heat. The structure and internal activities of the planet act as the source of this heat. Even though there is an infinite supply of this heat within the Earth's crust, it is dispersed unevenly, rarely concentrated, and frequently occurs at depths that are too big to be used for commercial purposes (Barbier, 2002). High capital costs, resource placement and quality at varying depths are major challenges to widespread deployment of geothermal resources (Soltani et al., 2021). The technology mostly used to extract this energy is the direct heat pump, with an installed capacity of 71.6 %, mostly in North America, Europe, and China. The technology is used in EU ports such as Stockholm, Antwerp, and Hamburg.

System capacity of some renewable energy sources are as shown in figure 8 showing higher capacities for the use of tidal and wave energy more than that of solar and wind. Indicating the need to invest into technologies to enable efficient tapping of their abundant potentials.

Renewable energy type	Generated power (kW or MW)
Wind turbine	2 MW up to 6 MW
Solar PV - rooftop	100 kW up to 2 MW
Solar PV - on-ground	1 MW up to 50 MW
Tidal energy converters	50 kW up to 750 kW
Wave energy converters	1.5 MW up to 250 MW

MW = Megawatt, kW = Kilowatt, PV = photovoltaic.

Figure 8. Renewable energy power capabilities (PIANC, 2019)

Chapter 2.4 DRIVERS TO DECARBONIZATION AND RENEWABLE ENERGY UPTAKE

Decarbonization is a term used to describe the reduction of carbon emissions, particularly as a result of anthropogenic activities. Carbon emissions are introduced into the atmosphere as a result of the combustion of fossil fuels. And as earlier highlighted, the industrialised world of today is highly dependent on fossil fuels for many activities. Over the years, the world as we know it is experiencing changes such as hurricanes, global warming, ocean acidification, sea-level rise, habitat loss as a result of population growth and anthropogenic activities. In order to mitigate these negative impacts and occurrences, industries and individuals must collectively work towards decarbonization goals. Key drivers for the decarbonization of processes include: knowledge and evidence of depleting natural reserves for crude, volatile fuel prices causing economic hardship, air pollution and pollutants, and increasing international, regional and local regulations for climate protection.

Chapter 2.4.1 Depleting resources

With increase in economic and population growth where global electricity demand in 2021 increased by 5% with almost half of the demand supplied by fossil fuel (IEA, 2021), the available oil reserve will not be able to sustain the increasing high rate of consumption. A study by Shafiee & Topal, (2009) used a modified formula from Klass model to calculate the estimated years that oil, coal and gas will become depleted as 35, 107 and 37years respectively using 2005 as base year. To this effect, the need to transition to alternative energy sources has become critical causing a shift to employing alternative energy sources of which renewables are amongst.

Chapter 2.4.2 Volatile oil prices

When oil prices hike such as was experienced during the 1973 Arab oil embargo; the Russian-Ukraine gas crisis in 2009 and 2022; the 2008 oil shock; the 2011 oil crises, and other notable oil crises (Accairo., 2015; Cherp & Jewell, 2011) the world is forced to deal with the repercussion from increased cost in operations and maintenance affecting the survivability of services and operations. In order to mitigate effects from such occurrences, countries are forced to invest in alternative sources of energy such as renewables to diversify supplies and improve their energy security. This shift to alternative energy sources contributes to decarbonization goals.

Chapter 2.4.3 Environmental impacts

The combustion of fossil fuel produces by-products of carbon, water, nitrogen and particulate matter. Some of these by-products are harmful to the environment, causing harm to human health. The harmful by-products are categorized into air pollutants and greenhouse gases. Air pollutants such as black carbon have a direct impact on human health and contaminate the environment, damaging assets, where about 5% of lung and trachea cancers are said to be attributed to black carbon emissions from ships in port(Abdaoui, 2021). Greenhouse gases such as carbon dioxide and nitrous oxide accumulate in the local and global atmosphere, changing the atmospheric content and properties over time (Baumler, 2022). Due to these negative effects, the use of fossil fuel is losing popularity amongst climate conservationists.

Chapter 2.4.4 Strict regulations

The Paris Agreement is one of the most promising initiatives to encourage the reduction of carbon emissions by states. While in the shipping industry, the IMO's initial GHG strategy developed in 2018 is the first of its kind to address climate change actions with practical steps and strategies. The Paris Agreement requires countries to minimize greenhouse gas emissions with the goal of maintaining a global temperature below 2^{o}c. Also, considering that emissions from ports as an industry account for approximately 3% of the total GHG emissions worldwide (Misra et al., 2017; Alamoush et al., 2020), GHG emissions by ports under the jurisdiction of the State must adopt measures for reducing their emissions through implementing renewable energy in power generation. As a result, the nation's economy will benefit from lower marginal costs of operation, cleaner emissions, and more efficient ports.

Chapter 2.5 Port operations in Nigeria

Nigeria is an oil producing country with 90% of its exports coming from fuel products. Port activities continue to grow as the country recorded a higher import value of 55,390 million dollars compared to its exports of 35,634 million dollars in 2020 for the first time in over fifteen years (UNCTAD, 2019). This growth in economic activities will require an equivalent increase in energy demand to sustain economic growth and diversification (Jamoh, 2018). Energy efficiency especially in ports is one strategy for securing economic growth for the nation that is aside tackling other challenges such as lack of infrastructure in ports that causes port congestion and increased vessel turn-around time as identified by Oruwari., (2021). Major ports around the world are shifting to the use of renewable energy sources to reduce dependence on conventional energy sources such as fossil fuels that have negative impact on society and the environment and this should be the direction for a country such as Nigeria.

Chapter 2.5.1 Current power supply in Lagos port

As earlier identified from Figure 6, about 68% of energy needs in the port is from diesel and gas, while 32% is from electricity. Electricity supply in Lagos Apapa port as reported by (INTELS, 2022) is mainly from diesel generators with a total of 15 generators (2 units of up to 50kVA diesel generators, 9 units of between 100-500kVA diesel generators and 4 Tower lights) and supplemented by supply from the national grid. Also, each of the five terminal operators as listed in figure 9, manages its own power generation as opposed to a collective system.

Terminal operators

Terminal	Operator	Type of concession	Depth (m)
1. Terminals A & B	Apapa Bulk Terminal Ltd	Bulk cargo	13.5
2. Terminals C & D	ENL Consortium Ltd	Multipurpose	11.0
3. Container Terminal	AP Moller Terminal	Containers	13.5
4. Terminal E	Greenview Dev. Nig.Ltd	Bulk cargo	13.5
5. Lilypond Container Depot	Lilypond	Containers	11.5

Figure 9. Terminal operators in Lagos Apapa port. (Source: NPA, 2018)

The integration of renewable energy for electricity generation is still unpopular despite the vast potential of renewable energy sources, such as average annual wind speeds of 3.5m/s and average solar irradiation of 6.13 kWh/m^2 in the region. Gas turbines and hydroelectricity are the main sources of power generation for the main grid, with 22 gas stations and 3 hydro on-grid generating units functioning in Nigeria's electricity supply sector (Oyewo et al., 2018). With an installed capacity of 13 308 MW, only about 6 158 MW was reported as operational in 2014 by NESP (2015). While actual generation is between 3000 MW and 4500 MW due to unavailability of gas, breakdowns, water shortages, and grid constraints with poor transmission. This has left industries and households to provide their own alternative electricity, mainly using petrol and diesel generators.

Only recently, on August 24th, 2022, Nigeria launched her energy transition plan, highlighting the country’s commitment and ambition to achieve carbon neutrality and ending energy scarcity. The country’s pathway to achieving net-zero emissions by 2060 was at the core of the agenda (Sustainable energy for all, 2022). In an effort to overcome this energy shortage, the National Renewable Energy and Energy Efficiency Policy (NREEEP) was adopted by the federal government in 2015, tasked with creating a framework for energy efficiency and RE development in Nigeria (Oyewo et al., 2018).

Chapter 2.6 MICROGRID SYSTEMS

A microgrid system can be described as "*a group of interconnected loads and Distributed Energy Resources (DERs) with clearly defined electrical boundaries that act as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid connected or island mode*" (US Department of Energy). Typical arrangement is presented in figure 10.

Advantages for the use of microgrids in facilities includes its ability to incorporate various sources of energy including renewables, ability to allow individuals act as both consumers and produces in the energy market (Çetinbaş et al., 2019) with possibilities to sell excess generated power, reduction in distribution line losses since production takes place locally in the same location as consumers offering flexible power systems (Milis et al. 2018). The system optimizes operations, increases resilience, permits bidirectional operations, and enhances cooperation among grid users. It is considered as the future of energy systems due its ability to integrate economic, environmental and socially acceptable forms of energy. (Tsao & Thanh, 2021). It also lowers the cost of electricity with reasonable pay-back time and contributes to clean emissions (Çetinbaş et al., 2019).

The system is most useful in remote locations where electricity from the national grid is not reliable or completely unavailable and for utilizing renewable energy sources. The system can include a smart control system such as SCADA to manage and control distribution, supplying electricity to facilities such as docks, heavy equipment (cranes), buildings of different sizes, lighting systems, EV infrastructure, campuses, hospitals, and cities.

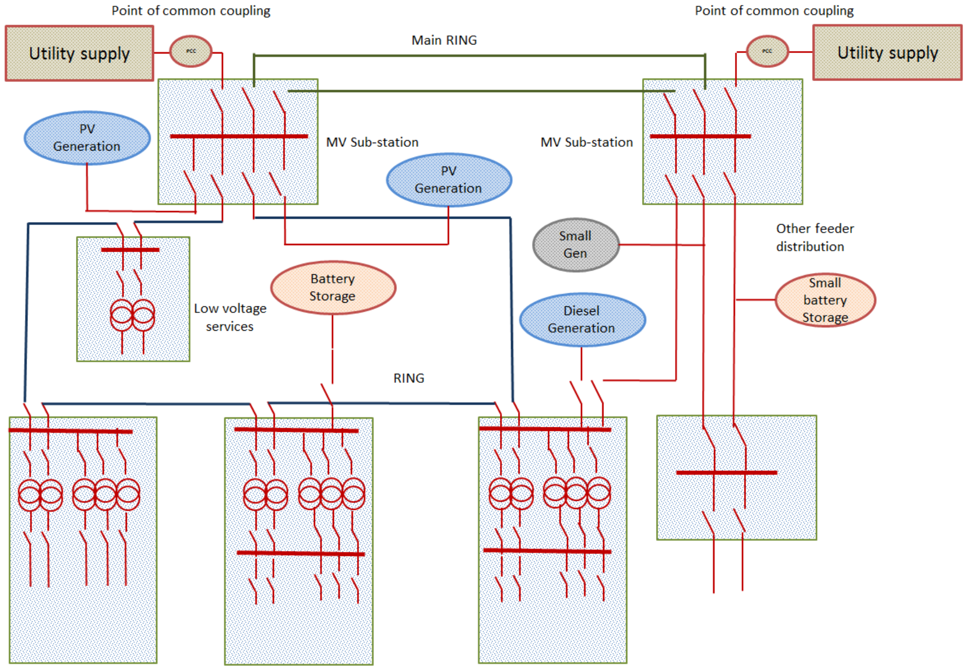


Figure 10. General organization of the electrical micro-grid

Ahamad et al., (2018) identified that with use of solar, wind energy and battery storage, 75% of a port's electricity demand could be added to the microgrid resulting in important cost savings. The application of renewable energy sources for power generation systems has improved energy reliability and sustainability, reduced energy cost and become more environmentally friendly as less fossil fuel is used (Sadiq et al., 2021; Misra et al., 2017).

Chapter 2.6.1 HOMER pro SOFTWARE

The Hybrid Optimization of Multiple Energy Resources (Homer) is a widely used and preferred analytical tool for simulating, optimizing and estimating cost implications of microgrid systems. Developed by the US department of energy's National renewable energy laboratory and used in over 190 countries, the software provides advance simulation and optimization. There are a number of other software that have been used in optimizing of hybrid renewable energy systems such as HYBRID 2, PVSYST, INSEL, SOMES, ARES, and PVF-chart, but HOMER is seen to be utilized more often and widely accepted (Sawle et al., 2016).

The software was utilized by Ma et al., (2014) to design a standalone hybrid solar-wind-battery system for a remote Island, Çetinbaş et al., (2019) utilized it to present designs, performance analysis, and optimization of a hybrid microgrid using different operating scenarios for a hospital, Bakar et al., (2021) utilized the software for the configuration and sizing of a hybrid microgrid using renewable energy from solar PV and wind turbines with batteries and cold ironing for the port of Aalborg. Getinet et al., (2020) designed a microgrid system using solar PV and wind turbines with batteries for a city in Ethiopia using the same software. These and many more studies have proven the preference for using HOMER in any microgrid modelling.

Chapter 2.7 CONCLUSION

From existing literature and applications, it is evident that the integration of renewable energy for electricity generation in seaport and harbour areas is feasible and beneficial economically, environmentally, and socially. The challenges to its implementation as identified include the high unpredictability of energy demand due to changing scenarios; the high capital cost of renewables; less predictability of renewable sources; lack of expertise; and lack of supporting policies. Some of these has led to a slower uptake in developing countries until very recently in the year 2015 that Nigeria developed a policy to transform its power generation and encourage renewable energy uptake. This creates a need and opportunity for feasibility studies such as this research aims to accomplish.

Chapter 3 METHODOLOGY

Chapter 3.1 INTRODUCTION

This chapter will detail all the research choices made, such as techniques and frameworks adopted. It explains how the study was designed in order to appropriately answer the research questions and achieve the aim and objectives of the research with justification. To recall, the study was carried out to: determine the current and future energy load profile of the Lagos port; determine the potential and feasible renewable energy sources for power generation in the specific geographical location; develop a conceptual design of energy mix with component sizing; optimize the system based on cost minimization and environmental impacts; and further explore the societal impacts.

Chapter 3.2 RESEARCH DESIGN

The design of this research adopts a quantitative approach through the use of a case study and using a computer software to model and simulate the microgrid system components by inputting relevant data as accurately as possible collected over a time frame of one year and based on data for the year 2021. The model is used to imitate the real-world operations of the system and to investigate the feasibility and confirm preconceived hypothesis in supporting the theory that using renewable energy is more beneficial as compared to the use of conventional fossil fuel for electricity generation in Nigeria for port use. This methodology is believed to be most appropriate as it is widely used in existing studies that involves Distributed energy resource design and implementation.

The research process is structured into five stages. The first stage is the conceptual design of the microgrid system using HOMER software with input data, the second stage is an optimization of the design to select the optimal design based on economic benefits through financial techniques such as Net present cost, payback period, Internal rate of return, and levelized cost of electricity. The third stage introduces a multi-attribute decision technique for ranking feasible alternative systems by prioritizing reduced carbon emission and including energy storage. The fourth stage carries out a sensitivity analysis for the design parameters that are less predictable and expected to change such as diesel fuel price and grid failures to determine how significant these changes affect the performance of the system. Lastly the fifth stage explores the societal impacts for implementation of microgrids using renewable energy as it affects the development of the country and port municipalities adopted from discussions and seminars by relevant maritime professionals.

Research philosophy: This research is adopting a positivist philosophy where the author has a preconceived idea that the use of renewable energy for electricity generation in port will have a positive impact economically and environmentally as it is evident from existing designs implemented in other ports. Societal impacts will be exploratory since impacts will be perceived differently by people from different geographical locations and backgrounds. Keeping in mind what the priorities of the society are.

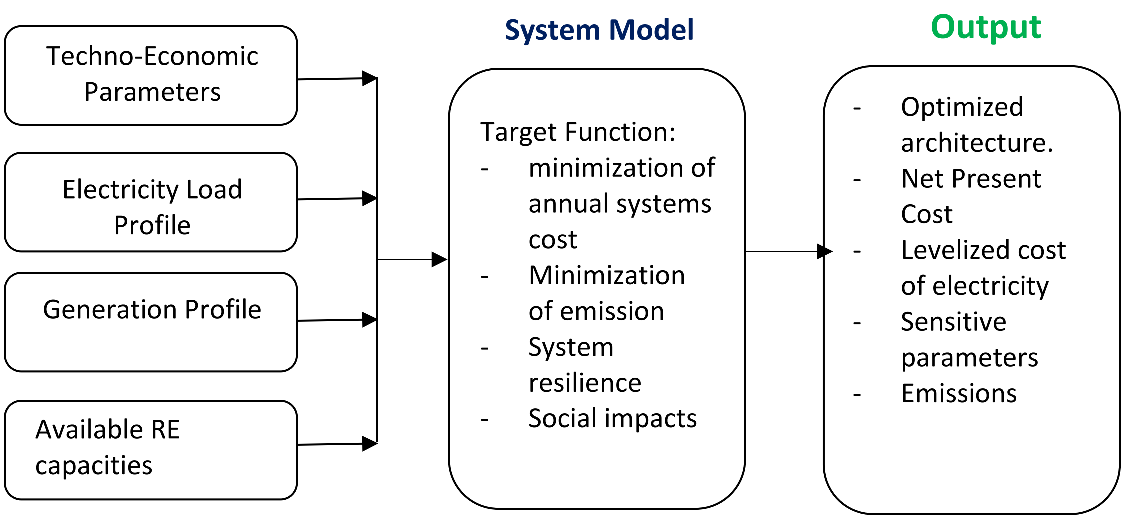


Figure 11. Research methodology inputs and outputs

Chapter 3.3 RESEARCH METHOD

Novelty methodology combines existing methodologies beginning with a single objective optimization for cost minimization, then a filtering technique to rank conflicting alternatives and lastly, a sensitivity analysis for variables. This process can be used in other ports with similar objectives.

Single objective optimization is a methodology used to find the best solution for a specific criterion. In this case, least NPC is used as an indicator for determining the least cost system. The Net Present Cost (Also known as Life cycle cost) is a term that describes the present value for all the capital and operational costs to be incurred in a project over the project lifetime. NPC is calculated using equation 1.

$C_{NPC} = C_P - C_R$ .... *Equation 1*

Where: C_P = present cost

C_R = present revenue

After determining the least cost architecture, other feasible combinations are considered through a filtering process to identify conflicting alternatives such as least emission system and improved system resilience through the use of batteries. Based on these alternatives, a multi-attribute decision making technique (TOPSIS methodology) is utilized.

The TOPSIS Methodology (a Technique for Order Preference by Similarity to Ideal Solution) developed by Hwang and Yoon (1981) is a multi-attribute decision-making technique that uses weighted attributes based on decision makers' perceived importance and preference, giving room for introducing rationality in the methodology. In this design, the decision-making will consider both financial and non-financial benefits in order to determine the winning investment architecture.

The technique starts by defining the objectives for the decision-making process. These are

1. Minimum Net present cost
2. Minimum GHG emission.

Therefore, the design with least distance to the positive ideal solution and longest distance to the negative ideal solution will be ranked top.

Finally, a sensitivity analysis is carried out for variables such as fuel cost and grid failure.

Chapter 3.4 Data collection methods

Data collection process utilized secondary data retrieved from recognised organizations such as NASA power for meteorological data, IRENA renewable energy statistics 2022 for cost of renewable energy components, Main grid electricity tariff from distribution company official website. While cost of fuel, inflation rate, discount rate, cost of batteries, operations and maintenance cost(O&M) can be estimated from actual market surveys in project location to present a realistic estimation for life cycle cost calculation.

In conclusion, the methodology selected for this study is location specific using data typical to the site location, and using a powerful optimization tool that compares the cumulated power generation resulting from the main grid, diesel generator, solar PV, wind turbines and battery storage to the daily energy demand from the port terminal. Assessing feasibility for integration of clean renewable energy while minimizing cost and emissions. Assessment criteria for optimizing cost considers net present cost, levelized cost of electricity, initial cost and operating cost. While environmental impacts consider renewable fraction as it reflects the emission levels.

Societal impacts consider literature, reports and discussions from seminars addressing decarbonization in shipping (such as the recent CHEK seminar at the World Maritime University from 30th to 31st August 2022) and the barriers to decarbonization as experienced in LDC's and SIDS presented by MTCC Africa and presentations by the Director of Climate Technology Centre and Network (CTCN).

Chapter 4 CASE STUDY FOR LAGOS PORT

The case study approach is used in this research to provide detailed results from an in-depth investigation for the performance of the microgrid system in a specific location or context. Data collected for the model are representative of real-life conditions so as to mimic the reality with a goal of understanding how the actual system will perform before implementation.

Chapter 4.1 MICROGRID SYSTEM RELATED RESOURCES

The system resources are the available resources such as the available site for component installation, wind characteristics (wind speed), solar irradiation, temperature, and financial capacity that will determine the project's viability while justifying the use of renewable energy sources.

HOMER pro is equipped with an in-app database for resources that includes wind speed, solar irradiation, and temperature from NASA power. The values were cross referenced with data from the global solar atlas and global wind atlas, accessed through https://globalsolaratlas.info/map?c=11.609193,8.261719,4 and https://globalwindatlas.info/ respectively. Data from these two sources were compared to NASA Power and found to be similar confirming to be accurate and valid. To collect the data, the location for the project was first determined so as to use only actual data for the specific port location.

Chapter 4.1.1 AVAILABLE AREA:

The area determined for the installation of renewable energy components such as solar panels and wind turbines is within the port facility location. This is important as the system is intended to function as a remote microgrid where power generation is concentrated in the same location as the consumer (or prosumer as the case may be). Figure 12 identifies a possible location and an estimation of the total rooftop area of port buildings that is considered for solar PV installation since existing designs have solar panels installed on wide open spaces such as the rooftops of port buildings.

Figure 12. Arial map showing location for solar PV installation.

Measurement of the rooftop of one of the port buildings using google maps shows

Length = 130m

Width = 50m

Area = 130 x 50

= 6,500 square meters.

Considering installation on all five port buildings

Estimated Available total area for solar panel installation = 5 X 6,500

= 32,500 square meters.

Chapter 4.1.2 SOLAR IRRADIATION:

Meteorological data for solar irradiation at the location coordinates will have a direct impact on the potential for solar power generation as seen in equation 2. This is the equation HOMER uses to calculate the output power from the PV array.

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}} \right) \left[1 + \alpha_P \left(T_c - T_{c,STC} \right) \right]$$

………… *Equation 2*

Where:

P_{PV} = PV output power

Y_{PV} = Rated capacity of PV array

F_{PV} = derating factor

$\overline{G}_T$ = Solar radiation incident in current time step

$\overline{G}_T$, STC = Incident standard radiation under test conditions of 1 kW/m^2

T_C = PV cell temperature in current time

$T_{C,STC}$ = PV cell temperature under standard test conditions of 25^{o}c.

(Source: HOMER energy)

Figure 13 shows the values for average annual clear-sky solar irradiance between 2002 and 2021, where the highest annual irradiance was experienced in 2019 with values of 6.24 kWh/m^2. Figure 14 takes a closer look at the monthly distributions for the reference year under investigation (2021), with an average solar irradiance of 6.13 kWh/m^2/month. Both sets of data were obtained from NASA's POWER database.

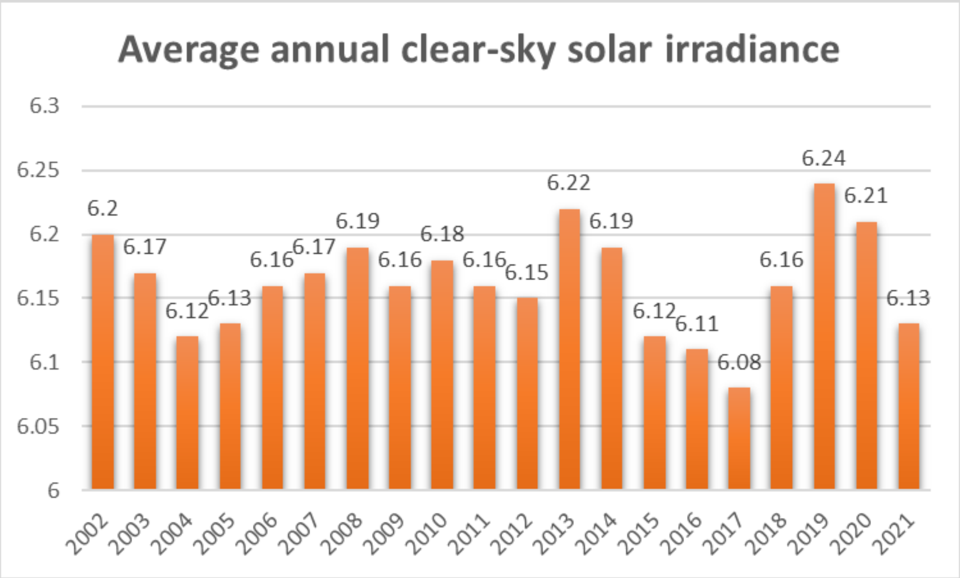


Figure 13. Annual solar irradiance for location in kWh/m^2

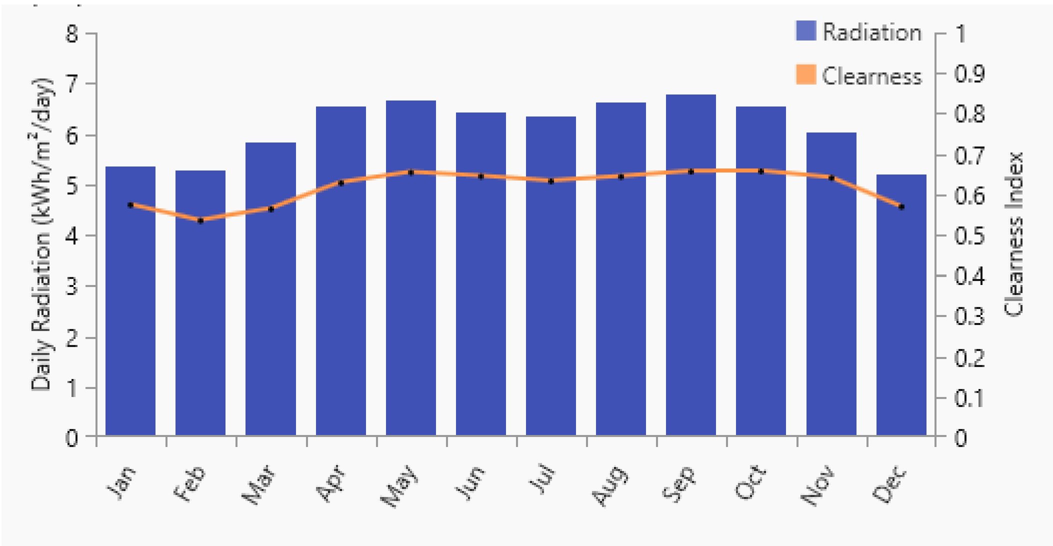


Figure 14. Solar GHI resources in 2021

Also, average monthly temperatures as measured for the year 2021 are shown in figure 15, which was inputted into the software for generated power calculations.

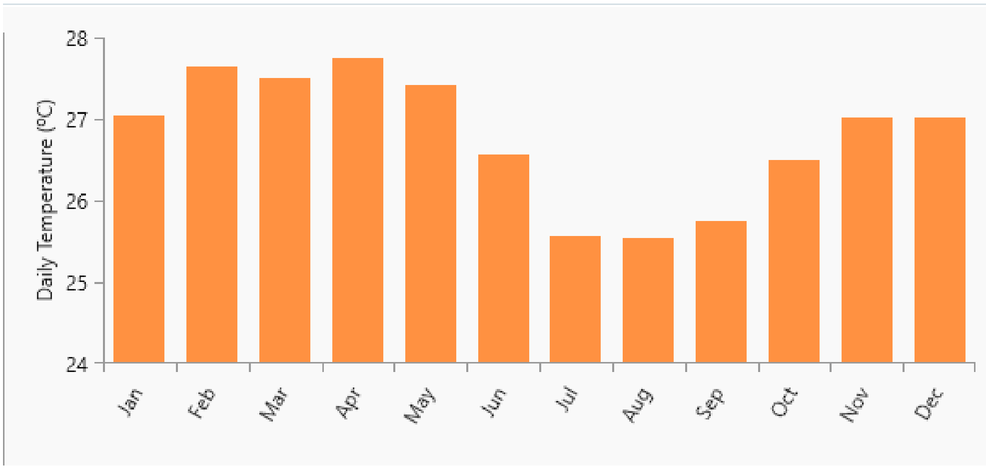


Figure 15. Average monthly temperature data for site in 2021

Chapter 4.1.3 WIND SPEED:

Power generation from wind turbines is highly dependent on the wind conditions of the location site, such as the wind speed and direction. A mathematical model for power generation from wind turbines is defined by equation 3 employed by Homer.

The lowest wind speeds are in the months of January, November and December.

HOMER calculates the output power from the wind turbine using equation 3.

$$P_w(v) = \begin{cases} 0, & 0 \le v \ge v_{in} \\ P_r \cdot \dfrac{v - v_{in}}{v_r - v_{in}}, & v_{in} \le v \ge v_r \\ P_r, & v_r \le v \ge v_{out} \\ 0, & v \ge v_{out} \end{cases}$$

…………… Equation 3

Where:

P_w = Output power of wind turbine

V= wind speed

P_R= turbine rated power

V_{IN} = Cut-in speed

V_{OUT} = Cut-out speed

P_R = Rated power of WT

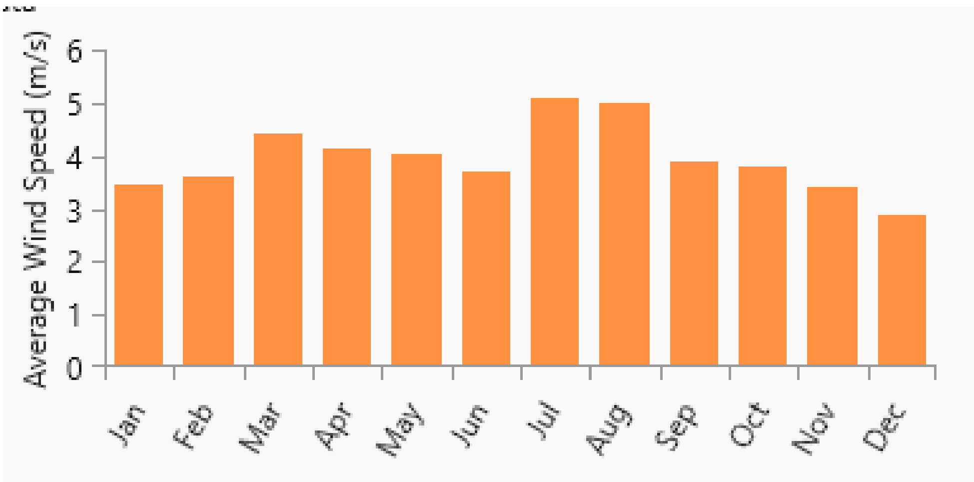


Figure 16. Average wind speed data at 50meters height for location in 2021

Chapter 4.1.4 LOAD PROFILE:

The design of microgrid systems is widely implemented in different land-based applications, but there are limitations to designing the same for the seaport sector considering uncertainty in renewable energy and load consumption. Without actual regular measurements of a port's energy load, determining the energy load profile for a seaport is challenging due to a complex operation pattern. The energy load will be different according to the vessel traffic, operations and consumers such as buildings, terminals, and lighting. Because there is no available data for energy consumption in the Lagos port, estimated load profile selected takes into account average typical values from a similar port terminal in the port of Genoa where data is available (see table 3). Using a baseline average load of 13,028 kWh/day, equivalent to 4,755,220 kWh/year, with peak periods between the hours of 0800 and 1800 hrs. Estimated hourly consumption is presented in figure 17. The research will be using this load data to represent energy demand for a single container terminal but the process can be replicated for other terminals and port offices.

Table 3 Energy consumption for terminals in Genoa. Source: (Acciaro et al., 2014)

Terminal	Consumption/year in kW h
VTE	(50% reefer) 19,000,000
SECH	4,500,000
Messina	5,000,000
Fruit Terminal	4,600,000
Stazione marittima	6,300,000
Oil terminal	2,500,000
Dry bulk terminal	5,000,000
Other	49,900,000

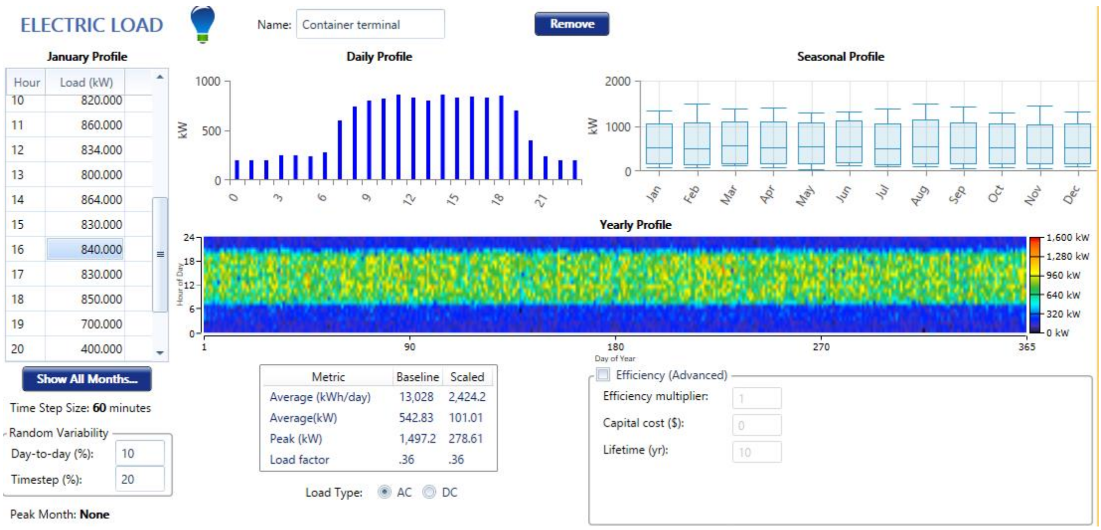


Figure 17. Load data for model

Chapter 4.2 MICROGRID SYSTEM COMPONENT

The system components are the individual components that collectively make up the microgrid system. From a general point of view main components are

- Point of common coupling (PCC)
- Renewable generation
- Cogeneration and trigeneration
- µCHP[1]
- EV charging points
- Battery Energy Storage Systems and UPS
- Electrical networks serving buildings
- Electrical substations at various level of voltages
- Frequency converters
- Protections
- SVC (Static Var Converter)

Chapter 4.2.1 MAIN NATIONAL GRID:

The system is designed to include electricity supply from the national grid but with the aim of maximizing fraction from renewables until generation from renewables is sufficient and well established. As earlier discussed, electricity supply from the national grid is not stable with demand much higher than supply, therefore supply to the port is rationed (load shedding) just like everywhere in the country. Average supply could last for about 10-15hrs a day. Also considering the frequent national grid collapse that will result in total blackout lasting about an average of two days for each failure, 10 outages per year is modelled into the system design to simulate grid failures.

Ikeja Electric distribution company is the electricity supplier for the port location and the main grid utility tariff charges for tariff class D3 is set at 32.66

[1] Micro combined heat plants

Naira/kWh, which is equivalent to $0.078/kWh. The grid sell back price is estimated at $0.050/kWh.

Chapter 4.2.2 SOLAR PV MODULES:

The PV module Jinko Eagle PERC60 300W from Jinko Solar was selected from the software database for the project. This is determined by the high efficiency of monocrystalline panels as compared to polycrystalline panels and popularity at project location. Further details are indicated in table 4.

Table 4 Solar PV description

Component	**Description**	**Source**
Manufacturer	Jinko solar	HOMER database
Model	Jinko Eagle PERC60 300W	HOMER database
Maximum power	300W	HOMER database
Efficiency	18.33%	HOMER database
Panel type	Flat plate	HOMER database
Capital cost	$0.30/W = $ 90	(IRENA, 2022)
Replacement cost	$320	(IRENA, 2022)
O&M cost	negligible	Assumed
Derating factor	88%	HOMER database
lifetime	25years	HOMER database

Chapter 4.2.3 WIND TURBINE:

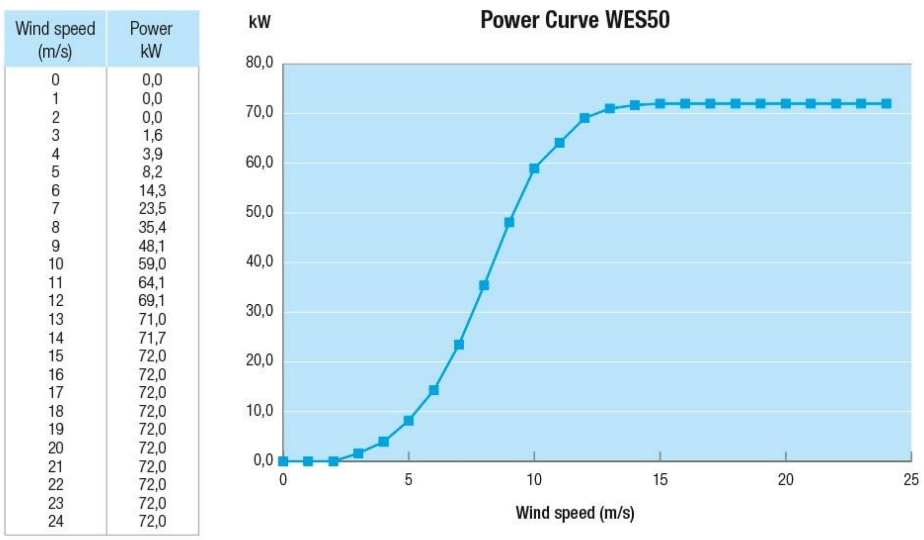
Due to the lower wind resources in the location, with a minimum wind speed recorded in December at 2.880 m/s and the highest in July at 5.090 m/s, a horizontal class III turbine is selected for the model. Wind turbines are categorised into class IEC I, II and III. Where class I turbines are best suited for locations with high wind speeds and class III for locations with low winds. A search space for optimization of between 0–4 turbine units has been chosen for this system architecture to model the optimal number of turbines.

Assuming initial cost of $780/kW for a new turbine as reported by IRENA for the year 2021, Total cost for a unit onshore wind time of capacity 72Kw = $56,160.

This amount is expected to decrease as global weighted average installed cost of turbines fell by 35% between 2010 and 2021 and expected to maintain a decrease of 5% year on year (IRENA., 2022). Details of turbine is as shown in table 5 and power curve in figure 18.

Table 5 Wind turbine description

Component	Description	Source
Manufacturer	Wind Energy Solutions	https://windenergysolutions.nl/wes/windturbine-wes-50/#toggle-id-1
Model	WES50	Manufacturer
Rated power	72 kW	Manufacturer
Cut in speed	<3 m/s (6.7mph)	Manufacturer
Cut out wind speed	25 m/s (56mph)	Manufacturer
Hub height	50m	modified
Life time	20 years	Manufacturer
Initial cost	$780/kW	(IRENA, 2022)
Replacement cost	$780/kW	(IRENA, 2022)
O&M cost	$100/year	Assumed



Wind speed (m/s)	Power kW
0	0,0
1	0,0
2	0,0
3	1,6
4	3,9
5	8,2
6	14,3
7	23,5
8	35,4
9	48,1
10	59,0
11	64,1
12	69,1
13	71,0
14	71,7
15	72,0
16	72,0
17	72,0
18	72,0
19	72,0
20	72,0
21	72,0
22	72,0
23	72,0
24	72,0

Figure 18. Power curve for wind turbine (Source: Wind energy systems)

Chapter 4.2.4 BATTERY STORAGE:

Battery storage units are critical components while utilizing renewable energy sources because the availability of these energy sources is less predictable and changes with seasons. Therefore, adding an energy storage system such as batteries helps to ensure continuous supply of power. When production is sufficient, excess energy is stored in the batteries to be used when generation is less than demand.

The ABB lithium-ion battery has been selected for this design. Details as shown in table 6.

Table 6. Battery storage description

Component	Description	Source
Manufacturer	Saft	HOMER database
Battery type	Lithium-ion	HOMER database
Nominal capacity	55kWh	HOMER database
Nominal voltage	720V	HOMER database
Roundtrip efficiency	97%	HOMER database
lifetime	20 years	HOMER database
Capital cost per unit	$ 60,000 per unit	Assumed
Replacement	$ 36,000	Assumed
O&M cost	$ 6,000/ year	Assumed
Initial state of charge	100%	HOMER database
Minimum state of charge	10%	HOMER database

Chapter 4.2.5 CONVERTER:

The converter is essential for converting DC supply from battery and solar to AC for the load. It acts as both an inverter and a rectifier. For this architecture, a search space for 0,20,40,60 kW is selected for optimization. Other details are shown in table 7.

Table 7. Converter description

Component	Description	Source
Manufacturer	ABB MGS100	HOMER database
Capacity	60kW	HOMER database
Inverter efficiency	95%	HOMER database
lifetime	15years	HOMER database

Capital cost per unit	70 $/kW	Assumed
replacement	70 $/kW	Assumed
O&M cost	7 $/kW	Assumed

Chapter 4.2.6 DIESEL GENERATOR:

Diesel generators are the existing main source of electricity in the port terminals due to unreliable supply from the main grid. They provide a reliable energy supply to the facility but at a high operating and maintenance cost as well as high air pollutants, GHG emissions and noise pollution.

Initial cost of diesel generator for this design is ignored as the facility already has them installed. O&M costs consider periodic servicing and changing of filters and lube oil after 200 running hours. Cost of diesel fuel is considered between $1.750 - $ 1.850 /litre. Other details as shown in table 8.

Table 8. Diesel generator description

Component	Description	Source
Manufacturer	Caterpillar	HOMER database
Model	CAT-725kVA-50Hz-PP	HOMER database
Capacity	580kW	HOMER database
Capital cost per unit	0	Already available
Replacement cost	$154.74 /kW = $ 89,749	(Çetinbaş et al., 2019)
O&M cost	$ 0.010/op. hour	(Çetinbaş et al., 2019)
Diesel fuel price	$ 1.750 - $ 1.850 /litre	
Lifetime	90,000 hours	

Other relevant assumptions taken are highlighted in table 9.

Table 9 Assumptions and Values

KEY ASSUMPTIONS AND VALUES			
S/N	Data	Value	Source
1.	Inflation rate	12.20 %	https://worldpopulationreview.com/country-rankings/inflation-rate-by-country
2.	Project lifetime	25 years	Assumed
3.	Discount rate	14 %	

4.	Outages from national grid per year	10	(Emodi & Diemuodeke, 2022)
5.	Diesel	$ 1.750 - $ 1.850 /litre	Market survey
6.	Simple tariff	$ 0.078/kWh	Ikeja electric tariff
7.	Grid sell back	$ 0.050/ kWh	Assumed

Chapter 5 RESULTS AND DISCUSSIONS

This chapter will present the results from the modelling and optimisation using HOMER, showing the winning energy mix based on a single objective for cost minimisation from integrating renewable energy sources in the port as compared to a base case for using diesel generators and the main national grid. From the range of feasible combinations, further analysis will be carried out based on multi-attribute decision making criteria that introduces environmental impacts from CO_2 emission using TOPSIS decision making method to rank the best designs. This chapter presents the statistical data in a systematic and intuitive form. It shows what was found from the data collected, presenting the data in a clear text such as tables and charts.

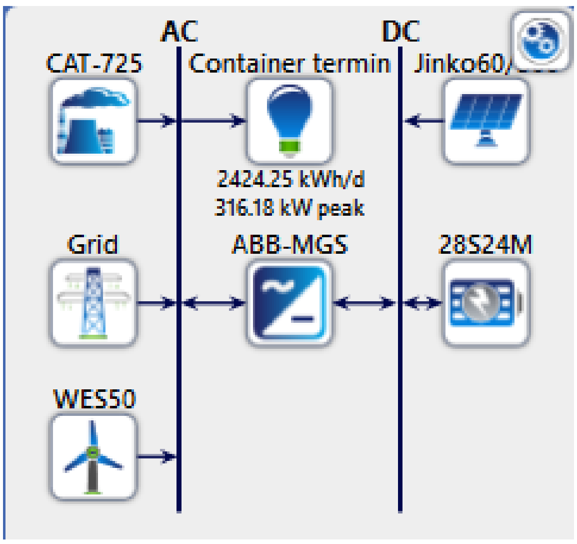


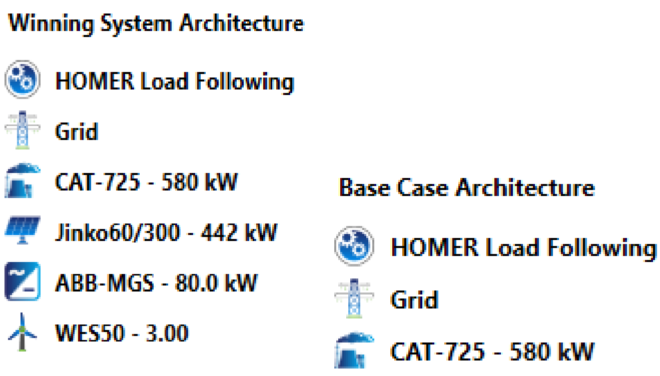
Figure 19. system schematic design

Based on the available meteorological data and estimated load profile for the terminal, the microgrid system configuration determined is as shown in figure 19. The system is designed to include both conventional systems already utilized in port that includes a 500kVA diesel generator and main grid, while renewable energy sources to be integrated include monocrystalline solar PV from Jinko and an 72kW wind turbine from Wind energy solutions. Energy storage system (ESS) using a li-ion battery is added and finally a converter for converting direct current to alternating current and vice versa as required.

Chapter 5.1 FEASIBLE DESIGNS

The optimization process simulated 63,211 solutions, of which 49,691 were feasible, while 13,520 were infeasible due to the capacity shortage constraint. From the feasible solutions, 7,829 were omitted as 480 lacked a converter and 5,269 for having an unnecessary converter. The remaining 41,862 combinations were automatically categorized into 8 combinations, representing results with significant differences, as the complete list of solutions shows minute differences in economic values.

The winning architecture from single cost minimisation objective as shown in figure 20, being the system with the least Net present cost (NPC) of $1.34M and Cost of electricity (COE) of $0.0719/kWh comprises of main grid, diesel generator, solar, wind turbine and converter with IRR of 13%, 7.1yrs simple payback period, ROI of 9.4%, and fraction of renewable energy delivered to load at 47%.



Cost Summary

	Base Case	Lowest Cost System
NPC	$1.76M	$1.34M
Initial Capital	$0.00	$240,389
O&M	$85,966/yr	$53,866/yr
LCOE	$0.0972/kWh	$0.0719/kWh

Figure 20. System architecture from winning system and base case

Cost summary comparing the lowest cost system to the base case system shows that the winning architecture will have economic benefits by the end of the project life. The system will save approximately $420,000 in Net present cost, $ 32,100 savings in operation and maintenance cost per year and cost of electricity will be less by $ 0.0253/kWh.

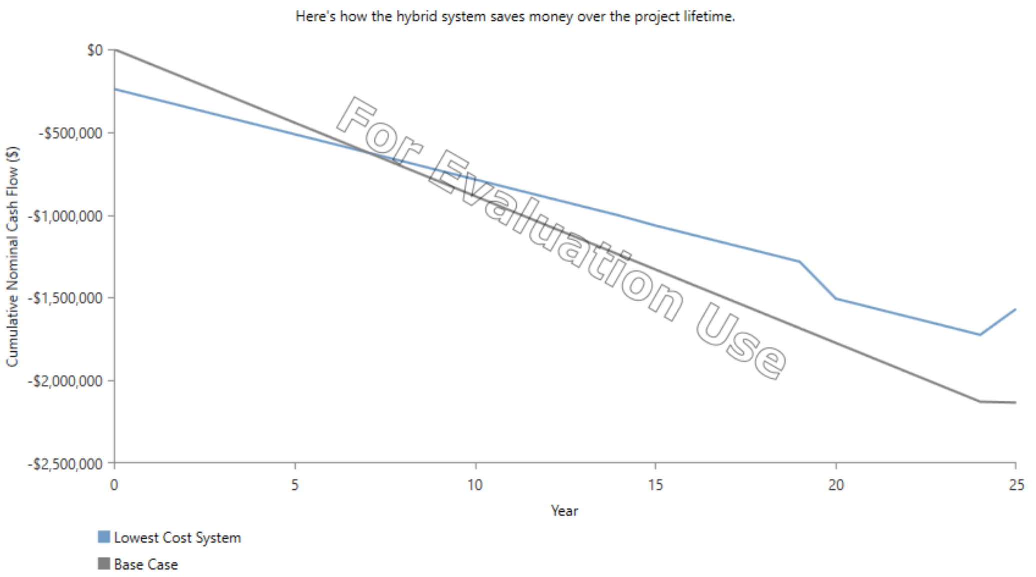


Figure 21. Cumulative nominal cash flow for base case and optimal case

Figure 21 shows a graph representing the cumulative nominal cash flow for the base and optimal case for the life of the project. It is evident that both the optimal system and base system are having negative nominal cash flows all through the life of the project. This indicates that the system has more cash outflows than inflows. To understand the implication of this indicator, it is important to understand what nominal cash flow is.

Nominal cash flow is a financial term that refers to the future rate and amount of cash coming into a business or going out of the business taking into account inflation rate. A negative value indicates a cash outflow while a positive value indicates a cash inflow while cumulated nominal cash flow is the sum of all the cash flows. Therefore, between the first five years of the project, the winning system will be having more expenses as compared to the base case. From the 6th year to the end of the project lifetime, the optimized system is shown to have lesser cash outflows as compared to the base system as such saving cost. Despite a high inflation rate of 12%, the use of renewable energy is shown to perform better economically than the use of the existing system in the long term.

Another economic indicator that HOMER uses for ranking the systems is the Levelized cost of electricity (LCOE) calculated by HOMER using equation 4.

$$COE = \frac{C_{ann,tot} - c_{boiler} H_{served}}{E_{served}}$$

... Equation 1

where: $C_{ann,tot}$ = annual total cost of the system [$/yr]

C_{boiler} = marginal cost of thermal energy [$/kWh]

H_{served} = total amount of thermal energy [kWh/yr]

E_{served} = total electrical load [kWh/yr] (source: HOMER energy).

With these economic indicators, HOMER is able to optimize and rank the feasible designs. The software model displays a categorized ranking as shown in figure 22 and an overall ranking that includes all the feasible designs in ascending order of Net present cost. Categorized designs results are sorted based on an algorithm to select designs with significant difference from the total number of feasible designs. In this case 8 designs out of the 41,862 feasible designs are ranked. Same ranking including mission values are further included in table 10.

Architecture						Cost			
Jinko60/300 (kW)	WES50	CAT-725 (kW)	28S24M	Grid (kW)	ABB-MGS (kW)	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)
442	3	580		999,999	80.0	$1.34M	$0.0719	$53,866	$240,389
442		580		999,999	80.0	$1.35M	$0.0747	$62,622	$71,909
439	4	580	1	999,999	80.0	$1.47M	$0.0768	$54,411	$356,122
455		580	1	999,999	80.0	$1.50M	$0.0827	$66,667	$133,803
	4	580		999,999		$1.73M	$0.0931	$73,635	$224,640
		580		999,999		$1.76M	$0.0972	$85,966	$0.00

Figure 22. Categorized feasible designs

Table 10. Optimized designs ranked on minimised cost

OPTIMIZED DESIGN RANKING BASED ON MINIMISED COST									
S/N	SOLAR PV (kW)	WIND Qty.	GRID	BATTERY	GEN	CONV.	NPC	Emission CO_2 (kg/yr.)	RE %
1	442	3	✓	X	✓	✓	$ 1.34 M	311,097	47.5
2	429	4	✓	X	✓	✓	$ 1.34 M	294,754	51.5
3	442	X	✓	X	✓	✓	$ 1.35 M	386,846	32.4
4	439	4	✓	✓	✓	✓	$ 1.47 M	289,394	52.2
5	455	X	✓	✓	✓	✓	$ 1.50 M	382,740	33
6	X	4	✓	X	✓	X	$ 1.73 M	465,777	20.4
7	X	4	✓	✓	✓	✓	$ 1.87 M	460,529	21
8	505	4	✓	✓	✓	✓	$1.47 M	286,296	52.8

Also, to note is that the winning architecture does not include a battery storage in the configuration. This omission will be beneficial for cost minimization but in reality, does not factor for system reliability in an event of a failure in generation. As such the author advises that other determining factors are to be taken into consideration in selecting the optimal design such as insisting on the least cost system that includes battery storage.

Chapter 5.2 MULTI-ATTRIBUTE DECISION MAKING

This is a process that involves making preference decisions based on multiple and usually conflicting attributes for available alternatives. From the results of feasible designs, emission values are shown to be conflicting with the results from cost minimization, where the least cost architecture is not the least emitting system and vice versa. Also, considering environmental impact from port electricity generation is currently a hot topic following the 2015 Paris agreement and IMO GHG reduction strategy targeted at reducing carbon emissions, the aim of this research will not be fulfilled without introducing a ranking criterion for emission minimization.

The emission taken into account is the CO_2 emission for each feasible architecture in (kg/yr.). Other air pollutants such as particulate matter have significant implications on the respiratory health of the people in port area, and as such, CO_2 is only taken as reference for other emissions as all emissions are shown to collectively increase or reduce proportionally to fraction of renewable energy penetration (see table 20). Table 11 shows the overall feasible designs ranked by sorting renewable energy fraction in descending order, and the top eight architectures are presented.

Table 11 Optimized designs ranked on minimised emissions

RANKING BASED ON RENEWABLE ENERGY FRACTION									
S/N	SOLAR PV (kW)	WIND Qty.	GRID	BATTERY	GEN	CONV.	NPC	Emission CO_2 (kg/yr.)	RE %
1	1,212	4	✓	2	✓	✓	$ 1.67 M	269,340	55.6
2	2,425	4	✓	X	✓	✓	$1.58 M	273,357	55.4
3	1,617	4	✓	X	✓	✓	$1.47 M	275,380	55
4	1,212	4	✓	X	✓	✓	$1.41 M	278,176	54.5
5	808	4	✓	X	✓	✓	$1.37 M	283,271	53.6
6	606	4	✓	1	✓	✓	$1.48 M	282,935	53.4
7	505	4	✓	2	✓	✓	$1.60 M	282,129	53.3
8	556	4	✓	1	✓	✓	$1.47 M	284,462	53.1

The winning architecture's renewable energy penetration is shown in figure 23. It shows how the renewable energy generated performs as compared to demand. The system is shown to produce sufficient renewable energy for the estimated load.

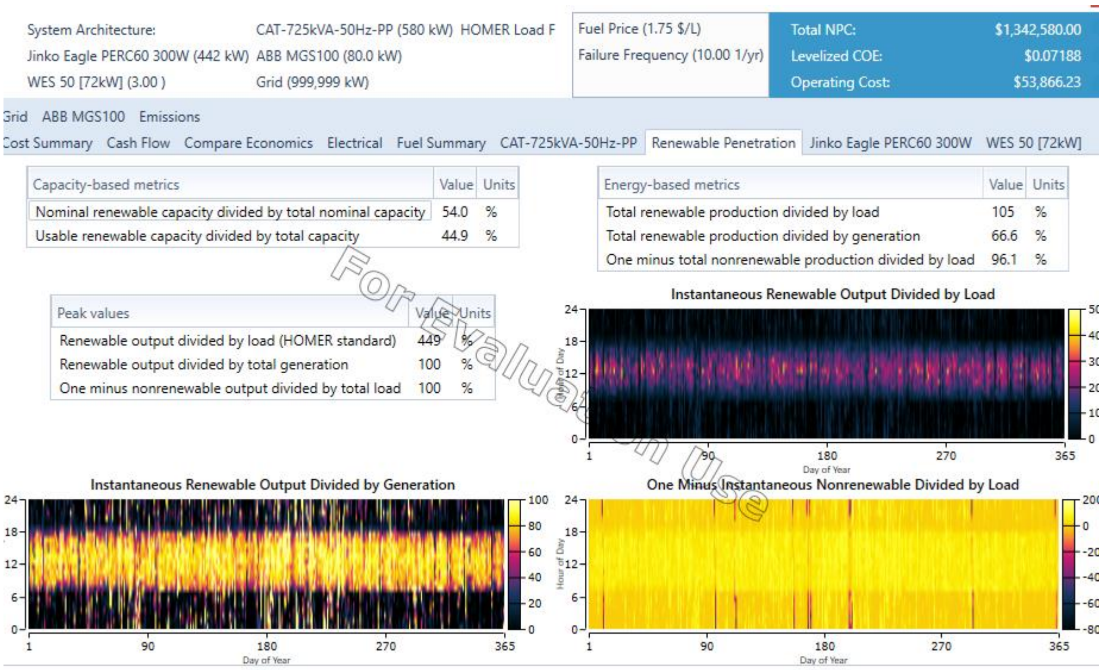


Figure 23. Winning system architecture renewable penetration.

Taking into account all these design considerations for cost minimisation, emission reduction and energy reliability through the use of energy storage systems, the researcher is selecting three designs amongst the feasible designs for further ranking using TOPSIS methodology by prioritizing preferences based on set of alternatives. The selected designs are the design with the least NPC, the design with the least CO_2 emissions, and the design that includes all renewable energy sources and an energy storage system with the least NPC. All systems are highlighted from tables 10 and 11 while a decision matrix is developed in table 12.

Table 12 Decision matrix

Design objectives		
Design architecture	Minimum NPC	Minimum Emission
System 1	1.34	311,097
System 2	1.47	289,394
System 3	1.67	269,340

The next step of the technique is to assign attributed weights for decision making. The researcher considers the increasing need for GHG emission reduction to have a higher weight as compared to cost minimization from the integration of renewable energy. Therefore, following the methodology principle for weight distribution, a value of 0.7 is assigned to GHG emission reduction and 0.3 is assigned to cost minimisation.

Table 13. TOPSIS method

Attributes	System 1	System 2	System 3	Att. Weight	Cost (1) / benefit (0)	SQRT
NPC	1.34	1.47	1.67	0.3	0	2.59719079
GHG emission	311,097	289,394	269,340	0.7	1	503064.8728

Next is to calculate normalised ratings for each attribute transforming the various attribute dimension values to non-dimensional values to allow for comparison.

Table 14 Normalized decision matrix

Normalized decision matrix			
Attributes	System 1	System 2	System 3
NPC	0.515942073	0.565996155	0.643002434
GHG emission	0.618403345	0.575261792	0.535398146

Weighted normalised ratings can be calculated by multiplying the normalised ratings by the associated attribute weight.

Table 15 Weighted normalized matrix

Weighted Normalized			
Attributes	System 1	System 2	System 3
NPC	0.154782622	0.169798846	0.19290073
GHG emission	0.432882341	0.402683254	0.374778702

The next step identifies the positive ideal solution and the negative ideal solution defined in terms of the weighted normalised values.

Table 16 Positive and negative ideal values

positive ideal	negative ideal

0.19290073	0.154782622
0.432882341	0.432882341

Next step is to calculate separation measures between alternatives to the positive ideal and then the negative ideal solutions

Table 17 Separation from Positive ideal values

(Vij-Pi)^2			
Attributes	System 1	System 2	System 3
NPC	0.00145299	0.000533697	0
GHG emission	0	0.000911985	0.003376033
Sep PI	0.038118108	0.038022124	0.058103639

Table 18 Separation from Negative ideal values

(Vij-Ni)^2			
Attributes	System 1	System 2	System 3
NPC	0	0.000225487	0.00145299
GHG emission	0	0.000911985	0.003376033
Sep Ni	0	0.033726427	0.069491173

Ranking of preference order chooses the alternative with the maximum CI

Table 19 System rankings

Attributes	System 1	System 2	System 3
CI	0	0.470064224	0.54462381
Rank	3	2	1

Ranking results from the TOPSIS methodology place system 3 as the preferred design, this is the architecture with least emissions, followed by system 2 in second place and system 1 in last place. This ranking is highly dependent on the weight given to emission reduction and will change in a situation where the decision maker prefers cost minimization over emission minimization.

Chapter 5.3 PERCEIVED SOCIETAL IMPACT

To begin with, integrating renewable energy sources with battery storage for storing energy during low peak periods of electricity demand that can be used to offset demand during high peak periods ensures a more stable electricity supply for the facility. With the assurance of stable and reliable electricity, it is believed that businesses will thrive better as it would eliminate unplanned and excessive costs from the purchase of diesel fuel to run standby generators.

It will increase consumer trust and boost the potential for investors to invest in the port facility due to its reliable operations guaranteed. This will in turn boost trade and grow the country's economy.

The implementation of this project will also create job opportunities for society, such as maintenance jobs, the importation of components and even locally sourced materials, and other related job opportunities.

Integrating renewable energy sources will improve the port's image as a model port for other ports in the region. Enjoy benefits from international organizations as a first mover in driving climate change actions for a sustainable world.

The investment will also make the port compliant with national agreements for climate change actions such as the country's commitment to the 2015 Paris Agreement to implement measures for the reduction of GHG emissions from anthropogenic activities with the goal of maintaining temperatures below 2^{o} c.

With an increase in renewable energy uptake, emissions of fossil fuel such as NOx, SOx, PM and Black carbon is expected to reduce resulting in a decrease of health externalities such as respiratory diseases, premature births and other health challenges attributed to air pollutants.

Chapter 5.4 SENSITIVITY ANALYSIS

The price of diesel fuel and the number of grid failures from the national grid are parameters or factors that are not easily predictable to be accurately modelled into the design. As such, modelling these factors will variable values will help to present a more realistic scenario and provide some insight as to the extend these changes will have on the economic performance of the investment. Figure 24 shows some of the sensitivity results where the price of fuel was taken as a constant at $1.75 and varying the number of outages of the external grid per year at 5, 10, 12, and 15. Corresponding effects on NPC show a directly proportional increase.

The sensitivity analysis shows the effect of grid failures and changes in fuel prices on the system's net present cost.

Sensitivity		Architecture						Cost		
Grid Failure Frequency (1/yr)	Diesel Fuel Price ($/L)	Jinko60/300 (kW)	WES50	CAT-725 (kW)	28S24M	Grid (kW)	ABB-MGS (kW)	NPC ($)	COE ($)	Operating cost ($/yr)
10.0	1.75	442	3	580		999,999	80.0	$1.34M	$0.0719	$53,866
12.0	1.75	442	3	580		999,999	80.0	$1.43M	$0.0765	$58,098
15.0	1.75	442	3	580		999,999	80.0	$1.55M	$0.0831	$64,107
5.00	1.75	442	2	580		999,999	80.0	$1.14M	$0.0623	$46,853
10.0	1.80	442	3	580		999,999	80.0	$1.35M	$0.0725	$54,455

Figure 24 sensitivity results

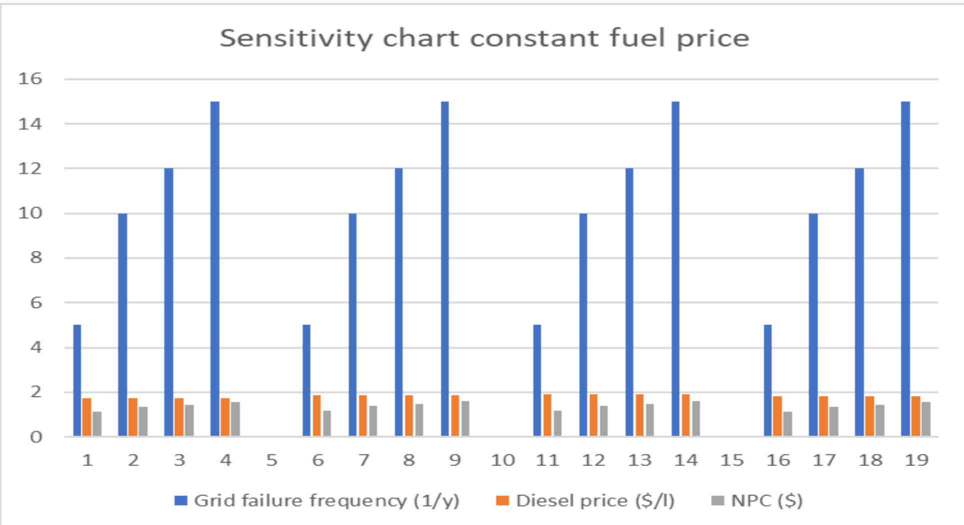


Figure 25 Sensitivity chart with constant fuel price

Figure 25 shows sensitivity results when diesel fuel is constant at $1.75 per litre and the frequency of grid failures varied by 5, 10, 12, and 15 failures per year to determine the corresponding change in NPC, which revealed a progressive pattern of increasing NPC with increasing frequency of grid failures.

This process was repeated for diesel prices at $1.8, $1.85, and $1.9 for the second, third, and fourth sets, respectively.

Figure 26 shows results when fuel prices are kept constant while grid failures are altered between 5, 10, 12, and 15 failures per year. The corresponding change in the NPC of the system shows negligible changes. Indicating that fuel price change within the simulated range is a less sensitive parameter that would not affect the investment's economic performance.

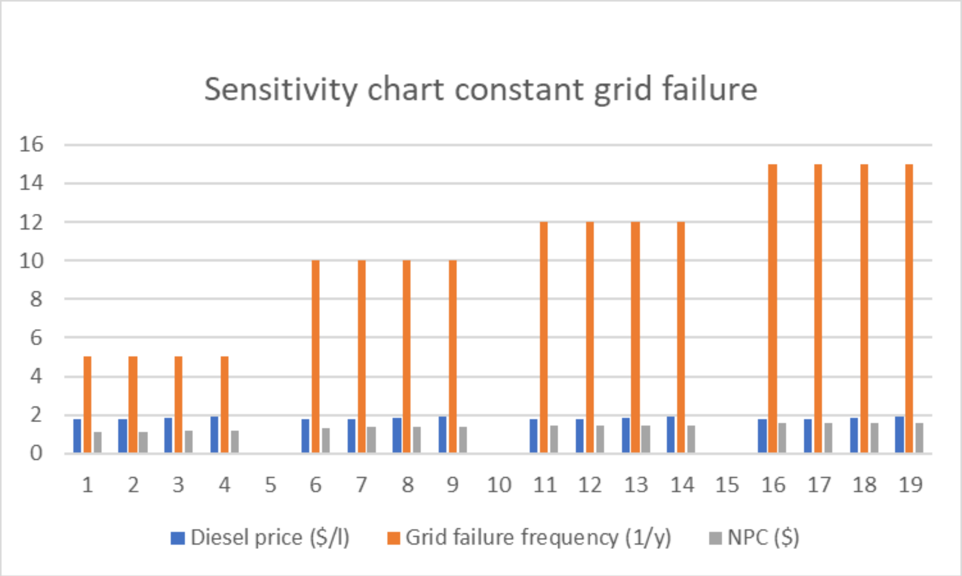


Figure 26 Sensitivity chart with constant grid failures

DISCUSSIONS:

When we think in terms of optimized operations aiming at economic benefits, reduction of emissions, use of renewables, and increased reliability, it appears that often the electrical infrastructure of a port is not well suited to foster these objectives. Different solution appears more adequate. In fact, there are different ways how the electrical grid of a port may be reorganized or replaced to cope with the flexibility required by the multiplicity or requirements of port areas; furthermore, one possibility that add flexibility and manageability is to split the micro-grid in many nano-grids or even pico-grids and to control generation, distribution, import/export from the connected electrical utility and storage as one VPP (Virtual power plant)

This discussion section will attempt to interpret the findings and results by linking them to prior research and to the objectives. In order to do this, each research question will be considered one at a time.

Question 1: What are the significant energy consumers in the port and what is the current and near-future energy load profile for port operations?

From the literature review chapter, the existing volume of seaborne trade into the country and especially the Apapa port is seen to be increasing yearly as new records are attained. It is also logical to predict that as the nation aims to diversify from current crude oil dependence and tap into her blue economy potentials, maritime trade will expand, attracting more vessels and port visits to her waters which will in turn increase the energy demand profile of the port. Also, just as the emerging economies of Asia and Far middle east are changing the maritime traffic, it is expected that developing countries of Africa will attract more vessel traffic in the near future.

Port machineries are becoming more gigantic and sophisticated with electrification of cargo handling equipment, use of electric driven vehicles and implementing automation and internet of things. All these processes will require a significant amount of power generation. Aside cargo handling activities, other port services such as warehousing, repairs and maintenance workshops and port offices complex are contributing to the energy demand of the port.

Question 2: What are the feasible renewable energy sources and technologies such as solar, wind, and geothermal energy for the port location?

Based on meteorological data and technology readiness in commercial volumes, use of hydro-power, solar PV and wind turbines are dominating the renewable energy markets. For hybrid microgrid systems as used in remote locations such as the port complex, solar PV and onshore wind turbines are considered to be the most fitting renewable energy sources. With average monthly solar irradiance of 6.13kWh/m^2, solar PV technology is shown to be feasible. With average monthly wind speeds of 3.5m/s, the use of class III wind turbines is also feasible in the location. From economic analysis of the proposed architecture, power generation using wind and solar are cost effective with potentials to be cheaper compared to using diesel generators for power generation for the port, making renewable energy an attractive option for use.

Other renewable energy sources such as tide and ocean currents are promising but are still in the research and development stages and expensive to implement in commercial scale.

Question 3: What is the optimal energy component sizing and combination with minimum investment cost and maximized environmental and social benefits for the port authority and its stakeholders?

Optimization using HOMER software produced a winning system architecture from cost optimization with an energy mix that includes supply from the grid with a design limit of 999,999kW; a backup 580kW diesel generator; a 442kW solar panel; an 80kW converter; and 3 units of wind turbine with an initial investment of $240,389. The system is able to supply the required load with an operation cost of $53,866/year. power production of 35,760 kWh. COE is $ 0.0719 as compared to the present cost of the national grid at $0.078/kWh, which is also not reliable and highly supplemented with the use of diesel generators, bringing COE to $0.0972. It shows that the optimised design will be better economically and produce fewer emissions of approximately 264,273Kg/yr of carbon dioxide, equivalent to a 45.93% reduction. NOx reduction of 568kg/yr with a 71.27% reduction and a SOx emission reduction of 1143kg/yr at a 46.96% reduction. As compared to base architecture, which consists only of the grid and the diesel generator, can produce 38,380 kWh of load with an NPC of $1.76 M, COE of $0.0972, operating cost of $85,966, and emissions as shown in figure 20.

Quantity	Value	Units
Carbon Dioxide	575,370	kg/yr
Carbon Monoxide	12.6	kg/yr
Unburned Hydrocarbons	7.33	kg/yr
Particulate Matter	3.11	kg/yr
Sulfur Dioxide	2,434	kg/yr
Nitrogen Oxides	1,365	kg/yr

Figure 27 Emission figures base architecture

Quantity	Value	Units
Carbon Dioxide	311,097	kg/yr
Carbon Monoxide	11.9	kg/yr
Unburned Hydrocarbons	6.94	kg/yr
Particulate Matter	2.94	kg/yr
Sulfur Dioxide	1,291	kg/yr
Nitrogen Oxides	797	kg/yr

Figure 28 Emission figures winning architecture

Table 20. Comparing base and wining systems emission values

EMISSIONS (kg/yr)	BASE CASE	WINNING CASE	DIFFERENCE	Percentage reduction
CO_2	575,370	311,097	264,273	45.93 %
CO	12.6	11.9	0.700	5.56 %
BC	7.33	6.94	0.390	5.32 %
PM	3.11	2.94	0.170	5.47 %
SO_X	2,434	1,291	1,143	46.96 %
NO_X	1,365	797	568	41.61 %

Question 4: How much savings in electricity bills is attainable with the implementation of the proposed microgrid system and if the project is able to recover investment cost and when?

The winning system has a simple payback period of 7.1 years, which means that the initial investment will be fully recovered during this time without taking into account the time value of money, such as the inflation rate, which affects the future value of money.

Internal rate of return is shown to be 13%. This is a percentage that shows how much the project is returning the investor as compared to the set cut off ratio set at 14%. This shows that the investment is not as good as the investor will prefer but it still returns above the current inflation rate and with the possibility for incentives from the government for implementing clean renewable energy, the project will have a good financial potential. The ROI, another financial indicator shows 9.4% which is the return on investment of the investment.

The winning system does not include battery storage which is considered not feasible as even though it is good for cost minimization but not for system reliability and resilience as production during low peak periods cannot be utilized for peak periods. Although this design includes the option of selling excess production back to the national grid, this may not be possible in practice due to the lack of existing regulations and national policies that support this initiative, introducing some trade-off scenarios for the port authority to consider.

Table 10 presents other categorized feasible combinations ranked from the least NPC to the highest. According to the list, the winning combination is the least expensive design but not the least environmentally friendly when considering the environmental implications of CO2 emissions. This introduces a challenge considering multiple attributes for the project to be cost effective as well as minimise emissions. The second architecture is shown to have a similar NPC as the winning architecture but with a lower carbon emission while the third combination has a much lesser emission as compared to the winning architecture.

This result supports existing studies that claim that the use of renewable energy in a microgrid system has a positive impact on the environment and public health as well as protects the port's vulnerability to extreme natural and manmade disasters (Molavi et al., 2020).

In conclusion, results and findings from the research methodology adopted demonstrates benefits to the integration of renewable energy for port electricity generation. The computer model was designed with data that is typical for the location to give a close representation of how the actual system will perform. Renewable energy is therefore shown to have economic benefits for this project location with financial savings of approximately $420,000 in Net present cost. Environmental benefits show a 47.6% renewable energy fraction for the lowest cost system and a 55.6% renewable energy fraction for the winning architecture from multi-objective decisions.

These results corroborate with existing literature findings for economic and environmental benefits for the uptake of renewable energy as compared to fossil fuel.

Chapter 6. CONCLUSION AND RECOMMENDATIONS

Efforts for the decarbonization of the energy sector, particularly from shipyards and ports has been overlooked for a while, considering the percentage of emission contributed by ports is only about 3% out of the entire global shipping emission. This cannot longer be overlooked with increasing growth in seaborne trade and port participation where energy load profiles are increasing. The use of renewable energy for electricity generation in ports is one of the widely implemented measure to significantly contribute to energy sustainability, energy security and green transitioning of ports. This measure is proven to have substantial benefits economically, environmentally, and socially, through increasing employment rates and promoting a healthy environment for the people living around the port municipality.

Hybrid microgrid systems is a technological advancement that utilizes distributed energy sources including the freely available and abundant renewable energy sources of wind, solar, tide, ocean current and geothermal energy amongst others to generate clean, reliable and emission free energy for port operations.

The integration of this system is capital intensive at initial stages but is shown to be cost effective in the long term. Therefore, to encourage the uptake of this technology, the role of policy cannot be over-emphasized. These policies and an enabling business environment will attract investors to buy into these RE projects. Unfortunately, developing countries are usually seen as risky investment locations due to an unstable economy and poor infrastructure with limited region-specific research for implementation.

This study adopted a methodology using a combination of existing methodologies that includes modelling and simulation of a microgrid combination using computer software with a single objective optimization goal in a case study context for the Lagos port. The optimization results selected a winning architecture that combines supply from national grid, 580kW diesel generator, 440kW monocrystalline solar PV, 3 units of 75kW wind turbine and a converter without batteries. The system is able to save approximately $420,000 in total as compared to the base with about 45.93% reduction in CO2 emissions, 41.61 % in NOx and 46.96 % in Sox emissions.

To further rank the available alternatives, other attributes were considered to provide a holistic approach in determining the best system combination considering least emission and battery storage using TOPSIS technique for multi-attribute ranking and the results show that the best system to implement will be the system with least emission comprising of 1,212kW solar PV, 4 units of wind turbine, grid supply, 2 battery storage systems, diesel generator and converter at a Net present cost of $1.67 million confirming feasibility of project with undeniable economic and environmental benefits to integrating renewable energy.

It is therefore recommended that for the growth of uptake of renewable energy in Nigeria, there is a need for the government to introduce an incentive scheme for first movers and subsidies for the import of renewable energy components to encourage all sectors and small businesses to be able to afford integrating renewable energy, especially solar PV, since the country experiences abundant sunshine all year round. This will reduce the demand on the national grid and provide for remote regions that do not have access to the grid. With a reliable and affordable electricity supply to more regions in the country, businesses will thrive, boosting the economy of the nation.

Some key barriers to the uptake of renewable energy in the African region, or other LDC's and SID's, are the competing nature of renewable energy projects amongst the country’s priority scale. These countries have other challenges that require more resource allocation and only a very small percentage of the budget is allocated to ocean resources or sustainability goals in the country.

It is therefore in the opinion of the researcher that the port authorities and decision makers must look at the uptake of renewable energy in a more holistic manner beyond its environmental benefits, but also considering its economic and social benefits. It is a win-win situation with both theoretical and actual evidence for its benefits.

Although this study attempted to present a close to reality model of the microgrid system, a number of assumptions such as port load profile and meteorological data were taken from secondary data, thereby giving room for future further research to consider using real measurements that will be more accurate.

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Appendices