

**ELECTRIFICATION OF CARGO HANDLING EQUIPMENT  
USING GRID AND RENEWABLE POWER IN KENYA  
PORTS AUTHORITY.**

**JUMA BOY JUMA**

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

2023

## 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): .....

Supervised by: .....

Supervisor's affiliation: .....

## Acknowledgements

Firstly, my sincere gratitude goes to Almighty Allah for his mercies and bountiful grace that enabled me to study in the world maritime University. Secondly, my earnest appreciation goes to the International Maritime Organization and World Maritime University for their generosity and Consideration of Sponsoring my studies. Similarly, My utmost appreciation to my employer Kenya Ports Authority for granting me the opportunity to further my studies and supporting me throughout the process.

I also wish to extend my earnest appreciation to my supervisor, Dr. F. Ballini, for his inspirational guidance and ever-present support equally I also wish to thank Dr. S. Alessandro and Dr. Anas. S. Alamoush for their critical assistance through their imparted knowledge and critic in the realization of this dissertation. My gratitude extends to the Department of Maritime Energy Management led by Prof. A. Olcer for granting us the relevant skills and tools to realize the MEM objectives.

Special thanks to my spouse and Children for their never-ending support, encouragement, and endurance throughout this journey and to my dear Mother and Sisters. In addition, I would like to thank my friend Kelvin K. Nyambegera for his support and invaluable assistance. Special tribute extends to Eng. Mathews Amuti for his encouragement.

Lastly, I wish to recognize the exemplary MEM class of 23 colleagues, World Bristo and Scefe, for their valuable friendship and support.

## Abstract:

Title of Dissertation: ELECTRIFICATION OF CARGO HANDLING EQUIPMENT USING GRID AND RENEWABLE POWER SOURCES IN KENYAN PORTS AUTHORITY.

Degree: Master of Science

The increase of stringent environmental regulation in the race against time to prevent the full impact of climate change has compelled the whole maritime Industry to explore sustainable energy sources to reduce its overdependence on fossil fuels. This extends to port facilities as they play a critical role in the maritime supply chain as a node of intermodal transport and energy hub. Emissions from port cargo handling operations have garnered substantial attention due to their unwarranted effects. Electrification of CHE presents itself as a viable alternative with considerable environmental and socio-economic benefits.

This study presents a comprehensive analysis of electrifying RTGs using Grid power and charging Electric Terminal Tractors using solar energy. The primary objectives were to evaluate this proposed solution's environmental impact and financial viability. The study includes a conceptual electric terminal design based on the Mombasa Port Development Project Phase II terminal, and the implementation cost estimates. The financial analysis investigated the payback period, Net Present value, and internal rate of return to assess the project's cost-effectiveness. A Monte Carlo simulation sensitivity analysis was also conducted to account for uncertainties.

Results from the environmental and financial analysis revealed significant benefits; this approach contributes to a 90% reduction of air emissions and a potential 92% saving on consumption at 100% electrification. The finding highlights the potential advantages of adopting electrification in port terminals that align with global sustainable goals. Considering all, recommendations were made to the Kenya Ports Authority and parent agencies.

KEYWORDS: Electrification, CHE, ERTG, ETT.



## List of Tables :

Table 4.3:1 Technical Readiness Level.....	20
Table 4.5:1 contains the inputs required for data acquisition. ....	24
Table 6.1:1 KPA monthly energy consumption Source: KPA Port Electrical Engineering .....	41
Table 6.2:1 RTG motor drive rating source: Liebherr RTG technical specifications.....	44
Table 6.2:2 Formula definition. ....	45
Table 6.2:3 ERTG power demand calculation.....	45
Table 6.2:4 Transformer specs.....	48
Table 6.2:5 HV and LV panel summary Source: Author.....	48
Table 6.2:6 Shift schedules at KPA Source: KPA.....	51
Table 6.3:1 Estimated costs of electrifying MPDP II operations.....	64
Table 7.2:1 Annual fuel consumption for the conventional RTGs and TT in KPA .....	67
Table 7.4:1 Emission factors for respective modes of energy: Solar energy produces zero NOX, SOX, and P.M2.5 .....	70
Table 7.6:1 Total annual emission in tonnes and related social costs for business-as-usual scenario .....	72
Table 7.6:2 Estimated total annual consumption costs .....	72
Table 7.6:3 Total annual emission in tonnes and related costs after MPDP II electrification (scenario 2) .....	73
Table 7.6:4 Total annual consumption costs after MPDP II electrification (scenario 2).....	74
Table 7.6:5 Total annual emission in tonnes and related costs after MPDP I & II electrification (scenario 3) .....	75
Table 7.6:6 Total annual consumption costs after MPDP I & II electrification (scenario 3) .....	76
Table 7.6:7 Total annual emission in tonnes and related costs after 100% electrification (scenario 4).....	77
Table 7.6:8 Total annual consumption costs after 100% electrification (scenario 4).....	78
Table 7.8:1 summarizes annual Consumption savings from MPDP II Electrification.7.8:2 .....	82
Table 7.8:3 Estimated potential revenue from carbon trading. ....	84
Table 7.8:4 shows cost savings/generated from MPDP II electrification per year .....	84
Table 7.9:1: Estimated 15 year cashflow for MPDP II Electric Terminal .....	85
Table 7.10:1 SWOT Analysis of Port Electrification .....	88

## List of Figures

Figure 3.4:1 Illustration of emission and energy consumption estimates methodology.....	12
Figure 4.1:1 Cable reel system .....	16
Figure 4.1:2 Busbar system .....	17
Figure 4.2:1 ETT layouts. Source ANY Europe (SANY, 2023) .....	18
Figure 4.5:1 Illustrating solar energy generation potential.....	24
Figure 4.5:2 Solar irradiation profile of Mombasa for 2022. Source: Author: generated using Python and MS Excel.....	25
Figure 5.1:1 ISO 50001 Plan-Do-Check and Act. Adopted from Ballini (2023) class lecture.....	29
Figure 5.1:2 European ports' top ten priority list over the years. Source: ESPO Environmental Report 2022.....	30
Figure 5.1:3 Sustainable Development Goals. Source: UN SDG goals: <a href="https://www.un.org/sustainabledevelopment/news/communications-material">https://www.un.org/sustainabledevelopment/news/communications-material</a> .....	31
Figure 5.3:1 Solar arrays on building rooftops at the Port of Rotterdam source (PortTech, 2023) .....	36
Figure 6.1:1 Kilindini harbor aerial view Source: Google Maps, location Kilindini harbor. ....	37
Figure 6.1:2 Single line diagram of KPA electrical reticulation network : proposed ERTG substation.....	40
Figure 6.2:1 CHE distribution in KPA container terminal source: (KPA, 2022)):2022 KPA annual Bulletin .....	43
Figure 6.2:2 Single line diagram for the proposed ERTG substation .....	50
Figure 6.2:3 DC fast charger with split power provisions.....	53
Figure 6.2:4 Aerial view for the proposed 2MW solar plant.....	57
Figure 6.2:5 Annual Solar Power Generation Potential at KPA 2022 Source: Author6.2:6 .....	58
Figure 6.2:7 Regular shift charging profile showing fleet energy consumption and charging pattern.....	59
Figure 6.2:8 second double shift charging profile showing fleet energy consumption and charging pattern. Source: Author .....	60
Figure 6.2:9 Proposed MPDP II Electric Terminal Layout. ....	61
Figure 7.8:1 Price of one metric Tonne of carbon in euros in September 2023, equating to USD 93.21 at the current rate. Source: <a href="https://tradingeconomics.com/commodity/carbon">https://tradingeconomics.com/commodity/carbon</a> 7.8:2 .....	83
Figure 7.9:1 MPDP II NPV profile Source: Author .....	86
Figure 7.9:2 NPV probability curve indicating the likelihood of occurrence; generated using crystal ball monte Carlo simulation.....	87
Figure 7.9:3 NPV sensitivity analysis. ....	87

## List of Abbreviations

AC	Alternating Current
ANSI	American National Standards Institute
BESS	Battery Energy Storage System
BMS	Battery Management System
BPA	Busan Port Authority
CAAP	Clean Air Action Plan
CHE	Cargo Handling Equipment
CII	Carbon Intensity Index
CO <sub>2</sub>	Carbon Dioxide
CPI	Consumer Price Index
CRS	Cable reel System
CT	Current Transformer
DC	Direct Current
DOE	Department of Energy
DNI	Direct Normal Irradiance
EEDI	Energy Efficiency Existing Ship Index
EER	Energy Efficiency Ratio
EEXI	Energy Efficiency Existing Ship Index
EF	Emission Factor
ERTG	Electric Rubber Tired Gantry
ESPO	European Sea Ports Organization
ETT	Electric Terminal Tractor
GMA	Global Monitoring for Environment and Security
GHG	Greenhouse Gas
GP	Green Ports

GPP	Green Port Policy
HV	High Voltage
ICAO	International Civil Aviation Organization
IEA	International Energy Agency
ISO	International Organization for Standardization
LCOE	Levelized Cost of Electricity
MARPOL VI Annex VI	International Convention for the Prevention of Pollution from Ships, Annex VI
MS	Microsoft
MT	Metric Ton
MW	Megawatt
MVA	Mega Volt-Ampere
NGO	Non-Governmental Organization
NLTC	No Load Tap Changer
NPV	Net Present Value
ONAN	Oil Natural Air Natural
PBP	Payback Period
PM	Particulate Matter
POLB	Port of Long Beach
PV	Photovoltaic
RMS	Root Mean Square
RTG	Rubber Tyred Gantry
SGR	Standard Gauge Railway
SOX	Sulphur Oxides
SS	Substation
TEU	Twenty-Foot Equivalent Unit
TT	Terminal Tractor

UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
UNHRC	United Nations Human Rights Council
UNCTAD	United Nations Conference on Trade and Development
USD	United States Dollar
WMU	World Maritime University
ZE	Zero Emissions
NZE	Near Zero Emissions



## CHAPTER 1: INTRODUCTION

### 1.1 Background

Decarbonization has been at the center of urgent global concern in recent history. The rising global temperature due to increased greenhouse gas emissions has stayed true to its predictable effects of changing the climate in mostly undesirable ways (UNHRC, 2019) evident by devastating and unpredictable environmental conditions across the globe that cause significant loss by claiming numerous lives and laying waste to the environment (IPCC, 2022)

Intergovernmental Panel on Climate Change (IPCC) report attributes the growth in GHGs to anthropogenic activities that entail the combustion of fossil fuels and industrial processes, with an estimated 79% coming from energy production, industry development, transport, and construction sectors (IPCC, 2023). With the current trends, projected GHG emissions abatement measures from current national determined contributions (NDCs) adopted from the Paris Agreement are still insufficient to limit the temperature rise below 1.5 °C and will make it difficult to limit it below 2 C beyond 2050. These compounding Climate Change effects, coupled with a shrinking window of opportunity for a sustainable future, have forced the global community in every sector to act in efforts to tackle the effects of climate change, the maritime industry being no exception.

Shipping accounts for 80% of global trade by volume (UNCTAD, 2022) Although hailed as the most efficient mode of transport per ton-mile (Bjerkan & Seter, 2019) it has a global contribution of 2.89 % of the total GHG emissions. In 2022, the maritime industry experienced a 4.7% increase in emissions, and this trend is likely to continue as the global fleet is projected to grow by an annual average of 2.1 % between 2023 and 2027 (UNCTAD, 2022). This can be attributed to increased trade demand from emerging economies and population growth.

The Authority in global maritime matters, the International Maritime Organization (IMO), has been at the forefront of efforts to curb emissions from the maritime industry by

adopting the IMO's initial strategy to reduce emissions (2018) through its legal instrument MARPOL VI chapter 4. This has seen the adoption of technical measures, EEXI and EEDI, and operational measures, SEEMP, DCS, and CII, that address the emissions from international seagoing vessels. Despite all measures in place, shipping emissions are still predicted to increase to 90%-130% of 2008 emission levels by 2050 (IMO, 2020) further emphasizing the need for rapid action across the maritime value chain.

Ports and terminals play an essential role in the maritime transport network (Alamouh et al., 2020); they act as nodes that link maritime transport to other modes of transport, consequently becoming the center of pollution from anthropogenic activities heavily reliant on fossil fuels (Chen, J. et al., 2019) Although contended that emissions from ports constitute a small portion of the maritime supply chain, ports as an industry account for 3% of the global emissions (Acciaro & Wilmsmeier, 2015; Alamouh et al., 2020; Misra et al., 2017) .nevertheless IMO has recognized the essential roles of ports in decarbonizing the maritime industry by adopting a resolution urging port states to voluntarily cooperate with all shipping stakeholders in reducing GHG emissions (IMO, 2019),

This research proposal explores the role of ports in emerging economies in the context of the Kenya Ports Authority(KPA) in decarbonizing the maritime industry. This could show how addressing the carbon emission challenge early on could be viable and cheaper by using grid power and renewable energies to power port operations. There are numerous technical options to improve energy effectiveness and lower GHG emissions in ports, as stated by (Iris & Lam, 2019) and the use of electricity as an energy source, for example, cold ironing and electrification of equipment, autonomous vehicles, energy storage systems, reefer cooling technologies, renewable sources and clean fuels, and lighting technologies (Iris & Lam, 2019) are some of these alternatives.

One of the alternative Electro mobility (e-mobility) in ports increases energy efficiency and generates fewer GHG emissions (Iris & Lam, 2019)as CO2 emission-generated Cargo handling equipment (CHE), i.e., terminal tractors and rubber-tired gantries at

container terminals, have been proven to be the primary sources of pollution from port operations as stated (Yu et al., 2017).

## 1.2 Problem Statement

Reducing air pollution has been a top priority for Kenya Ports Authority, demonstrated by implementing a green port policy in line with United Nations sustainable development goals (SDG), in particular SDG 13 Climate Action and SDG 7 affordable and clean energy to reduce greenhouse emissions. This has led to various implementation of maiden projects, such as cold ironing in the Port of Mombasa, to address emissions from ship vessels in the facility.

Although vessels calling at ports are the primary source of GHG emissions in port facilities (UNCTAD, 2022) on land operational activities, emissions contributions cannot be overlooked. Activities from the operational equipment such as trucks, utility cars, transport buses, tag masters, reach stackers, top loaders, rubber-tired gantries (RTGs), and folk lifts depend entirely on fossil fuel. With the inevitable expansion of the facility due to increased cargo throughput, all port operations are expected to increase to meet the demand; thus, it is highly essential to investigate sustainable and economical alternative energy solutions that will assist in reducing emissions without compromising port productivity.

## 1.3 Aims and Objective:

Through the following objectives, this research aims to determine the plausibility of adopting or employing grid and renewable energy solutions to address emissions issues from operations vehicles.

1. To explore the energy technological competency of zero-emission CHE

2. To assess available energy alternatives with reference to green ports in the maritime industry
3. To illustrate the potential of reducing emissions from port operations through electrification

#### 1.4 Research Questions:

This research aims to determine how grid power and renewable energy sources can be pivotal in reducing carbon emissions at the Port of Mombasa in the ensuring process; the following research questions should be addressed.

1. What is the technological competency of zero-emission CHE?
2. Can an alternative fuel/energy source replace fossil fuel at the port facility?
3. How viable is the identified alternative fuel source and its implications?

#### 1.5 Research Scope:

This research will focus primarily on the Kenya Mombasa port container terminal, and this entails establishing an energy profile that determines the electrical power capacity, fuel consumption, and Air emissions from day-to-day cargo handling operations in the terminal.

The emission profile will be limited to air pollution from land cargo handling equipment: rubber tire gantries (RTGs) and Terminal tractors (TTs).

#### 1.6 Research Outline

This research determines the feasibility of adopting electro-mobility using Grid and renewable sources in the Port of Mombasa. This will entail a comprehensive literature review of similar projects in notable ports to establish an achievable path detailed in Chapter 2. The third chapter includes descriptive methods and criteria used to collect and

analyze crucial data elements for port operation electrification, followed by a technology assessment for the proposed solution in the Kenya Ports Authority container terminal in Chapter 4. The fifth chapter touches on the green port concept and greening solutions. Chapter 6 entails an electrical terminal concept design developed using AutoCAD. Chapter 7 is scenario modeling and analysis using Excel, and finally, chapter 8 covers discussion recommendations and conclusion.

## CHAPTER 2: LITERATURE REVIEW

## 2.1 Climate change and Global regulatory Frameworks:

In recent history, environmental protection has taken precedence due to prevalent effects of Climate change: Sea level rise, floods, severe drought, habitat loss, and extinction of biodiversity are some of the effects that have compelled the need for urgent action to mitigate climate change advancement.

The scientific community's consensus on the seriousness of climate change underscored the need for a concerted international effort. In 2015, The Paris Agreement was adopted. This historic agreement brought together 195 countries and set the goal of limiting global warming to well below 2 degrees Celsius above pre-industrial levels, with efforts to limit it to 1.5 degrees Celsius. Countries submitted nationally determined contributions (NDCs) outlining decarbonization strategies and emission reduction targets (UNFCCC, 2015). While the agreement introduces legally binding instruments for all state parties, aviation and shipping was omitted. This obligation was left solely to the international regulatory authorities: the International Maritime Organization (IMO) and the International Civil Aviation Organization (ICAO).

IMO faced the monumental task of addressing GHG emissions from global shipping, which it has been undertaking continuously since 1997, and the Paris Agreement's adoption intensified the pressure. On 13 April 2018, the Marine Environment Protection Committee adopted the MEPC. 301(72) resolution: initial IMO strategy on reduction of GHG emissions from ships (IMO, 2018). The strategy aimed to reduce total annual GHG emissions from international shipping by at least 50% compared to 2008 levels and encourage efforts towards becoming carbon neutral by the end of the century.

The committee also adopted the MEPC 323(74) resolution on invitation to member states to encourage voluntary Cooperation between the ports and Shipping sectors to contribute to reducing GHG emissions from Ships (IMO, 2019). This regulation aimed to facilitate financial, Technical, Operational, and regulatory Cooperation between primary stakeholders to reduce ship emissions in ports by providing cleaner alternatives like on shore power supply, preferably from renewable sources.

## 2.2 Ports as Sources of Emission

The role of ports as an intermediary hub of multimodal transport hub is characterized by intense operational activities resulting from the cargo movement; these operations, however, are the primary sources of pollution, which pose serious public health and environmental concerns (Canepa et al., 2023; Poulsen et al., 2018a) Ports are regarded as the primary source of GHG emissions and other related air pollution in coastal cities. Stringent Environmental regulation and increasing public concern have compelled port Authorities to adopt and consider various 'port greening' measures to deal with the raised issues.

## 2.3 Technological responses in Ports

The development of zero-emission CHE technology as an abatement measure has seen substantial progress over the years. These improvements have mainly focused on prime movers: Yard trucks, Gantry cranes, reach stackers, straddle carriers, forklifts, and top handlers (CAAP, 2022; Parhamfar et al., 2023) because of the significant energy efficiency improvement potential of diesel-based internal combustion engines (ICE) particularly RTGs and TTs which represent the majority of CHE in most ports. These equipment are relied on to move vast amounts of containerized cargo for several hours a day, entailing that an alternative solution to conventional ICE equipment should be capable of similar fetes on a typical terminal operation day (CAAP, 2022).

Electric-RTG(ERTG), for instance, has gained significant market share in leading seaports, i.e., in Europe: Port of Koper and Port of Felixstowe (Iris & Lam, 2019; Pietrosanti et al., 2020), in Asia: Port of Kaohsiung and Port of Singapore (M. Sadiq et al., 2021; Yang & Chang, 2013a), and in North America: Port of long beach, Part of Savannah, Port of Miami, Port of Los Angeles and Port of Everglades (POLB, 2021) Between the years 2014 to 2025, the market share growth has a compound annual growth rate of 9:9% (GVR, 2023). The growing popularity of ERTGs can be attributed to increased efficiency, reduced mechanical maintenance, lower downtime, and decreased GHG and Air pollution (Alasali et al., 2019; Chen, D. et al., 2019; Vlahopoulos & Bouhouras, 2022; Yang & Chang, 2013b).Yang(2013) noted that ERTGs attained an

86.60% reduction in energy costs and a 67% reduction in GHG emissions in the Port of Kaohsiung.

#### 2.4 Renewable Energy Integration in ports

Swapping ICE for electric power offers lifesaving benefits but increases power requirements, compelling Port to explore alternative energy sources to meet emerging demands. Integration of renewable energy sources into the local Grid has lately been an employed option in various seaport around the globe (A. Rolán et al., 2019); energy generated from renewable sources such as wind, solar, tidal, and wave have gained prominence due to their numerous advantages such as their potential to produce clean and Sustainable energy that reduces GHG emission, improve air quality, provide energy security and flexibility., minimize energy costs and increase operation efficiency (A. Rolán et al., 2019; Qaiyum et al., 2023).

The generated power in port facilities is generally used for low-voltage applications; however, the produced potential necessitates inquiry if the scope of application could be broadened (Kang & Kim, 2017) to power e-mobility, particularly the Charging of electric TTs(ETTs).

## CHAPTER 3: METHODOLOGY

### 3.1 Introduction:

This section describes the research methods and approaches used in this study. It builds on literature on the electrification of CHE and Solar Power as Climate change abatement measures. It entails data processes (Collection, analysis, and presentation) on available resources that will assist in realizing the Research Objectives.

### 3.2 Research Design:

This study was based on a quantitative and desktop analysis approach, as this research combines two GHG abatement measures, CHE electrification and Renewable energy. Feasibility studies on E-mobility and available Data on Solar potential and resources on online databases were utilized as primary Sources for quantitative data analysis. Comprehensive research on secondary sources on the two principles was employed to establish a sustainable Container terminal Concept.

These secondary data were acquired from several credible sources, such as peer-reviewed articles on Science Direct, Google Scholar, and WMU Commons, and reports by Global Solar Atlas, IRENA, IEA, and KPA.

The acquired data is utilized to assess emissions from CHE in question. In this particular case, the main focus will be on RTGs and Terminal trucks; the two CHE handling equipment have been identified as significant polluters and energy Consumers in port terminals (CAAP, 2022; Martínez-Moya et al., 2019; Vujičić et al., 2013).

### 3.3 Conceptual Design:

An electric terminal concept design is developed using the AutoCAD student version; the design serves as a basis for assessing the feasibility and efficiency of port electrification. The concept is centered on electrical engineering considerations when developing an Electrical terminal. It includes the following key components.

- I) RTG power intake mode
- II) Electrical distribution network infrastructure
- III) PV plant development
- IV) ETT charging bay
- V) Battery Energy storage system

The concept design is based on the MPDP II container terminal in the Mombasa Port.

### 3.4 Data Analysis:

The Number of RGTs and TT in the port facility is essential to realize the objective. This information was sourced from the KPA annual bulleting 2022, which contains operation equipment inventory for the particular year.

#### 3.4.1 Emissions Baseline and Consumption Estimates:

An activity-based calculation of fuel Consumption estimates emissions. Using adopted formulas from the IMO Port emission toolkit Guide No1... the emission from respective CHE is given by:

$$E = FC * EF * Pop \dots\dots\dots Eq 3.1$$

Where; E= emission (kg CO<sub>2</sub>)

EF= fuel used emission factor [kgCO<sub>2</sub>/L]

Pop Count of equipment.

FC = Fuel Consumption of specified equipment per hour (l/hr)

The fuel Consumption data is also used to determine the energy consumed by baseline equipment per year. It involves translating fuel energy density (Mj) to a unit of energy (kWh) using the following equation:

$$E = FC \times U \times Op \dots\dots\dots Eq 3.2$$

where E= Energy in watt-hours (Diesel)

F.C= Fuel consumption (liters/h)

U= energy density (kWh/L) (Diesel)

Op= hours of operation.

Figure 3.4.1 illustrates the estimation methodology used to establish emission and consumption baselines.

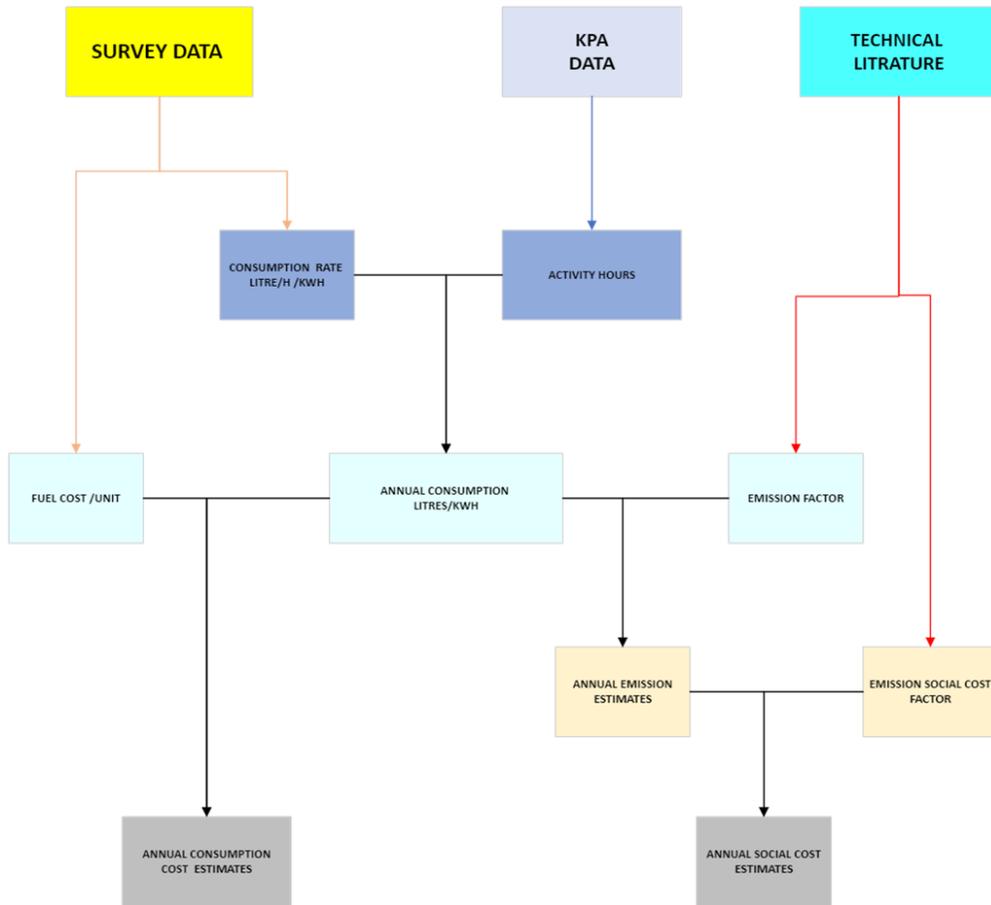


Figure 3.4:1 Illustration of emission and energy consumption estimates methodology

### 3.4.2 Solar Energy:

This study proposes using a solar microgrid to supply energy for the ETT charging station; the following formula obtains solar power generation of an area:

$$P = I_r * \eta * A \dots\dots\dots \text{eq 3.3}$$

Where

$P =$  Solar power kW

$I_r =$  Average solar irradiation (Daytime) W/m<sup>2</sup>

$\eta =$  Panel efficiency

$A =$  Area of Solar plant m<sup>2</sup>

Solar irradiance data is obtained from Copernicus<sup>1</sup>, processed using Python and presented using MS excel.

### 3.5 Financial Analysis:

MS Excel will be used for all required calculations. Project costs will include the cost of converting conventional RTGs to ERTGs, PV-charging installation Costs, and ETT costs. The cumulative cost of fuel Consumption by the RTGs and TTs was obtained by multiplying the current fuel cost at the facility by the fuel Consumption of the equipment. Subsequent emissions can then be related to external costs of public health. The estimated Power bill and Pollution Cost will be factored in to determine the project's viability. The cost will be appraised using Capital budget indices, specifically PBP, NPV, and IRR, and a sensitivity analysis using the Monte Carlo simulation.

### 3.6 SWOT Analysis:

The proposed concept is then assessed according to the environmental and financial analysis results to determine its strengths, weaknesses, opportunities, and threats using SWOT analysis.

---

<sup>1</sup> Copernicus is an online data repository tool developed by the European Union to monitor and store global atmospheric data; the information covers a wide range of specific variables related to wind, ocean, and solar worldwide.

### 3.7 Research Scope and Limitation:

This study focuses on the electrification potential of the Mombasa port container terminal, utilizing the MPDP II terminal as a reference; the hypothetical scenario models developed thereafter are based on the operational report year 2022.

While striving for a comprehensive assessment, the study is limited to general assumptions that do not thoroughly examine specific elements required for terminal electrification.

## CHAPTER 4 TECHNOLOGY ASSESSMENT

This section reviews the technological maturity of current zero-emission technologies and associated infrastructure of RTGs and TTs to determine if electrified alternatives to conventional CHE meet the minimum requirements posed by terminal operations; the electrically powered equipment and alternative power source need to demonstrate equal or better performances than their counterparts.

This is established by investigating the technology in question with three key parameters: Technical, Operational, and economic viability. Collectively, these parameters interact to determine the feasibility of implementation.

### 4.1 RTG crane.

The typical RTG crane is primarily used in container terminals to move containers weighing 20-45t. Conventional RTG has a diesel powertrain that consists of a diesel engine and an electric generator (Hoang et al., 2022). The engine's internal combustion provides mechanical motion, which is converted to electricity (AC) through induction by the generator. The generated power is used to perform various operations, i.e., trolley, horizontal movement of the trolley cabin along the girder, hoisting: the lowering and lifting movement of a spreader while moving containers, gantry movement of the RTG crane along the terminal yard.

Conventional RTGs are extensively employed in container terminals due to their ability to handle containerized cargo through successive lifting, lowering effectively, and staking operations (Söderberg et al., 2017) however, they are also subjected to several shortcomings that include mechanical breakdowns from moving parts, substantially increasing maintenance costs, high operational costs from heavy fuel consumption, and undesirable air emissions that are harmful to the environment and local community.

Full electrification of RTGs Involves replacing the diesel gen-set by connecting the RTG's electric drive directly to the electric Grid, and This can be achieved by the following processes (CAAP, 2022; Vujčić et al., 2013; Yang & Chang, 2013a)

#### 4.1.1 Cable reel system(CRS):

The CRS is a rotating cable drum mounted on the RTG. The cable is made of durable, flexible material designed to carry high-voltage electrical power from the Grid. The cable reel uses a slip ring assembly that taps power from the Grid and a cable reel that unwinds and winds the cable, providing a constant power supply when the crane moves forward and backward along its tracks.



Figure 4.1:1 Cable reel system

systemsource:Konecranes:www.konecranes.com/sites/default/files/download/poweroptionsfortgs.pdf

#### 4.1.2 Busbar System:

This conversion system employs an electric bus tour system in the form of rigid slides installed at a specific height along the container yard. The RTG connects to the busbar via collectors or Contact shores, enabling the crane to maintain constant Contact.



Figure 4.1:2 Busbar system

source:Konecranes:<https://www.konecranes.com/sites/default/files/download/poweroptionsforrtgs.pdf>

## 4.2 Electric Terminal tractors(ETT).

ETT eliminates the use of conventional ICE by utilizing an electric power train. The power train consists of vital technical components: i) an electric motor that converts electrical energy to mechanical energy, which enables the vehicle to move; ii) High Capacity Battery /Fuel cells that store electrical energy used to drive the motor. Lithium-ion batteries are the most commonly used in E-T.T due to their High energy density, long cycle life, and fast Charging capability, which is Ideal for heavy-duty applications, iii) Central Controller and Battery Management System (BMS): the controller determines the energy flow from the batteries to the motor, this ensures smooth, acceleration and deceleration which further increases the overall performance. At the same time, the BMS monitors the state of charge, temperature, and general health of the battery pack. Figure 4.2:1 shows a standard ETT layout.

To increase efficiency and range, modern ETT employs a regenerative power system that converts braking power into electricity that is fed back to the system.

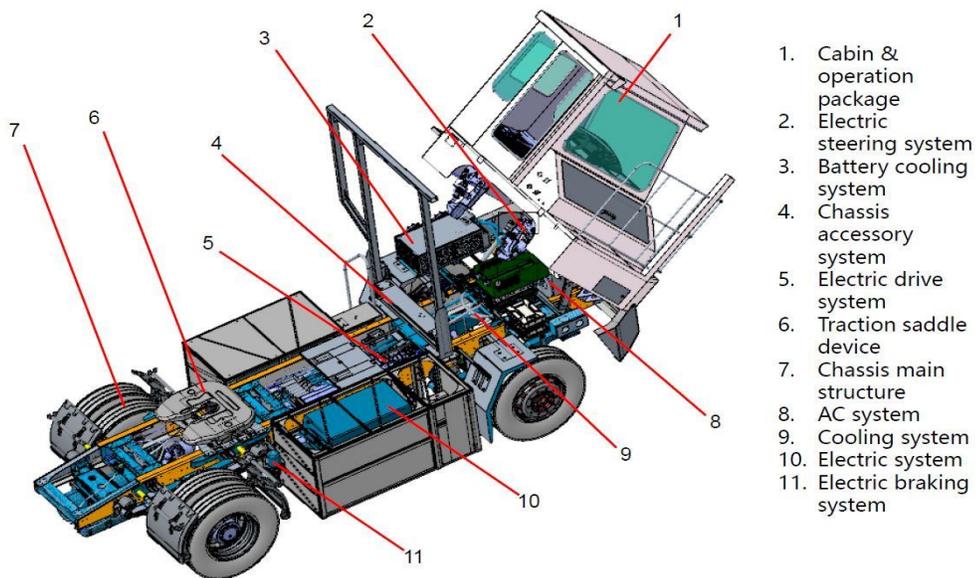


Figure 4.2:1 ETT layouts. Source ANY Europe (SANY, 2023)

ETT is characterized by zero tailpipe emission, Quiet Operation, and Reduced maintenance, substantially reducing environmental impact while Improving working Conditions and increasing economic benefits for the port facility.

Despite the numerous advantages, E-T-T operations are highly dependent on battery capacity, necessitating Charging infrastructure and planned breaks for recharging.

#### 4.2.1 Charging

A critical parameter that determines the adoption of ETT is charging time. Contemporary T. T requires a maximum of 10 mins to refill an empty 190 liter tank (POLB, 2021) whereas E-T-T charging is mainly determined by Battery capacity and Charging rate.

**I) Battery capacity:** Typically, the larger the capacity, the longer the charging duration; since the process involves transferring energy into the battery, a larger capacity will require more energy to charge, thus more time. Additionally, Batteries with higher capacities can generally handle higher Charging rates due to high-temperature tolerance when operating at high currents

**II) Charging rate** refers to the amount of energy transferred into the battery per unit of time, typically measured in watts (W) or amperes (A). Charging rates greatly influence charging times. Chargers with high ratings relative to battery capacity take a shorter time to charge than low-rated chargers. Charging Levels are charging standards that determine the charging rate; the higher the level, the faster the rate of charging, specifically power outputs and voltages used. There are currently three levels available: levels 1,2, and 3 respectively.

Levels 1 and 2 typically use' 120v and 240v alternating current outlets, respectively. Level 1 has an output power of around 115 kW, significantly lower than Level 2 power output, which ranges from 3kW to 22kW (Power Sonic). The two charging levels are employed

for relatively slow charging applications, generally overnight and during working hours. Level 3 employs direct current (DC) and typically operates between 300 v and 1000 v with a maximum current output of up to 400 A. Level 3 power output usually exceeds 50kw going up to 360 kW (power-sonic EV-DC 360) and is usually employed for long distance travels and situations where quick charging is required.

#### 4.3 Technical Assessment:

For this criterion, the technical readiness level (TRL) rating is utilized to assess the technical maturity of the proposed electric CHE. This method is often employed by manufacturers, researchers, and the federal government when determining the readiness of a particular technology. The rating ranges from TRL 1 as an Initial Concept to TRL9: fully matured and Commercial ready form. The definition of TRL adopted by the US Department of Energy (DOE) is provided in the table below (POLB, 2021).

Table 4.3:1 Technical Readiness Level.

Relative Stage of Development	Corresponding TRL #	DOE's TRL Definition / Description (condensed / abbreviated)
Systems Operations	TRL 9	Actual system in its final form and operated under full range of operating conditions.
Systems Conditioning	TRL 8	Actual system completed and qualified through test and demonstration. The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development.
	TRL 7	Full-scale, similar prototype system demonstrated in relevant environment. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment.
Technology Demonstration	TRL 6	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment; represents a major step up from TRL 5
Technology Development	TRL 5	Laboratory scale, similar system validation in relevant environment: basic technological components are integrated so that system configuration is similar to (matches) final application in almost all respects.
	TRL 4	Component and/or system validation in laboratory environment: basic technological components are integrated to establish that pieces will work together; this is relatively "low fidelity" compared with the eventual system.
Research to Prove Feasibility	TRL 3	These TRLs range from Initiation of active research & development (TRL 3) down to Basic principles observed and reported (TRL 1)
Basic Research	TRL 2	
	TRL 1	

Source: adapted from U.S. DOE, "Technology Readiness Assessment Guide," Table 1: Technology Readiness Levels, September 2011.

Source: (CAAP, 2022)

Conventional RTG cranes use a diesel-electric power train where a diesel generator produces electricity to power all system processes. To eliminate emissions from fuel combustion, the RTG diesel power train can be replaced or Converted to an Electric-RTG by connecting the cranes' electric drive to the electricity grid, using various cabling systems as elaborated in section 4.1.

Grid electric RTGs have a TRL 9 rating and are commercially available. Crane manufacturers like Shanghai Port Machinery Kalmar and Konecranes sell new ERTG and provide Conversion options. ERTGs in operation in different ports have demonstrated significant emission and operating Cost reduction potential, which come with environmental, social, and economic benefits.

Entirely electric terminal tractors are currently available with two leading technologies Battery- electric and fuel cell; the former technology is currently the most dominant in the markets owing to rapid advancement in Electric vehicle technologies. ETTs are currently rated at TRL 7 to 8, expected to reach TRL9 by or before 2024 (CAAP, 2022)

Notable TT manufacturers like Kalmar, Orange, and BYD have electric alternatives that meet the operational criteria of container terminals; this was corroborated by demonstration projects conducted at the San Pedro Bay Port Complex as part of their Clear Air Action Plan (CAAP, 2022).

#### 4.4 Operational assessment:

This part assesses the ability of an E-CHE to move cargo in a safe, efficient, and affordable manner comparable to or better than the baseline diesel power equipment. Critical operational criteria considered are ;

Endurance and fuel use: this refers to the time of operation between fueling /charging

Fueling/ Charging time and frequency; the ability of an E-CHE to meet operational needs without affecting Operations,

##### 4.4.1 Operator Safety and Comfort on the E-CHE.

CARB estimates endurance under two conditions. Single tank refers to a TT estimated operational time on a single full tank or charge, and Inter-shift: estimated operating time of a T. T fueling/Charging between Shifts assuming full tank/ Charge at the beginning of Shifts.

Baseline TT, with a diesel capacity of 190 Liters, has a single tank endurance of 20hr and an Inter-shift endurance of 30 hours. It also has a fueling rate of 38 L/min, capable of refueling from zero to full tank in less than 10 minutes.

CARB study on Zero emission yard trucks (CAAP, 2022) determined that battery electric could attain energy economic ratios (EER) between 5:3 to 7:0. EER refers to relative efficiency compared to baseline diesel-fueled ICE Counterparts; this means less energy requirement capacity for the same amount of work.

ETT from Kalmar and BYD with a 220kWh Capacity demonstrated a single tank endurance of 16 hr., barely managing two shifts of continuous operations and an Inter-shift endurance of 23 hr. The ETT had a charging rate of 120kw, requiring about 2 hrs. to fully charge the ETT from depletion. However, equipment manufacturers' technological advancement in charging infrastructure has substantially reduced charging time to 30 mins from the initial 2 hours (POLB, 2021). In 2023, Capacity Truck unveiled a 260kWh lithium-based truck that is expected to last an entire day of normal operations.

Operators' safety and comfort are comparable to the baseline equipment, with additional health benefits from eliminating emissions and reducing noise.

As mentioned, ERTGs are powered directly from the Grid. Endurance Concerns are addressed by continuous grid Connection, but operational efficiency losses may occur during staking lanes' transition depending on the technology used. Safe and comfort levels remain similar to baseline RTGs with reduced emission, noise, and vibrations.

#### 4.5 Solar Energy:

The opportunistic nature of charging E-T-T necessitates further exploring alternative energy sources that will reduce the burden on the Port electrical grid. Kidere (2010)

suggested integrating a solar microgrid to increase energy security and efficiency. Adopting solar energy for this application is the most viable option, given its abundance and cost-effectiveness compared to wind and tidal energy.

Kenya's location along the equator generally enjoys ample solar energy-generating potential. In Mombasa, the average annual direct normal irradiations (DNI) stand at 1627.5 kWh/m<sup>2</sup> per year, as indicated in the figure below.

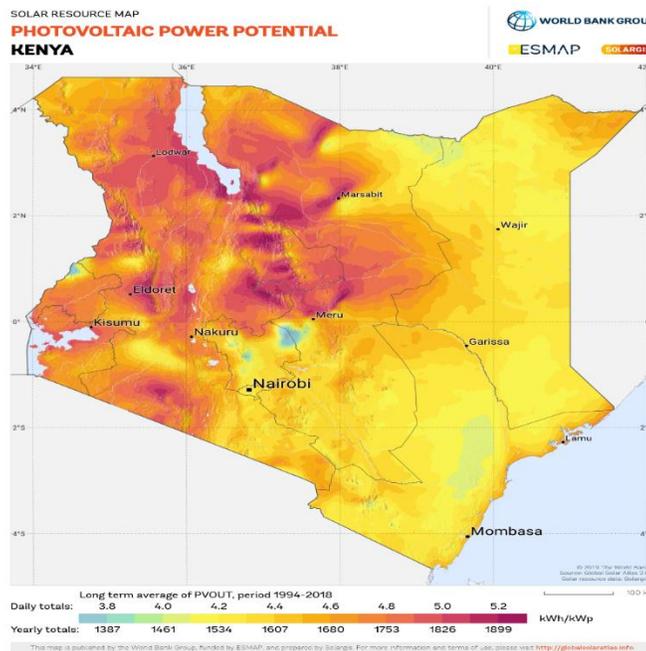


Figure 4.5:1 Illustrating solar energy generation potential.

Source: Solar atlas; @<https://globalsolaratlas.info>.

Using Copernicus and Python program the annual solar irradiation data of KPA is obtained and analyzed using inputs in Table 4.5:1.

Table 4.5:1 contains the inputs required for data acquisition.

Inputs	Units
--------	-------

1	Location	Kenya, Mombasa	Coordinates
2	Variable	Total Direct solar irradiation	MJ/m2
3	Duration	Annual Daytime (2022)	Hours (7 a.m. -6 p.m.)
4	Data Format	NetCDF	n/a

Source: Author

The data obtained contains 4630 data points representing the hourly irradiation average for the year 2022 between 7 a.m. and 6 p.m. Units used to represent the direct irradiation potential is in MJ/m2, which is divided by a unit of time (60\*60) to convert it to W/m2 using Python (Appendix A), The Figure 4.5:2 represents the annual solar irradiation in kW/m2 of the defined period for Mombasa.

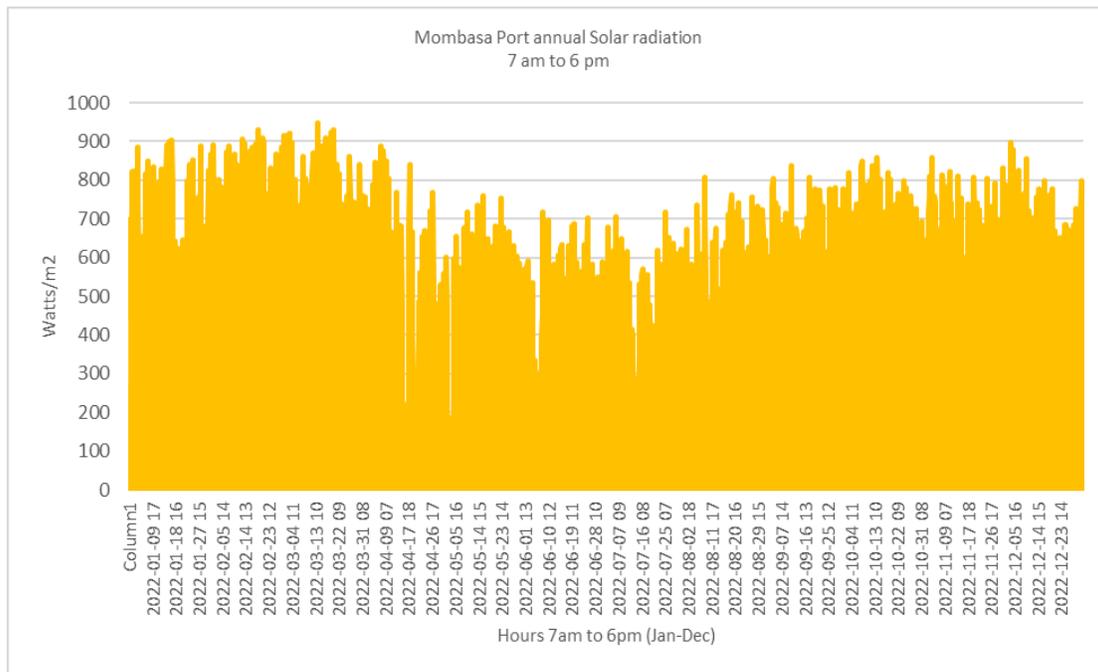


Figure 4.5:2 Solar irradiation profile of Mombasa for 2022. Source: Author: generated using Python and MS Excel

The above graph indicates that the location receives considerable solar irradiation throughout the year with an annual average of 337.5465304 W/m<sup>2</sup>; from this information, solar power generation potential can be obtained using equation 3.3.

#### 4.5.1 Photovoltaic panels:

Photovoltaic energy is derived from semiconductor cells, also called PV cells, that convert solar irradiation to electricity. This occurs when photons from sunrays dislodge electrons in the semiconducting material of the PV cells, creating an imbalance between the top and bottom surface, resulting in a Voltage potential between the cell terminal. (EIA, 2023) Typically, the electric energy a cell produces is low; thus, cells are electrically connected to form a panel, effectively increasing generating capacity. PV panels are categorized as

- i) Monocrystalline: which has high capacity and is highly effective in direct sunlight,
- ii) Polycrystalline: moderate capacity and effective with indirect sunlight,
- iii) Thin film: has the lowest capacity but is highly effective under indirect sunlight.

PV panels are further Connected to form arrays to increase capacity; however, the type of panel selected in an array is highly dependent on factors like geographical location, climate Conditions, required demand, and financial aspects (PIANC, 2014)Power generated by PV panels is in Direct current (DC); however, electrical distribution and transmission generally use Alternating Current (AC) due to higher efficiency.

Solar power systems employ inverters to convert DC to AC, which is crucial in regulating voltage and frequency to the desired standards, ensuring compatibility with the local Grid and equipment. Inverters can be fitted with optimizers that optimize energy production by employing maximum power point tracking (MPPT) algorithms that reduce external factor influence like shading and temperature Change.

#### 4.5.2 Battery Energy Storage System (BESS) :

The generated output from the Solar plants is characteristically unpredictable and uncontrollable; port operations require a stable power supply that can be affected by unpredictable power supply. An energy storage system, usually in the form of battery banks, is utilized to store excess energy generated by the Solar plant during sunny periods; the stored energy is used during the night and low production periods when solar irradiation is limited or unavailable. The BESS effectively Balances the system during rapid fluctuation, preventing unwarranted disruption to the system.

Lithium-ion batteries have recently become the go-to option for energy storage systems due to their high energy density and charge/discharge efficiency; although integrating a BESS significantly increases the initial costs of solar plants, they have proven an integral part when designing microgrids, which offer energy security and flexibility.

#### 4.6 Chapter Summary

The above sections has explored various technologies employed to electrify CHE (ERTGs & ETTs) as an alternative to fossil-powered equipment. It also looked into available renewable energy potential technology that could be integrated to supply clean Power for ETTs, and the general conclusion is that these technologies are mature and serve as enablers of Green Ports ( GP) practices as discussed in the following chapter.

## CHAPTER 5: GREEN PORTS AND GREEN PRACTICES

This chapter builds upon the technological assessment in chapter 4 and situates these solutions within a GP context, exploring how the technologies globally contribute to the GP concept briefly highlighting best practices and their relevance in influencing the KPA sustainability drive.

### 5.1 Green Ports:

Green ports (GP) have various definitions depending on the scholar or author; however, all have an overarching theme of sustainability: Environmentally, socially, and economically. GP ensures that all operation and technical measures are ecologically centered on minimizing negative externalities. Key determining factors of green ports are:

**i) Energy consumption** from all port operations remains critical in determining ports' sustainability, leading to clean energy adoption and integration becoming the hallmark of green ports. Notable ports like the Port of Antwerp, Port of Rotterdam, Port of Los Angeles, and Port of Vancouver have integrated clean energy to power their everyday

operations, significantly reducing emissions. A key example is the adoption of onshore power systems by leading ports to reduce emissions from ships at berth (Poulsen et al., 2018b)

ii) Green ports further double down on **efficient energy** utilization by employing Energy management frameworks that reduce overall consumption in the facilities. ISO 50001 has become a prerequisite for green port status: the standards' certification denotes that the Certified Port has met all set requirements of energy efficiency practices to attain a green status. The framework embraces a comprehensive approach featuring the plan-do-check and Act cycle, as seen in Fig Figure 5.1:1, a systematic approach to continuous improvement. The Port of Antwerp is among the few ports that meet the criterion for certification (PoAB, 2023)

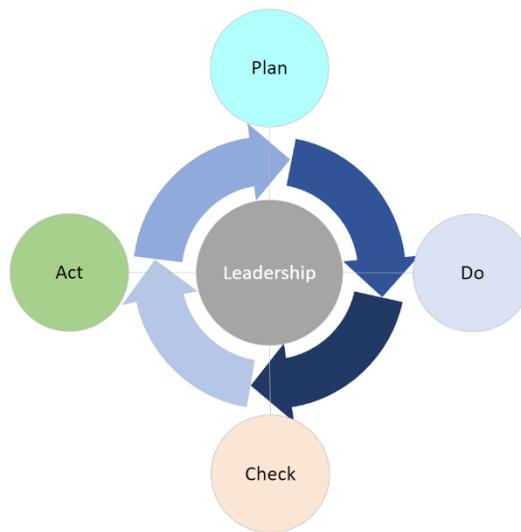


Figure 5.1:1 ISO 50001 Plan-Do-Check and Act. Adopted from Ballini (2023) class lecture.

### 5.1.1 EcoPorts:

As the decarbonization era continues to evolve, the maritime Industry and GP are poised to play a critical role in shaping a more sustainable future; a notable example is the Ecoport initiative of European ports formed in 1997 by proactive ports that aimed to raise awareness on the conservation of the environment through collaboration and resource sharing (ESPO, 2023). The initiative was integrated into the European Sea Ports Organization (ESPO) in 2011, where its influence could be observed through a paradigm shift of European ports' priorities from a development-centric to an environmentally conscious way of thinking. Figure 5.1:2 shows the top 10 environmental priorities of the European port sector over the years, where climate change, energy efficiency, and air quality have observably taken precedence in recent years.

	1996	2009	2013	2018	2019	2020	2021	2022
1	Port development (water)	Noise	Air quality	Climate change				
2	Water quality	Air quality	Garbage/Port waste	Energy consumption	Energy consumption	Climate change	Climate change	Air quality
3	Dredging disposal	Garbage/Port waste	Energy consumption	Noise	Climate change	Energy efficiency	Energy efficiency	Energy efficiency
4	Dredging operations	Dredging operations	Noise	Relationship with the local community	Noise	Noise	Noise	Noise
5	Dust	Dredging disposal	Ship waste	Ship waste	Relationship with the local community	Relationship with the local community	Relationship with the local community	Water quality
6	Port development (land related)	Relationship with the local community	Relationship with the local community	Port development (land related)	Ship waste	Ship waste	Water quality	Relationship with the local community
7	Contaminated land	Energy consumption	Dredging operations	Climate change	Garbage/Port waste	Water quality	Ship waste	Ship waste
8	Habitat loss/degradation	Dust	Dust	Water quality	Port development (land related)	Garbage/Port waste	Dredging operations	Garbage/Port waste
9	Traffic volume	Port development (water)	Port development (land related)	Dredging operations	Dredging operations	Dredging operations	Port development (land related)	Port development (land related)
10	Industrial effluent	Port development (land related)	Water quality	Garbage/Port waste	Water quality	Port development (land related)	Garbage/Port waste	Dredging operations

Figure 5.1:2 European ports' top ten priority list over the years. Source: ESPO Environmental Report 2022 while the GP concept has made significant progress, challenges persist since balancing economic progress, and sustainability has proven to be a delicate task (Roh et al., 2016), considering that multiple viewpoints will have different priorities. Moreover, the concept is highly based on volunteerism, and the Initial associated costs of green investments are

capital intensive, making its universal adoption onerous, a sentiment echoed among developing nations.

### 5.1.2 GP in Developing Nations

The GP concept in developing nations faces unique challenges (maritime Africa) primarily related to governance models, financing, infrastructure, regulatory, technological, and socio-cultural factors (INAL, 2023) However, it also holds immense potential for sustainable economic growth and preserving the ecosystem (UNCTAD, n.d)thus consequently contributing to achieving the United Nations Sustainable Development Goals, in particular, SDG 7: by integrating renewable power in port energy systems, SDG 8: by creating jobs and promoting economic growth through adoption of new technology and infrastructure, SDG 9: by promoting innovation and environmental conscious industrial development SDG 11: through improving port-city relations by minimizing emissions and noise, SDG 13: by promoting clean fuels with minimal global warming impacts and SDG 14: through Conservation practices, waste management and ballast water regulations (UN SDGs, 2023).



Figure 5.1:3 Sustainable Development Goals. Source: UN SDG goals: <https://www.un.org/sustainabledevelopment/news/communications-material>

Laudable efforts have been made by ports in developing nations in Africa, with notable examples like the Port of Tanger Med, the first and only Port in Africa with the ECOports status presented by ESPO, Kenya Ports Authority with the procuring of energy-efficient cargo handling equipment and the Pointe- Noire Port Authority which delved into water treatment and waste management. (MaritimAfrica, 2019) Port Authorities in developing nations show willingness to implement the greening concepts as it becomes a new

standard of modernization of port facilities, further enhancing their competitiveness by aligning with global sustainability.

## 5.2 Greening through Electrification

Leading green ports around the globe employ numerous climate abatement measures; however, port electrification remains a leading contender among the available options. Electrification plays a crucial role in achieving the goals of green ports by reducing emissions, improving air quality, and promoting sustainable practices that align with global efforts to combat climate change. Following are some of the ports that have employed electrification of CHE and integrated renewable energy in efforts to mitigate undesired externalities resulting from port operations.

### 5.2.1 POLA & POLB:

Also referred to as the San Pedro Bay Port Complex, it is located in California along the coast of the Pacific Ocean. SPBPC is a vital driver of economic growth and employment in the region: the two ports handle the most Containerized cargo per vessel call than any other port complex around the globe, with a combined throughput that accounted for 29% of United States International trade in 2022. The port complex handled 19 million TEU in the same year. Achieving a ten-year TEU handling average of 16.9 million with a 3-2% yearly growth rate. (CBRE, 2023)

The rapid growth of the port complex in the last decades has led to increased air pollution. Air quality concerns prompted communities and environmental groups to advocate for measures to mitigate the negative impacts of port operations on public health and the environment. (Densberger & Bachkar, 2022)

In 2006, the SPBPC adopted the Clean Air Action Plan, which was revised and updated in 2010 and later, in 2017, the CAAP entails a strategy to reduce emissions of nitrogen oxides (NOx), sulfur Oxides (SOx), particulate matter (PM), volatile organic compounds

(VOCs) and GHG from all port operation in all key cargo movement sectors. The latest CAAP update set new long-term objectives that entail a 100% transition to zero-emission drayage truck and cargo handling Equipment.

This initiative has resulted in various demonstrations of technologies to achieve zero emission operation at the terminals. Among them is the electrification of CHE projects throughout the terminals; some ongoing projects are noted below.

#### *5.2.1.1 The Zero-emission Terminal Equipment Transition Project.*

POLB- this demonstration project involved retrofitting nine diesel-powered RTGs to grid-powered electric gantry cranes, employing 12 battery electric yard trucks, and deploying a smart yard tractor charging bay at the SSA marine pier. The project estimates to reduce annual GHG emissions by 1323 tons and NOx emissions by 27 tons. (POLB&POLA, 2021)

#### *5.2.1.2 Sustainable Terminals Accelerating Regional Transformation (START) project*

the START project is a multiregional zero-emission and near Zero demonstration project involving POLB, Part of Oakland and Port of Stockton; it showcases emission reduction measures replicable throughout the supply chain from ZE container vessels delivering goods handled by ZE CHE equipment: Electric Y. T, Battery electric forklift, LE hauling trucks and Grid powered RTGs totaling 102 ZE and NZE vessels and CHE: START anticipates to offset annual emissions by 12, 821.7 MT CO<sub>2</sub>e, 25.796 tons NO<sub>x</sub> and 0-2682 ton of PM (POLB&POLA, 2021)

#### *5.2.2 Port of Busan*

It is the main Port of South Korea, situated at 35°6'34"M and 129°3'34" E in the southern Korean peninsula. It was established in 2004 to foster national economic growth as an international logistics and shipping center. BPA handles 40% of the mentioned exports and 80% of its containerized cargo

Evident by its sheer operational capacity, BPA is characterized by unwarranted externalities from its daily operation. Thus, in December 2009, the Korean government enacted a bill for low carbon Green growth that initiated a five-year National plan for green growth that started from 2009-2013. This entailed the development of elaborate strategies aimed at mitigating and preventing the effects of Climate change on land and Ocean areas. BPA, a critical organization with substantial contributions, was compelled to innovate Ideas and policies for green port development.

This led to the Conversion of 186 diesel-powered RTGs to Electric RTGs. The process involved cost-sharing between the Korean government and the 13 terminal operators on a fifty-fifty basis. The conversion process was estimated to cost USD 400,000 per RTG. Despite the high capital cost, the Conversion yielded favorable environmental and financial results. GHG emissions decreased by 64.4%, while energy consumption reduced by 84% (OECD, 2010)

### 5.3 Greening through Renewables

The use of solar has been widely adopted in various ports worldwide; however, the application is limited. In most studies, solar energy is utilized to supply power for low voltage applications: Power for buildings and lighting of the Port facility. Literature on the electrification of CHE using solar energy is severely limited. The Idea is only mentioned as an area for potential research (Alamouh et al., 2020) Nonetheless, implementing these concepts in notable ports around the globe indicates that combining the two measures in ports might yield much more desirable results.

### 5.3.1 Port of Rotterdam:

Hailed as Europe's largest seaport, with a 40 km Length and 10 km wide, the Port accommodates 30,000 seagoing and 130,000 river ships annually. It ranks fifth and eleventh globally as the most crucial bulk and Container port, respectively. In 2021, the Port processed a record 15.3 million TEUs, signifying a 6.6% Total increase compared to the previous year (PortTechnology, n.d) Consequently, the Port of Rotterdam is the most polluting Port In Europe. An emission study by The European NGO Transport and Environment established that the port activities produce 13.7 million tons of CO<sub>2</sub> annually (PoR, 2022)

Strict EU regulations have compelled concerned authorities to adopt ambitious sustainable measures to achieve carbon neutrality by 2050- Some measures included adapting solar power as a source of energy; this was accomplished by utilizing rooftops of large buildings as solar plant sites. In 2016, 11000 solar panels with a capacity of approximately 32MWp were installed on rooftops at the Cool Port, followed by an extra 3100 P. V panels with an annual capacity of 750 MWh at the Frigo Care's rooftop in 2023, a Solar park on Patrizia building was commissioned, it had a capacity of 25MWp that brought the total capacity on rooftops to almost 90 MW.



Figure 5.3:1 Solar arrays on building rooftops at the Port of Rotterdam source (PortTech, 2023)

The solar plant has a capacity of 8000 households in annual consumption, excess electricity from the plant is supplied to the National Grid. (PortTech, 2023) The Port Authority estimates a further 130-150 MWp potential to be explored, which will significantly assist in achieving the Port determined Climate targets. So far, the generated power is used in low-voltage applications and refrigeration.

#### 5.4 Chapter summary

This chapter presented global GP practices centered around electrification of CHE and renewable energy integration which suggest that the technologies are both technologically mature and operationally viable for integration at KPA.

## CHAPTER 6: CASE STUDY KENYA PORTS AUTHORITY

### 6.1 Kenya Ports Authority (KPA):

KPA is a statutory agency established on 20 January 1978 by the Kenyan parliament. KPA is under the Ministry of Transport and Infrastructure. The Authority's principal mandate is to manage and operate all sea and inland ports in Kenya, namely Mombasa Port, Lamu Port, Kisumu Port, Old Port, and Shimoni Port. It provides essential Marine Services: Pilotage, Maintenance of channel (dredging), Drydocking, towage, and Cargo handling: Container cargo, General Cargo, and dry and liquid bulk cargo. The Authority is responsible for Developing Port infrastructure and establishing more minor scheduled ports along the Kenyan coastline and inland waters. Mombasa Port is situated in Kenya's second most populous city. The city has long historical ties with the Port dating back to 1800. Geographically, KPA is located at 04°04'13" S and 39°39'52" E along the natural Kilindini harbor that extends seven nautical miles in length and has a 300 m width; the harbor has a depth of 15m, which is maintained occasionally by the Authority.

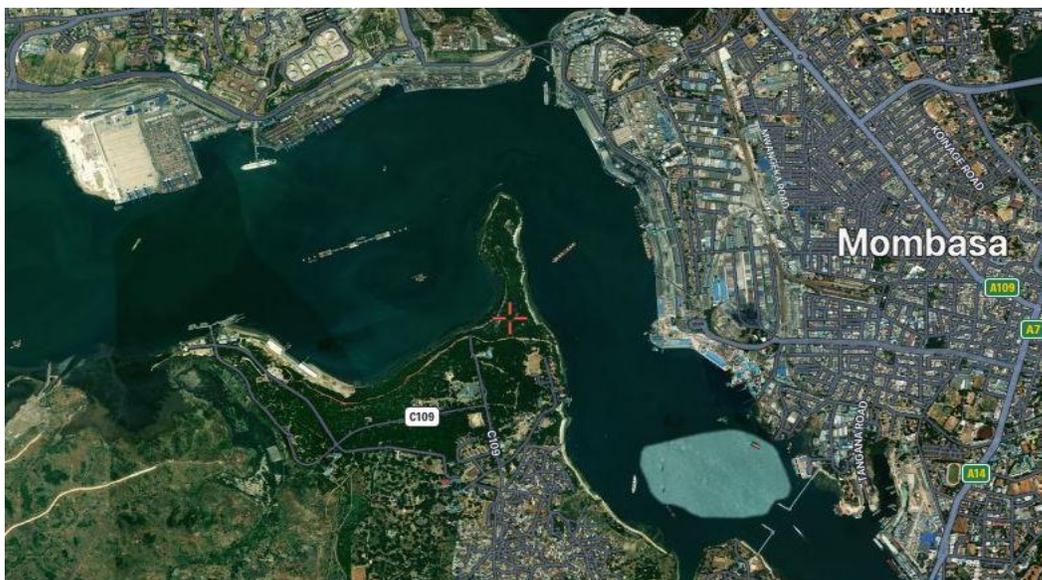


Figure 6.1:1 Kilindini harbor aerial view Source: Google Maps, location Kilindini harbor.

The location has a strategic advantage with an extensive logistic reach that allows the Port to Serve a vast hinterland through various modes of transport. The logistic chain

extends to various regional countries, including Uganda, Tanzania, Rwanda, the Democratic Republic of Congo, Burundi, Ethiopia, Somalia, and South Sudan.

#### 6.1.1 KPA Green Port policy:

In 2016, the Authority implemented its Green Port Policy, with a core mandate of protecting the environment from undesirable externalities that resulted from Port Operations.

As an ISO 9001-certified organization, the Authority based the green port policy's foundation on the 150 14001 Environmental Management System (EMS) to facilitate easy adoption and certification of the system. The GPP, through its objectives, among others, prioritized the well-being of the immediate community affected by pollution from the Port. It also recognized the urgent need to adopt measures to reduce GHG emissions through reducing energy consumption and employing clean alternative Solutions to minimize fossil fuel dependence.

Some of the proposals entailed providing onshore power for vessels at berth, electrification of Cargo handling Equipment, and use of renewable power.

#### 6.1.2 Port Energy Profile.

Implementing emission reduction measures through electrification requires immense energy capacity. It is then crucial to understand the Ports' electric energy profile.

#### 6.1.3 Power Supply:

The Mombasa port is connected to the National grid by two sources: the main dedicated 132kV Kipevu line at substation M and the 33kr supply at substation K. The main 132 kV line is supplied to a 15 MVA transformer, which is stepped down and distributed through a network of interconnected substations throughout the facility.

The power is distributed at 11kv, 6.6k, 3.3kV, or 415V, depending on the required demand. The Mombasa port has a total of 21 substations ( M, K, A, B, B2, C, D, D2, E, E2, F, G, L, N, Q, S, T, U, V Y, And New Kipevu SS ) as shown in Figure 6.1:2, distributing power to critical facilities including KPA Headquarter building, Container Terminal , Conventional cargo terminal, New Kipevu Oil terminal and New service Area (Musyoka, 2013)

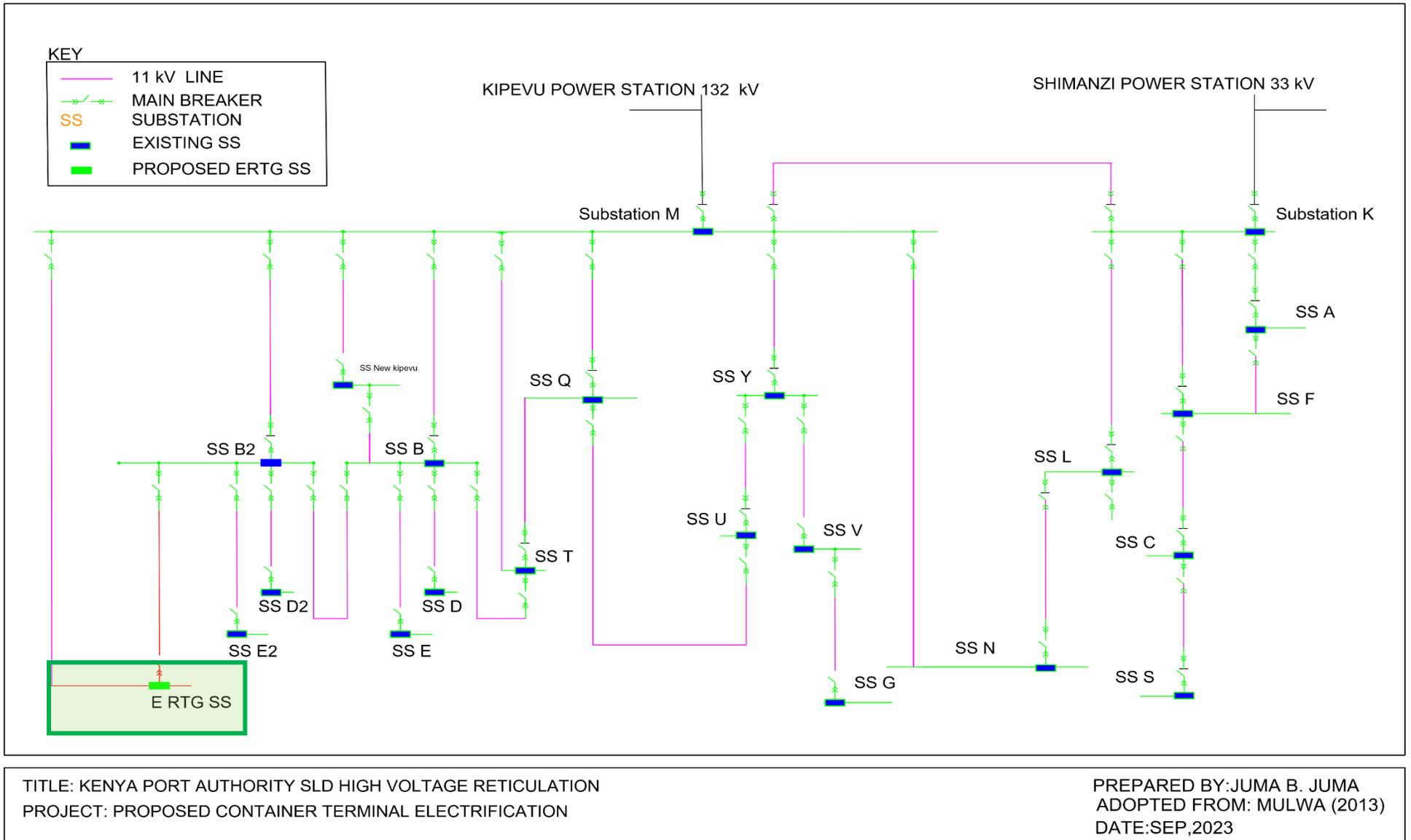


Figure 6.1:2 Single line diagram of KPA electrical reticulation network  : proposed ERTG substation

#### 6.1.4 Power Demand:

KPA consumes considerable electric energy with a monthly average of 2038 MWh, cumulating to 24.46 GWh annually. The high consumption can be attributed to electric-powered gantries, where the ship-to-shore and Rail-mounted gantries account for 66% of the consumed energy (Kidere, Port Electrical). Table 6.1:1 shows the monthly energy Consumption for the 2022-2023 financial year.

Table 6.1:1 KPA monthly energy consumption Source: KPA Port Electrical Engineering

Month 2022-2023 Financial Year	Total Demand KWh	Peak Demand kVA
JULY	2034863.00	4200.00
JUNE	2470225.00	4356.00
MAY	2012387.00	4656.00
APRIL	2361527.00	4632.00
MARCH	2087412.00	4128.00
FEB	2182082.00	4452.00
JAN	2074487.00	4116.00
DEC	1904101.00	3900.00
NOV	1993595.00	3948.00
OCT	2453788.00	3684.00
SEP	1116400.00	3624.00
AUG	1769520.00	3888.00
<b>Total</b>	<b>24460387.00</b>	
<b>Average</b>	<b>2038365.58</b>	
New Demand After ERTGs	26602110.61	
		High Demand
		Low Demand

The above information establishes that the maximum peak demand of 4.6 MVA accounts for 30% of the provided capacity (15 MVA ), determining that the available energy infrastructure can safely handle electrification projects of at least twice its current installed capacity.

#### 6.1.5 The Mombasa Port Container Terminal:

Located on the Kipevu half of the Port, it plays Mombasa a crucial role in handling, storing, and transferring shipping containers to and from various modes of transport, i.e., rail, with the standard gauge railway (SGR), road, through hauler truck and sea: through seagoing vessels. The Authority's aspiration of becoming a leading world-class facility has seen it increase its capacity to handle vast containerized cargo throughput. Accomplished through the implementation of Mombasa Port Development Plan phase I and II, which increased a Port handling capacity by 450,000 TEU, successfully raising the total annual capacity to 2.1 million T.EU.s. (KPA, 2022)

The terminal is equipped with various specialized equipment: Ship-to-shore gantries, rail-mounted gantries, Rubber tired gantries, Reach stackers, terminal tractors, empty container handlers, and harbor mobile cranes, among others that enable it to handle vast cargo throughout. Consequently, the terminal is noted to be the largest consumer of energy (Kidere, 2017) and producer of air emissions due to diesel-powered CHE.

#### 6.2 Electrical Terminal Concept Design: MPDP II

KPA operations are predicted to increase over the coming years, as indicated by the 2.1% cumulative annual growth (KPA, 2022); however, this comes at the cost of increased undesired externalities of air pollution. To address this, the study explores CHE's electrification to reduce port operations' environmental impact. This proposal investigates:

Converting conventional diesel-powered RTGs into grid tied ERTGs and,

Employing E-T. T powered by solar energy.

Figure 6.2:1 shows the distribution of crucial CHE at the CT (KPA, 2022) where RTGs and TT account for 81% of the operational fleet, thus influencing the choice of equipment in focus.

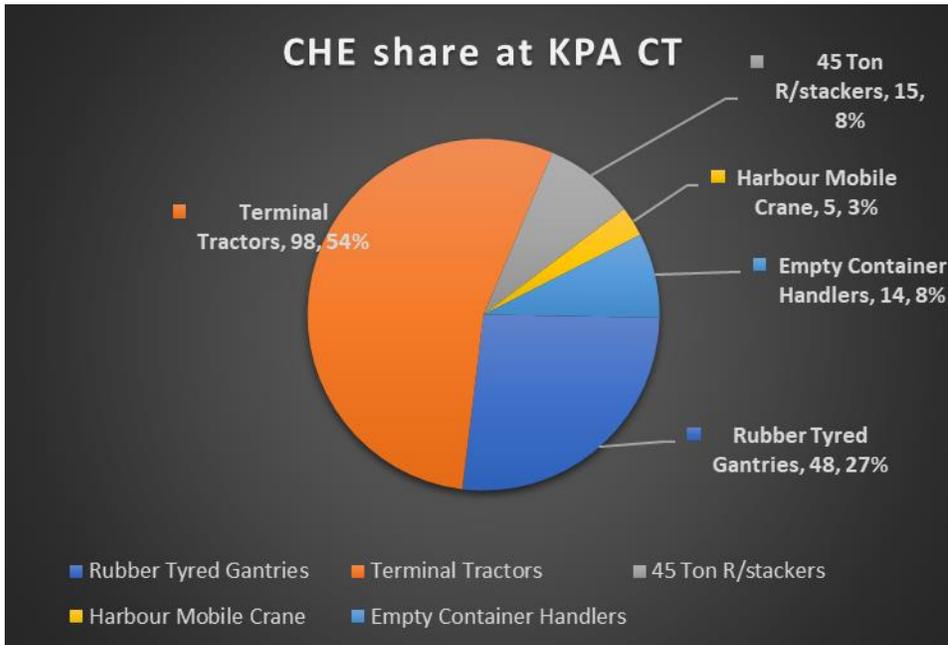


Figure 6.2:1 CHE distribution in KPA container terminal source: (KPA, 2022):2022 KPA annual Bulletin

Phase II of the Mombasa Port Development Project will be used to model the proposed E-Terminal due to its modern layout. The proposed designs presented in this section are based on power demand and infrastructure requirements of ERTGs and battery ETT. Various literature is used to derive the critical assumption required for the model.

6.2.1 ERTG

6.2.1.1 ERTG Power Demand:

A study by Papaioannou et al (2017), on the hybridization of RTGs investigated two gensets, 47 kW and 165 kW, respectively, to be fitted by a regenerative energy storage system and determined that peak demand power was 320 kW for a similar load a similar study by Chen et al (2017) established a peak lifting power demand of 292 kW granted that the conditions might be different the two studies indicate the required Power per RTG (Chen, Z. & Pak, 2017; Papaioannou et al., 2017); alternatively, actual components data can be utilized to calculate the required demand to avoid oversizing the Electrical infrastructure. The table below shows the typical Liebherr 40.6-ton RTG motor drive power used for normal gantry operations.

Table 6.2:1 RTG motor drive rating source: Liebherr RTG technical specifications

Liebherr RTG Drive power		RATED POWER	
1	Hoist unit (40.6 t)	1 X 190	kW AC
2	Trolley unit	2 X 18	kW AC
3	Gantry travel unit (8 wheels)	4 X 35	kW AC

Power demand can then be obtained using the following series of equations.

$$S_{ERTG} = \sqrt{(P_{ERTG}^2 + Q_{ERTG}^2)} \text{ (kVA)} \dots\dots\dots \text{Eq 6.1}$$

$$P_{ERTG} = \sum P_{in}$$

$$Q_{ERTG} = \sum Q_{in}$$

$$P_{in} = (P_{out} / EER) \text{ (kW)}$$

$$P_{out} = (P_{Rated} * L.F)$$

$$Q_{in} = P_{in} * \tan(\cos^{-1}(P.F))$$

Where

Table 6.2:2 Formula definition.

$S_{ERTG}$	= Apparent Power (kVA)	(Transformer Sizing. 2019)
$P_{ERTG}$	= Active Power (kW)	
$Q_{ERTG}$	= Reactive Power (kVAr)	
$P_{in}$	= Input Power (kW)	
$P_{out}$	= Output Power (kW)	
$P_{Rated}$	= Rated motor Power	
EER	= Efficiency Factor	(EERE, n.d)
LF	= Motor Load Factor	
cos-1	= cosine inverse	(Transformer Sizing. 2019)
tan	= tangent	
PF	= Power factor	(KNDGC, 2021)

Using the above information, the required load is calculated in the table below.

Table 6.2:3 ERTG power demand calculation

ERTG LOAD CALCULATION									
Motors	Rated Power(kW)	Quantity	Load Factor	output Power (kW)	Power factor	Input Power (kW)	Input Power (kVar)	Input Power (kW)	Input Power (kVar)
Hoist	190	1	0.75	142.5	0.9	158.3333333	76.68433327	158.3333	76.68433
Trolly	18	2	0.75	13.5	0.9	15	7.264831573	30	14.52966
Gantry	35	4	0.75	26.25	0.9	29.16666667	14.12606139	116.6667	56.50425
						Total		305	147.7182
						Required kva for one ERTG		338.888889	

Source: Author

From the above calculation, a single ERTG will require 338.89 kVA for its normal operations. Since MPDP II CT has sixteen staking blocks (15 for general containers and 1 for reefers) where 16 RTGs can operate simultaneously, the required load becomes.

$$\begin{aligned} \text{Total ERTG load} &= S_{\text{ERTG}} * 16 \text{ units} \dots\dots\dots \text{Eq 6.2} \\ &= 5422.22 \text{ kVA} \end{aligned}$$

## 6.2.2 ERTG: Infrastructure requirements:

### 6.2.2.1 Power supply mode:

Refers to the mechanism of energy supply between the Grid and the RTG described in Chapter 4. For this application, this study proposes using a busbar system to power the ERTG. The system is less expensive to employ compared to other options. The installations use modular frames and concrete blocks that are easy to construct, the frames house vertical conductor lines that supply power to the crane along the stacking block. Additionally, the system has simple maintenance requirements: contact brushes that need replacement every two years are simple to replace and Cheap (Sugimura, 2023).

### 6.2.2.2 Substation:

Is at the centre of the electrical power system at the terminal. It ensures, reliable and safe delivery of electricity by facilitating necessary voltage conversion using transformers, Control: by employing various control devices like switchgear, Circuit breakers, and Isolators that allow operators to manage the flow of electricity, isolate faults, and reroute power as required. The substation is also designed to protect the power system and equipment from Short Circuit faults using various relays that quickly detect and isolate faults.

Substation B2 is the primary power station at the terminal that supplies power to two other small capacity substations: SSD2, which provides utility power to the admin blocks and

workshop area, and CSS E2, which is dedicated to reefer containers. This concept model proposes an additional compact substation with a main 11kV incomer From SSM and an 11kV redundant incomer from SSB2 as illustrated in Fig 6.2(ERTG SS).

**I) Transformer size:** The transformer plays a vital role in converting the 11 kV high voltage supply from SS M to 415 v utility voltage used by the E- RTGs

using the acquired demand, the size of the transformer can be calculated as

$$\text{TX rating} = S_{\text{ERTG}} * \text{D.F} * \text{EAF} \dots\dots\dots\text{Eq 6.3}$$

Where

TX rating =is the transformer-rated capacity,

$S_{\text{ERTG}}$  =is the total ERTG demand,

DF =refers to the Design factor, considering that transformers must operate at 80% of rated capacity at full load conditions.

EAF =is the equipment availability factor in 2022. KPA had an average availability factor of 88% to account for maintenance and breakdowns.

Thus, transformer size becomes.

$$\begin{aligned} \text{TX rating} &= 5422.22 \text{ kVA} * 1.2 * 0.8 \dots\dots\dots\text{Eq 6.4} \\ &= 5725. 84 \text{ kVA} \end{aligned}$$

For this application, two 3MVA 11kV/0.4kV step-down transformers would be sufficient to supply the required power to the terminal. Key features are summarised in the table below

Table 6.2:4 Transformer specs. Adopted from <https://www.scotech-electrical.com/transformer/distribution-transformer/3-mva-3000-kva-11kv-power-distribution.html>

1	Type	Oil Immersed Power Transformer
2	Frequency	50 HZ
3	Phase	3 phase
4	Vector Group	Dyn11
5	Impedance	7%
6	Cooling Type	ONAN
7	Standard	IEC60076
8	Accessories	Standard Configuration
9	Tap Changer	NLTC

**II) Switchgear:** at the center of the substation will be two medium Voltage switchgear that receives 11kV incoming supply from substations M and B, which is fed to the two 3 MVA transformers to be stepped down to 415 v. The stepped-down voltage is then fed to low voltage switchgear panels where it is distributed to respective busbar feeder points.

The table below summarizes the key components of HV and LV panels required.

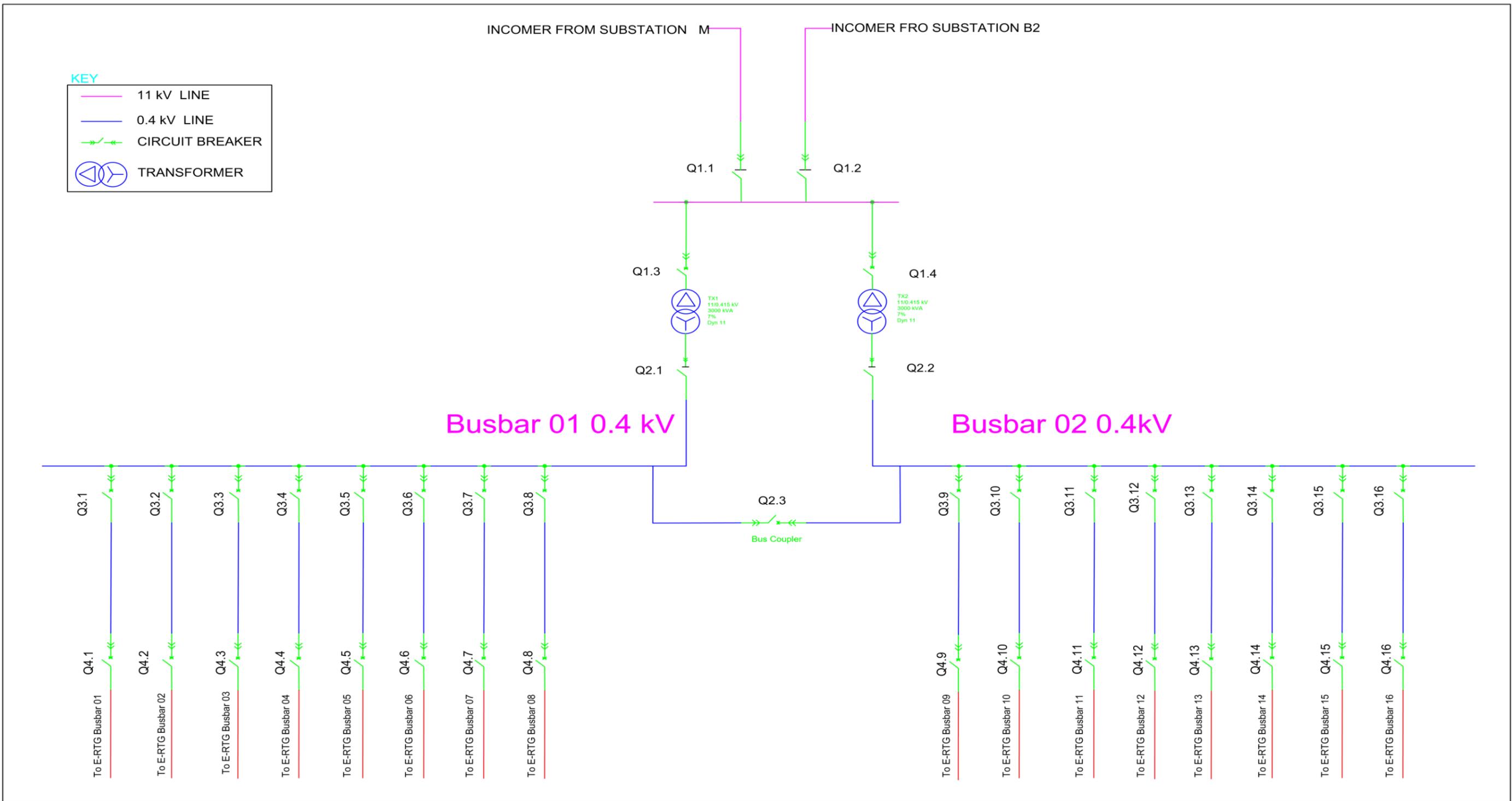
Table 6.2:5 HV and LV panel summary Source: Author

	Components	HV	LV
1	Voltage rating	11 KV	0.4 kV
2	Enclosure	Metal Clad, modular and compact	Metal Clad, modular and compact
3	Protection	ANSI, IEC standard for Current, Voltage, Power, and Frequency	ANSI, IEC standard for Current, Voltage, Power, and Frequency
4	Metering	Include measurements for Apparent power (KVA), Active	Include measurements for Apparent power (KVA), Active

		Power, Reactive Power (kW), Power factor, kWh, kVAh, kVARh RMS, and frequency.	Power, Reactive Power (kW), Power factor, kWh, kVAh, kVARh RMS, and frequency.
5	Control	Three mode operations (live, test, and isolation), Gas insulated (GMA), Three position interlock System, vacuum main Circuit Breaker, Rated Power >11 kV <24 kV, operating current 1250 A, Standard; IEC compliant	Produced and type tested to applicable IEC standards, rated voltage up to 600 v, operating current main breaker 7kA with short circuit current 100 kA, operating current to ERTG busbar 1000A with short circuit current 42 kA

Apart from the above primary components, the concepts will also account for HV and LV cables required for the applications. General considerations will include cable Ampacity, Voltage drop, insulation type, temperature coefficients, length, and conducting material.

The HV side cables will run from the primary side of the transformer via switchgear to SS M, while LV cables will run from the secondary side to respective feeder points at the MPDP II terminal. Fig 6.2:2 shows a single-line diagram of the proposed ERTG substation.



TITLE: KENYA PORT AUTHORITY ELECTRICAL RUBBER TIRED GANTRY SUBSTATION  
 PROJECT: PROPOSED CONTAINER TERMINAL ELECTRIFICATION

PREPARED BY: JUMA B. JUMA  
 DATE: SEP, 2023

Figure 6.2:3 Single line diagram for the proposed ERTG substation

### 6.2.3 ETT

To determine the required infrastructure, it is essential to calculate the required battery capacity of an ETT to ensure similar or better performance compared to conventional TT.

Two Important factors determining operation in KPA are operating hours and shift schedule. In the last five years, KPA had an average container berth occupancy of 78% (KPA, 2022) which indicates to the operating hours in a year, translating to ~19 hrs. a day.

The port operations have a triple shift schedule system divided into three eight-hour daily shifts that provide around-the-clock services throughout the year. During peak operation, shifts are extended to form a 16-hour double shift to meet the required demand. The table below illustrates a typical shift schedule of KPA terminal operations.

Table 6.2:6 Shift schedules at KPA Source: KPA

SHIFT	TIME (24HR)																							
	1st SHIFT								2nd SHIFT								3rd SHIFT							
Normal shift	0600	0700	0800	0900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400	0100	0200	0300	0400	0500
First Double shift	0600	0700	0800	0900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400	0100	0200	0300	0400	0500
Second Double shift	0600	0700	0800	0900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400	0100	0200	0300	0400	0500
Third double shift	0600	0700	0800	0900	1000	1100	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300	2400	0100	0200	0300	0400	0500

Normal shift	
Double shift	
Inter-Shift charging	

The schedule includes a 1hr break between shifts to account for update meetings and health breaks.

#### 6.2.3.1 ETT Battery Capacity

Provided, a typical ICE T. T operates for 19 hrs. a day with a Consumption rate of 9.5 liters per hour (CAAP, 2022) the Energy Consumed for a baseline ICE TT in a regular shift is given as:

$$ED = C. R \times ED \times OT/\text{shifts.} \dots\dots\dots\text{Eq 6.5}$$

Where:

ED = Energy Demand per shift for diesel engines (kWh)

ED = Energy density per liter of diesel (kWh/l)

OT = Operating time per day

Shifts = Number of shifts in a day

$$= 9.5 \text{ liters/hr.} \times 10.64 \text{ kWh/l} \times 19\text{hr}$$

$$= 640.17 \text{ kWh}$$

Granted that an ETT has an Energy Economy Ratio<sup>2</sup> (EER) of 5:3 to 7 (CAAP, 2022) the required energy becomes.

$$E_{ETT} = ED / EER \dots\dots\dots\text{Eq 6.6}$$

Where:  $E_{ETT}$  = energy required by a battery Electrical Terminal Truck per Shift. (kWh)

EER= Energy Economy Ratio (CAAP, 2022)

ED= Energy consumed by diesel-powered terminal truck

$$= 640.17 \text{ -kWh/shift} / 5.3$$

$$= 120.7 \text{ kWh/shift.}$$

for a double shift =  $ED \times 2$

$$= 241.4 \text{ kWh}$$

For this application, the 260-kWh capacity ETT provided by Capacity Trucks will be adequate to complete an entire double shift without inter-shift charging.

---

<sup>2</sup> Energy Economy Ratio (EER): a ratio of efficiency of a fuel compared to a baseline fuel.

#### 6.2.4 ETT Infrastructure:

As determined by the shift schedule presented in the above section, the KPA Container terminal operations provide a 1hr window between shifts, and this can be utilized to Charge ETT before a shift begins.

##### 6.2.4.1 ETT charger

To ensure that ETTs are ready for operation when required, a level 3 DC charger will be required. The Electric Vehicle Energy Storage Company (EVESCO) offers a 360kW DC fast charging option that is ISO 15118 compliant and supports CHAdeMO and CCS2<sup>3</sup> charging connectors. The product shown in the figure below is also IPS4-rated, making it ideal for various locations and Conditions.



The EvDC-360 (EU) can charge an individual E-T-T with 360kw or split the power to 180 kW to Charge two ETTs simultaneously.

Figure 6.2:4 DC fast charger with split power provisions

---

<sup>3</sup> Combined Charging System :DC fast charging plug standard (CCS2-For European market)

source:power-sonic.com EVDC-360(EU) Fast Charger

Considering the determined charging rate and ETT battery capacity, the charging time for the ETT in the provided window can be calculated (Beale, 2022) as

$$T = B.C/C.C \quad \dots\dots\dots\text{Eq 6.7}$$

Where:

- T = Charging time
- B.C = ETT battery storage capacity
- CC = DC Charger charging capacity

Determining charging rate at different charging capacity assuming ETT battery capacity is at 0%.

Charging rate per min at 180 kW

$$\begin{aligned} T @ 180kW &= 260 \text{ kWh} / 180 \text{ KW} \\ &= 1.44 \text{ hrs. or } 86 \text{ mins} \\ &= 260 \text{ kWh} / 86 \text{ min} \\ &= 3 \text{ kWh/min} \end{aligned}$$

Charging rate per min at 360 kW

$$\begin{aligned} T @ 360kW &= 260 \text{ kWh} / 360 \text{ KW} \\ &= 0.72 \text{ hrs. or } 43 \text{ mins} \\ &= 260 \text{ kWh} / 43 \text{ mins} \\ &= 6 \text{ kWh/min} \end{aligned}$$

Determining the time used to charge ETT after one shift: battery capacity at 54%, the time it takes to charge is given as:

$$T = ED/\text{shift} / CR/\text{min} \dots\dots\dots\text{Eq 6.8}$$

Where:

ED/shift = ETT energy demand per shift

CR/min = Charging rate per min

$$T = 120.7 \text{ kWh} / 3\text{kWh/min}$$

$$= 40 \text{ min} \quad @ 180 \text{ kW}$$

$$T = 120.7 \text{ kWh} / 6\text{kWh/min}$$

$$= 20 \text{ min} \quad @ 360 \text{ kW}$$

*6.2.4.2 Charging Bay capacity:*

This research proposes replacing the diesel ICE TTs in phases of 10% to 20% of the current fleet, which amounts to 10 or 20 ETT. Power required at the charging bay is thus determined by the Number of Charging units per station; this proposal recommends a charging bay that can Charge 10 ETT at a time.

Thus,

$$\text{Power Demand} = \text{Charging Capacity} \times \text{Units} \dots\dots\dots\text{Eq 6.9}$$

$$= 180\text{kw} \times 10 = 1800\text{kw.}$$

### 6.2.5 Solar Microgrid

The opportunistic nature of charging E-T-T necessitates exploring alternative energy sources, which will reduce the burden on the Port electrical grid. Kidere (2017) and Alex (2023) suggested integrating a solar microgrid to Improve energy security and efficiency. Following this line of thought, this study proposes using a solar microgrid to supply energy for the charging station. Adopting solar energy for this application is the most viable option, given its abundance and Cost-effectiveness compared to wind and tidal energy.

Critical considerations of establishing a solar plant to power ETT charging stations are power demand, Solar generation potential, area required, Infrastructure, and Energy Storage.

#### 6.2.5.1 Solar Plant Capacity:

Charging bay power demand calculations indicate that the solar plant with a minimum output of 1.8 MW will be required to adequately supply the ETT Charging station. The solar capacity is multiplied by the load demand with a derating factor of 1.2 to account for losses and ensure safe operations under various conditions.

Solar plant capacity = 1800kW \* 1.2 = 2160 kW rounded up to 2.2 MW .....Eq 6.10

#### 6.2.5.2 Plant Area:

Considering that the required power is 2.2 MW and the determined average solar irradiation is 337.54W/m<sup>2</sup>, the needed area can be calculated by re-arranging equation 3.3 as follows: assuming a panel efficiency of 0.2 (Jinko Solar, 2022).

$$A = \frac{P}{\eta * I_r} \dots\dots\dots \mathbf{Eq\ 6.11}$$

Where

P = Solar power kW

$I_r$  = Average solar irradiation (Daytime) W/m<sup>2</sup>

$\eta$  = Panel efficiency

An area of Solar plant m<sup>2</sup>

Area = 2200 kW / 337.54W/m<sup>2</sup> \* 0.2

= 32588.1 m<sup>2</sup>

Kidere (2017) identified potential solar generation sites within the Port that accumulated to 205,555 m<sup>2</sup>, potentially generating 52,417 MWh of energy annually. This research recommends that the barren stretch between SGR rails and Gate 21 access lanes would be Ideal, considering its potential area of 40601 m<sup>2</sup> (combined) and its proximity to the terminal. Figure 6.2:4 represents an aerial view of the actual site for solar module installation.



Figure 6.2:5 Aerial view for the proposed 2MW solar plant.

Source: [https://www.mapdevelopers.com/area\\_finder.php](https://www.mapdevelopers.com/area_finder.php) :Location Kenya Ports Authority

### 6.2.5.3 Battery Energy Storage System (BESS)

Although the solar plant is designed to supply an average power of 2.2 MW, the intermittent nature of solar irradiation poses a considerable challenge: from the developed solar power generating model, it can be observed that from the same area and panel efficiency the plant can generate a high output of up to 6.1 MW and a low of 0 MW depending on the irradiation as seen in Figure 6.2:5 to avoid disruption in the system a battery energy storage system (BESS) can be employed to store excess power during the day to be utilized low generation periods and night Charging.

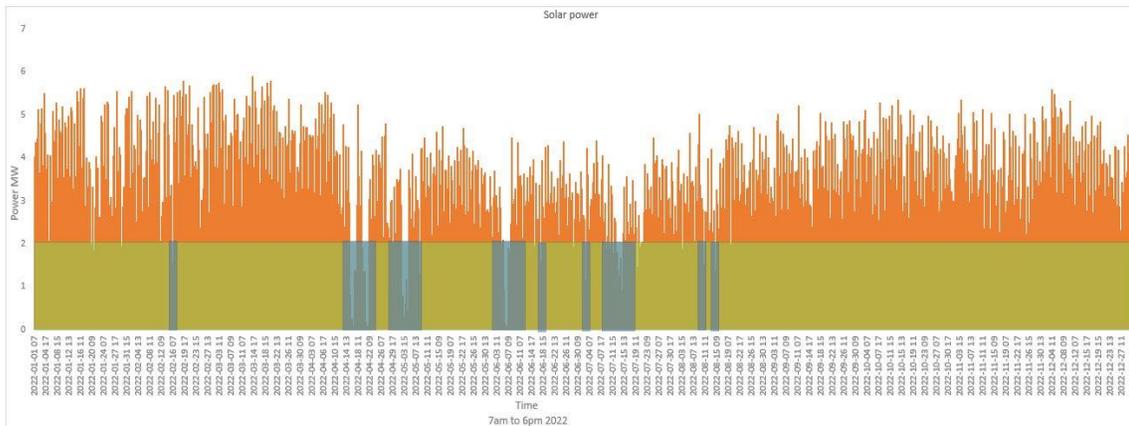


Figure 6.2:6 Annual Solar Power Generation Potential at KPA 2022 Source: Author6.2:7

The BESS should be able to cover at least two inter-shift charging sessions before depletions. As shown in **Table 6.2:6**

The capacity required for the BESS can be obtained by calculating the energy demand to charge ten ETT for two inter-shift charging sessions, Assuming ETT with 260 kWh capacity using 120.7 kWh/shift, energy demand for ten ETTs becomes.

$$\begin{aligned}
 \text{Energy BESS} &= \text{Demand /shift} * \text{Units} * \text{Charging sessions} \dots\dots\text{Eq 6.12} \\
 &= 120.7 * 10 * 2 \\
 &= 2,414 \text{ kWh} \\
 \\
 \text{Loss adjustment} &= \text{Energy BESS} * 120\% \\
 &= 2896.8 \text{ kWh}
 \end{aligned}$$

Considering the required demand per shift, a 260 kWh ETT could efficiently operate for one double shift; however, given the charging capacity of 180 kW per unit, it would require more than an hour to recharge to total capacity, which is more than the provided charging window. Inter-shift charging could be exercised to prevent this or increase the charging capacity to 360 kW. Figures 6.2:7 and 6.2:8 represent regular and double-shift charging profiles, respectively.

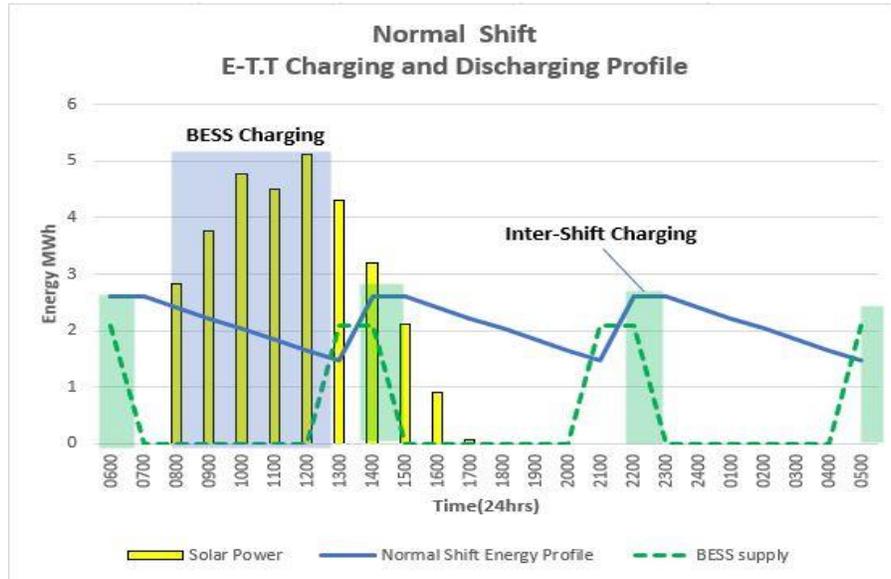


Figure 6.2:8 Regular shift charging profile showing fleet energy consumption and charging pattern.

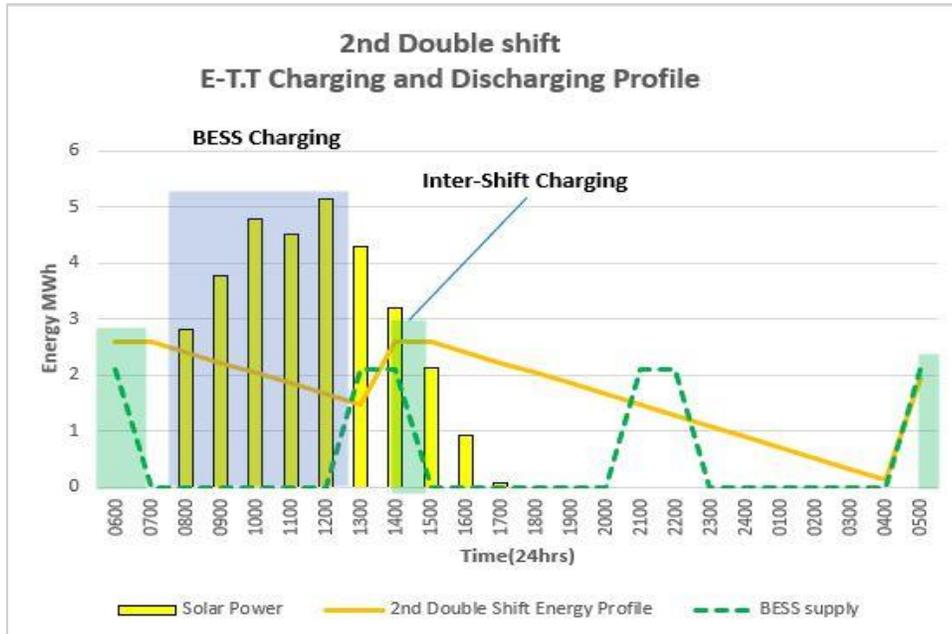


Figure 6.2:9 second double shift charging profile showing fleet energy consumption and charging pattern. Source: Author

In summary, this section briefly highlighted the critical components of electrifying the MPDP II terminal with ERTGs powered by the main Grid through a network of Electrical infrastructure that consists of busbars, distribution cables, and a substation that houses the transformers and switchgear. It also touched on ETT powered by a standalone solar microgrid that aims to take advantage of the abundant solar resources available throughout the year. The following figure illustrates the general layout of the proposed terminal.



Figure 6.2:10 Proposed MPDP II Electric Terminal Layout.

This figure represents the general layout of the proposed terminal. It shows the position of the new Substation (ERTG SS) from where the required power distribution to the terminal will commence.

The SSERTG will also house the solar-powered Charging Bay control and monitoring unit. This figure was produced using the AutoCAD student version by adopting an existing terminal layout.

### 6.3 Proposed project implementation cost:

Establishing the viability of this proposal, the project requires a cost estimate, a crucial element that determines the securing of investments. Cost estimates of critical components are listed below:

#### I) RTG conversion:

A similar study by Sugimura (2023) mentioned that the cost of converting RTGs to ERTGs in Hakata Port, equated to \$ 239397.26, including the infrastructure cost required for a busbar mode ERTG.

#### II) ETTs

literature on ETT cost is limited; general equipment estimates are three times conventional TT, most with values between USD 270000-300000, including Charging infrastructure. An average of \$ 285,000 will be used for this concept (Zack Ruderman, 2022).

#### III) PV Plant:

IRENA, in its 2022 report on the cost of renewables, valued one kW of utility-scaled power Plant at \$ 876 / kW; the cost included Hardware purchase, Installation, and Soft Cost (IRENA, 2023). The resultant cost of the proposed plant becomes.

$$\begin{aligned} \text{Plant Cost} &= \text{Capacity} \times \text{Cost per kilowatt} \dots\dots\dots\text{Eq 6.13} \\ &= 2100\text{kW} * 876 \text{ \$/kW} \\ &= \$ 1,839,600 \end{aligned}$$

#### IV) BESS:

The World Bank priced a 1 kWh of battery storage at 378 \$/ kWh based on the Bloomberg NEF energy storage System cost survey. The Costs included the required infrastructure and installation (WORLD BANK, 2020).

$$\begin{aligned}
 \text{BESS price} &= \text{Cost per kilowatt-hour} * \text{Storage Capacit.....Eq 6.14} \\
 &= 378 \text{ \$/ kWh} * 2900 \text{ kWh} \\
 &= \$ 1,096,200
 \end{aligned}$$

**V) Substation:**

Mulwa (2013) estimated the cost of constructing a substation fully equipped with High and low-voltage switch gears and a Cabling system for a similar project at \$ 426825.00 in 2012 (Musyoka, 2013); the Value equates to 566,302.54 current value after inflation adjustments, using CPI Inflation Calculator a product of bureau of statistics of the US.

**VI) Transformers:**

The retail price for one 3 MVA Schneider transformer is valued at 4200000 Indian rupees (IndiaMart, 2023), equating to \$ 50,000 after dollar conversion.

The total cumulative project cost includes. a 5% project contingency cost and 16% Value-added Tax (reflecting the current rate in Kenya) of the total sum. Table 6.3:1 below summarizes the Cost breakdown.

Table 6.3:1 Estimated costs of electrifying MPDP II operations

<b>MPDP II Electric Terminal cost summary :</b>	
<b>Cost for:</b>	<b>\$</b>
16 RTGs conversions inclusive of Busbar mode infrastructure	\$3,830,356.16
20 E- TTs inclusive of charging infrastructure	\$5,700,000.00
1 Substation	\$426,825.00
2 3MVA transformers	\$101,219.58
2.2 MW Solar plant	\$1,839,600.00
2.9 MWh BESS	\$1,096,200.00
<b>Sub Total</b>	<b>\$12,994,200.74</b>
5% contingency	\$649,710.04
<b>Total</b>	<b>\$13,643,910.78</b>
16% V.A,T	\$2,183,025.72
<b>TOTAL WITH V.A.T</b>	<b>\$15,826,936.50</b>

The obtained cost will be used to assess the proposed project viability in section 7.8.

## CHAPTER 7: SCENARIO MODELLING AND ANALYSIS

This section will look at the impact of electrification on air pollution reduction and associated costs through modeling different implementation scenarios of port electrification.

### 7.1 Air Emissions

Air emissions from port operation-related activities include CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>x</sub>, and P.M<sub>2.5</sub>; although the list is non-exhaustive, the listed are the most prevalent in ports (Canepa et al., 2023) these emissions can further be categorized into two.

i) Air pollutants have direct social and environmental effects on the community close to the area of operation, and their effects are near-term. The main agents in this category are Nitrogen oxide (NO<sub>x</sub>), Sulphur oxides (Sox), and Particulate matter (P.M<sub>2.5</sub>).

ii) Greenhouse gases (GHG): emissions in this category affect the environment globally regardless of their production area; these gases are responsible for absorbing terrestrial heat, increasing atmospheric temperatures, and consequently causing global warming. CO<sub>2</sub> is commonly regarded as the primary GHG.

### 7.2 Emission Baseline:

RTGs and TT constitute 80% of diesel-powered CHE: 48 RTGs and 98 TT. To comprehend the effectiveness of CHE electrification, it is essential to establish annual emissions from the two types of equipment IMO- in port emission, toolkit guide No. 1 provided a formula (GEF-UNDP-IMO, 2018) for assessing emission from CHE given as

$$E = \text{Fuel Consumption} \times EF \times FCF \times CF \dots\dots\dots\text{Eq 7.1}$$

Or

$$E = \text{Energy} * \text{EF Grid} \dots \text{Eq 7.2}$$

Where:

E = emissions, grams/year

Fuel Consumption = fuel consumed, litres

EF = emission factor, grams of pollutant per litre of fuel consumed, g/litre

Energy = annual energy consumption

EF grid = Grid emission factor

FCF = fuel correction factors are used to adjust from a base fuel associated with the EF and the fuel being used (dimensionless)

CF = control factor to reflect changes in emissions due to the installation of emissions reduction technologies not initially reflected in the emission factors, (dimensionless)

### 7.3 Fuel Consumption:

CARB (2021) assessment report on CHE determined the consumption rate of RTGs and TT were 16 l/hr and 9.5 l/hr, respectively, considering the number of operating hours at the terminal per day established in section 6.2, the fuel consumed in a day by an RTG and TT can be calculated as

$$F.C/day = C.R * O.T \dots\dots\dots Eq 7.3$$

Where:

FC/day= Fuel consumed in a Day

C.R= Consumption rate per hour for the specific equipment

O. T= Daily operating hours

Whereas annual fuel consumption by a single piece of equipment becomes:

$$\text{Fuel consumption Annual} = F.C/day * 365 \dots\dots\dots Eq 7.4$$

Moreover, fuel consumed by the whole fleet is calculated as:

$$\text{Total fuel consumption} = \text{Annual FC} * \text{Number of Units of specific equipment} \dots\dots\dots Eq 7.4$$

Table 7.3:1 Annual fuel consumption for a conventional RTG and TT in KPA

	Consumption Rate (l/hr)	Operating Time /day	Fuel consumption litres/day	Annual fuel consumption (litres) /year
RTG	16	19	304.00	110960.00
TT	9.5	19	180.50	65882.50

Key assumption:

CHE consumption rates used are from standard port equipment used in similar ports.

## 7.4 Energy Demand from Electrification of RTG and TT

This section delves into the associated energy demand resulting from electrification.

### 7.4.1 E RTG :

Energy efficiency is one of the key selling points for ERTG. Claus et al. (2017) noted that ERTG consumes an average of 3.02 kWh per move compared to 2.21 l/move for conventional RTGs. By multiplying fuel used per move by the diesel density per litre, the kWh equivalent per move can then be calculated using the following formula below,

$$E D.EQ = E.D * F.C/move \dots\dots\dots Eq 7.5$$

Where:

E D. EQ = Energy Demand equivalent of diesel per move in kWh

E. D = Energy density of diesel per liter (GOV.UK, 2016)

FC/move = Fuel consumption per move (Claus et al., 2017)

$$\begin{aligned} E D. EQ &= 10.7 \text{ kWh/l} * 2.21 \text{ l} \\ &= 23.64 \text{ kWh / move} \end{aligned}$$

The Energy Economy Ratio can then be obtained by:

$$\begin{aligned} EER &= \text{Energy per move diesel} / \text{Energy per move Electrical} \\ &= 23.64 \text{ kWh/move} / 3.02 \text{ kWh/ move} \\ &= 7.83 \end{aligned}$$

Considering the obtained EER annual energy consumption for an ERTG is then calculated as:

$$\text{E.C ERTG} = (\text{F.C RTG} * \text{E.D}) / \text{EER} \dots\dots\dots\text{Eq 7.6}$$

Where:

EC ERTG = annual energy consumption for an ERTG

FC RTG = annual Fuel consumption of a conventional RTG (Table 7.4:1)

EER = Energy Economy Ratio

$$\begin{aligned} \text{E.C ERTG} &= (110960 \text{ l / year} * 10.7 \text{ kWh/l}) / 7.786 \\ &= 152448.06 \text{ kWh/ year} \end{aligned}$$

The energy demand from a single ERTG equates to **152448.06 kWh** annually.

Assumption: the proposed ERGTs are fully electric.

#### 7.4.2 ETT:

Section 6.2.3 established that an ETT requires 120.7 kWh to operate for a single shift, accumulating to 362.1 kWh/day (3 shifts) and 128907.6 kWh/year

### 7.5 Emissions and Cost factors:

Emission factors (EF) refer to the amount of specific pollutant or GHG emitted per litre of diesel an equipment consumes, expressed in grams per litre (g/l). EF is developed from engine tests subjected to various test conditions.

Grid emission factor (EFGrid) Refers to the total associated CO<sub>2</sub> emissions produced from grid energy production; this value depends on the Grid's energy mix. Kenya's energy

mix stands at 75% renewables and 25% fossil fuel (IRENA, 2023) with a combined grid emission factor of 0.4 kgCO<sub>2</sub>/kWh (UNFCCC, 2020).

Considering that the ETTs are powered by solar energy, the tail emissions are considered to be zero.

Social costs of emissions are monetary estimates of socio-economic damages imposed on society from the emission of air pollutants and GHGs. These include health impacts, i.e., respiratory diseases, cardiovascular issues, premature deaths, and environmental impacts, i.e., such as acid rain and climate change.

Table 7.4:1 summarises the emission and cost factors of the primary air emissions from the Port of Mombasa. Literature on Kenyan grid emission factors omitted EF for NO<sub>x</sub>, SO<sub>x</sub>, and P.M assumptions of the values were obtained from the Nordic energy mix, which had a comparable CO<sub>2</sub> EF to a Kenyan grid.

Similarly, factors on the social cost of emissions in Kenya were not available at the time of this research. Values used were adopted from the European Union ETS/ATNI assessment report published in 2020. The report delved into the primary sources of emission in the region and their consequent unintended societal and environmental costs (ETC/ATNI, 2020).

Table 7.5:1 Emission factors for respective modes of energy: Solar energy produces zero NO<sub>x</sub>, SO<sub>x</sub>, and P.M2.5 (EIA, 2022), and associated emission cost per tonne

Emission Factors kg/l		Emission Factors kg/kWh (Grid)	Emission Factors kg/kWh (solar)	Emission Cost/tonne (\$)
CO <sub>2</sub>	2.66	0.4	0	51
NO <sub>x</sub>	0.005692	0.00032	0	18020
SO <sub>x</sub>	1.61E-05	0.00007	0	20638
P.M 2.5	0.002006	0.00003	0	75320

## 7.6 Energy cost:

The current price of diesel at the time of this research, as determined by the Energy and Petroleum Energy Authority (EPRA) of Kenya, is \$ 1.22 /litre (EPRA, 2023) while the price of 1 kWh for the financial year 2022-2023 at KPA was \$ 0.12 /kWh (KPA, 2023). For solar-generated power, this model assumes the IRENA LCOE estimate of \$ 0.049 /kWh (IRENA, 2023),

## 7.7 Case Scenario:

This section explores different case scenarios of port electrification by comparing emission production, social costs, and energy consumption costs for 2023.

The annual emissions will be obtained by multiplying the respective emission factors of pollutants by the total annual energy consumption for all equipment in operation.

$$\text{Emissions} = \text{Total energy consumption} * \text{Emission factor} \dots\dots\dots\text{Eq 7.7}$$

Obtained emissions are then multiplied by their respective cost factor to find associated social externalities costs.

$$\text{Social cost} = \text{Emissions} * \text{Emissions cost factors} \dots\dots\dots\text{Eq 7.8}$$

Consumption cost is the product of fuel of Energy use per year and current market rates of fuel/electricity.

$$\text{Consumption cost} = \text{Annual fuel/energy used} * \text{cost} / (\text{l or kWh})\dots\dots\text{Eq 7.9}$$

### 7.7.1 Scenario one:

This is set at 0% electrification, and the entire RTG and TT fleet is diesel-powered: all 48 RTGs and 98 TT. This scenario will be the baseline for assessing port electrification's effectiveness at different phases.

Table 7.7:1 Total annual emission in tonnes and related social costs for business-as-usual scenario Source: Author

Emissions from Diesel powered	Consumption/unit (litres)	Units	Emissions ( Tonnes )				Cost of emissions \$			
			CO2	NOx	SOx	PM	CO2	NOx	SOx	PM
RTG	110960	48	14167.37	30.32	0.09	10.68	722536.0128	546323.9662	1769.706189	804727.6533
TT	65882.5	98	17174.25	36.75	0.10	12.95	875886.7551	662275.5372	2145.307893	975522.7151
		<b>Total</b>	<b>31341.62</b>	<b>67.07</b>	<b>0.19</b>	<b>23.64</b>	<b>Total 1598422.768</b>	<b>1208599.503</b>	<b>3915.014081</b>	<b>1780250.368</b>

<b>Baseline Emissions Total</b>	<b>31432.52</b>	<b>Baseline social cost of emissions</b>	<b>\$4,591,187.65</b>
---------------------------------	-----------------	--	-----------------------

The baseline scenario establishes an annual net total emission of 31432.52 tonnes, with CO2 as the primary polluted agent representing 99% of all the emissions from RTGs and TTs. Conversely, the total cost of air emission cumulated to \$ 4,591,187.65, although representing less than 1% of the total emissions, associated costs of P.M represented 38% of the total costs of externalities.

Table 7.7:2 Estimated total annual consumption costs Source: Author

Diesel powered	Consumption/unit (litres)	Diesel cost ( \$/l)	Units	Annual cost
RTG	110960	1.2	48	\$6,391,296.00
TT	65882.5	1.2	98	\$7,747,782.00
			<b>Total</b>	<b>\$14,139,078.00</b>

RTGs represented 45% of consumption costs despite representing 33% of the equipment.

### 7.7.2 Scenario Two:

Considers electrification of MPDP II container terminal proposed in chapter 6, where 16 conventional RTGs are converted to ERTGs and 20 diesel-powered TTs are replaced with ETTs

Table 7.7:3 Total annual emission in tonnes and related costs after MPDP II electrification (scenario 2) Source: Author

Emissions from	Consumption/unit	Units	Emissions ( Tonnes )				cost of emissions \$			
			CO2	NOx	SOx	PM	CO2	NOx	SOx	PM
Diesel powered	(litres)									
RTG	110960	32	9444.9152	20.21176346	0.057166592	7.12274432	\$481,690.68	\$364,215.98	\$1,179.80	\$536,485.10
TT	65882.5	78	13669.3011	29.25179047	0.082735244	10.30850301	\$697,134.36	\$527,117.26	\$1,707.49	\$776,436.45
		<b>Total</b>	<b>23114.2163</b>	<b>49.46355393</b>	<b>0.139901836</b>	<b>17.43124733</b>	<b>Total \$1,178,825.03</b>	<b>\$891,333.24</b>	<b>\$2,887.29</b>	<b>\$1,312,921.55</b>
Electric powered	(kWh)									
E-RTG	152448.06	16	975.667584	0.780534067	0.001092748	2.28463E-05	\$49,759.05	\$14,065.22	\$22.55	\$1.72
TT	60979.22	20	0	0	0	0	\$0.00	\$0.00	\$0.00	\$0.00
		<b>Total</b>	<b>975.667584</b>	<b>0.780534067</b>	<b>0.001092748</b>	<b>2.28463E-05</b>	<b>Total \$49,759.05</b>	<b>\$14,065.22</b>	<b>\$22.55</b>	<b>\$1.72</b>
		<b>Difference from Baseline</b>	<b>7251.74</b>	<b>16.83</b>	<b>0.05</b>	<b>6.20</b>	<b>\$369,838.69</b>	<b>\$303,201.04</b>	<b>\$1,005.17</b>	<b>\$467,327.10</b>
		<b>% Difference</b>	<b>23%</b>	<b>25%</b>	<b>26%</b>	<b>26%</b>	<b>23%</b>	<b>25%</b>	<b>26%</b>	<b>26%</b>

<b>Baseline Total</b>	<b>31432.52</b>		ne social cost of emi:	<b>\$4,591,187.65</b>
<b>Scenario 2 combined</b>	<b>24157.70</b>		<b>Scenario 2</b>	<b>\$3,449,815.66</b>
<b>Difference (Tonnes)</b>	<b>7274.82</b>		<b>Difference</b>	<b>\$1,141,371.99</b>
<b>% Difference from</b>	<b>23%</b>		<b>% Difference</b>	<b>25%</b>

This case scenario showed that the electrifying MPDP II terminal has the potential to reduce net emissions from RTGs and TTs by 23% and reduce the cost of externalities by 25 %, with the highest saving coming from the reduction of PM<sub>2.5</sub> emissions.

Table 7.7:4 Total annual consumption costs after MPDP II electrification (scenario 2).Source: Author

<b>Diesel powered</b>	<b>Consumption/unit (litres)</b>	<b>Diesel cost ( \$/l)</b>	<b>Units</b>	<b>Annual cost</b>
RTG	110960	1.2	32	\$4,260,864.00
TT	65882.5	1.2	78	\$6,166,602.00
			<b>Total</b>	<b>\$10,427,466.00</b>
<b>Electric powered</b>	<b>Consumption/unit (kWh)</b>	<b>Electricity cost ( \$/kWh)</b>		
E-RTG	152448.06	0.12	16	\$292,700.28
TT	60979.22	0.049	20	\$59,759.64
			<b>Total</b>	<b>\$352,459.91</b>
		<b>Combined Diesel and Electric consumption</b>	<b>Combined Difference (D+E)</b>	<b>% Difference from Baseline</b>
RTG		\$4,553,564.28	\$1,837,731.72	29%
TT		\$6,226,361.64	\$1,521,420.36	20%
<b>Net Total</b>		<b>\$10,779,925.91</b>	<b>\$3,359,152.09</b>	<b>24%</b>

Conversely, this scenario shows that electrifying the MPDP II terminal will reduce the net cost of fuel consumption by 24 % and RTG consumption by almost 30%.

### 7.7.3 Scenario Three:

This is based on electrifying MPDP phases I and II by converting 32 conventional RTGs to ERTGs (sixteen per phase) and replacing 49 diesel TTs with ETT.

Table 7.7:5 Total annual emission in tonnes and related costs after MPDP I & II electrification (scenario 3) Source: Author

Emissions from Diesel powered	Consumption/unit (litres)	Units	Emissions ( Tonnes )				cost of emissions \$				
			CO2	NOx	SOx	PM	CO2	NOx	SOx	PM	
RTG	110960	16	4722.4576	10.10588173	0.028583296	3.56137216	\$240,845.34	\$182,107.99	\$589.90	\$268,242.55	
TT	65882.5	49	8587.12505	18.37612478	0.051974704	6.475854455	\$437,943.38	\$331,137.77	\$1,072.65	\$487,761.36	
		<b>Total</b>	<b>13309.58265</b>	<b>28.48200651</b>	<b>0.080558</b>	<b>10.03722662</b>	<b>Total</b>	<b>\$678,788.72</b>	<b>\$513,245.76</b>	<b>\$1,662.56</b>	<b>\$756,003.91</b>
Emissions from Electric powered	Consumption/unit (kWh)										
E-RTG	152448.06	32	1951.335168	1.561068134	0.004370991	9.1385E-05	\$99,518.09	\$28,130.45	\$90.21	\$6.88	
TT	60979.22	49	0	0	0	0	\$0.00	\$0.00	\$0.00	\$0.00	
		<b>Total</b>	<b>1951.335168</b>	<b>1.561068134</b>	<b>0.004370991</b>	<b>9.1385E-05</b>	<b>Total</b>	<b>\$99,518.09</b>	<b>\$28,130.45</b>	<b>\$90.21</b>	<b>\$6.88</b>
		<b>Difference from Baseline</b>	<b>16080.71</b>	<b>37.03</b>	<b>0.10</b>	<b>13.60</b>	<b>\$820,115.96</b>	<b>\$667,223.30</b>	<b>\$2,162.25</b>	<b>\$1,024,239.58</b>	
		<b>% Difference</b>	<b>51%</b>	<b>55%</b>	<b>55%</b>	<b>58%</b>	<b>51%</b>	<b>55%</b>	<b>55%</b>	<b>58%</b>	

<b>Baseline Total Emissions</b>	<b>31432.52</b>	<b>Baseline social cost of emissions</b>	<b>\$4,591,187.65</b>
<b>Scenario 3 combined</b>	<b>15301.08</b>	<b>Scenario 3 Combined cost of</b>	<b>\$2,077,446.57</b>
<b>Difference (Tonnes)</b>	<b>16131.44</b>	<b>Difference</b>	<b>\$2,513,741.08</b>
<b>% Difference from</b>	<b>51%</b>	<b>% Difference</b>	<b>55%</b>

This scenario represents 55 % of net equipment electrification, which also corresponds to 55% of annual social cost savings. Although RTG electrification is at 66%, their emission reduction potential effect is reduced due to the remaining diesel-powered TT, resulting in a net emission reduction of 51%.

Table 7.7:6 Total annual consumption costs after MPDP I & II electrification (scenario 3) Source: Author

Diesel powered	Consumption/unit (litres)	Diesel cost ( \$/l)	Units	Annual cost
RTG	110960	1.2	16	\$2,130,432.00
TT	65882.5	1.2	49	\$3,873,891.00
			<b>Total</b>	<b>\$6,004,323.00</b>
Electric powered	Consumption/unit (kWh)	Electricity cost ( \$/kWh)	unit	
E -RTG	152448.06	0.12	32	\$585,400.55
TT	60979.22	0.049	49	\$146,411.11
			<b>Total</b>	<b>\$731,811.66</b>
		Combined Diesel and Electric consumption	Combined Difference (D+E)	% Difference from Baseline
	RTG	\$2,715,832.55	\$3,675,463.45	58%
	TT	\$4,020,302.11	\$3,727,479.89	48%
	<b>Net Total</b>	<b>\$6,736,134.66</b>	<b>\$7,402,943.34</b>	<b>52%</b>

Consumption-related costs were reduced by 52% compared to the baseline consumption costs, where ERTGs and ETTs contributed 10% of the net cost.

7.7.4 Scenario Four:

This scenario Investigates 100% electrification of RTGs and TT. Table below highlights the full potential of CHE electrification at the terminal from an emission reduction and Social cost-saving perspective:

Table 7.7:7 Total annual emission in tonnes and related costs after 100% electrification (scenario 4). Source: Author

Emissions from Electric powered	Consumption/unit (kWh)	Units	Emissions ( Tonnes )				Social cost of emissions \$			
			CO2	NOx	SOx	PM	CO2	NOx	SOx	PM
E -RTG	152448.06	48	2927.002752	2.341602202	0.009834729	0.000205616	149277.1404	42195.67167	202.9691422	15.48701841
TT	60979.22	98	0	0	0	0	0	0	0	0
		<b>Total</b>	2927.002752	2.341602202	0.009834729	0.000205616	<b>Total</b> 149277.1404	42195.67167	202.9691422	15.48701841
		<b>Difference from Baseline</b>	28414.62	64.72829255	0.179864567	23.63561977	<b>\$1,449,145.63</b>	<b>\$1,166,403.83</b>	<b>\$3,712.04</b>	<b>\$1,780,234.88</b>
		<b>% Reduction</b>	<b>91%</b>	<b>97%</b>	<b>95%</b>	<b>100%</b>	<b>91%</b>	<b>97%</b>	<b>95%</b>	<b>100%</b>

<b>Baseline Total</b>	<b>31432.52</b>	<b>Baseline social cost</b>	<b>\$4,591,187.65</b>
<b>Scenario 4 combined</b>	<b>2929.35</b>	<b>Scenario 4</b>	<b>\$191,691.27</b>
<b>Difference (Tonnes)</b>	<b>28503.16</b>	<b>Difference</b>	<b>\$4,399,496.39</b>
<b>% Difference from</b>	<b>91%</b>	<b>% Difference</b>	<b>96%</b>

Complete electric transition reduces net emissions by 90% while reducing eternity costs by 96%. Resultant emissions from implementation are entirely from Grid. The emissions could further be reduced by increasing the share of renewable in the National power grid

Table 7.7:8 Total annual consumption costs after 100% electrification (scenario 4). Source: Author

iesel powered	Consumption/unit (litres)	Diesel cost ( \$/l)	Units	Annual cost
G	110960	1.2	0	\$0.00
	65882.5	1.2	0	\$0.00
			<b>Total</b>	<b>\$0.00</b>
electric powered	Consumption/unit (kWh)	Electricity cost ( \$/kWh)		
RTG	152448.06	0.12	48	\$878,100.83
	60979.22	0.049	98	\$292,822.21
			<b>Total</b>	<b>\$1,170,923.04</b>
		Combined Diesel and Elec	Combined Difference (D+E)	% Difference from Baseline
RTG		\$878,100.83	\$5,513,195.17	86%
TT		\$292,822.21	\$7,454,959.79	96%
Net Total		\$1,170,923.04	<b>\$12,968,154.96</b>	<b>92%</b>

Completely Electrifying RTGs and TTs also come with substantial economic benefits, potentially reducing energy costs by 92% compared to baseline consumptions.

## 7.8 Financial Analysis:

This section explores the financial viability of electrifying the Port of Mombasa. Full electrification, although possible, cannot happen at once due to operational disruptions, extensive capital Investment, and uncertainty of proposal practicality and reliability. For these reasons, this section investigates the financial feasibility of adopting the solution at the MPDP II terminal. Key capital budgeting metrics used to assess the project are Payback period (PBP), net present value (NPV), and Internal rate of return (IIR).

### 7.8.1 Payback period (PBP):

estimates the time required to recover the initial investment by measuring the time it takes for cumulative flow to break even or surpass the initial investment, calculated as follows (Burns & Walker, 1997)

$$\text{Payback Period} = \text{Initial investment} / \text{Annual cash flow} \dots\dots\dots \text{Eq 7.10}$$

Although PBP is straightforward and gives an indication of the time taken to recover the initial investment, It overlooks changes in the value of money over time due to inflation and other factors and does not account for cashflow beyond the payback period the NPV metric tries to account for the mentioned PBP drawbacks.

### 7.8.2 Net Present Value (NPV):

accounts for the value of money by summing all cashflows discounted to the present value of money over time. The formula is as follows (Burns & Walker, 1997):

$$NPV = \sum_{t=0}^n \frac{CF_t}{(1+k)^t} - CF_0 \dots\dots\dots \text{Eq 7.11}$$

Where:-

$CF_t$  = is the sum of all Cash flow.

$K$  = is the cashflow discounting factor.

$CF_0$  = is Initial Investment Cost.

A positive NPV indicates a wealth-creating investment, while a negative NPV points to loss generation by the proposed project.

### 7.8.3 Internal Rate of Return (IRR):

is an additional metric used to determine the discount rate when cash flow breaks even or NPV equates to zero, expressed as follows (Burns & Walker, 1997).

$$CF_0 = \sum_{t=0}^n \frac{CF_t}{(1+k)^t} \dots\dots\dots \text{Eq 7.12}$$

Where:

$CF_t$  = is the sum of all Cash flow.

$K$  = is the cashflow discounting factor.

$CF_0$  = is the net present value at zero.

It is measured against the cost of capital; IRR values higher than C. P indicate a profitable investment.

#### 7.8.4 Determining cashflow:

Cashflow refers to the movement of money into and out of an investment project, described as revenues and expenses occurring recurrently over a period in relation to an initial investment (Appuhami, 2008).

##### *7.8.4.1 Capital expenditure (CAPEX) and Operational expenditure (OPEX):*

Represents the investment made to upgrade and acquire long-term assets or infrastructure. It is categorized as an outflow of cash. In this case, the cost of electrifying MPDP II in section 6.5 is determined as the CAPEX for this model concept. OPEX refers to the cost of generating revenue i.e. recurrent costs: repair and maintenance (M&R). The M&R cost is assumed to be constant for diesel-powered and Electric equipment for Simplification purposes.

##### *7.8.4.2 Consumption saving:*

Section 7.6.2 highlighted the potential fuel saving from the electrification of the MPDP II terminal. For this analysis, the savings will be considered as cash inflow, as illustrated in Table 7.8:1

Table 7.8:1 summarizes annual Consumption savings from MPDP II Electrification.7.8:2

Baseline MPDP II DIESEL POWERED TERMINAL				
Diesel powered	Consumption/unit (litres)	Diesel cost ( \$/l)	Units	Annual cost
RTG	110960	1.2	16	\$2,130,432.00
TT	65882.5	1.2	20	\$1,581,180.00
			<b>Total</b>	<b>\$3,711,612.00</b>
MPDP II ELECTRIC POWERED TERMINAL				
Electric powered	Consumption/unit (kWh)	Electricity cost ( \$/kWh)		
E-RTG	152448.06	0.12	16	\$292,700.28
TT	60979.22	0.049	20	\$59,759.64
			<b>Total</b>	<b>\$352,459.91</b>
		<b>Difference in consumption cost</b>		<b>% Difference</b>
	<b>RTG</b>	\$1,837,731.72		86%
	<b>TT</b>	\$1,521,420.36		96%
	<b>Net Total saving</b>	<b>\$3,359,152.09</b>		<b>91%</b>

7.8.4.3 Potential Carbon revenue:

Section 7.5 above established the social cost savings from emission reduction; although relevant, it is not easy to attribute the savings to the abatement measure from a port operational perspective. A more realistic approach is accounting for emissions saved as carbon credit, a Concept that allows entities producing fewer emissions than the allocated allowance to trade the excess allowance as carbon credits. The European Union Emission Trading System (EU. ETS), the most prominent and Comprehensive cap-and-trade program, values one metric tonne of carbon at USD 93.21 equivalent at the time of this research.

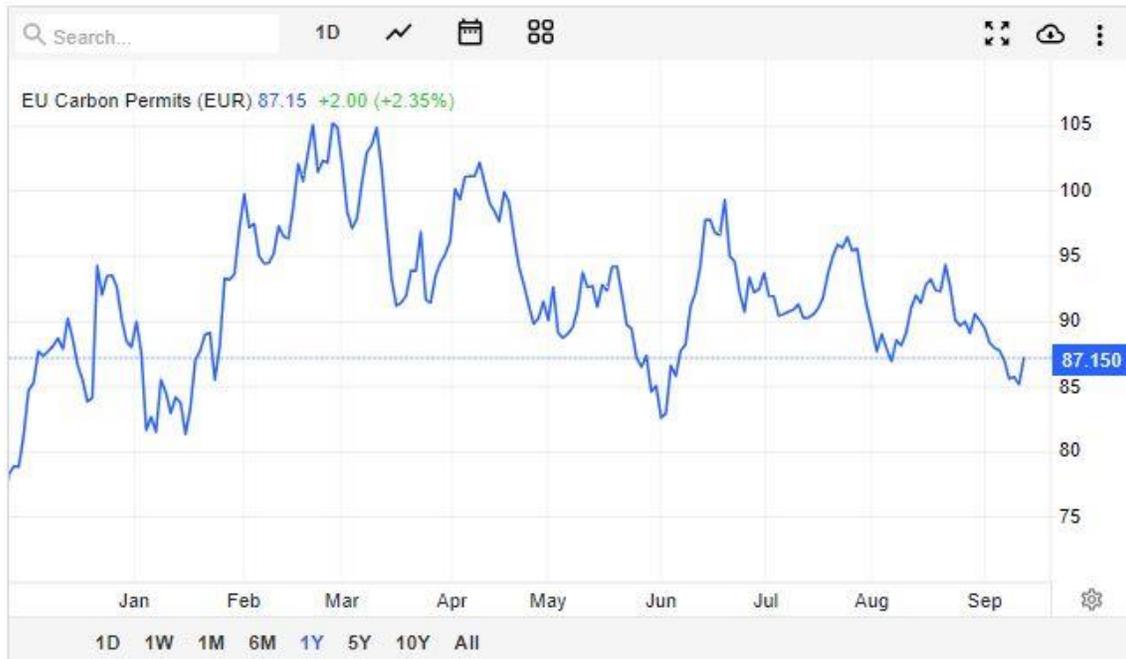


Figure 7.8:1 Price of one metric Tonne of carbon in euros in September 2023, equating to USD 93.21 at the current rate. Source: <https://tradingeconomics.com/commodity/carbon>

The system only accounts for GHGs; consequently, CO<sub>2</sub> as the primary emitted agent. The Table 7.8:3 calculates the potential cost of emission reduction at the electrified terminal.

Table 7.8:3 Estimated potential revenue from carbon trading.

Baseline MPDP II DIESEL POWERED TERMINAL				
Diesel powered	Consumption/unit (litres)	Emission factor	Units	Annual Emission (Tonnes)
RTG	110960	2.66	16	4722.46
TT	65882.5	2.66	20	3504.95
			<b>Total</b>	<b>8227.41</b>
MPDP II ELECTRIC POWERED TERMINAL				
Electric powered	Consumption/unit (kWh)	Emission factor	Units	Annual Emission (Tonnes)
E-RTG	152448.06	0.4	16	975.67
TT	60979.22	0.04	20	48.78
			<b>Total</b>	<b>1024.45</b>
		<b>Difference in Emissions</b>		<b>% Difference from Baseline</b>
	RTG	3746.79		79%
	TT	3456.17		99%
	Net emissions reduced		<b>7202.96</b>	<b>88%</b>
Cost per Tonne( \$ / tCo2)	Emission reduced (Tonnes)		Carbon credit	
93.21	7202.96		<b>\$671,387.50</b>	

From the above calculation, the total amount saved/generated from implementing the proposal is summarized in Table 7.8:4 below.

Table 7.8:4 shows cost savings/generated from MPDP II electrification per year

<b>Net consumption saving</b>	<b>\$3,359,152.09</b>
<b>Carbon credit</b>	<b>\$671,387.50</b>
<b>Total Revenue saving/generated</b>	<b>\$4,030,539.58</b>

### 7.8.5 Project Appraisal

Assuming an equipment life span of 15 years and a discount rate of 8.5%, equivalent to Kenyan inflation rates as of August 2023 (TRADING ECONOMICS, 2023), the key metrics can be computed using an Excel spreadsheet as shown in Table 7.9:1

Table 7.8:5: Estimated 15 year cashflow for MPDP II Electric Terminal

MPDP II ELECTRIFICATION PROJECT						
	Interest rate	0.085				
	Year	Net Cash Flow (\$)	CCF	8.5% D.R	DCF	CDCF
CAPEX	0	<b>-\$15,826,936.50</b>	<b>-\$15,826,936.50</b>	1	<b>-\$15,826,936.50</b>	<b>-\$15,826,936.50</b>
CASH INFLOW	1	<b>\$3,359,152.09</b>	<b>-\$12,467,784.41</b>	1.085	\$3,095,992.71	<b>-\$12,730,943.79</b>
	2	<b>\$3,359,152.09</b>	<b>-\$9,108,632.32</b>	1.177225	\$2,853,449.50	<b>-\$9,877,494.29</b>
	3	<b>\$3,359,152.09</b>	<b>-\$5,749,480.23</b>	1.277289125	\$2,629,907.37	<b>-\$7,247,586.92</b>
	4	<b>\$3,359,152.09</b>	<b>-\$2,390,328.14</b>	1.385858701	\$2,423,877.76	<b>-\$4,823,709.15</b>
	5	<b>\$3,359,152.09</b>	\$968,823.94	1.50365669	\$2,233,988.72	<b>-\$2,589,720.43</b>
	6	<b>\$3,359,152.09</b>	\$4,327,976.03	1.631467509	\$2,058,975.78	<b>-\$530,744.65</b>
	7	<b>\$3,359,152.09</b>	\$7,687,128.12	1.770142247	\$1,897,673.53	\$1,366,928.88
	8	<b>\$3,359,152.09</b>	\$11,046,280.21	1.920604338	\$1,749,007.86	\$3,115,936.75
	9	<b>\$3,359,152.09</b>	\$14,405,432.30	2.083855707	\$1,611,988.81	\$4,727,925.56
	10	<b>\$3,359,152.09</b>	\$17,764,584.39	2.260983442	\$1,485,703.98	\$6,213,629.54
	11	<b>\$3,359,152.09</b>	\$21,123,736.48	2.453167034	\$1,369,312.42	\$7,582,941.96
	12	<b>\$3,359,152.09</b>	\$24,482,888.57	2.661686232	\$1,262,039.10	\$8,844,981.05
	13	<b>\$3,359,152.09</b>	\$27,842,040.66	2.887929562	\$1,163,169.67	\$10,008,150.73
	14	<b>\$3,359,152.09</b>	\$31,201,192.75	3.133403575	\$1,072,045.78	\$11,080,196.51
	15	<b>\$3,359,152.09</b>	\$34,560,344.84	3.399742879	\$988,060.63	\$12,068,257.14
	PBP	4.71	years			
	NPV	<b>\$12,068,257.14</b>				
	IRR	<b>20%</b>				

The model estimates a PBP period of a little under five years: an impressive turnaround regarding the scale of the proposal, a positive NPV of \$12,068,257.14 after the estimated life span, indicating to wealth generation, and an IRR of 20%, more than twice the discount rate as seen in Fig Figure 7.9:1.

The above model only considered consumption savings in the analysis; if the carbon revenue is included, the NPV and IRR become \$17,643,617.74 and 25%, respectively, with a PBP period of 3.9 years.

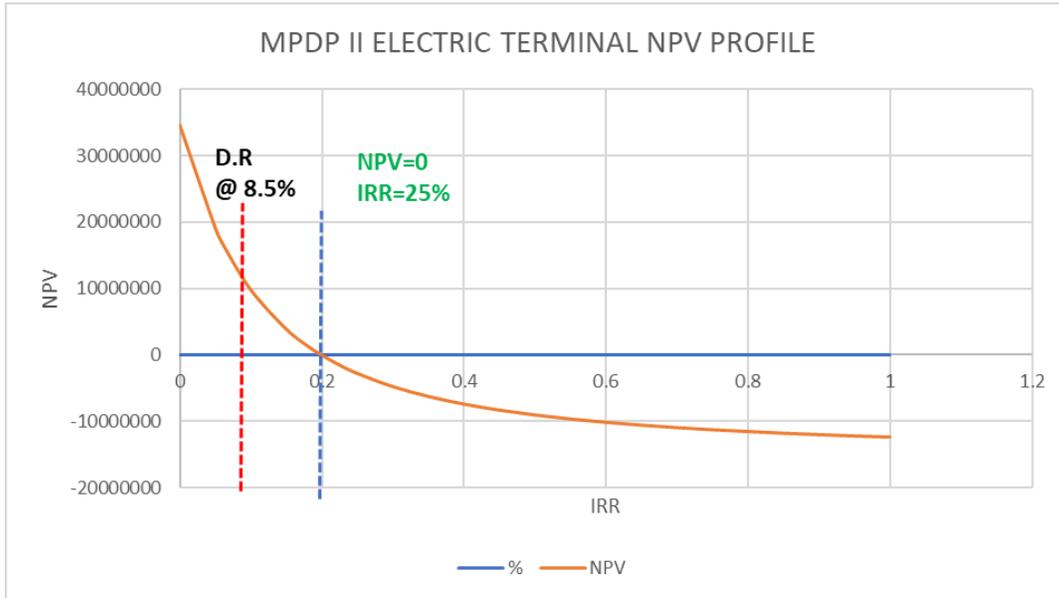


Figure 7.8:3 MPDP II NPV profile Source: Author

The above assessment metrics indicate to a viable proposal with considerable potential; this is further emphasized when using Monte Carlo simulation: the NPV could be observed between the 50 and 70 percentiles of a 10000 trial simulation as illustrated in Figure 7.9:2 The sensitivity analysis determined the project interest rate to be the significant contributor to cost variance as seen in Figure 7.9:3.

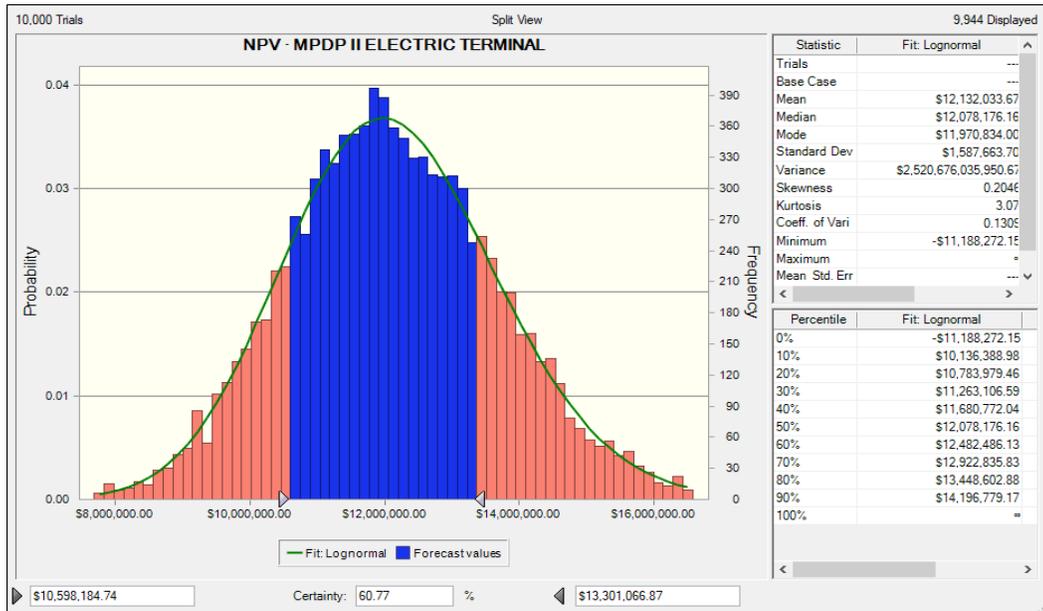


Figure 7.8:4 NPV probability curve indicating the likelihood of occurrence; generated using crystal ball monte Carlo simulation.

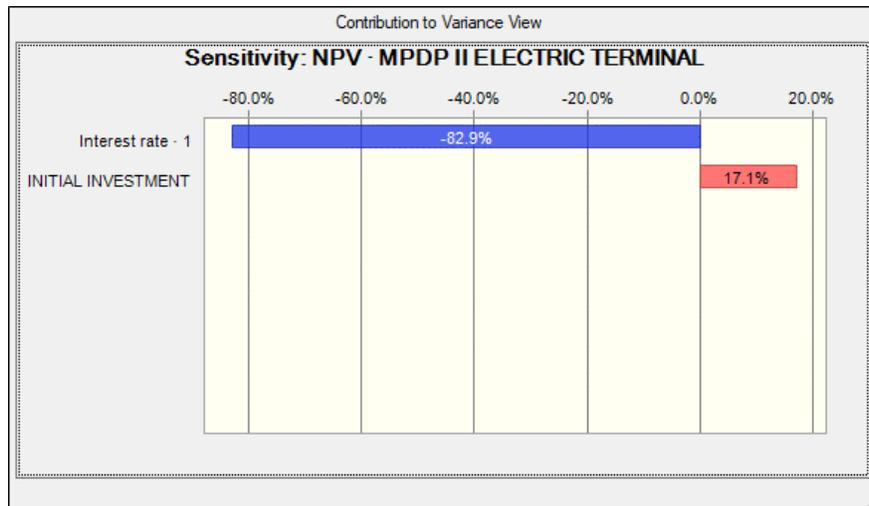


Figure 7.8:5 NPV sensitivity analysis.

From the above analysis, Electrification of the port terminal proves to be an attractive investment to undertake.

## 7.9 SWOT Analysis:

The sections above highlighted how electrifying KPA container terminals could be achieved and the resultant benefits to be gained; however, a holistic analysis is required to inform the development strategies by better understanding the strengths, weaknesses, opportunities, and threats associated with the proposal. Table 7.19 summarizes assessments from the perspectives mentioned above.

Table 7.9:1 SWOT Analysis of Port Electrification

Strength	Weaknesses
<ul style="list-style-type: none"> <li>• Environmental sustainability: through reduction of GHG emissions, air pollution, and noise.</li> <li>• Cost savings: through reduction of fuel consumption.</li> <li>• Operational efficiency: through reduced downtime from equipment.</li> <li>• Improved public health: through the reduction of harmful air pollutants</li> <li>• Increases Reputation: Electrification denotes an environmentally responsible and socially conscious organization.</li> </ul>	<ul style="list-style-type: none"> <li>• Capital intensive: upfront costs can be substantial, posing a financial challenge for the Authority</li> <li>• Infrastructure Requirements: the proposal necessitates significant terminal modifications to accommodate electric equipment and charging stations</li> <li>• Technical Challenges: electrification comes with different technical requirements, which may require capacity building, potentially leading to change resistance</li> <li>• Power supply reliability: unreliable power supply from the Grid may severely hinder operations that may lead to inefficiencies and revenue loss</li> </ul>

Opportunities	Threats
<p>Competitive advantage: electrification can attract customers who prioritize sustainability, thus gaining a competitive edge.</p> <p>Partnership and collaboration: cooperation with various technology and government agencies can lead to innovations and funding opportunities</p> <p>Incentives: The electrification proposal can be leveraged to gain incentives from international and national stakeholders in the form of tax breaks and grants for the implementation of the project</p>	<p>Cost Overruns: unforeseen expenses during implementation can lead to overutilization of funds.</p> <p>Energy prices Volatility: fluctuation of energy prices can affect long-term savings associated with electrification</p> <p>Market resistance: concerns about increased cost of operations or operational disruption due to electrification can potentially affect market acceptance.</p>

Source: Author

## CHAPTER 8: CONCLUSION AND RECOMMENDATION:

This research explored the technological maturity of electrifying port operations by assessing zero-emission CHE and renewable energy technology. It assessed the

feasibility of adopting the measures through quantitative analysis of energy requirements, emission reduction potential, and consumption cost reduction by establishing a business-as-usual baseline and simulating different scenarios of electrification levels at the KPA Container terminal. It also assessed the associated cost of implementation by creating a conceptual terminal model and conducting a financial analysis using analytic indices of PBP, NPV, and IRR, then finalized by conducting a sensitivity analysis of the financial indices using Monte Carlo simulation. Through the process, the following conclusions and recommendations were reached.

### 8.1 Conclusion:

Electrification of seaports as part of the transition to a sustainable maritime Industry addresses the over-dependence of fossil-based energy at the port facility; the solution has proven to be the most effective technical measure for decarbonizing on-land port operations through emission reduction and energy efficiency additionally, as an abatement measure it has demonstrated immense potential to increase environmental, social, and economic sustainability, which grants the port facilities their social license to operate while adhering to global sustainable development goals.

This study subtly contrasts using Grid and renewables as an alternative to fossil fuels, granted all applications are context-specific; however, using renewable power sources has shown the most significant emissions reduction potential and cost-effectiveness when comparing grid-powered ERTGs and Solar energy-powered ETTs. It highlighted that grid-powered equipment is as effective as the grid energy mix.

The different scenarios of KPA electrification highlighted the cost of not acting. The baseline scenario showcased the damage of port operation to immediate communities by determining the annual social cost incurred in public health, granted that funds utilized do not equate to saved lives. Scenario four highlighted the full potential of electrification that resulted in 96% savings on social cost, meaning better public health and fewer premature deaths.

Financial analysis shows that long-term savings can easily offset the Investment Costs, determined by the relatively brief payback period of 4.7 years for electrifying the MPDP II container terminal. Moreover, the project is anticipated to generate wealth for the Authority from the positive NPV and IRR metrics, provided that no disruption occurs in the global maritime supply chain..

While the transition is commendable, it is not without challenges. key barriers include high upfront capital investments, technological gaps in some CHE ,operational disruption , grid reliability concerns, resistance to change and policy or regulatory uncertainties which can significantly hinder rapid uptake of electrification.

Conversely ,Kenya's renewable-rich grid (over 76%) ,the declining costs of solar and storage technologies, existing international practical models ,growing stakeholder demand for cleaner logistics, and strengthened national and international health and environmental regulations are strong drivers that support the adoption of port electrification. Furthermore, this transition will position KPA as an Eco-friendly trade hub, ushering in a new generation of Ports in the region and gaining a competitive advantage.

The findings of this research align with previous studies, which come to a similar deduction on the benefits of electrification, emphasizing the environmental and financial potential of electrification. Although the Studies were conducted in different Contexts, the conclusions are undeniably similar.

Although conclusive, this research was limited to general assumptions due to the solution's novelty and data sensitivity. This consequently led to more questions that might be further explored. The future areas to be studied may include circularity and energy generation to power CHE in ports.

In summation, this study concludes with an assertion of satisfactorily addressing the set objective and research questions by establishing electrification as a viable alternative to fossil fuel with undeniable environmental, social, and economic benefits.

## 8.2 Recommendation:

- **Feasibility Study on Electrification:** The Kenyan Government should undertake a comprehensive feasibility study on electrification to determine the practicality of the solutions and identify the risks associated with undertaking the abatement measure. It should also include a localized study on Social Cost to affirm the actual impact of pollution on the immediate community and port employees. This will emphasize the need to adopt abatement measures like electrification.
- **Incentives and Financial Support:** Sensitivity analysis determined that the discount rate was the primary contributing factor to Capital Cost variance; incentives from the Government in the form of low-interest rates on loans would significantly reduce overall implementation costs.
- **International Collaboration:** this study also urges the Government and relevant Authorities to collaborate with international stakeholders prominent in the electrification fields in developing universal standards that will aid the adoption and integration of the solution. Lack of homogeneity in equipment standards may hinder port decarbonization progress, necessitating a cooperative approach when developing Electric alternatives for CHE.
- **Technical capacity** remains one of the biggest hurdles in combating climate Change. Relevant authorities should put a deliberate effort into building technical and regulatory capacity to ensure that the required expertise is available to address emerging issues in the field from all perspectives.

## References

- A. Rolán, P. Manteca, R. Oktar, & P. Siano. (2019). *Integration of Cold Ironing and Renewable Sources in the Barcelona Smart Port*10.1109/TIA.2019.2910781
- Acciaro, M., & Wilmsmeier, G. (2015). Energy efficiency in maritime logistics chains. *Research in Transportation Business & Management*, (17), 1-7.

- Alamouh, A. S., Ballini, F., & Ölçer, A. I. (2020). Ports' technical and operational measures to reduce greenhouse gas emission and improve energy efficiency: A review. *Marine Pollution Bulletin*, 160, 111508. 10.1016/j.marpolbul.2020.111508
- Alasali, F., Luque, A., Mayer, R., & Holderbaum, W. (2019). A comparative study of energy storage systems and active front ends for networks of two electrified RTG cranes. *Energies*, 12(9), 1771.
- Appuhami, B. (2008). The Impact of Firms' Capital Expenditure on Working Capital Management: An Empirical Study across Industries in Thailand. *International Management Review*, 4(1)
- Beale. (2022). *Battery Charge Time Calculator*. <https://footprinthero.com/battery-charge-time-calculator>
- Bjerkan, K. Y., & Seter, H. (2019). Reviewing tools and technologies for sustainable ports: Does research enable decision making in ports? *Transportation Research Part D: Transport and Environment*, 72, 243-260.
- Burns, R. M., & Walker, J. (1997). Capital budgeting techniques among the Fortune 500: A rationale approach. *Managerial Finance*, 23(9), 3-15.
- CAAP. (2022). *2021 UPDATE: FEASIBILITY ASSESSMENT for CARGO-HANDLING EQUIPMENT*. (). [https://cleanairactionplan.org/wpfd\\_file/2021-cargo-handling-equipment-feasibility-assessment-report-final/](https://cleanairactionplan.org/wpfd_file/2021-cargo-handling-equipment-feasibility-assessment-report-final/)
- Canepa, M., Ballini, F., Dalaklis, D., Frugone, G., & Sciutto, D. (2023). Cold Ironing: Socio-Economic Analysis in the Port of Genoa. *Logistics*, 7(2), 28.
- CBRE. (2023). *2022 Global Seaport Review: Los Angeles/Long Beach, California*. (). <https://www.cbre.com/insights/local-response/2022-global-seaport-review-los-angeles-long-beach>
- Chen, D., Niu, W., Gu, W., & Schofield, N. (2019). Game-based energy management method for hybrid RTG cranes. *Energies*, 12(18), 3589.
- Chen, J., Zheng, T., Garg, A., Xu, L., Li, S., & Fei, Y. (2019). Alternative maritime power application as a green port strategy: Barriers in China. *Journal of Cleaner Production*, 213, 825-837.
- Chen, Z., & Pak, M. (2017). A Delphi analysis on green performance evaluation indices for ports in China. *Maritime Policy & Management*, 44(5), 537-550.
- Claus, Burger, Olivier, Ruelle, , W. L., & , G. S. (2017). HOW TO REDUCE OPEX COSTS FOR RTG TERMINALS. [https://www.porttechnology.org/wp-content/uploads/2019/05/062-064\\_3.pdf](https://www.porttechnology.org/wp-content/uploads/2019/05/062-064_3.pdf)

- Densberger, N. L., & Bachkar, K. (2022). Towards accelerating the adoption of zero emissions cargo handling technologies in California ports: Lessons learned from the case of the Ports of Los Angeles and Long Beach. *Journal of Cleaner Production*, 347, 131255.
- EERE. (n.d). *DETERMINING ELECTRIC MOTOR LOAD AND EFFICIENCY*. (). <https://www.energy.gov/eere/amo/articles/determining-electric-motor-load-and-efficiency>
- EIA. (2022, *Solar energy and the environment*. <https://www.eia.gov/energyexplained/solar/solar-energy-and-the-environment.php#:~:text=Solar%20energy%20technologies%20and%20power,larger%20effects%20on%20the%20environment>.
- EIA. (2023). Solar explained Photovoltaics and electricity. <https://www.eia.gov/energyexplained/solar/photovoltaics-and-electricity.php>
- EPRA. (2023). *Retail Petroleum Prices*. (). <https://www.epra.go.ke/services/petroleum/petroleum-prices/>
- ESPO. (2023, *EcoPorts Green your Port*. <https://www.ecoport.com/>
- ETC/ATNI. (2020). *ETC/ATNI Report 04/2020: Costs of air pollution from European industrial facilities 2008–2017*. (). <https://www.eionet.europa.eu/etcs/etc-atni/products/etc-atni-reports/etc-atni-report-04-2020-costs-of-air-pollution-from-european-industrial-facilities-200820132017>
- GEF-UNDP-IMO. (2018). Port Emissions Toolkit, Guide No. 1, Assessment of Port Emissions. Global Maritime Energy Efficiency Partnerships (GloMEEP) and International Association of Ports and Harbors (IAPH).
- GOV.UK. (2016). *Fuel Conversion Factors*. (). [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment\\_data/file/47732/7309-cca-draft-technical-guidance-app-b.xls](https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/47732/7309-cca-draft-technical-guidance-app-b.xls)
- GVR. (2023). *Rubber Tired Gantry Crane Market Size, Share & Trends Analysis Report By Type (8-wheeler, 16-wheeler), By Power Supply (Diesel, Electric, Hybrid), By Region, And Segment Forecasts, 2018 - 2025*. (). <https://www.grandviewresearch.com/industry-analysis/rubber-tired-gantry-rtg-crane-market>
- Hoang, A. T., Foley, A. M., Nižetić, S., Huang, Z., Ong, H. C., Ölçer, A. I., Pham, V. V., & Nguyen, X. P. (2022). Energy-related approach for reduction of CO2 emissions: A critical strategy on the port-to-ship pathway. *Journal of Cleaner Production*, 355, 131772. 10.1016/j.jclepro.2022.131772

- INITIAL IMO STRATEGY ON REDUCTION OF GHG EMISSIONS FROM SHIPS, MEPC.304(72)Cong. (2018).  
[https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.304\(72\).pdf](https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.304(72).pdf)
- Invitation to Member States to Encourage Voluntary Cooperation between the Port and Shipping Sectors to Contribute to Reducing GHG Emissions from Ships, MEPC 7418 ADD.1.Cong. (2019).
- IMO. (2020). *Fourth IMO GHG Study 2020 Full Report*. (). [https://greenvoyage2050.imo.org/wp-content/uploads/2021/07/Fourth-IMO-GHG-Study-2020-Full-report-and-annexes\\_compressed.pdf](https://greenvoyage2050.imo.org/wp-content/uploads/2021/07/Fourth-IMO-GHG-Study-2020-Full-report-and-annexes_compressed.pdf)
- INAL, O. B. (2023). An Overview of Green Ports and Sustainable Development Goals. Paper presented at the *International Conference on Scientific and Academic Research*, , 1 409-413.
- IndiaMart. (2023, *Schneider Three Phase 3MVA Oil Cooled Distribution Transformer*.  
<https://www.indiamart.com/proddetail/schneider-three-phase-3mva-oil-cooled-distribution-transformer-23057027997.html>
- IPCC. (2022). *Climate Change 2022: Impacts, Adaptation and Vulnerability*. (). Intergovernmental Panel on Climate Change.  
[https://report.ipcc.ch/ar6/wg2/IPCC\\_AR6\\_WGII\\_FullReport.pdf](https://report.ipcc.ch/ar6/wg2/IPCC_AR6_WGII_FullReport.pdf)
- IPCC. (2023). *SYNTHESIS REPORT OF THE IPCC SIXTH ASSESSMENT REPORT (AR6)*. ().  
[https://report.ipcc.ch/ar6syr/pdf/IPCC\\_AR6\\_SYR\\_LongerReport.pdf](https://report.ipcc.ch/ar6syr/pdf/IPCC_AR6_SYR_LongerReport.pdf)
- IRENA. (2023). *ENERGY PROFILE KENYA*. (). [https://www.irena.org/-/media/Files/IRENA/Agency/Statistics/Statistical\\_Profiles/Africa/Kenya\\_Africa\\_RE\\_SP.pdf](https://www.irena.org/-/media/Files/IRENA/Agency/Statistics/Statistical_Profiles/Africa/Kenya_Africa_RE_SP.pdf)
- Iris, Ç, & Lam, J. S. L. (2019). A review of energy efficiency in ports: Operational strategies, technologies and energy management systems. *Renewable and Sustainable Energy Reviews*, 112, 170-182. 10.1016/j.rser.2019.04.069
- Jinko Solar. (2022). *JINKO SOLAR TIGER P TYPE 400W MONO BLACK FRAME*. ().  
[https://solarity.eu/products/solar-panels/jinko-solar/?gclid=EAlaIqobChMI6dPDw8yb\\_glV8wWiAx2nvQYxEAAAYASAAEgJrwfD\\_BwEhttps://solarity.eu/products/solar-panels/jinko-solar/?gclid=EAlaIqobChMI6dPDw8yb\\_glV8wWiAx2nvQYxEAAAYASAAEgJrwfD\\_BwE](https://solarity.eu/products/solar-panels/jinko-solar/?gclid=EAlaIqobChMI6dPDw8yb_glV8wWiAx2nvQYxEAAAYASAAEgJrwfD_BwEhttps://solarity.eu/products/solar-panels/jinko-solar/?gclid=EAlaIqobChMI6dPDw8yb_glV8wWiAx2nvQYxEAAAYASAAEgJrwfD_BwE)
- Kang, D., & Kim, S. (2017). Conceptual model development of sustainability practices: The case of port operations for collaboration and governance. *Sustainability*, 9(12), 2333.
- Kidere, M. M. (2017). Analytical assessment of port energy efficiency and management.: a case study of the Kenya Ports Authority.

- KENYA NATIONAL GRID DISTRIBUTION CODE, (2021). <https://www.epra.go.ke/wp-content/uploads/2021/05/Draft-Kenya-National-Distribution-Grid-Code-KNDGC-30-04-2021-2.pdf>
- KPA. (2022). 2022 Annual Review & Bulletin of Statistics. <http://www.kpa.co.ke/>
- KPA. (2023). *Annual Report and Financial Statements*. (). <https://www.kpa.co.ke/pages/annual-financial-reports.aspx>
- M. Sadiq, S. W. Ali, Y. Terriche, M. U. Mutarraf, M. A. Hassan, K. Hamid, Z. Ali, J. Y. Sze, C. -L. Su, & J. M. Guerrero. (2021). *Future Greener Seaports: A Review of New Infrastructure, Challenges, and Energy Efficiency Measures*10.1109/ACCESS.2021.3081430
- MaritimAfrica. (2019). THE CONCEPT OF “GREEN PORT” IN AN AFRICAN CONTEXT. <https://maritimafrika.com/en/the-concept-of-green-port-in-an-african-context/>
- Martínez-Moya, J., Vazquez-Paja, B., & Gimenez Maldonado, J. A. (2019). Energy efficiency and CO2 emissions of port container terminal equipment: Evidence from the Port of Valencia. *Energy Policy*, 131, 312-319. 10.1016/j.enpol.2019.04.044
- Misra, A., Panchabikesan, K., Gowrishankar, S. K., Ayyasamy, E., & Ramalingam, V. (2017). GHG emission accounting and mitigation strategies to reduce the carbon footprint in conventional port activities—a case of the Port of Chennai. *Carbon Management*, 8(1), 45-56.
- Musyoka, M. D. (2013). Monetary and ecological cost-benefit analysis of onshore power supply: a case study of the port of Mombasa.
- OECD. (2010). *ENVIRONMENTAL IMPACTS OF INTERNATIONAL SHIPPING: A CASE STUDY OF THE PORT OF BUSAN*. (). [https://one.oecd.org/document/ENV/EPOC/WPNEP/T\(2010\)2/FINAL/en/pdf](https://one.oecd.org/document/ENV/EPOC/WPNEP/T(2010)2/FINAL/en/pdf)
- Papaioannou, V., Pietrosanti, S., Holderbaum, W., Becerra, V. M., & Mayer, R. (2017). Analysis of energy usage for RTG cranes. *Energy*, 125, 337-344. 10.1016/j.energy.2017.02.122
- Parhamfar, M., Sadeghkhani, I., & Adeli, A. M. (2023). Towards the application of renewable energy technologies in green ports: Technical and economic perspectives. *IET Renewable Power Generation*,
- PIANC. (2014). *Sustainable Ports: A Guide for Port Authorities*.
- Pietrosanti, S., Alasali, F., & Holderbaum, W. (2020). Power management system for RTG crane using fuzzy logic controller. *Sustainable Energy Technologies and Assessments*, 37, 100639.

- PoAB. (2023, *Port of Antwerp continues to focus on sustainable energy policy.* <https://newsroom.portofantwerpbruges.com/port-of-antwerp-blijft-inzetten-op-duurzaam-energiebeleid>
- POLB. (2021). *Assessment of Public Truck Charging and Fueling Near the Port of Long Beach.* (). <https://polb.com/environment/our-zero-emissions-future/#program-details>
- POLB&POLA. (2021). *2020 ANNUAL REPORT AND 2021 PRIORITIES Technology Advancement Program.* (). <https://sustainableworldports.org/wp-content/uploads/San-Pedro-Bay-Ports-Clean-Air-Action-Plan-2020-Technology-Advancement-Program.pdf>
- PoR. (2022, *T&E study of CO2 emissions in European seaports.* <https://www.portofrotterdam.com/en/news-and-press-releases/te-study-of-co2-emissions-in-european-seaports>
- PortTech. (2023, *Port of Rotterdam increases use of solar power.* Port of Rotterdam increases use of solar power
- PortTechnology. (n.d, n.d). *Port of Rotterdam Authority.* <https://www.porttechnology.org/listings/port-of-rotterdam/>
- Poulsen, R. T., Ponte, S., & Sornn-Friese, H. (2018a). Environmental upgrading in global value chains: The potential and limitations of ports in the greening of maritime transport. *Geoforum*, 89, 83-95. 10.1016/j.geoforum.2018.01.011
- Poulsen, R. T., Ponte, S., & Sornn-Friese, H. (2018b). Environmental upgrading in global value chains: The potential and limitations of ports in the greening of maritime transport. *Geoforum*, 89, 83-95.
- Qaiyum, S., Margala, M., Kshirsagar, P. R., Chakrabarti, P., & Irshad, K. (2023). Energy Performance Analysis of Photovoltaic Integrated with Microgrid Data Analysis Using Deep Learning Feature Selection and Classification Techniques. *Sustainability*, 15(14)10.3390/su151411081
- Roh, S., Thai, V. V., & Wong, Y. D. (2016). Towards Sustainable ASEAN Port Development: Challenges and Opportunities for Vietnamese Ports. *The Asian Journal of Shipping and Logistics*, 32(2), 107-118. 10.1016/j.ajsl.2016.05.004
- SANY. (2023, *SANY TERMINAL TRACTOR SM4600T0BEV.* [https://www.sanyeurope.com/wp-content/uploads/2023/08/SANY\\_Terminal\\_Tractor\\_SM4600T0BEV\\_2-Seiter\\_WEB\\_EN.pdf](https://www.sanyeurope.com/wp-content/uploads/2023/08/SANY_Terminal_Tractor_SM4600T0BEV_2-Seiter_WEB_EN.pdf)
- Söderberg, Peter, Hirvonen, Ari, Salonen, & Heikki. (2017). CARGO HANDLING EQUIPMENT HOW TO REDUCE AIR EMISSIONS . <https://www.porttechnology.org/wp->

[content/uploads/2019/05/074-076\\_Cargo\\_Handling\\_Equipment\\_How\\_to\\_Reduce\\_Air\\_Emissions.pdf](content/uploads/2019/05/074-076_Cargo_Handling_Equipment_How_to_Reduce_Air_Emissions.pdf)

Sugimura, Y. (2023). *Climate Change Countermeasures in Ports Toward Carbon Neutrality: Empirical Analysis and Potential New Countermeasures*. Springer Nature.

TRADING ECONOMICS. (2023). *Kenya Inflation Rate*. (). <https://tradingeconomics.com/kenya/inflation-cpi>

ELECTRICAL TECHNOLOGY and INDUSTRIAL PRACTICE (Producer), & . (2019). *Transformer Sizing*. [Video/DVD] <https://www.youtube.com/watch?v=nxhUgQvdLVQ>

UN SDGs. (2023, *THE 17 GOALS*. <https://sdgs.un.org/goals>

UNCTAD. (2022). *Review of Maritime Transport 2022*. (). [https://unctad.org/system/files/official-document/rmt2022\\_en.pdf](https://unctad.org/system/files/official-document/rmt2022_en.pdf)

UNCTAD. (n.d). Sustainable smart ports for African countries, including Small Island developing States, to “recover better” from COVID-19. <https://unctad.org/project/sustainable-smart-ports-african-countries-including-small-island-developing-states-recover>

UNFCCC. (2015). *The Paris Agreement*. ().

UNFCCC. (2020). *Grid Emission Factor for the Republic of Kenya*. (). [https://cdm.unfccc.int/sunsetcms/storage/contents/stored-file-20201230125121808/ASB0050-2020\\_PSB0055.pdf](https://cdm.unfccc.int/sunsetcms/storage/contents/stored-file-20201230125121808/ASB0050-2020_PSB0055.pdf)

UNHRC. (2019). *Climate change and poverty :Report of the Special Rapporteur on extreme poverty and human rights*. (). [https://www.ohchr.org/sites/default/files/HRBodies/HRC/RegularSessions/Session29/Documents/A\\_HRC\\_29\\_31\\_en.doc](https://www.ohchr.org/sites/default/files/HRBodies/HRC/RegularSessions/Session29/Documents/A_HRC_29_31_en.doc)

Vlahopoulos, D., & Bouhouras, A. S. (2022). Solution for RTG crane power supply with the use of a hybrid energy storage system based on literature review. *Sustainable Energy Technologies and Assessments*, 52, 102351. 10.1016/j.seta.2022.102351

Vujičić, A., Zrnić, N., & Jerman, B. (2013). Ports sustainability: A life cycle assessment of zero emission cargo handling equipment. *Strojniski Vestnik-Journal of Mechanical Engineering*, 59(9), 547-555.

WORLD BANK. (2020). *Economic Analysis of Battery Energy Storage Systems*. (). <https://openknowledge.worldbank.org/server/api/core/bitstreams/74e7025c-ec3c-5c23-8816-1e10d32a327a/content>

Yang, Y., & Chang, W. (2013a). Impacts of electric rubber-tired gantries on green port performance. *Research in Transportation Business & Management*, 8, 67-76.

- Yang, Y., & Chang, W. (2013b). Impacts of electric rubber-tired gantries on green port performance. *Research in Transportation Business & Management*, 8, 67-76. 10.1016/j.rtbm.2013.04.002
- Yu, H., Ge, Y., Chen, J., Luo, L., Tan, C., & Liu, D. (2017). CO2 emission evaluation of yard tractors during loading at container terminals. *Transportation Research Part D: Transport and Environment*, 53, 17-36. 10.1016/j.trd.2017.03.014
- Zack Ruderman. (2022). Do electric yard trucks deliver fleets lower total cost of ownership? <https://www.fleetequipmentmag.com/electric-yard-trucks-cost/>

## Appendices

### 9.1 Appendix 1

```
# Atmospheric data reader WMU 2023 #

from netCDF4 import Dataset

import numpy as np

import matplotlib.pyplot as plt

import netCDF4

f = Dataset('7am to 6pm.nc')

time = f.variables['time']

t_unit =f.variables['time'].units

latitude = f.variables['latitude']

longitude = f.variables['longitude']

solar = f.variables['fdir']

# Create matrix of zeros for variables

Solar=np.zeros((len(time),int(len(latitude)),int(len(longitude))))

dates=netCDF4.num2date(time[:].squeeze(), t_unit, only_use_cftime_datetimes=False,
only_use_python_datetimes=True)
```

```

#Specify location of energy plant
latKPA=-4.07
lonKPA=39.66

Latitude = np.zeros(len(latitude))
Longitude = np.zeros(len(longitude))

for j in range (1, len(Latitude)):
    Latitude[j] = latitude[j]
for j in range (1, len(Longitude)):
    Longitude[j] = longitude[j]

indexLat=np.abs((latKPA-Latitude)).argmin()
indexLon=np.abs((lonKPA-Longitude)).argmin()

# Calculate resultant solar irradiation

Solar = solar[:, 0:int(len(latitude)), 0:int(len(longitude))]/(60*60)

# Visualise the solar
image3=plt.imshow(Solar[12, :, :], extent=[longitude[:].min(), longitude[:].max(),
latitude[:].min(), latitude[:].max()])
plt.colorbar(image3, label='Solar irradiation [W/m2]')
plt.scatter(lonKPA, latKPA, c='r')
plt.xlabel("Longitude")
plt.ylabel("Latitude")

```

```

plt.show()

# Visualise solar irradiation for chosen location
plt.plot(dates,Solar[:,indexLat,indexLon]/1e2, label='Solar irradiation [kW/m2]')
#plt.legend()
plt.xlabel("Time")
plt.ylabel("Solar irradiation [kW/m2]")
plt.grid()
plt.show()

Eta=0.23
Ar=24293.56552
GRID=np.zeros(len(time))      # Battery energy storage system of 1MW/12MWH
Solarpower=np.zeros(len(time))
SolarEnergy=np.zeros(len(time))

for k in range (1, len(time)):

    GRID[k]=200000      #DISCHARGING
    Solarpower[k]=Solar[k,int(indexLat/2),int(indexLon/2)]*Eta*Ar
    SolarEnergy[k]=Solarpower[k]*len(time)

Solarenergy = np.sum(SolarEnergy)
print("Solarenergy", Solarenergy)
#Visualise solar power for chosen location
plt.plot(dates,Solar[:,indexLat,indexLon]/1e6, label='Solar irradiation [kW/m2]')

```

```

plt.plot(dates,np.where(Solarpower < GRID,GRID, np.nan)/1e6 ,label='GRID
[MW]',c='g',linestyle="dashed")

plt.plot(dates,Solarpower/1e6, label='Solar power [MW]')

plt.legend()

plt.xlabel("Time")

plt.ylabel("Solar Power (MW) ")

plt.grid()

plt.show()

plt.scatter(Solar[:,indexLat,indexLon],Solarpower/1e3)

plt.legend()

plt.xlabel("Time")

plt.ylabel("Solar Power (MW) ")

plt.grid()

plt.show()

#save variables data

np.savetxt('solar_KPA_2023_7am to 6pm.txt',Solar[:,indexLat,indexLon], fmt='%10.16f')

np.savetxt('datesatm_solar_KPA_2023_7am to 6pm.txt',dates, fmt='%str')

np.savetxt('Solarpower_KPA_2023_7am to 6pm.txt',Solarpower, fmt='%10.16f')

```