OPTIMAL ENERGY CONTROL OF A RUBBER TYRED GANTRY CRANE WITH POTENTIAL ENERGY RECOVERY

By

SIBONGILE FLORINA PHIRI

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Central University of Technology, Free State

Promoter: Prof. K. Kusakana

Co-Promoter: Dr. B.P. Numbi

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DECLARATION

I, SIBONGILE FLORINA PHIRI, student number , do hereby declare that this research project, which has been submitted to the Central University of Technology Free State, for the degree: Doctor of Engineering in Electrical Engineering, is my own independent work and complies with the Code of Academic Integrity, as well as other relevant policies, procedures, rules and regulations of the Central University of Technology, Free State.

This project has not been submitted before by any person in fulfilment (or partial fulfilment) of the requirements for the attainment of any qualification.

S.F. Phiri Date: 12 August 2021

DEDICATION

Firstly, I would like to thank God for his mercy and blessings that he bestowed upon me throughout this trying time as I was writing this dissertation. I never imagined I would complete this research, as I experienced great challenges, completing this thesis seemed to be a dream that would never become a reality.

Furthermore, I dedicate this research and tribute to my late parents, Mosala Phiri and Masibongile Phiri, for inspiring me to live with purpose and meaning. I promised myself to make you proud with this achievement, wherever you are. I wish you could still be alive today to share the success of my graduation with me.

I am highly indebted to my beloved husband, my greatest gift from God, for his enduring love, for believing in me for so long. I could have never done this without your faith, support, and constant encouragement. I appreciate you for teaching me to believe in myself, in God and in my dreams, your enormous personal sacrifice and unconditional love. I am thankful to have you as my life partner, even though I have been an absent wife, still you took the burden of taking care of our family in my absence.

Wholeheartedly to my son, for your patience and understanding. I have spent much time away and you never complained, hence the encouragement I got from you to achieve my academic goals, as well as your lifetime benefit. You shall forever be my continuous source of pride and enlightenment.

I would certainly not miss mentioning my siblings, for it is your support and encouragement that saw me through this dissertation, thank you very much for being there for me during my research.

To my mother-in-law Mamphepi Masupha, thank you a thousand times for being there for me when I needed your support, Mom. I am extremely grateful to have you in my life. I am deeply indebted to you.

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Last, but not least, I would like to sincerely thank those who could not be mentioned here, however, played a role towards the completion of this dissertation. Your support did not go unnoticed.

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ABSTRACT

Seaports and rail terminals use Rubber Tired Gantry (RTG) to organise container aisles, loading, and moving cargo-containers. They operate as the link between the cranes and the means of transportation by road, rail, or sea connections. The handling of containers and the motion of RTG cranes are powered by electric motors, which are powered mainly by two sources, namely the standalone diesel powered and the grid connection from the local electrical network.

Looking at an operation efficiency and energy management's point of view, the main problem occurring in RTG crane system, is that the majority of electrical energy or fuel consumed comes from hoisting containers with different weights to several heights; additionally, the peak demand increases when the RTG crane handles heavier containers. Furthermore, during the lowering phase of the containers, potential power is dissipated as heat through resistor banks, used for braking purposes.

To solve these problems, this work developed optimal energy management models of the proposed hybrid diesel/battery and hybrid grid/battery RTG cranes, respectively, to minimize the total electricity costs.

The first model was based on the optimal energy management model for a RTG crane, supplied by a hybrid diesel generator/battery system. The aim of the model is to reduce the energy cost spending and CO_2 emission, by minimizing the amount of fuel consumed by the diesel generator and maximizing the potential energy recovered through the regenerative braking during the container lowering phase. As a case study, a 40 tonne RTG crane, operating in South Africa, has been selected. The demand profile, size of the diesel generator, as well as the battery storage system are used as input for the developed model. Simulations, for a complete RTG handling cycle, have been conducted, to evaluate the techno-economic performances of the developed model use, to optimally dispatch the power flow in the system during the different phases of operation.

As compared to the baseline case, where the diesel generator is used alone to accommodate the same demand, the simulation results for the selected day of operation have shown that, using the proposed model, a 40.6% reduction in the operation cost, as well as CO2 emission, is achievable in the case of the proposed system, without energy recovery; 82.17% is achievable in the case where the energy recovery is included. Looking further into the stochastic nature of the demand, the analysis of a year of operation has revealed that 76.04% in operation costs may be potentially saved, using the proposed system. The result of the true payback period analysis has shown that the overall investment cost may be recovered in 1.36 years. Additionally, it may be observed, from the results, that the peak power demand on the diesel generator, has been reduced. This may assist in reducing the power rating and the initial cost of the diesel generator.

The second model was based on the optimal energy management model for the grid powered electric RTG, with a battery storage system. The aim of the model is to reduce the operation cost, by minimizing the component linked to the maximum demand charges from the grid, as well as the component linked to the Time of Use (ToU) pricing structure. As a case study, a RTG crane operating in South Africa, has been selected. The load profile, the battery storage system, ToU tariff, as well as the maximum demand charges, are used as input for the developed model. Simulations, for a complete RTG handling cycle, have been conducted, to evaluate the techno-economic performances of the developed model, used to optimally dispatch the power flow in the system during the different phases of operation. Three main configurations have been simulated as energy sources for the RTG crane, namely, the exclusive supply from the grid, grid/battery hybrid system without energy recovery during the lowering phase and grid/battery hybrid with energy recovery, during the lowering phase.

As compared to the baseline, the simulation results have shown that, using the proposed model, a possible 50.36%, 60.6% and 64.4% cost reduction, per full handing cycle, is possible in off-peak standard and peak pricing period, for the selected winter day. Table 2 further shows that the maximum demand charges, for a full load in any of the pricing periods is USD 2 639.39, when the baseline is considered. This may be reduced by 45.20%, to USD 1446.24, when the RTG crane is supplied by the optimally controlled hybrid system, with energy recovery.

The yearly analysis has revealed that the break-even point of the proposed optimally controlled hybrid grid/Battery, with energy recovery, suppling the RTG crane, may take place after 1.36 years, corresponding to USD 121 900. For the 20 years' project lifetime, the computed lifecycle, in the case of the proposed optimally controlled grid/Battery with energy recovery, is USD 1 425 000. However, when solely the baseline is considered, the projected lifecycle cost is USD 5 384 000. There is a potential cost saving of USD 3 950 000, corresponding to 73.53%. The result of the true payback period analysis has shown that the overall investment cost may be recovered in 1.716 years. Additionally, using the proposed system, the peak power demand on the grid has been reduced. This may assist in reducing the size of the inverter by more than 50%, which may lower the initial cost of the system.

These results further demonstrate that, using the proposed optimal control models, the peak power demands on the grid, or on the DG, have been reduced. This may assist in reducing the size of the inverter, or of the DG by more than 50%, which may lower the initial cost of the system. This, in turn, serves as a greater incentive for seaports and rail terminals to implement these energy management strategies, reducing their operating cost and increasing their benefits.

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LIST OF ABBREVIATIONS

AC	Alternating Current
ANN	Artificial Neural Network
ARIMAX	Autoregressive Integrated Moving Average
CO_2	Carbon Dioxide
DC	Direct Current
DG	Diesel Generator
DSM	Demand Side Management
EMS	Energy Management System
ESS	Energy Storage System
FC	Fuel Cell
FESS	Flywheel Energy Storage System
FLC	Fuzzy Logic Controller
GA	Genetic algorithm
GBC	Game-Based Controllers
IEEE	Institute of Electrical and Electronic Engineers
IPOPT	Interior Point OPTimizer
KERS	Kinetic Energy Recovery System
KVA	Kilovolt-Ampere

KWH	Kilowatt-Hour
LCC	Lifecycle cost
LMI	Linear-Matrix-Inequality
MAPE	Mean Absolute Percentage Error
MATLAB	Matrix Laboratory
MPC	Model Predictive Control
OF	Objective Function
OPTI	Optimization
PBP	Payback Period
PMS	Power Measurement System
POET	Performance, Operation, Equipment and Technology Efficiency
POF	Port of Felixstowe
RTG	Rubber Tired Gantry
SCs	Supercapacitors
SMPC	Stochastic Model Predictive Control
SOC	State of Charge
STS	Ship to Shore
TOU	Time-of-Use
UC	Ultracapacitor
UK	United Kingdom

USD	United States Dollar
VFD	Variable Frequency Drive
VSDG	Variable Speed Diesel Generator
VSG	Variable Speed Generation

CHAPTER I: INTRODUCTION

1.1. BACKGROUND

To cater for the growing world seaborne transport sector, harbours should enhance the efficiency of their handling and transfer infrastructure, in terms of the performance, operation, equipment and technology. Terminals use Rubber Tired Gantry (RTG) to organise container aisles, loading and moving cargo-containers. They operate as the link between the cranes and the means of transportation by road, rail, or sea connections [1].

RTGs' operation may be summarised into three essential movements [2]:

- Hoisting and lowering the spreader, with or without the load.
- Moving the trolley, left and right, with or without the load.
- Gantry movement, to move the entire RTG crane.

The handling of containers and the motion of RTG cranes are powered by electric motors. For example, RTG cranes at the Durban Container Terminal, South Africa, operate daily, up to 24 hours, 362 days a year continuously [1]. This means that a substantial amount of electrical energy is consumed. There are two main types of RTG cranes, namely the standalone diesel powered, and the grid connected types.

1.1.1. Diesel RTG cranes

In cases where the utility grid is well established and reliable, RTGs are directly supplied from the grid. However, in cases where the grid is unreliable or cannot adequately respond to the RTG's load demand (when electrical grid is weak, or not available and requires a cable reel, a feeding cable, and a transformer; feeding electricity from the grid to the crane is avoided), diesel generators (DGs) are used as the preferred alternative power source. This said, the majority of RTG cranes are powered by DG, with power ratings of 410 kW and a fuel consumption of 14 L per hour, emitting close to 36.96 kg CO_2/hr, which represents approximately 20% of diesel fuel emissions from cargo handling equipment at ports [3].

Diesel powered RTGs use constant-speed diesel generators to supply the electrical power required for the various handling operations performed by the cranes, as well as by the auxiliary equipment, such as lights and air conditioning used by the operator's control house [4]. However, the drawback of constant-speed DGs, is that they operate at a constant speed, irrespective of the change in magnitude of the load they are supplying [5]. Therefore, in instances where the RTG is idle or operating in a phase where less power is required, the DG runs at a significantly low load factor, resulting in a significantly high specific fuel consumption, translated in an important amount of diesel fuel wasted and a high quantity of pollutant gases are emitted [6].

Various authors have analysed the operation of diesel-powered RTGs on an operation efficiency and energy management's point of view and the results have shown, in general, that RTG cranes are operated inefficiently, due to several factors, such as:

- The RTG cranes are not powered down when idle, or when the lifting phase is not performed. Therefore, a constant-speed DG runs at an unnecessarily high speed when idling, resulting in high fuel consumption and excessive CO_2 emissions [7].
- The need for peak power on an RTG's diesel engine, exists solely for 4% of the total handling cycle's period [8].
- Due to the stochastic nature of the containers' weight to be handled, the diesel generators supplying RGT cranes often work with an output power below their rated capacity. Therefore, their specific fuel consumption is high, as with any DG operating at a low-load factor, which has a direct effect on the operation cost, since more fuel is used [9].
- The power from the lowering phase is dissipated as heat through resistor banks, used for braking purposes [10].

1.1.2. Electric grid powered RTG cranes

Diesel-powered RTG cranes are dominating the sector, as opposed to electric powered cranes [7]. However, the high operating costs, pollution, and noise emissions, associated with the use of diesel-powered RTG cranes, are steering harbours towards replacing these cranes with electric RTG cranes, with less negative impacts on the environment and operate on higher energy efficiency, as mentioned earlier in [6]. According to Naicker and Allopi [1], the use of electrical, compared to diesel-powered RTGs, may reduce the pollutant emissions by 60–80%, the operation costs by 50% and the maintenance costs by approximately 30%. In ports, during various handling cycles on the electric powered RTG cranes, significant peak power demands are drawn from the grid, which lead to high maximum demand charges and in the worst case, could result in a momentary power cut in the considered port terminal. Therefore, the traditional way of solving this problem, is the reinforcement of the electrical infrastructure in the port, by upgrading the cables, transformers, and substations; however, this is particularly costly [11].

1.1.3. Hybrid retrofitted RTG cranes with energy storage systems

During the lowering phase, the hoisting motor is not operational, as the lowering movement is driven by the weight of the load. Therefore, the movement has the potential to produce electricity, with a regenerated power close to 60% of the peak power supplied to the RTG crane's demand; the power regeneration phase laps between 30 to 40% of a full handling cycle's duration [12].

One way of harvesting the energy from an RTG crane's lowering phase, is by using the regenerative braking method, where the potential energy from the container moving down is used to run the hoisting motor in a generator mode and produce electricity. This regenerative energy is harvested, stored in a medium, such as flywheel [13], fuel cell [14], supercapacitor [15-16] or battery and may later be used to reduce the power demand on the supply, during the subsequent RTG's hoisting and trolley moving phases.

1.2. PROBLEM STATEMENT

Looking at an operation efficiency and energy management's point of view, the main challenge occurring in the RTG crane system is that the majority of electrical energy or fuel used, stems from hoisting containers with various weights to several heights. Additionally, the peak demand increases when the RTG crane handles heavier containers. Furthermore, during the lowering phase of the containers, potential power is dissipated as heat through resistor banks, used for braking purposes.

In hindsight, the following prominent sub-problems were identified:

- Sub-problem 1: Diesel RTG cranes are not powered down when idle, or when the lifting phase is not performed. Therefore, a constant-speed DG runs at an unnecessarily high speed when idling, resulting in high fuel consumption and excessive CO_2 emissions and the need for peak power on an RTG's diesel engine, exists solely for 4% of the total handling cycle's period [13-14]. Due to the stochastic nature of the containers' weight to be handled, the diesel generators, supplying RGT cranes, often operate with an output power below their rated capacity. Therefore, their specific fuel consumption is high, as with any DG operating at a low-load factor, which has a direct effect on the operation cost, since more fuel is used [16-18].
- Sub-problem 2: Throughout various handling cycles on the electric powered RTG cranes, in addition to the energy cost, significant peak power demands are drawn from the grid, which leads to maximum demand charges which, in the worst case may result in a momentary power cut in the considered port terminal. Therefore, the traditional way of solving this problem, is the reinforcement of the electrical infrastructure in the port, by upgrading the cables, transformers, and substations. However, this is particularly costly [11].
- Sub-problem 3: The use of storage systems may result in a decrease of the energy charges, reduce the peak demand and its associated maximum demand charges, as well as levelling the demand profile. However, the resultant operation efficiency is

not solely based on the equipment or technology used. Therefore, given the stochastic nature of the load to handle, the RTG crane with a storage system, achieves a low operation efficiency, when not optimally managed.

1.3. OBJECTIVES

The aim of this work was the development of optimal energy management models of the proposed hybrid diesel/battery and hybrid grid/battery RTG cranes, respectively, to minimize the total electricity costs. Therefore, to achieve this aim, the objectives were as follows:

- To conduct a review of available literature on diesel and electric RTG cranes based on the Performance, Operation, Equipment and Technology (POET) framework.
- To develop an optimal energy management model for the RTG, supplied by a hybrid diesel/battery system. The aim of the model is to reduce the energy cost spending, by minimizing the amount of fuel consumed by the DG and maximizing the potential energy recovered through the regenerative braking that takes place during the lowering phase.
- To develop an optimal energy management model for the RTG supplied by a hybrid grid/battery system. The aim of the model is to reduce the operational cost, by minimizing the maximum demand charges from the grid, as well as the resultant energy charges linked to the Time of Use (ToU) pricing structure.
- To conduct techno-economic analyses, comparing the performances of the proposed hybrid diesel/battery and hybrid grid/battery RTG cranes to their respective baselines, for the same operating conditions.

1.4. RESEARCH METHODOLOGY

To achieve the objectives of the study, the methodology is as follows:

- Literature review: A thorough review of literature, performance, operation, equipment, and technology related to RTG cranes, has been conducted. This review included the types of RTG cranes, controls strategies, type of energy storage used for retrofitting as energy recovery, as well as the artificial intelligence techniques applied to the RTG optimal operation control.
- System variables identification: The first system consists of hybrid diesel/battery system supplying a RTG crane with energy recovery (Model 1), while the second system consists hybrid grid/battery system supplying a RTG crane with energy recovery (Model 2). Optimal energy management models were developed and applied to these models, to reduce their total energy charges, respectively. The independent variables, the control variables as well as state variables are identified and included in the respective developed models.
- Data collection (input variables) and case study:
  - The maximum weight of the container to be handled, which influences the demand in kW, the amount of energy recovered, as well as the duration of the cycle, has been collected from a 40-tonne crane manufactured by "Konecranes". This data was previously validated by other studies available in the literature.
  - The diesel generator characteristics, as well as fuel cost.
  - The battery characteristics.
  - The maximum demand charges, as well as ToU tariff.
  - The case study is based on the operating condition in the Durban harbour, in South Africa.
- Models' development: The different steps in developing the optimal energy management models for the proposed RTG cranes, are shown in Figure 1.1: These models were developed using MATLAB software.

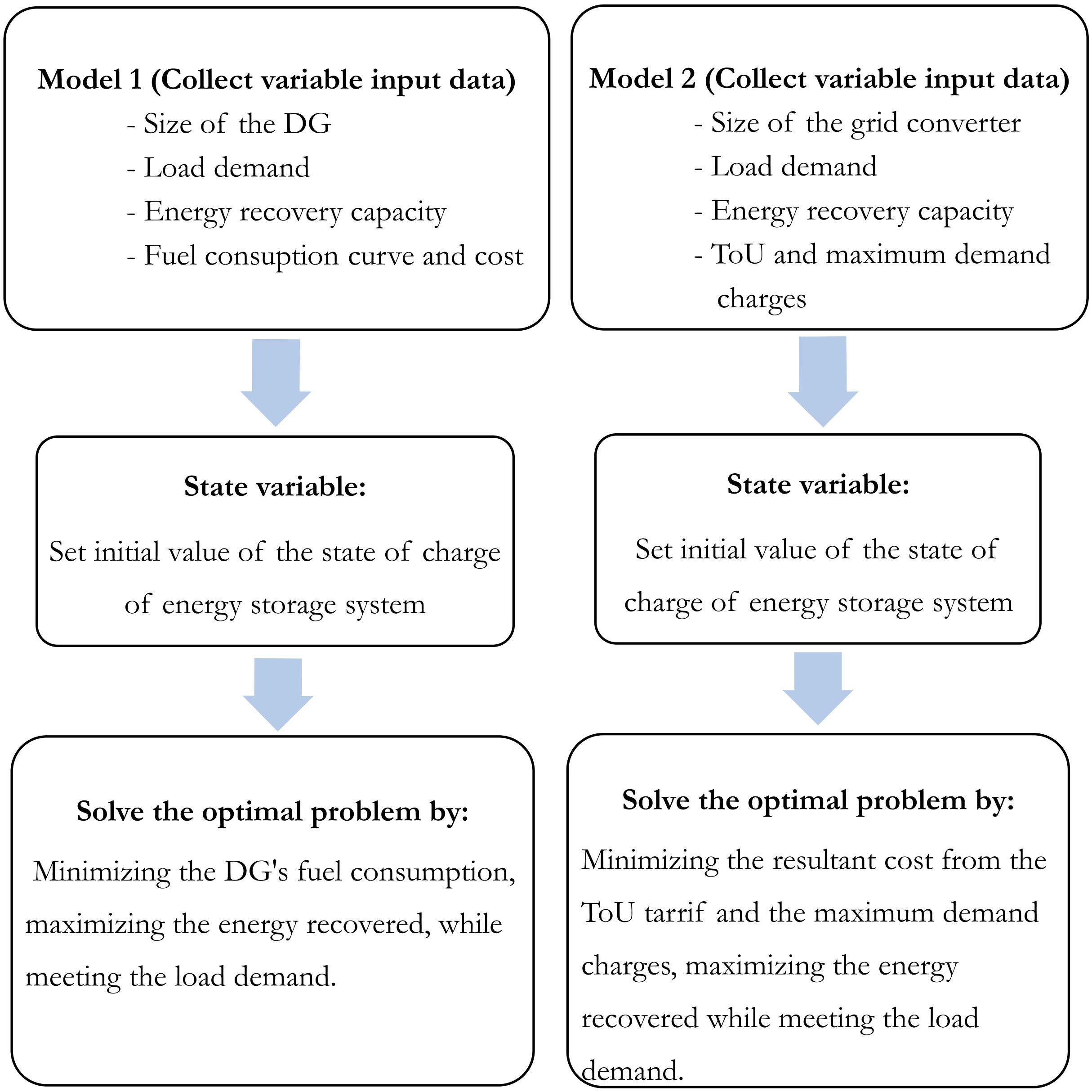

Figure 1.1: Flowchart of methodology and research design

- Due to the quadratic nature of the DG's fuel consumption curve, as represented in the objective function, as well as the restricted power flows, the optimization problem of Model 1 is of a non-linear nature, which may be solved using "fmincon", in the OPTI-toolbox of MATLAB [19].
- Based on the maximum demand, as well as the exclusive nature of the power flows developed in the model, the problem to solve is of a nonlinear optimization nature, the optimization problem of Model 2 may be solved using the Interior Point OPTimizer (IPOPT), in the OPTI-toolbox of MATLAB [20].

- Simulation results and discussion:
  - For the hybrid diesel/battery system supplying the RTG crane, simulations are conducted to evaluate the effectiveness of the proposed optimal energy management model, applied to the battery integrated DG supplying the RTG crane's demand, with regenerative energy capabilities, for a full load cycle. Three main scenarios are simulated and discussed. These are the RTG crane's demand, supplied solely by the DG (Baseline), the RTG crane's demand, supplied by the battery integrated DG system and the RTG crane's demand, supplied by the battery integrated DG, with energy recovery through regenerative braking. The simulation results are further analysed in terms of the economic and environmental performance of the optimally controlled battery integrated DG system, supplying the RTG crane.
  - For the hybrid grid/battery system supplying a RTG crane with energy recovery, simulations are conducted, to evaluate the effectiveness of the proposed optimal energy management model, applied to the grid powered RTG crane's demand, equipped with a battery storage system and regenerative energy capabilities, for a full load cycle. Three main scenarios are simulated and discussed; are the grid powered RTG crane (Baseline), grid powered RTG crane with a battery storage system without energy recovery and the grid powered RTG crane with a battery storage system, with energy recovery through regenerative braking. The simulation results are further analysed, in terms of the economic performance of

the optimally controlled grid powered RTG crane, with battery storage system and energy recovery capabilities.

1.5. CONTRIBUTIONS TO KNOWLEDGE

As compared to the various research currently available on the energy management of hybrid RTG cranes, the key contributions of this work are:

- Most studies have used control techniques, such as closed-loop PI controller and set-point control (SoC, power, voltage, or frequency), to manage the operation of RTG cranes. Studies focussing on power management systems were limited to the use of optimization algorithms, such as Genetic Algorithm, Fuzzy Logic and Game-based controllers. However, the current work uses a deterministic non-linear optimization approach to solve the power dispatch problem and minimize the energy cost resulting from operating the system.
- Available studies, based on hybrid diesel/battery RTG cranes' energy management, predominantly focus on diesel fuel savings, limiting their analysis on the energy cost for a cycle or day. The current study goes beyond the cost saving, performing a lifecycle cost analysis to assess the payback period and the breakeven point achieved when comparing the proposed optimally controlled system, with the DG solely used as the baseline.
- From the available studies, there is a lack of work combining the cost saving of grid powered RTG cranes with a battery, based on the maximum demand charges, as well as the time of use pricing structure. These two cost components will be included in the model developed in this work.
- In this work, the stored energy recovered from the lowering of the containers is optimally dispatched, reducing the peak power and energy required from the DG or the grid. This aspect was not considered in the majority of the works available in the literature.

1.6. HYPOTHESIS

- The implementation of the optimal energy management model applied to the hybrid DG/battery RTG crane, will reduce the operation cost, the amount of CO_2 emitted, as well as the peak power demand on the DG.
- The implementation of the optimal energy management model applied to the hybrid grid/battery RTG crane, will reduce the operation cost, as well as the peak power demand on the grid.

1.7. DELIMITATION

The study was conducted with the following limitations:

- In relation to the battery and DG's sizing, modern, advanced, and accurate metaheuristic or deterministic optimization methods have been successfully used to solve optimal sizing problems of hybrid energy systems. Therefore, this work does not deal with the optimal sizing of the proposed system.
- In relation with the energy storage system, solely the battery is considered. Further storage systems such as flywheel, fuel cell or supercapacitor, are not considered.
- In relation to the energy management approach, solely the open-loop optimal energy management was considered.
- In relation to the load demand, the energy required for the gantry movement is not considered, as it is a minimal part of the total energy demand.

1.8. PUBLICATIONS DURING THE STUDY

Conference papers:

- Phiri, S. F., K. Kusakana, and B. P. Numbi. “Optimal Energy Control of a Rubber Tyre Gantry with Potential Energy Recovery”. In 2018 *Open Innovations Conference (OI)*, pp. 124-128. IEEE, 2018.
- Phiri, S. F. and K. Kusakana. “A review of Rubber Tyred Gantry cranes energy efficiency improvements based on energy monitoring, energy storage systems and optimal operation control strategies”. *Submitted.*

Journal articles:

- Phiri, S. F., K. Kusakana, and B. P. Numbi. “A survey of technical efficiency in crane systems using POET structure”. In *Journal of Physics: Conference Series, vol. 1577, no. 1, p. 012037*. IOP Publishing, 2020.
- K. Kusakana, Phiri, S. F. and B. P. Numbi. "Optimal energy management of a hybrid diesel generator and battery supplying a RTG crane with energy recovery capability." *Energy Reports* 7 (2021): 4769-4778.

1.9. THESIS LAYOUT

This thesis has been divided into five chapters.

Chapter I presents the background of the work, the problem statement, aim and objectives, methodology, contributions to knowledge, hypothesis, as well as delimitations of the study.

Chapter II reviewes the available literature published on the efficiency improvement of RTG cranes, including the general operation and main components of a RTG crane, the energy monitoring of RTG cranes during their operations, the different energy storage systems used in retrofitting RTG cranes, as well as the different strategies and algorithms used for the optimal control and energy management of RTG cranes.

Chapter III describes the development of an optimal energy management model, as well as the technical and economic simulations conducted for the RTG supplied by a hybrid DG/battery system, to reduce the energy cost spending and CO_2 emissions, by minimizing the amount of fuel consumed and maximizing the potential energy recovered through the regenerative braking taking place during the lowering phase.

Chapter IV describes the development of an optimal energy management model for the grid powered electric RTG, with a battery storage system. The aim of the model is to reduce the operation cost, by minimizing the component linked to the maximum demand charges from the grid, as well as the component linked to the Time of Use (ToU) pricing structure.

Chapter V concludes the work of this thesis and sets the stage for future studies.

CHAPTER II: A REVIEW OF RUBBER TYRED GANTRY CRANES ENERGY EFFICIENCY IMPROVEMENTS BASED ON ENERGY MONITORING, ENERGY STORAGE SYSTEMS AND OPTIMAL OPERATION CONTROL STRATEGIES

2.1. INTRODUCTION

In this Chapter, the available literature published on the efficiency improvement of RTG cranes are reviewed and discussed. These studies are related to performance, operation, equipment, or technology efficiency of RTG cranes. The layout of this Chapter is as follows: Section 2.2 describes the general operation and main components of a RTG crane; Section 2.3 looks at the energy monitoring of RTG cranes during their operations; Section 2.4 presents the different energy storage systems used in retrofitting RTG cranes; Section 2.5 reviews the different strategies and algorithms used for the optimal control and energy management of RTG cranes and Section 2.6 outlines the key findings on reviewed literature.

2.2. GENERAL DESCRIPTION OF THE RTG CRANES

Seaports and rail terminals use RTG cranes to organise container aisles, loading, moving cargo-containers and they operate as the link between the cranes and the means of transportation by road, rail, or sea connections [1]. Using Figure 2.1, the RTGs' operation may be summarised into three essential movements [2]:

- Hoisting and lowering the spreader, with or without the load.
- Moving the trolley, left and right, with or without the load.
- Gantry movement, to move the entire RTG crane.

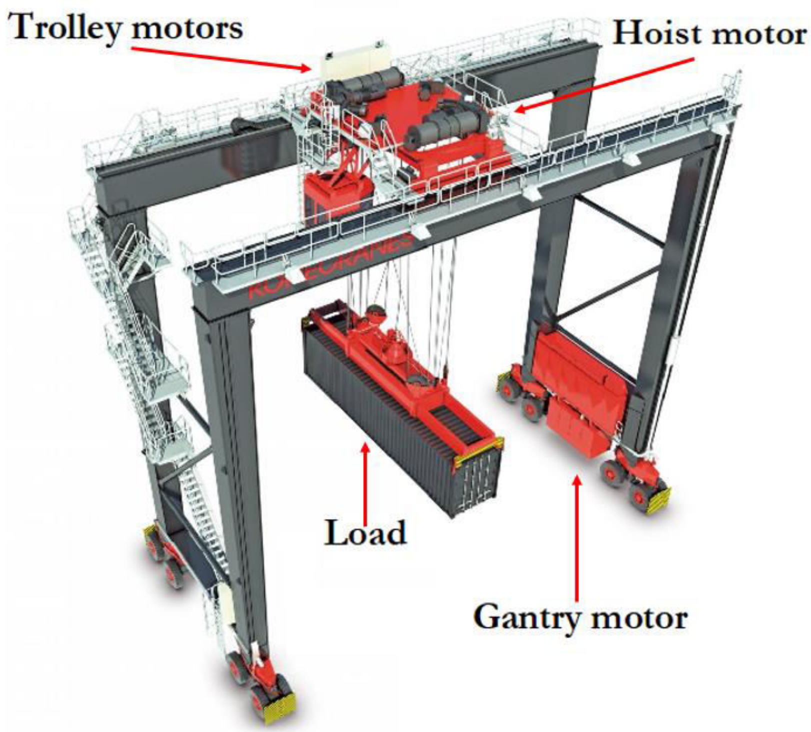

Figure 2.1: RTG crane motors and movements

Most of the energy needed by RTG cranes is in response to the demand from the electric motors (trolley, the gantry, and the hoist motors), used for the different movements described above. The electrical energy is primarily supplied to the various motors from diesel generators or from the electrical grid. This energy is converted from AC to DC by a rectifier and then fed to a DC bus. The voltage of the DC bus varies, depending on the operation phase; decreasing during the lifting or when the trolley motors are used and increasing during the regenerative braking phase, occurring when the load is lowered. The energy regenerated during the lowering of the load is fed into the DC bus, allowing other electric motors to use part of the recovered energy. The surplus of energy may be dumped into the brake resistors [21], fed into the load grid [22] or stored into a suitable medium, depending on the configuration available [23]. The two configurations will be the focus of Chapter 3 and Chapter 4, respectively.

2.3. RTG CRANES ENERGY USAGE MONITORING AND FORECASTING

The load demand is highly non-linear, as it depends on the weight of the load to be handled. Analyses on RTG cranes' energy usage, as well as the approximate duration of a handling cycle, have been analysed by a few authors.

Papaioannou et al [24] considered the energy used by the various motors of a crane of the RTG type, using Port of Felixstowe data. The collected data was analysed, in terms of active and idle modes as well as, the energy usage by the various motors, to determine that half of the energy consumed would be recoverable. As a result, the demand was reduced, and the overall system efficiency was increased. Therefore, the payback time of energy storage system decreased. They further estimated the recovery of energy saved up to 32,600 litres of fuel, as well as 8100 tonnes of CO_2 annually.

Alasali et al [25] further considered the electrical load forecasting as an important tool to assess any financial or technical risks that may occur in the future, an investigation for short-term load forecasting for electrified RTG crane demand model was tested on two different RTG cranes, using data from PORT OF FELIXSTONE (POF), in the UK. The aim of this model was to minimise utility risks and power costs, as well as increasing competitiveness. In their research, they implemented and tested several models, to forecast the RTG crane a day ahead of the load. The results disclosed the usefulness of the forecast models and the estimated number of cranes moves, and the container gross weights were accurate.

Harrison et al [26], presented a Power Measurement System (PMS) for the RTG crane system, to understand the power flows during operation conditions of the RTG. A bespoke data analysis tool has been developed in MATLAB and the data has been used to verify the simulations of RTG. The system measurement was installed on an RTG in March 2016, to record power flow measurements during the times of RTG Crane operation, as well as to validate and used as a part of the simulations of the RTG cranes. Therefore, the successful results of PMS have been established.

KosucK et al [27], investigated the energy efficiency of the overhead crane, focusing on both the travelled distance and lifting and lowering the heights of a suspended payload. To improve the energetic efficiency of the overhead crane, they targeted the hoisting load, as it consumed more energy. The research analyses were based on hybrid model development using the kinetic, dynamic relationships, typical equations, and experimental data of the control systems energy consumption. The machine learning tool was further used to evaluate the behaviour of energy consumption at Atlantic port of Morocco, to repair factors that could influence the production around the terminal port.

Wilmsmeier and Spengler [28], presented that the busbar powered RTGs, equipped with online braking, may reduce energy braking, and may reduce energy consumption by up to 60%, identifying the energy consumption levels and profiles of various container types. The cost approach was recommended, as the approach makes it possible to determine which area of operation is concerned, what amount of energy is consumed and establishes a set of detailed indicators.

Alasia et al [29] introduced a model of two forecasts, to generate a 24 hr, three phase active power forecast, for a single electrical RTG crane. The model methods used were the Autoregressive Integrated Moving Average (ARIMAX) and Artificial Neural Network (ANN). The aim of the research was to study and analyse the three-phase active power, to discover the relationship between the active power, the gross weight of containers and the number of moves of the RTG crane hourly. According to the mean absolute percentage error (MAPE), ANN was more accurate than ARIMAX.

2.4. ENERGY STORAGE SYSTEM FOR ENERGY MANAGEMENT OF RTG CRANES

As stated in Chapter 1, one of the aims of this work is to minimize total electricity costs of diesel or grid powered RTG cranes. One of the solutions is the use of energy storage systems, to achieve both peak shaving [30,31], as well as shifting of the demand [32,33]. Some benefits of energy storage systems are power smoothing [34], voltage and frequency control [35] and energy cost savings [36]. Using energy storage systems may result in minimizing the need to expand the electrical infrastructure and reducing overall costs [37,38].

Several authors have analyzed the techno-economic benefits of using various types of energy storage systems with RTG cranes. A few of the main studies are highlighted in the sections below.

2.4.1. Battery storage system

In the work from Yoshihara [39], various kinds of energy saving systems were proposed for RTG crane; a Lithium-ion battery was selected in the proposed system. The power demand required while hoisting up the load and regenerative power during lowering mode energy are analyzed. The RTG crane system would require energy storage system, to utilize regenerative. The fuel consumption of DG has been reduced by 25-60%, with the use of lithium battery storage.

Niu et all [40] presented the system utilizing a diesel-generator, to reduce fuel consumption, as well as the battery connected to dc link, to reduce power electronics for the system and improve the battery efficiency. Their experimental results showed a 57% reduction of fuel consumption, compared to a conventional RTG crane system.

Wei et al [41] established the dynamic model of the hybrid RTG crane, analyzing the operation features in different modes. The battery charging cost was further analyzed and the reported results revealed that the new RTG saves 70%, compared to the conventional RTG crane.

Xia et al [42] studies on various types of RTG lithium battery transformation technologies, have been carried out thoroughly. The research showed that the technology of high-power water-cooled lithium battery, was considered as the optimal applicable technology of RTG energy saving transformation, as it has preferable energy efficiency and stability operation. The safety and service lifetimes have been greatly improved, and the cost of reconstruction and maintenance was reduced. As a result, a wider application is possible, as it could produce great economic and environmental benefits.

2.4.2. Supercapacitors

The super capacitor could further be used as storage for RTG crane system. It could be charged while hoisting down and the regenerative energy could be stored in the super capacitor (operating as ESS), further than wasted in the braking resistor.

Corral-Vega et al [43], presented the use of a crane powered by a hybrid powertrain, combining fuel cell and ESS. This hybrid powertrain was designed and evaluated, based on FC and SCs together, with a new EMS for a RTG crane. The load associated with the trolley and lifting systems and the load associated with the auxiliary services of the crane, were considered in that model. Research simulations proved that the model was suitable to be used for the crane system and the performance of the new EMS implemented was used to control the FC and SCs. The results further showed that the hybrid system is capable in meeting appropriate working cycles of the crane. The energy efficiency of the crane was increased by 294%, while energy dissipated in the braking resistor decreased by 55% and the cost reduction by 50%.

Chen et al [44], discussed that super capacitors could be used as a storage device and applied in many fields, such as peak power demand and regenerative braking. To reuse the RTG renewable energy, the supercapacitor may be associated with regenerative braking in 'hoist-down' braking operation, to contribute to energy recovery and rapid energy consumption, related to acceleration operation of a RTG crane.

Kim and Sul [45] proposed a hybrid energy system, consisting of a diesel-engine generator and a supercapacitor, to improve the RTG crane performance. The supercapacitor was considered to contribute to the energy recovery to save energy, which is typically wasted by a braking resistor, during the regenerative braking in the "Hoist-Down" braking operation and the rapid energy consumption related to acceleration in the "Hoist-Up" operation of the RTGC. To study the behaviors of the proposed system, the simulations were performed under unfavorable operating conditions. Several experiments were carried out, and performance of the proposed system was evaluated with a real RTGC. The proposed system results indicated that the fuel consumption could be cut down by 35% and the emission of the engine by more than 40%.

Corral-Vega et al [46], discussed the potential solution for a diesel RTG crane system analysis, based on the hybrid configuration of a diesel generator, SCs as ESS and new energy management system, evaluated for a 65 tons RTG crane. The lifting and the trolley systems (three induction motors and two DC/AC inverters) and the auxiliary services, were considered as the loads for the study. The results of the research are the improvement of energy efficiency by 40% and the diesel fuel consumption was reduced by 20%.

Mostafa et al [47], investigated the economic efficiency of peak demand reduction in ship to shore (STS) cranes, based on the ultracapacitor (UC) energy storage sizing, aiming to reduce the peak power absorbed by UC sizing. Their results confirmed that the UC energy storage successfully reduced the peak demand, increasing the load factor, as well as a reduction in power and energy cost.

Chunhe Chang et al [15], analyzed the relation of energy flows of the RTG crane system, to solve the problem where the existing RTG crane consumes massive generating/braking energy through resistance, producing plenty of heat, that causes excessive fuel consumption and exhaust emission during operation. Firstly, the structure and principle of the RTG energy saving system was suggested and examined the topology and principle of the bidirectional DC/DC converter. They further proposed a voltage equalization method for a RTG energy saving system, named the active voltage equalization method, and the design of active voltage equalization circuit parameters and control strategy were given, after analyzing a model for supercapacitor voltage equalization strategy. The simulation analysis of the series connection of supercapacitors module was performed. Therefore, most importantly, the improvement of energy saving was confirmed. Their results on theoretical analysis and simulation result confirmed that the active control circuit may be more efficient in solving the problem of the partial over-voltage of the supercapacitor groups. This method may be applied on higher charging or discharging currents. Therefore, it is of high value to be used in the system of the RTG energy saving system.

In the works of Chang et al [48], a model for a supercapacitor voltage equalization strategy was studied. The proposed model included the active voltage equalization method, based on a buck-boost converter. The voltage equalization circuit, the design of active voltage equalization circuit parameters, as well as the control strategy were analyzed and provided. Simulation results presented that the method for equalizing the voltage may avoid over-voltage of each cell and possess practical and value for the supercapacitor RTG energy saving system.

Bolonne and Chandimal [49] further presented the hybrid energy source comprised of a Lithium-ion battery bank and supercapacitor bank, connected to DC link through bi-directional DC/DC and VSDG. The sizing of hybrid energy system was controlled by a state machine controller. The method of an active voltage equalizer was proposed for the RTG energy saving system. The simulation results were performed by the analysis of the series connection of supercapacitor module for the proposed method of the system.

Medora and Kusko [50], discovered the battery management as ESS and the battery (SoC) was highly recommended before the appropriate selection of the battery to be used in RTG crane system operation, during the discharge profile of different loads conditions. A supercapacitor was further recommended as an additional energy storage to the battery, to improve the energy delivered to the system and to extend the battery life. To conclude, the supercapacitors are therefore identified to be an effective storage system for high peak currents and improve the performance of the storage systems and battery lifespan.

2.4.3. Flywheels

Flynn et al [51], discussed the flywheel storage system, to be used in RTG crane to reduce the fuel consumption and emissions output of the system. Flywheels are further described as important storage, to reduce peak power demand from the diesel engine increasing engine life. The research results revealed that fuel saving could be up to 35% with the use of the flywheel storage. The authors further described the purpose of FESS. FESS could cut peak demand from the diesel engine and increase engine life. Furthermore, flywheels motors were identified to possibly capture the regenerative energy and deliver it for the next container lift. Therefore, this could reduce fuel and diesel engine emission. Their research detailed the operation and experimental results of a novel long-life flywheel motor and its drive system, that could capture the regenerated energy and provide it further for subsequent container lifts.

Tan, Kai Hou and Fook Fah Yap [52], investigated the amount of energy and fuel consumption that could be reduced in RTG cranes in container terminals, by using the simulation. They further introduced a hardware-in-loop system that included a FESS, a Variable Frequency Drive (VFD) and brake resistors, to validate simulation results. The simulation results presented in their research have been produced, by using RTG crane and FESS mathematical models. The results revealed that 30% of energy could be saved, relative to a conventional RTG.

Xu et al [53], investigated a kinetic energy recovery system (KERS) for a RTG crane, based on a flywheel. KERS has been discussed or shown as optimal and used to meet the peak energy requirements of the crane during both acceleration and regenerative braking. The research further presented the access to reuse the regenerated power in a diesel RTG, through an integrated KERS, whereby flywheel was discussed as a protection solution that stores energy mechanically instead chemically, could further work like a dynamic battery, to ensure the reliability to support high power. KERS has been concluded as high power energy storage, energy density and virtually an infinite number of charge-discharge cycles, where batteries and ultra-capacitors are not capable.

Ahamad et al [54], have proposed an integration of the Harbor and flywheel energy storage (FES). The aim was to integrate both the Harbor and FES, to avoid the crane consuming more power from grid during the lifting process of the container. They further discussed the FESS energy harvesting modelling from the harbor electrical cranes. They researched how to avoid the energy wasted during the lowering process of the container, further discussed on the methods control of the system among the grid, crane and flywheel as energy storage, to recover wasted energy during the container lowering mode. A harbor electrical crane system was selected for computer simulation to demonstrate the effectiveness of the proposed methodology.

Binti et al [55] investigated the cost effectiveness based on an electrical flywheel system to reduce electrical consumptions from electrical power networks while improving the efficiency of system. Furthermore, the development of an effective control methodology has been carried out in this study and reported results show that the proposed method was successful, as the energy could be effectively harvested from the crane into FESS during its operation (lifting) and used as quality supply. Furthermore, it could improve or increase the Harbor power system' energy efficiency.

2.5. OPTIMAL CONTROL FOR RTG CRANES

Optimal operation control is a powerful method that is proposed in the literature, to discover solutions for various energy management problems [56-57]. Recently, a few studies have been conducted and published on various control methods applied to the operation of RTG cranes.

Aguiar et all [58], presented a state-space fuzzy model of overhead cranes and a fuzzy control design method, based on parallel distributed compensation, a linear-matrix-inequality

(LMI) feasibility problem was formulated to ensure the closed-loop Lyapunov stability, bounded control inputs, quick positioning of the supporting cast and suppression of load oscillations and collisions. The proposed fuzzy control approach for cranes was more effective and robust.

Alasali et al [59], presented a paper where the aim was to improve the reliability and economic performance for ESS parameters, considering uncertainty in RTGs electrical demand with the use of the stochastic management system. The development of stochastic optimal controller utilizing on Genetic Algorithm (GA) has been carried out to reduce the peak demand on cranes network. The collected data from the Port of Felixstowe was used for simulations, comparing the stochastic control system with the standard set-point controller. The results indicated a 28.7% using a GA controller model and 23.9% for a set-point controller for RTG the crane peak demand reduction.

Cuong et al [60], proposed an algorithm control for RTG cranes using the combination of fraction-order calculus, sliding mode and adaptive control to robust behaviour against uncertainties. Simulation and experiment results showed the advantage of using adaptive fractional order sliding mode control, to track, actuated states and stabilizing unactuated states, regardless of parametric uncertainties and unknown disturbances.

Hussein and Petering [61], introduced a fuzzy logic controller (FLC), based on linguistic rules, the test has been carried out, showing storage performance and energy consumption has been reduced as a result. FLC was used to maximize the potential benefits of adding energy storage to RTG Cranes. Simulation analysis was carried out using collected data from Felixstowe port and it may be concluded that, from their reported research, the FLC control strategy has successfully increased the energy saving by 32%, while standard control system (PI) control by 26%.

Pietrosanti et al [62], compared a Fuzzy Logic Controller (FLC) to a standard control system (PI), for a RTG crane operating with an energy storage system. The comparison criteria were the energy and fuel consumption, as well as the control impact on the energy device. The results of the FLC control strategy have indicated that the energy savings have increased by 32% and perform 26% better, as compared to the PI controller.

Kusakana et al [63], presented an optimal energy management model for a RTG crane supplied by a hybrid diesel generator/battery system. The aim of the model is to reduce the energy cost spending and CO_2 emission by minimizing the amount of fuel consumed by the diesel generator, and maximizing the potential energy recovered through the regenerative braking during the container lowering phase. As compared to the baseline case where the diesel generator is used alone to handle the same demand, the simulation results for the selected day of operation have shown that using the proposed model, a 40.6% reduction in the operation cost as well as CO_2 emission is achievable in the case of the proposed system without energy recovery; while 82.17% is achievable in the case the energy recovery is included. Looking further into the stochastic nature of the demand, the analysis on a year of operation have revealed that 76.04% in operation cost can be potentially saved using the proposed system.

Chen et al [64], developed a game theory-based energy management method for a hybrid DG/battery/supercapacitor, modelled as a multi-agent system, supplying a RTG crane. The simulation results showed that a hybrid DG/battery/supercapacitor may adequately respond to the RTG's demand, while reducing the fuel consumption.

Alasali et al [65], implemented the development of optimal energy management and MPC strategies, to improve the energy performance of an electrical distribution network for RTG crane system equipped with ESS. The optimal cost function was used together with the real-time electricity price, power grid specifications and energy storage system parameters. The results attained revealed that the optimal controller has improved the storage devices performance for peak reduction and cost savings.

Alasali et al [66], presented the verification of an optimal energy control strategy based on a stochastic model predictive control (SMPC) algorithm, to improve the reliability and economic performance of a network of RTG cranes, under a given ESS and network specification. The simulated results successfully indicated that SMPC controllers could reduce the electrical energy cost and peak demand for the RTG crane system.

Bayasgalan et al [67], did the development of variable speed generation (VSG) system with an energy saving function, to reduce fuel consumption of the RTG crane. The feasibility verification for the proposed VSG system and IBC was performed, by comparing the simulations and experiment studies. As a conclusion, the system was improved, and the fuel consumption was reduced by 35.7% and 21.3%.

2.6. KEY FINDINGS AND SUGGESTIONS

After reviewing the main available publications on RTG cranes' efficiency, the following were observed:

- The majority of studies have used control techniques, such as closed-loop PI controller, set-point control (SoC, power, voltage, or frequency) to manage the operation of RTG cranes. Studies focussing on power management systems were limited to the use of optimization algorithms, such as Genetic Algorithm, Fuzzy Logic and Game-based controllers.
- Available studies, based on hybrid diesel/battery RTG cranes' energy management, predominantly focus on diesel fuel savings, limiting their analysis on the energy cost for a cycle or day.
- From the available studies, there is a lack of work combining the cost saving of grid powered RTG cranes with battery, based on the maximum demand charges, as well as the time of use pricing structure.

- From the available studies, the optimal power flow of a RTG crane, retrofitted, with energy recovery was not studied.

As suggestions to respond to the above findings, the followings are proposed:

- Using deterministic non-linear optimization approach to solve the power dispatch problem and minimize the energy cost resulting from operating the system.
- Compute a lifecycle cost analysis, to assess the payback period and the breakeven point achieved when comparing the proposed optimally controlled system, with the DG or grid alone used as baselines.
- Include the maximum demand charges, as well as the time of use pricing structure in the cost saving calculation of grid-powered or DG RTG cranes with battery.
- In this work, the stored energy recovered from the lowering of the containers is optimally dispatched to reduce the peak power and energy required from the DG or the grid. This aspect was not considered in most of the works available in the literature.

CHAPTER III: OPTIMAL ENERGY MANAGEMENT OF A HYBRID DIESEL GENERATOR AND BATTERY SUPPLYING AN RTG CRANE WITH ENERGY RECOVERY CAPABILITY

3.1. INTRODUCTION

In this Chapter, an optimal energy management model for the RTG supplied by a hybrid DG/battery system, is developed. The aim of the model is to reduce the energy cost spending, by minimizing the amount of fuel consumed by the DG and maximizing the potential energy recovered through the regenerative braking that takes place during the lowering phase.

As a case study, an RTG crane operating in South Africa, has been selected. The load profile, size of the DG, as well as the battery storage system, are used as input to the model developed.

Simulations, for a complete RTG handling cycle, have been conducted to evaluate the techno-economic performances of the developed model used, to optimally dispatch the power flow in the system during the different phases of operation. Three main configurations have been simulated as energy sources for the RTG crane, namely DG alone, DG/Battery without energy recovery during the lowering phase and DG/Battery with energy recovery during the lowering phase.

3.2. MODEL DEVELOPMENT

3.2.1. Proposed system description

Figure 3.1, shows the proposed system with its different electrical components. The RTG crane has a powertrain with a diesel engine driving a self-excited AC generator, regulated by a variable voltage control circuit. The DG is connected to the DC bus through an AC/DC rectifier; the gantry, hoist and trolley AC electric motors are fed from the DC bus, through their respective DC/AC inverters.

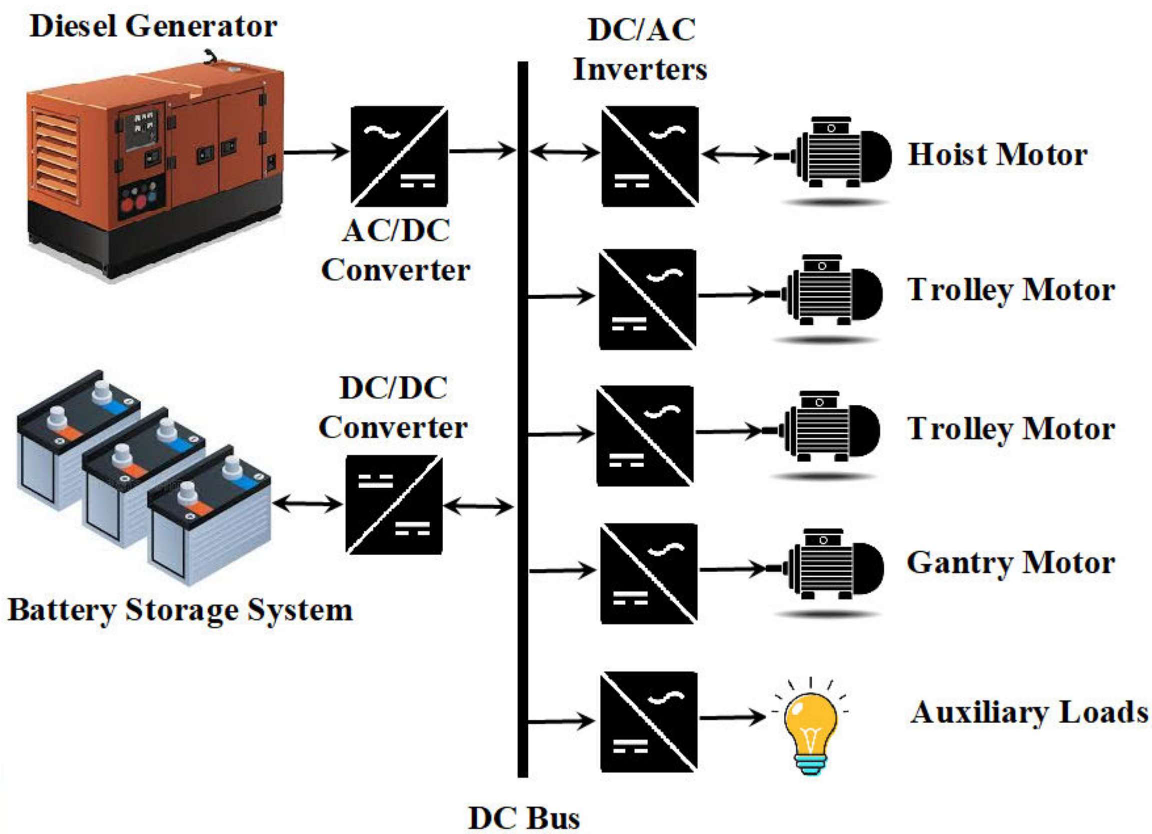

Figure 3.1: Diesel powered RTG crane with its main electrical components

A peak voltage may be reached, when the hoist motor operates in the lowering phase, since the motor acts as a generator. Therefore, regenerative energy is produced, while increasing the voltage on the DC bus, which is harvested during the regenerative braking process and stored in the battery. This means that solely the hoist inverter may allow a bidirectional power flow (working as a rectifier in the regenerative mode).

The battery storage system is connected to the DC bus through a bidirectional inverter DC/DC converter, to allow the charging and discharging processes.

The different operation phases of an RTG crane are given in the following sequences: hoist up (with container), trolley right (with container), hoist down (with container), hoist up (without container), trolley left (without container) and hoist down (with container). During the first half cycle, the RTG handles a load, and not during the second half cycle. Therefore, the load demand may either be positive during the hoist up, trolley left and right, or be negative during the lowering processed.

3.2.2. Optimal energy management model of the hybrid DG/battery RTG crane

3.2.2.1. Proposed model's main powerflows

The different powerflows in the proposed system are shown in Figure 3.2. It may be seen that the power from the DG may be used to supply the load (P_1) or/and to recharge the battery (P_2), depending on the SoC. In other instances, the battery power (P_3) may be used alone or in conjunction with the DG, to supply the various motors. However, during the energy regenerative process, the battery is recharged using the power recovered (P_4) from the hoist motor operating as a generator, while the DG is not used to supply the load. Therefore, there is a need to optimally manage the power flow, with the objective of minimizing the operation cost, which is mainly linked to the DG fuel consumed (P_1 and P_2). The DG's hourly fuel consumption, *FC*, may be expressed by the following non-linear equation [19]:

$$FC = aP_{DG}^2 + bP_{DG} + c \tag{3.1}$$

Where: *a* (L/kWh^2); *b* (L/kWh); *c* (L/h) are the parameters of the selected DG's fuel consumption curve and P_{DG} is the DG's output power.

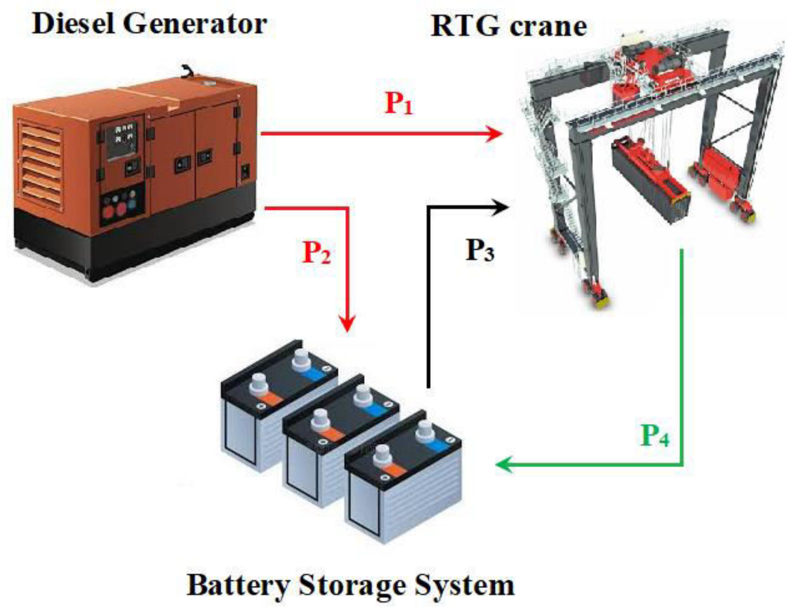

Figure 3.2: Main powerflows (control variables)

3.2.3.2. Objective function

The main aim of the model is to minimize the amount of fuel and the cost linked to the DG supplying operations of an RTG, while handling containers. Additionally, the energy recovered through the regenerative process, during the lowering of containers, should be maximised. The objective function (*OF*) may be modelled as:

$$OF = \min \sum_{j=1}^{N} (f_c \times (P_{1(j)} + P_{2(j)}) \times \Delta t) + \max \sum_{j=1}^{N} (P_{4(j)} \times \Delta t)$$

(3.2)

Where: f_C is the diesel fuel price per litre; j is the sampling interval under consideration with N the total of optimization interval and Δt is the length of each sampling interval.

The first component of the developed objective function ensures that the energy cost from the diesel generator used to supply the load, or to charge the battery, is minimised. The second component ensures that the energy recovered, through the regenerative process, is maximised through the battery charging.

3.2.3.3. Load balance

From the operation given in Figure 3. 2, the load balance may be given as:

$$P_{L(j)} = P_{1(j)} + P_{3(j)} - P_{4(j)} \tag{3.3}$$

This means that, for any selected sampling interval "*j*", the load may be supplied by either the DG or the battery or operates in the regenerative braking mode.

3.2.3.4. Diesel generator power constraints

For any sampling interval "*j*", the summation of powers from the DG required to supply the load and to recharge the battery should be less or equal to the DG's rated power. This condition may be expressed as:

$$P_{1(j)} + P_2 \leq P_{DG}^{Rated} \tag{3.4}$$

3.2.3.5. Dynamics of the energy storage's SoC

For any given optimization interval "*j*" the resultant battery's SoC may be expressed as:

$$SoC_{(j)} = SoC_{(0)} \times (1-\delta) + \frac{\Delta t}{E_n} \times \left(\eta_{ch} \times \sum_{i=1}^{j} (P_{2(j)} + P_{4(j)}) - \frac{\sum_{i=1}^{j} P_{3(j)}}{\eta_{disc}} \right)$$

(3.5)

Where: $SoC_{(j)}$ is the SoC at the considered optimization sample; $SoC_{(0)}$ is the SoC at the previous optimization sample; E_n is the nominal storage capacity of the considered battery in kWh; η_{ch} and η_{disch} are, respectively, the efficiencies of the battery's charging and discharging processes and δ is the battery self-discharging coefficient, dependent on the selected battery type and condition.

3.2.3.6. Variables limits

Each control variable, or power flow, may be modulated between a minimum and a maximum value, according to the system's design specifications, while following the manufacturers' design and operation specifications. As described in the previous section, it is solely the maximum power of the PV that varies, depending on the available solar resource. These may be modelled as:

$$P_1^{\min} \leq P_{1(j)} \leq P_1^{\max}$$

(3.6)

The power flow P_1 is limited by the size or power rating of the considered DG.

$$P_2^{\min} \leq P_{2(j)} \leq P_2^{\max}$$

(3.7)

The power flow $P_{2,}$ is limited by the power rating of the considered DG, as well as by the battery's maximum charging current and the system's voltage.

$$P_3^{\min} \le P_{3(j)} \le P_3^{\max}$$

(3.8)

The power flow P_3 is limited by the power rating of the considered battery storage system.

$$P_4^{\min} \le P_{4(j)} \le P_{4(j)}^{\max}$$

(3.9)

The power flow P_4, is limited by peak power rating from the regenerative system, as well as by the battery's maximum charging current and the system's voltage.

The minimum SoC of the battery, depends on the battery type, while the maximum SoC is always 100%. This may be modelled as:

$$SoC^{\min} \le SoC_{(j)} \le SoC^{\max} \qquad (3.10)$$

3.2.3.7. Restricted power flows

This restriction is applied to power flows that may not occur concurrently in the same considered optimization sample. In the case of the battery, the charging and discharging processes may not occur simultaneously. Using Figure 3.2, this condition may be expressed as:

$$(P_{2(j)} + P_{4(j)}) \times P_{3(j)} = 0$$

(3.11)

Additionally, the regenerating braking mode may not take place when the load is supplied by the DG or the battery (hoisting). This condition may be expressed as:

$$(P_{1(j)} + P_{3(j)}) \times P_{4(j)} = 0$$

(3.12)

3.2.3.8. Fixed-final state condition

For the repeated execution of the optimization process in subsequent optimization horizons; the battery's SoC at the beginning should be equal to the one at the end of the horizon. This condition may be modelled as:

$$\sum_{j=1}^{N} (P_{2(j)} + P_{4(j)} - P_{3(j)}) = 0$$

(3.13)

3.2.3.9. Processing steps of the developed energy management algorithm

The processing steps of the proposed energy management system, as depicted in Figure 3.2, can be summarised as follows:

- Step 1: Start the optimal control process for the open-loop scheme by identifying the different control variables.
- Step 2: Set the time horizon of the control structure and/or the control horizon for the open-loop scheme.

- Update system parameters at a sample of time. This is chosen to be at $t = i$ where $i = [1 \ldots N]$.
- Step 3: Read the energy flows on each component as well as the demand through the energy management system as described in Figure 3.1.
- Step 4: Compute the energy management system strategy based on equations 3.2 to 3.13.
- Step 5: Find the optimal solution of the control variables. If this solution is not optimal, repeat step 2 to 4 to get the optimal solution.
- Step 6: Generate the optimal solution for open loop.

3.2.3.10. Solver selection

Due the quadratic nature of the DG's fuel consumption curve, as represented in the objective function, as well as due to the restricted power flows, the optimization problem is of a non-linear nature, which may be solved using "*fmincon*", in MATLAB [19].

It should be noted that the simulations are performed using a computer with a processor Intel (R) Core (TM) i7-9750H CPU@ 2.60 GHz, 6 cores with 16GB physical installed memory.

3.3. CASE STUDY DESCRIPTION

Analyses on RTG cranes' energy usage, as well as the approximate duration of a handling cycle, have been analysed by a few authors, previously described in [24,26,49]. These references show that the load demand is highly non-linear and is not influenced by the variation of seasons.

For the case study considered in this Chapter, Figure 3.3 gives the measured power profile with the energy consumed considered as positive, while the energy produced from the regenerative process is negative. Due to the stochastic nature of the containers' weight to be handled in different cycles, the energy used, as well as energy recovered and the length of the different cycles, differ significantly.

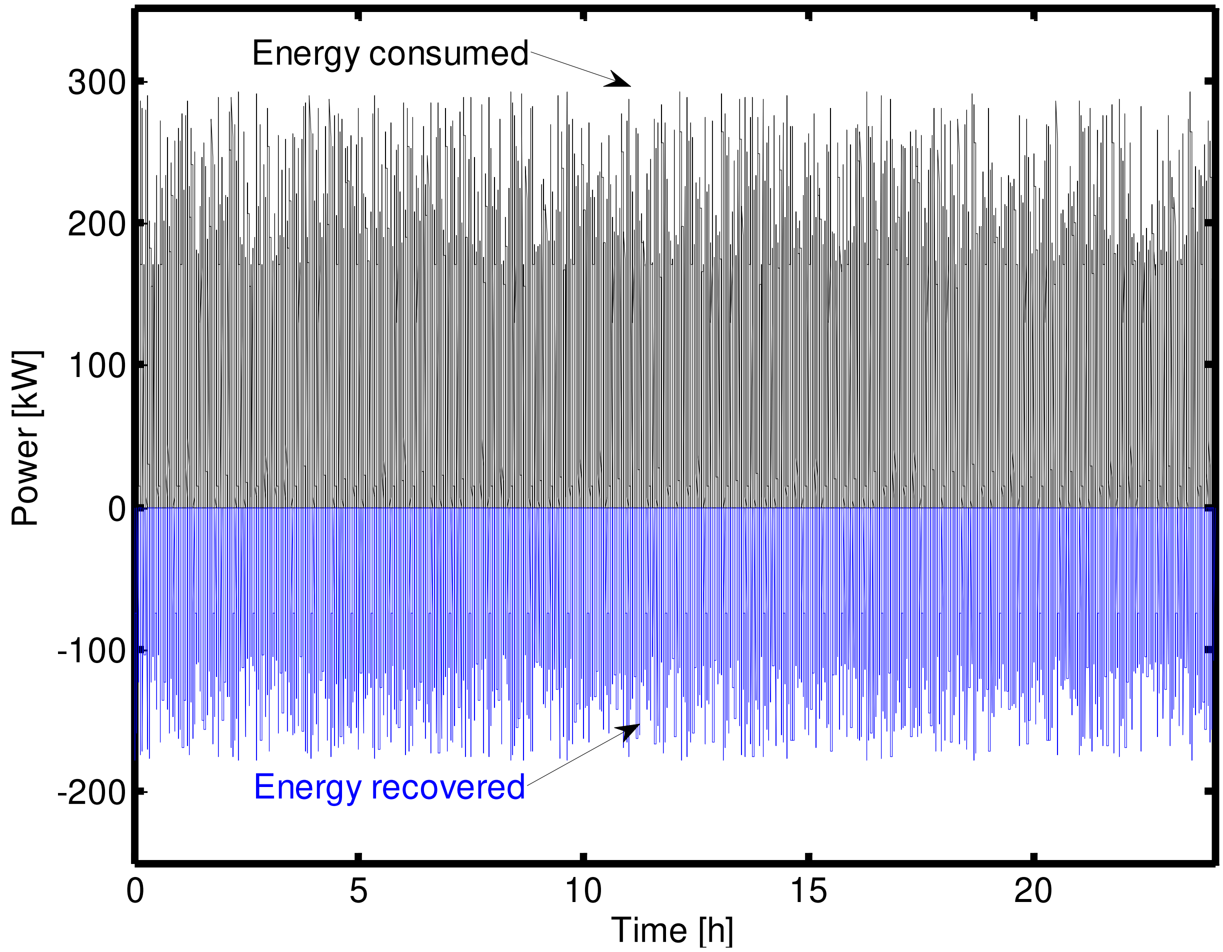

Figure 3.3: Daily measured energy profile (used and recovered)

Additionally, the daily profile is made of 540 cycles, with 64 sampling intervals per cycle and 4 variables to be optimised in each interval. Thus, the number of possible combinations for simulation is too high to compute. Therefore, to ensure that the discussion is clear and to analyse the behaviour of the system in each handling phase, the simulation horizon has been shortened and focuses on a single cycle, to emphasise on the dynamic of the system controlled, using the developed model.

Focusing on one cycle with a 40T container considered as full load, the full handling cycle takes to 160 seconds, as shown in Figure 3.4. The peak demand during the hoist up phase is 292 kW, with an average demand of 24.8 kW and the possibility of a peak regenerated power of 178 kW, achievable during the hoist down phase. For a full cycle, at full load (worst case), the details on the power required during all the handling phases, are presented in Figure 3.4. The main phases are the hoisting up phase (approximately 35 sec), trolley moving left phase (approximately 25 sec), lowering load phase (approximately 30 sec), hoisting up at no load (approximately 20 sec), trolley moving right at no load (approximately 25sec) and lowering trolley at no load (approximately 25 sec).

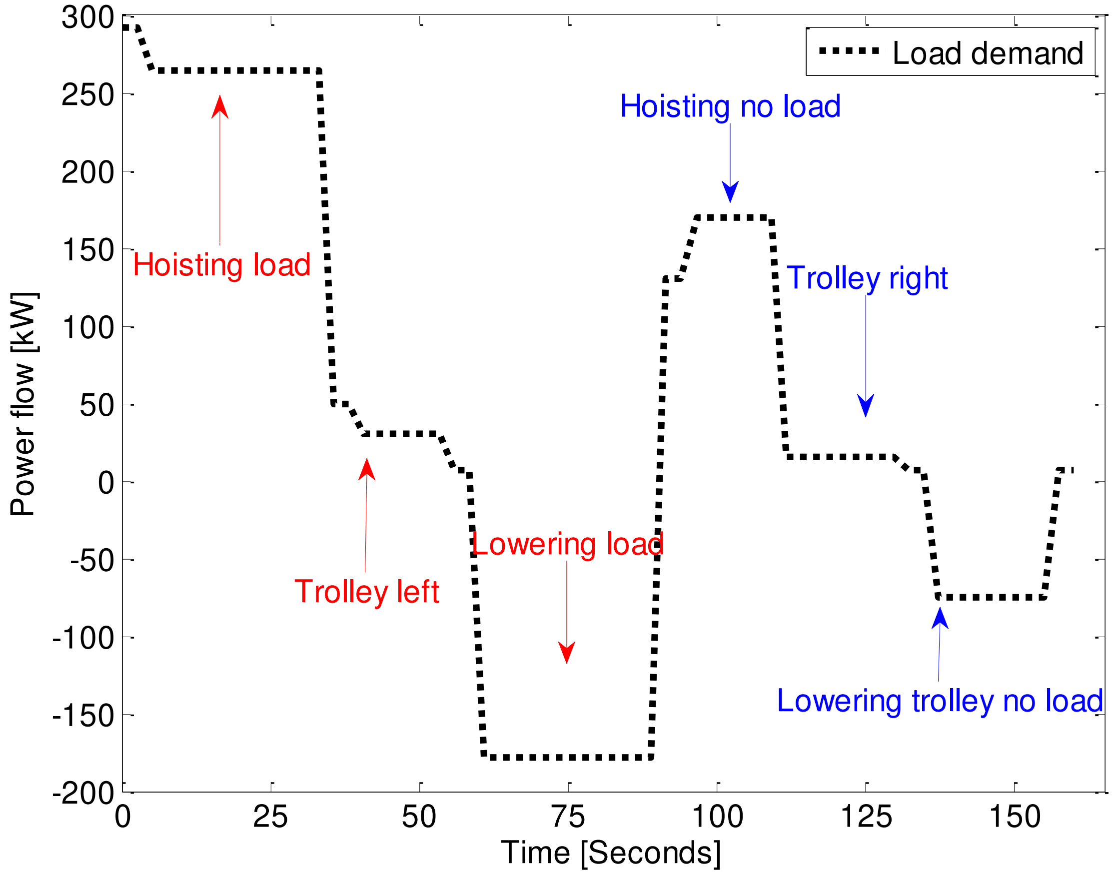

Figure 3.4: 40T RTG crane typical cycle power profile (full load)

The simulation parameters of the DG (from the manufacturer [63]) and battery, as well as other inputs to the developed model, are given in Table 3.1.

Table 3.1: Simulation parameters

Parameter	**Value**
Sample interval	2.5 second
DG power rating	410 kW
a	0.0074 (L/kWh^2)
b	0.233 (L/kWh)
c	0.4200 (L/h)
Battery storage capacity	128 kWh
SoC_0	50%
SoC^{max}	100%
$SoC^{\min}$	30%
η_{Ch}	85%
η_{Disc}	95%
Hoist motor	292 kW
Trolley motor 1	30 kW
Trolley motor 2	30 kW

3.4. SIMULATION RESULTS AND DISCUSSION

Simulations are conducted to evaluate the effectiveness of the proposed optimal energy management model, applied to the battery integrated DG supplying the RTG crane's demand, with regenerative energy capabilities, for a full load cycle (as described in Section 3.1). Three main scenarios are simulated and discussed. These are:

- The RTG crane's demand supplied by the DG only (Baseline).
- The RTG crane's demand supplied by the battery integrated DG system.
- The RTG crane's demand supplied by the battery integrated DG, with energy recovery through regenerative braking.

In relation to the battery and DG's sizing, modern, advanced, and accurate metaheuristic or deterministic optimization methods have been successfully used, to solve optimal sizing problems of hybrid energy systems. Therefore, this work does not deal with the optimal sizing of the proposed system. The main goal of this work is to reduce the operation cost spending, by minimizing the amount of fuel consumed by the DG and maximizing the potential energy, recovered through the regenerative braking occurring during the lowering phase.

The RTG crane used in this work is the Hybrid Power Pack manufactured by Konecranes, which includes a DG, as well as a high-power lithium battery pack with an autonomy of approximately 2 hours [40]. The methodology for sizing the DG and the battery storage system, is reported in Ref [68].

3.4.1. Baseline: RTG crane's demand supplied by the DG only

The sole supply of the RTG crane's load demand by the DG, is considered as the baseline for comparison, with the developed optimal energy management model applied to the proposed hybrid system.

As the sole energy source, Figure 3.5 shows that the DG operates in a load following manner and that the load factor is low.

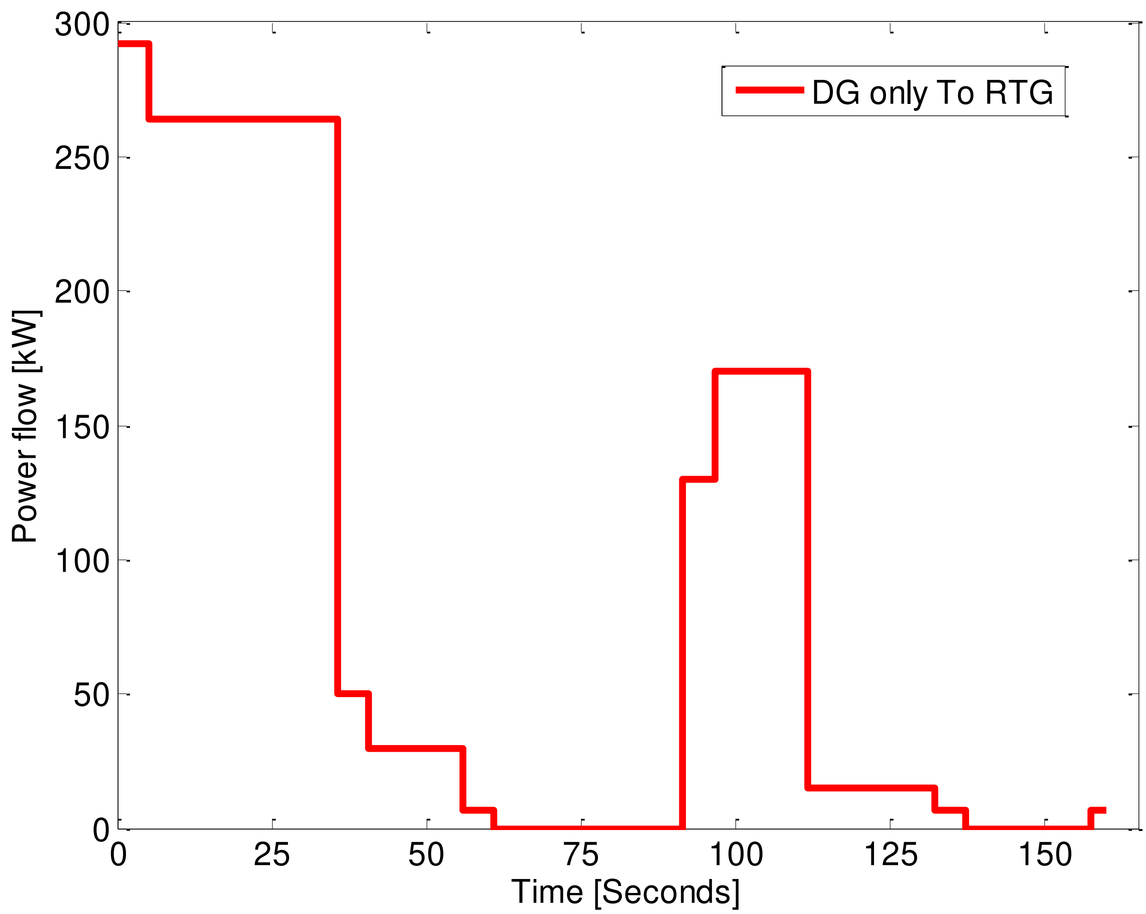

Figure 3.5: Baseline power profile (DG only)

3.4.2. The RTG crane's demand supplied by DG/Battery without energy recovery

In this case, the developed optimal energy management model is applied to the RTG crane supplied by the battery integrated DG. The role of the battery in this arrangement is to supply the load demand, as well as to increase the load factor on the DG, with the aim of decreasing the DG's specific fuel consumption.

In this case, the RTG crane's load demand is supplied by the DG, operating in conjunction with the battery storage in a hybrid system configuration. However, there is no energy recovery through the regenerative braking during the hoist down phase; the braking resistances are used to dissipate the generated energy into heat. Therefore, the battery may solely be recharged by the DG.

The powerflows in the system are managed using the developed optimization model, with the aim of minimizing the operation cost through the DG's fuel consumption. Figure 3.6 shows the operation strategies on the powerflows, while Figure 3.7 shows the corresponding SoC's dynamics, during the different operation phases.

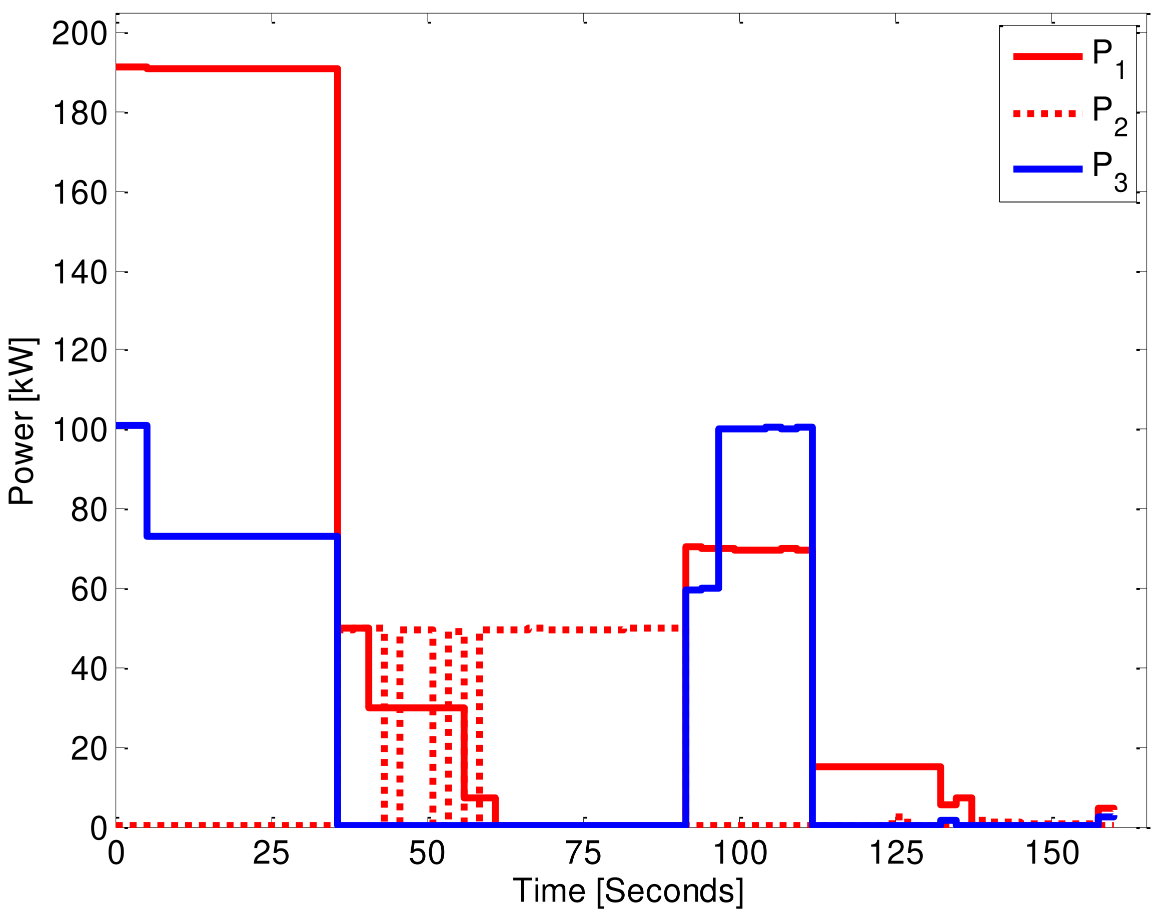

Figure 3.6: Hybrid DG/Battery without energy recovery

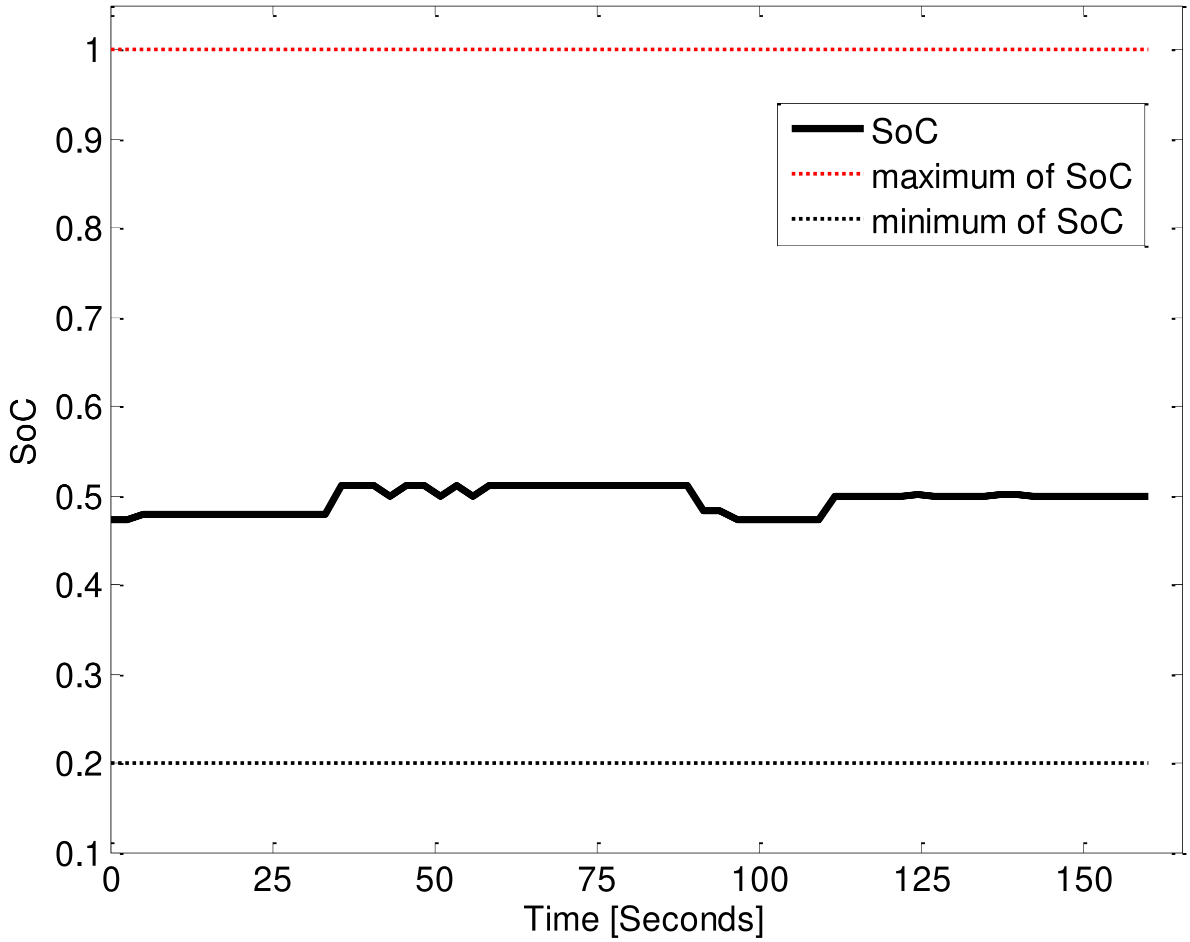

Figure 3.7: Dynamic of the SoC in the Hybrid DG/Battery without energy recovery

3.4.2.1 Hoisting up phase

During the hoist up phase (at full load), Figure 3.6 shows that the load is supplied by the power from the DG, with a contribution of the power from the battery system.

3.4.2.2 Trolley left phase.

During this phase, the container is moved to the left, using the trolley, which results in a lower load demand. Therefore, Figure 3.6 shows that the power required during this phase is exclusively supplied by the DG. It may further be noticed that the DG is used to recharge the battery; this increases the load factor on the DG during this phase. The corresponding SoC of the battery shows a small increase, as shown in Figure 3.7.

It may be seen that the peak power demand, in this phase, is currently 190 kW, which is 35% less than in the baseline case, where the DG is used alone to supply the RTG crane. This means that the DG's size may be reduced.

3.4.2.3 Lowering load phase

During the hoist down phase (at full load), there is no power from the DG, or from the battery to supply the load demand. It may be seen in Figure 3.6 that the DG is used to recharge the battery, which is translated by a small increase in the corresponding SoC (Figure 3.7). It is generally at this stage that the energy recovery through the regenerative braking system is achieved. However, in this case, it is assumed that there is no energy recovery, and the power is dissipated through the resistor brakes.

3.4.2.4 Hoisting up phase: No load

During this hoist up phase (at no load), Figure 3.6 shows that the load demand is supplied by the DG and the battery; the corresponding SoC is decreasing during this phase (Figure 3.7).

3.4.2.5 Trolley right phase: No load

During this phase, the trolley is being moved to the left (at no load) and the demand is principally met by the DG (Figure 3.6). The battery is neither charged nor discharged during this phase, as seen from the stationary SoC (Figure 3.7).

3.4.2.6 Hoisting down: No load

During this hoist down phase, Figure 3.6 shows that there is a lack of power from the DG to supply the load or to recharge the battery. Similarly, the battery is neither charged nor discharged during this phase, as seen from the stationary SoC (Figure 3.7).

3.4.3. The RTG crane's demand supplied by DG/Battery with energy recovery

In this case, the RTG crane's load demand is supplied by the DG, operating in conjunction with the battery storage system. In addition, there is a possibility of energy recovery through the regenerative braking during the hoist down phase. This energy is converted and stored in the battery storage system. Therefore, the optimization model is applied, to manage the power flows from the different sources, in addition to the one from the energy recovery system, to achieve the minimum operation cost and DG fuel consumption during a full handling cycle taken as the optimization window.

The peak power demand is further reduced to 190 kW; corresponding to a 35% reduction, compared to the baseline.

3.4.3.1. Hoisting up phase

As in the previous case, Figure 3.8 shows that, during to hoist up phase, the load demand is met by the power from the DG with a contribution of the power from the battery system.

3.4.3.2. Trolley left phase.

During this phase, where the loaded trolley is moved to the right, Figure 3.8 shows that the demand is principally met by the DG, which further provides a significantly small contribution to the battery charging process. It may further be noted that at around this time, the battery is also supplying the load with a small power contribution, which is linked to the SoC increase, shown in Figure 3.9.

3.4.3.3. Lowering load phase

During the hoist down phase, Figure 3.8 shows that there is a lack of power from the DG to supply the load demand or to recharge the battery. However, it may be seen that the energy recovery, through the regenerative braking system, is taking place. This energy recovered is used to recharge the battery. An increase in the battery SoC is noticeable from Figure 3.9.

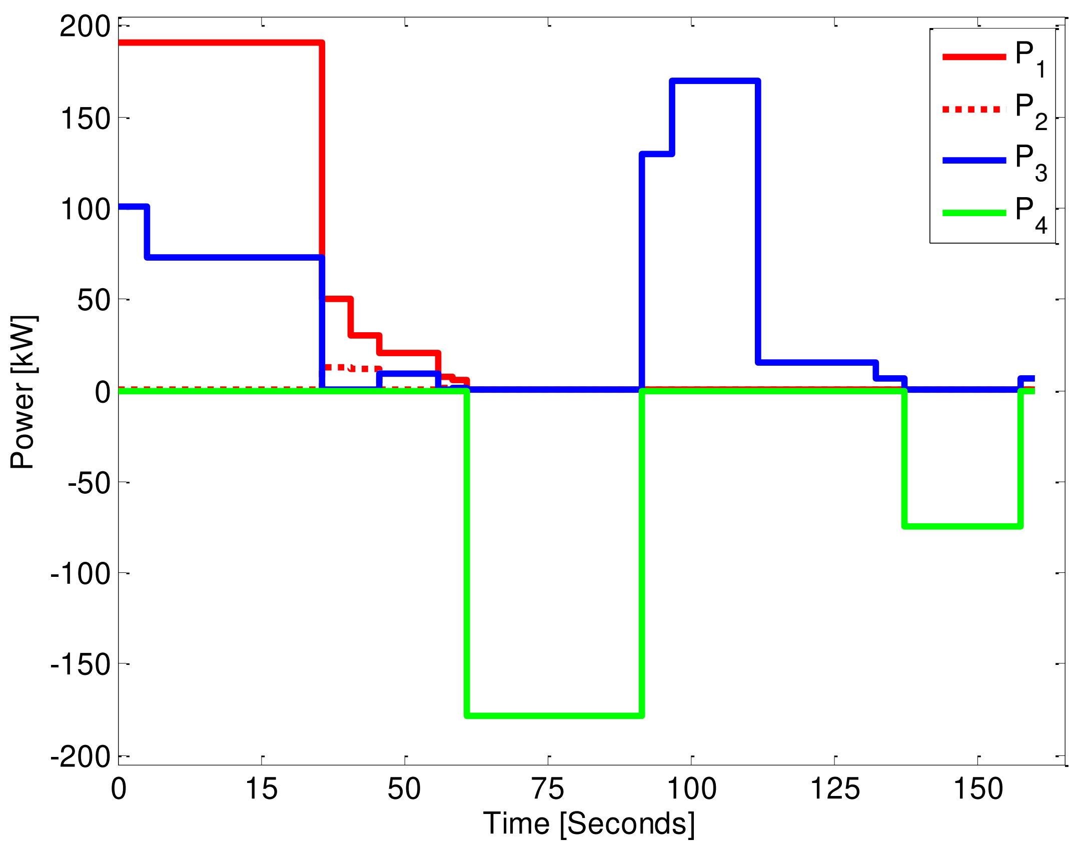

Figure 3.8: Hybrid DG/Battery with energy recovery from the regenerative braking

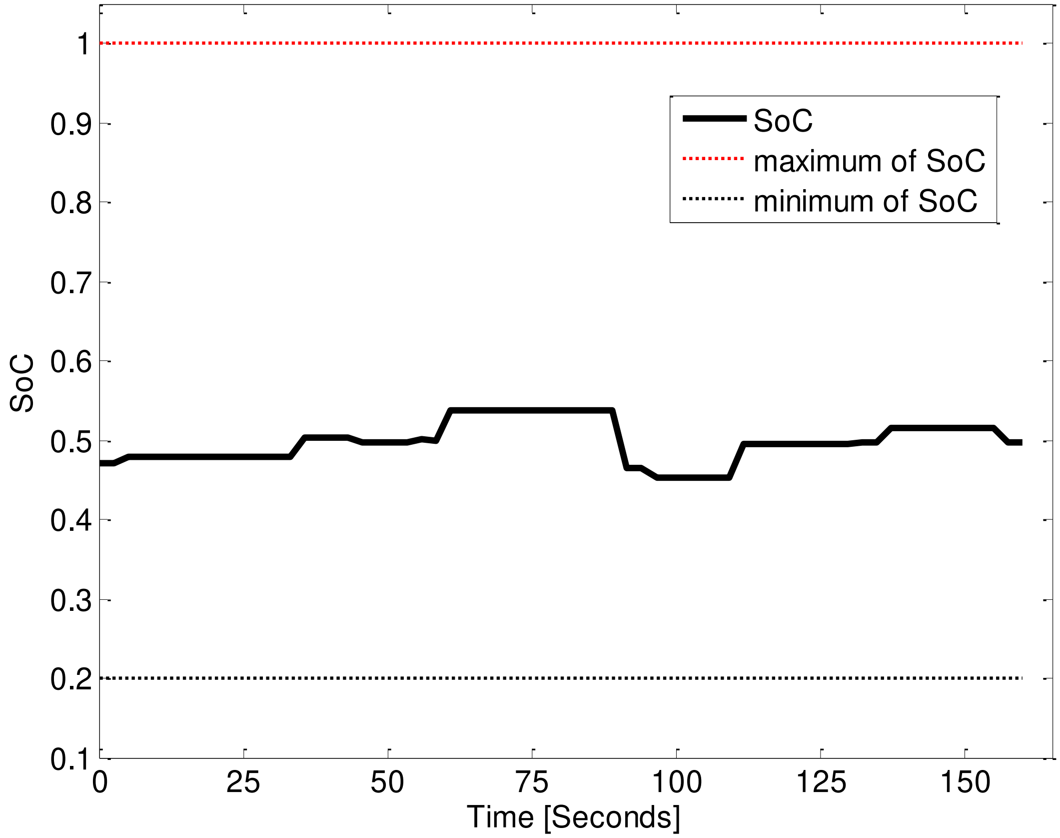

Figure 3.9: Dynamic of the SoC in the Hybrid DG/Battery with energy recovery

3.4.3.4. Hoisting up phase: No load

During this hoist up phase, Figure 3.8 shows that the load demand is exclusively supplied by the battery, while the DG is not used. The corresponding SoC decreases during this phase, as shown in Figure 3.9.

3.4.3.5. Trolley right phase: No load

During this phase, Figure 3.8 shows that the trolley is moved to the left (at no load) and the demand is exclusively met by the battery, while the DG is not used. The corresponding SoC of the battery is shown in Figure 3.9.

3.4.3.6. Hoisting down: No load

During this hoist down phase (at no load), Figure 3.8 shows that there is energy recovered through the regenerative braking system and stored in the battery, which is translated by an increase in the SoC (Figure 3.9). Additionally, it may be clearly seen that the DG is not used (Figure 3.8).

3.5. ECONOMIC AND ENVIRONMENTAL ANALYSIS

3.5.1. Results for the selected RTG handling cycle

The simulation results are further analysed, in terms of the economic and the environmental performance of the optimally controlled battery integrated DG system, supplying the RTG crane. At the time of the simulation, the price of 1 L of diesel fuel was 1.018 USD, in South Africa. Table 3.2 shows that a 45.97% reduction in cost, as well as a CO_2 emission is achievable in the case of the proposed system without energy recovery; while 82.12% is achievable in the case the energy recovery is included.

Table 3.2: Operation Cost and CO_2 emissions saving for the considered cycle.

Supply options (Scenario)	**Fuel consumed (L)**	**Energy cost ($)**	**CO_2 emission (kg)**	**Saving (%)**
Baseline	0.522	0.531	1.38	-
Hybrid system (without energy recovery)	0.282	0.287	0.744	45.97
Hybrid system with energy recovery	0.0933	0.095	0.246	82.12

The cumulative fuel consumption curves of the proposed optimally controlled system, versus the baseline, are given in Figure 3.10, where the difference in fuel consumed may be noticed at the end of the considered simulation horizon.

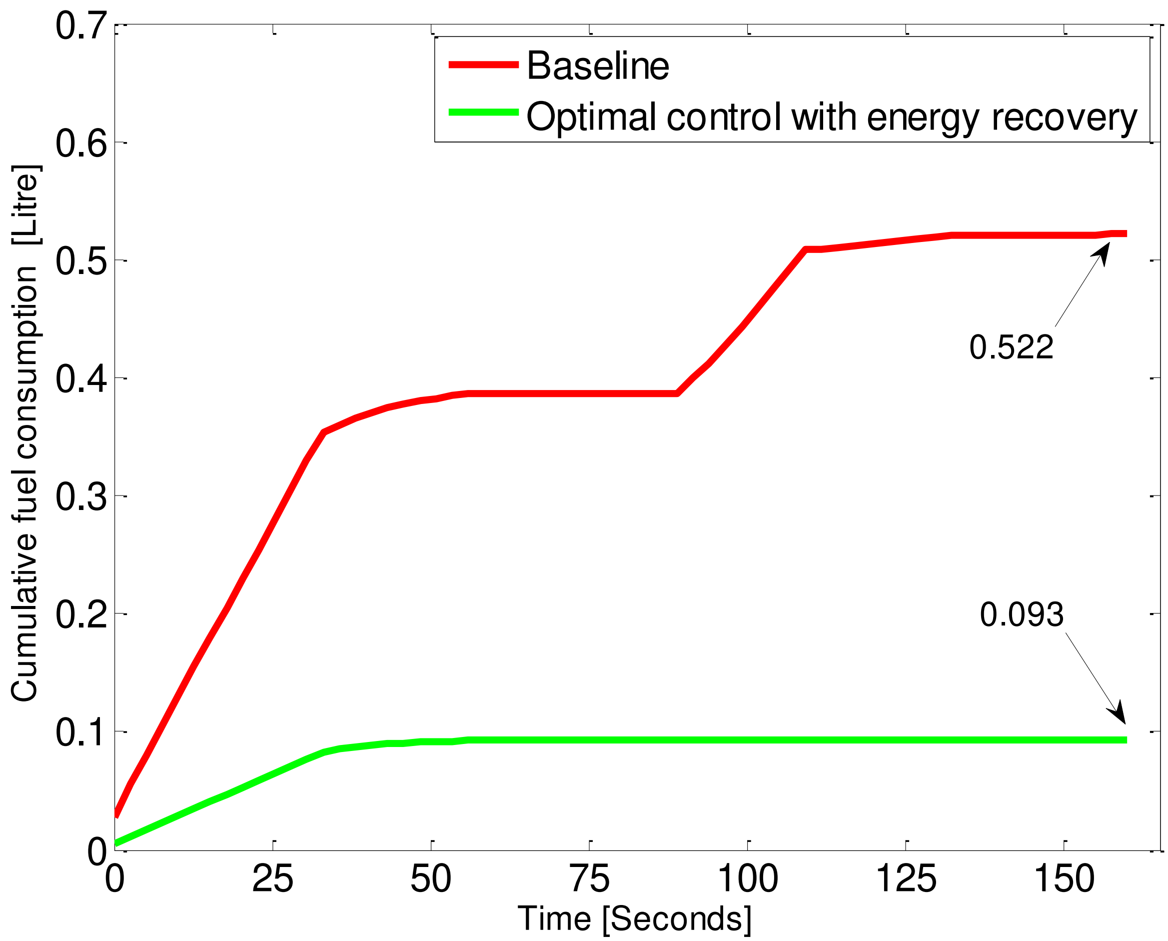

Figure 3.10: Cumulative cost comparison between the Hybrid DG/Battery with energy recovery and the baseline for the considered handling cycle

3.5.2. Lifecycle analysis

Due to the intensive computation power required to perform the simulation, the analysis conducted in Section 3.5.1 was limited to solely one handling cycle of 160 seconds, where only the operation cost linked to the DG fuel consumption was considered. However, given the stochastic nature of the weight to be handled in the different cycles, the energy used, energy recovered, as well as the length of the different cycles, will differ significantly. Therefore, there is a need to perform a lifecycle cost analysis, including all the various costs (initial, operation and maintenance replacement), to better assess the economic benefits of the proposed system's savings, when compared to the baseline.

3.5.2.1. Annual cost analysis

As explained in Section 3.4, due to the computation power required to consider a daily optimisation horizon simultaneously, the simulations have been performed for each hour separately and the results have been summed up, to present the daily operation cost achievable for the demand, given in Figure 3.3.

As an example, Figure 3.11 shows the progression of the cumulative fuel consumption comparison between the proposed system, with energy recovery and the DG as baseline, for the first optimization hour; the operation for the twenty-three subsequent hours is optimized, using the same methodology.

As discussed in Ref. [1], RTG cranes continuously work daily up to 24 hours, for 362 days a year and are only turned off for 3 days, for maintenance. Therefore, considering the daily operation cost computed, the annual cost may be calculated as per Table 3.3.

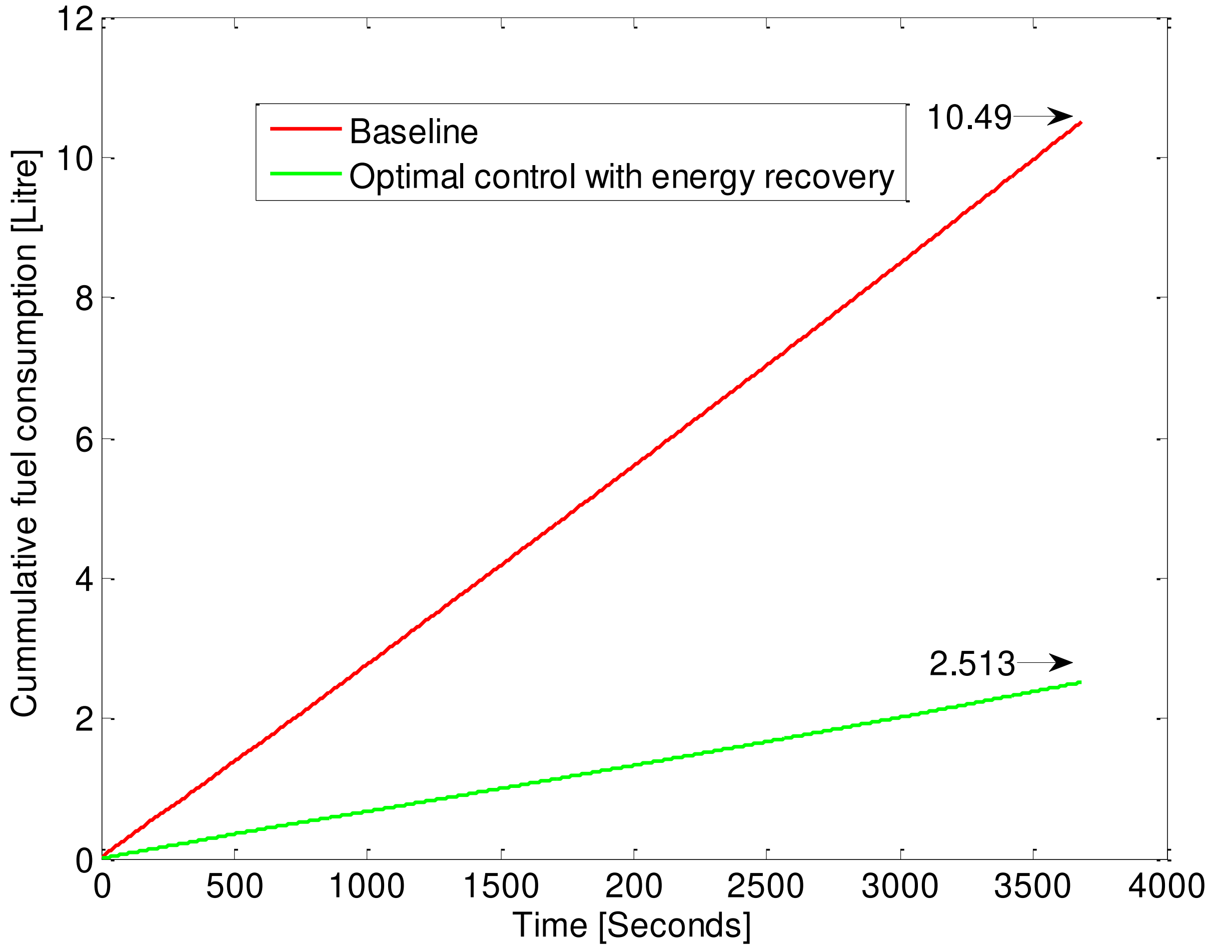

Figure 3.11: Cumulative cost comparison between the Hybrid DG/Battery with energy recovery and the baseline for the hour of operation

Table 3.3: Annual operation cost and CO_2 emissions saving.

Supply options (Scenario)	Fuel consumed (L)	Energy cost ($)	CO_2 emission (kg)	Saving (%)
Baseline	91 137.12	92 777.58	240 939.2	-
Hybrid system with energy recovery	21 832.994	22 225.98	57 719.88	76.04

3.5.2.2. Lifecycle cost analysis

The energy savings are further a function of the battery storage system's size. Therefore, a lifecycle cost (LCC) analysis is conducted, to provide a better indication of the project cashflow over the system's operation lifetime, taken as 20 years. This may be computed as:

$$LCC = C_{I(i)} + C_{R(i)} + C_{OM(i)} + C_{EC(i)} - C_{S(i)}$$

(3.14)

Where: C_I, C_S, C_R, C_{OM} and C_{EC} are the initial cost, salvage cost, replacement cost, operation and maintenance cost, as well as the energy cost respectively, linked to each of the components of the system.

For simulation purposes, the yearly operation and maintenance cost is taken as 1% of the equipment initial cost; this is associated to an annual average inflation rate of 5.3% [69]. The bill of quantity for the additional equipment to achieve the hybrid DG/Battery with energy recovery, is given in Table 3.4.

Table 3.4: Bill of quantity for the battery and inverter

Component	**Size**	**Price (USD)**	**Life years)**
2 x Blue Nova Lithium Iron Battery 65kWh [72]	128 kWh	59 952.98	10
3 x ABB PVS 100KW Inverter Three Phase incl AC+DC Protection [73]	300 kW	30 221.88	20
Total capital		***90 174.86***	

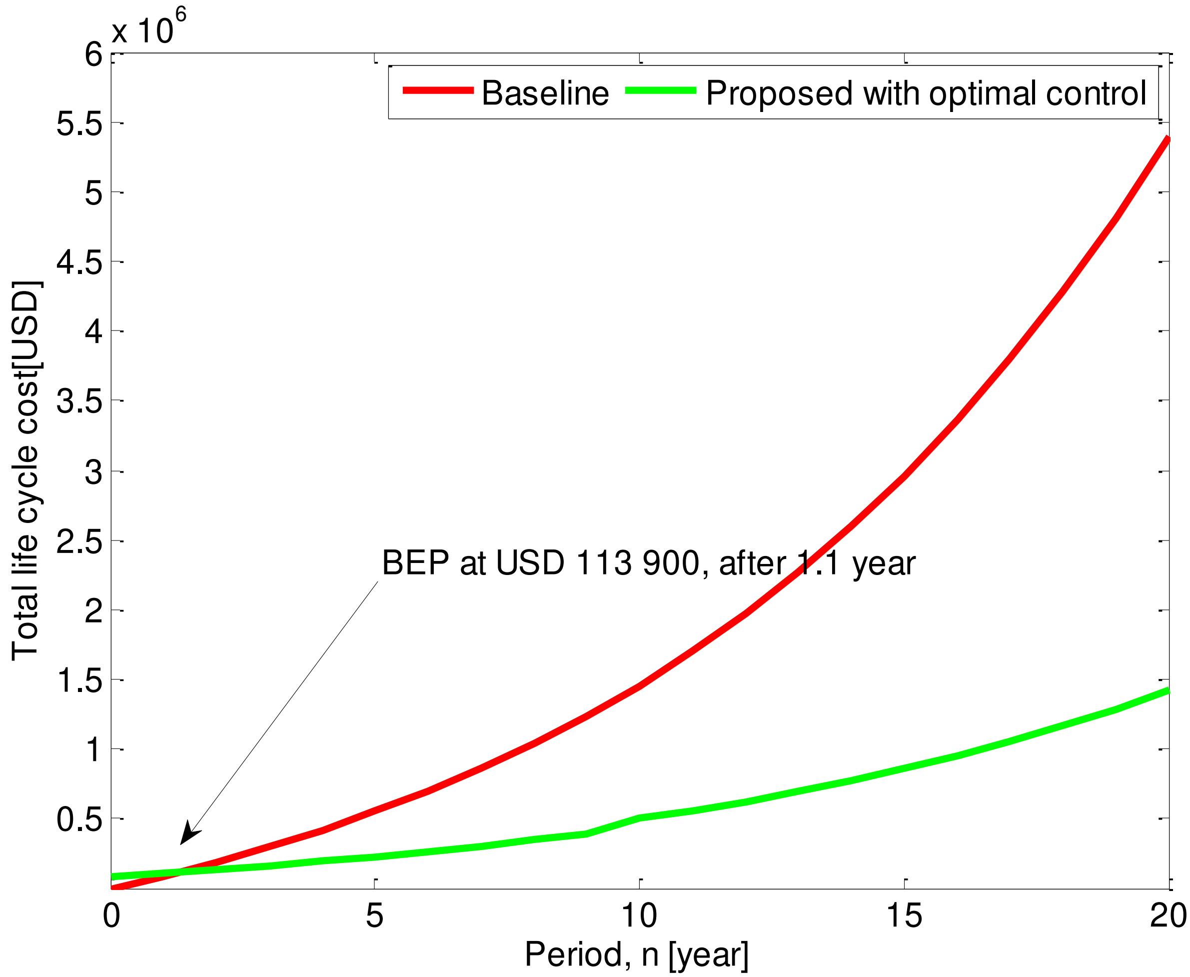

Figure 3.12 The break-even point of the proposed optimally controlled DG/Battery

As compared to the baseline, Figure 3.12 shows that the break-even point of the proposed optimally controlled DG/Battery, with energy recovery supplying the RTG crane may take place after 1.1 years, corresponding to USD 113 900. For the 20 years' project lifetime, the computed lifecycle, in the case of the proposed optimally controlled DG/Battery with energy recovery, is USD 1 426 000. However, when solely the baseline is considered, the projected lifecycle cost is USD 5 391 000. There is a potential cost saving of USD 3 965 000, corresponding to 73.55%

3.5.2.3. Payback Period

In addition to the LLC, a "true" payback period (PBP) analysis is conducted, to assess the economic performance of the system and discover the amount of time it takes to recover the investment made on the battery, as well as the bidirectional inverter from the operation cost saving, as compared to the baseline [70]. The true PBP may be computed as the quotient of the present worth of the total costs (PW_{TC}), to the the yearly average of the present worth of the overall benefit ($PW_{TB\text{-}av}$).

$$"True"\ PBP = \frac{PW_{TC}}{PW_{TB-av}}$$

(3.15)

The PW_{TB} is computed as:

$$PW_{TB} = AB\left[\frac{(1+r)^n - 1}{r(1+r)^n}\right]$$

(3.16)

Where: AB is the yearly benefit and r is the rate.

Using the annual cost savings obtained in Section 3.5.2.1, the true payback period is computed using the online tool available from Ref. [71] and the results show that the simple payback period is 1.28 years. The true or discounted payback period is 1.360 per year and the cash flow return rate is 77.24% per year.

3.6. CONCLUSION

Therefore; in this chapter, an optimal energy management model for an RTG crane, supplied by a hybrid DG/battery system, is developed, with the aim to reduce the energy cost, by minimizing the amount of fuel consumed by the DG and maximizing the potential energy recovered through the regenerative braking taking place during the lowering phase. As a case study, a Hybrid Power Pack Konecranes RTG crane, operating in South Africa, has been selected. The load profile, size of the DG, as well as that of the battery storage system, were used as the input to the model developed. Simulations, for a complete RTG handling cycle, have been conducted, to evaluate the techno-economic performances of the developed model used, to optimally dispatch the power flow in the system during the different phases of operation. Considering a 40 T full load, three main configurations have been simulated as an energy source for the RTG, namely DG alone, DG/Battery without energy recovery during the lowering phase and DG/Battery with energy recovery, during the lowering phase.

As compared to the baseline, the daily simulation results have shown that using the proposed model, a 45.97% reduction in cost, as well as CO_2 emission, is achievable in the case of the proposed system, without energy recovery; while 82.17% is achievable in the case the energy recovery is included.

Due to the intensive computation power requirement to perform the simulation, most authors in the available literature have limited their analysis to one handling cycle, where solely the operation cost linked to the DG fuel consumption was considered. However, given the stochastic nature of the weight to be handled in the various cycles; the energy used, energy recovered, as well as the length of the various cycles, will differ significantly. Therefore, this study has taken a step further in the analysis of RTG cranes' operation, where the simulation results for a year of operation have revealed that 76.04% in operation costs may be potentially saved, using the proposed system.

As compared to the DG alone, the break-even point of the proposed optimally controlled DG/Battery, with energy recovery, supplying the RTG crane may take place after 1.1 years, corresponding to USD 113 900.

The result of the true payback period analysis has shown that the overall investment cost, may be recovered in 1.36 years. Additionally, using the proposed system, the peak power demand on the DG has been reduced. This may assist in reducing the size of the DG by more than 50%, which may lower the initial cost of the system.

CHAPTER IV: OPTIMAL ENERGY MANAGEMENT OF A RTG CRANE SUPPLIED BY A HYBRID GRID/BATTERY WITH ENERGY RECOVERY CONSIDERING THE TIME OF USE AND MAXIMUM DEMAND CHARGES

4.1 INTRODUCTION

In this work, an optimal energy management model for the grid powered electric RTG, with a battery storage system, is developed. The aim of the model is to reduce the operation cost, by minimizing the component linked to the maximum demand charges from the grid, as well as the component linked to the Time of Use (ToU) pricing structure. As a case study, an RTG crane, operating in South Africa, has been selected. The load profile, the size of the battery storage system, ToU tariff, as well as the maximum demand charges, are used as input for the developed model. Simulations, for a complete RTG handling cycle, have been conducted to evaluate the techno-economic performances of the developed model, used to optimally dispatch the power flow in the system during the different phases of operation. Three main configurations have been simulated as energy sources for the RTG crane, namely, the exclusive supply from the grid, grid/battery hybrid system without energy recovery, during the lowering phase and grid/battery hybrid with energy recovery, during the lowering phase.

4.2 MODEL DEVELOPMENT

4.2.1. Proposed system description

The AC power, which is supplied from the grid to the RTG crane system, is converted to DC by the unidirectional rectifier, as seen in Figure 4.1. The DC power is distributed through the DC bus to the gantry, hoist, and trolley AC electric motors through their respective DC/AC inverters. During the lowering of the load, the hoist motor operates as a generator with the generated power passing to the DC link, which is recovered and stored in the battery bank, whose energy is further used to assist to lift the next load and minimise the need of power from the grid. It should be noted that solely the hoist and the battery converters may allow for a bidirectional power flow.

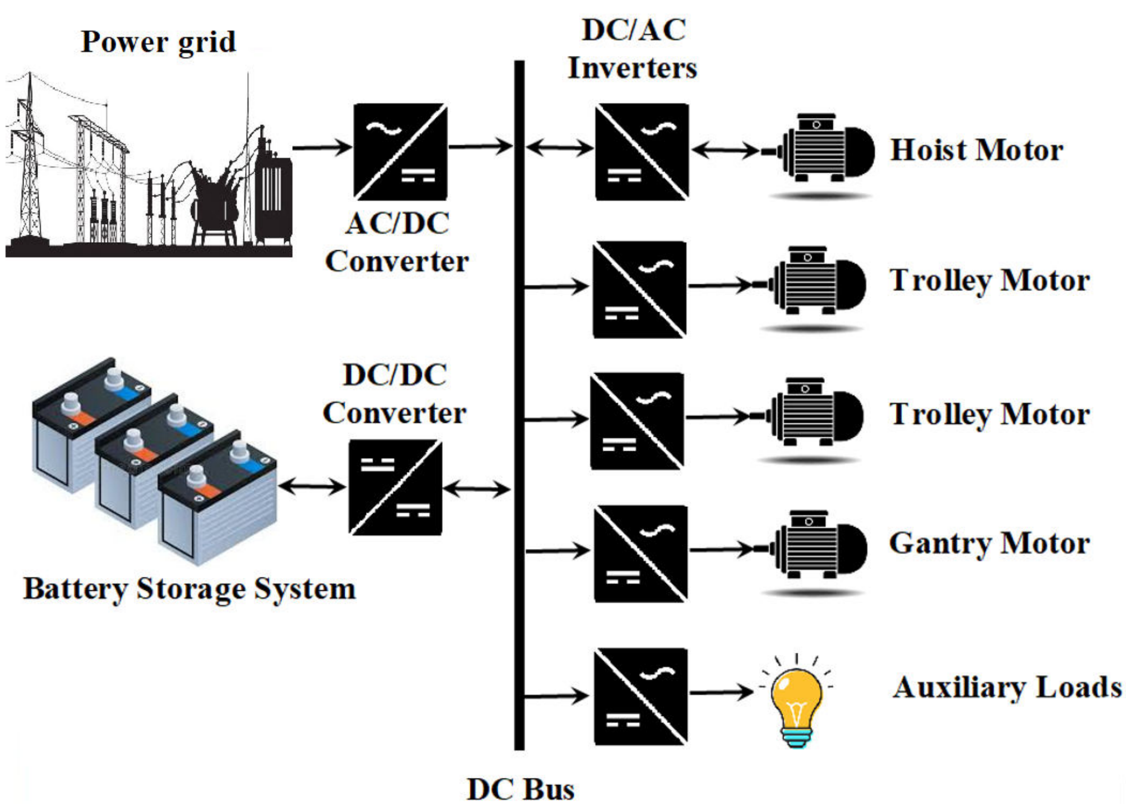

Figure 4.1: Grid powered RTG crane with its main electrical components

The different operation phases of an RTG crane are given in the following sequences: hoist up (with container), trolley right (with container), hoist down (with container), hoist up (without container), trolley left (without container) and hoist down (with container). During the first half cycle, the RTG handles a load, while it does not, during the second half cycle. Therefore, the load demand may either be positive during the hoist up, trolley left and right; or negative during the lowering processed.

4.2.2. Optimal energy management model of the grid powered RTG crane with a battery storage system

4.2.2.1 Proposed model's main powerflows

The system's main powerflows are seen in Figure. 4.2. The grid power may be used to supply the RTG crane motors (P_1) and/or to recharge the battery (P_2), depending on the SoC. Depending on the operating condition, the battery power (P_3) may be used alone or in conjunction with the grid, to supply the RTG motors. It should be noted that, during the energy regenerative process, the battery is recharged using the power recovered (P_4) from the hoist motor operating as a generator, while there is no power drawn from the grid. Therefore, an optimal power flow scheme should be implemented, to decrease the cost of power supplied from the grid, depending on the maximum demand charges, as well as on the applicable time of use tarrif.

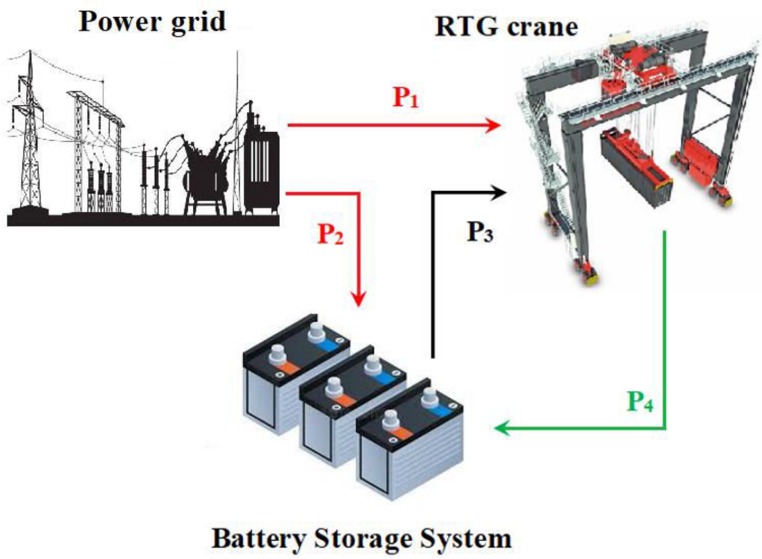

Figure 4.2: Main powerflows (control variables)

4.2.2.2 Objective function

The main aim of the model, is to minimize the total bill from the electricity supplied from the grid, based on the maximum demand charges, as well as on the ToU tariff. Additionally, the energy recovered through the regenerative process, during the lowering of containers, should be maximised. The objective function (*OF*) may be mathematically expressed as:

$$OF = \min \sum_{j=1}^{N} (\rho_j \times (P_{1(j)} + P_{2(j)}) \times \Delta t) + \min \sum_{j=1}^{N} (\delta_i \times (P_{1(j)} + P_{2(j)})) + \max \sum_{j=1}^{N} (P_{4(j)} \times \Delta t)$$

(4.1)

Where: ϱ_j is the grid energy cost linked to the applicable ToU; δ_j is the maximum demand charge over the considered optimization interval; j is the selected j^{th} interval where the optimization is taking place; N is the overall number of sample interval and Δt is the duration of each sampling interval.

The first part of the objective function ensures the minimization of the energy cost imported from the grid subjected to the ToU. The second part ensures the minimization of the maximum demand charges linked to the power imported from the grid. The third component ensures that the regenerative energy recovered is maximised through the battery charging process.

4.2.2.3 Load balance

From the operation given in Figure 4.2 the RTG demand balance may be given as:

$$P_{L(j)} = P_{1(j)} + P_{3(j)} - P_{4(j)} \tag{4.2}$$

This means that, for any selected sampling interval "*j*", the load may be supplied by either the grid or the battery; or operate in the regenerative braking mode.

4.2.2.4 Power grid constraints

For any sampling interval "*j*", the sum of powers drawn from the grid, needed to supply the RTG's demand or to recharge the battery, should be less or equal to the AC/DC converter's maximum power. This condition may be expressed as:

$$P_{1(j)} + P_2 \leq P_{Grid}^{Max} \tag{4.3}$$

4.2.2.5 Dynamics of the energy storage's SoC

For any given optimization interval "*j*", the resultant battery's SoC may be expressed as:

$$SoC_{(j)} = SoC_{(0)} \times (1-\alpha) + \frac{\Delta t}{E_n} \times \left(\eta_{ch} \times \sum_{i=1}^{j} (P_{2(j)} + P_{4(j)}) - \frac{\sum_{i=1}^{j} P_{3(j)}}{\eta_{disc}} \right)$$

(4.4)

Where: $SoC_{(j)}$ is the SoC at the considered optimization sample; $SoC_{(0)}$ is the SoC at the previous optimization sample; E_n is the nominal storage capacity of the considered battery in kWh; η_{ch} and η_{disch} are respectively the efficiencies of the battery's charging and discharging processes; and a is the battery self-discharging coefficient dependent on the selected battery type and condition.

4.2.2.6 Variables limits

Each control variable value, or power flow, may vary between a few limits, according to the system's design specifications, while following the manufacturers' operation specifications. For the proposed system, these may be modelled as:

$$P_1^{\min} \le P_{1(j)} \le P_1^{\max}$$

(4.5)

The power flow P_1 is limited by the size or power rating of the AC/DC converter.

$$P_2^{\min} \le P_{2(j)} \le P_2^{\max}$$

(4.6)

The power flow P_2 is limited by the power rating of the AC/DC converter as well as by the battery's maximum charging current and the system's voltage.

$$P_3^{min} \le P_{3(j)} \le P_3^{max}$$

(4.7)

The power flow P_3 is limited by the power rating of the considered battery storage system's DC/DC converter.

$$P_4^{min} \le P_{4(j)} \le P_{4(j)}^{max}$$

(4.8)

The power flow P_4 is limited by the peak power rating from the regenerative system, as well as by the battery's maximum charging current and the system's voltage.

The minimum SoC of the battery depends on the battery type, while the maximum SoC is constantly 100%. This may be modelled as:

$$SoC^{min} \le SoC_{(j)} \le SoC^{max}$$

(4.9)

4.2.2.7 Restricted power flows

This restriction is applied to power flows that may not occur concurrently in the same considered optimization sample. In the case of the battery, the charging and discharging processes may not occur simultaneously. Using Figure 4.2 this condition may be expressed as:

$$(P_{2(j)} + P_{4(j)}) \times P_{3(j)} = 0$$

(4.10)

Additionally, the regenerating braking mode may not take place when the load is being supplied by the grid or the battery (hoisting). This condition maybe expressed as:

$$(P_{1(j)} + P_{3(j)}) \times P_{4(j)} = 0$$

(4.11)

4.2.2.8 Fixed-final state condition

For the repeated execution of the optimization process, in subsequent optimization horizons, the battery's SoC, at the beginning, should be equal to the one at the end of the horizon. This condition may be modelled as:

$$\sum_{j=1}^{N}(P_{2(j)} + P_{4(j)} - P_{3(j)}) = 0$$

(4.12)

4.2.2.9 Processing steps of the developed energy management algorithm

The processing steps of the proposed energy management system, as depicted in Figure 4.2 can be summarised as follows:

- Step 1: Start the optimal control process for the open-loop scheme by identifying the different control variables.

- Step 2: Set the time horizon of the control structure and/or the control horizon for the open-loop scheme.
- Step 3: Read the energy flows on each component as well as the demand through the energy management system as described in Figure 4.1.
- Step 4: Compute the energy management system strategy based on equations 4.1 to 4.12.
- Step 5: Find the optimal solution of the control variables. If this solution is not optimal, repeat step 2 to 4 to get the optimal solution.
- Step 6: Generate the optimal solution for open loop.

4.2.2.10 Solver selection

Based on the maximum demand, as well as the exclusive nature of the power flows developed in the model, the problem to solve is of a nonlinear optimization nature. This may be solved using the Interior Point OPTimizer (IPOPT) in the OPTI-toolbox of MATLAB [20].

4.3 CASE STUDY DESCRIPTION

As stated previously, the cost of energy purchased from the grid, is defined by the ToU tariff. The ToU tariff structure consists of three pricing regions, which are: peak, standard and off-peak pricing [72]. The times at which these tariffs are charged, are depicted in Eq. (4.13), for the low demand season and Eq. (4.14), for the high demand season:

$$\rho(t)=\begin{cases}\rho_k; t\in T_k, T_k=[7,10)[18,20);\\ \rho_o; t\in T_o, T_o=[0,6)[22,24);\\ \rho_s; T_s, T_s=[6,7)[10,18)[20,22);\end{cases}$$

(4.13)

$$\rho(t)=\begin{cases}\rho_k; t\in T_k, T_k=[6,9)[17,19);\\ \rho_o; t\in T_o, T_o=[0,6)[22,24);\\ \rho_s; T_s, T_s=[9,17)[19,22);\end{cases}$$

(4.14)

Where: ϱ_k , ϱ_0 , ϱ_s are the energy cost during peak; off-peak and standard pricing period, respectively. The associated ToU and maximum demand charges, are given in Table 4.1.

The same demand as the one used in Chapter III is used here, for simulation purposes. The simulation parameters of the grid and battery, as well as other inputs to the developed model, are given in Table 4.1.

Table 4.1: Simulation parameters

Parameter	**Value**
Sample interval	2.5 second
Battery storage capacity	128 kWh
SoC_0	50%
SoC^{max}	100%
SoC^{min}	30%
η_{Ch}	85%
η_{Disc}	95%

Hoist motor	292 kW
Trolley motor 1	30 kW
Trolley motor 2	30 kW
ϱ_k (summer peak rate)	0.092 USD/kWh
ϱ_0 (summer off-peak rate)	0.054 USD/kWh
ϱ_s (summer standard rate)	0.063 USD/kWh
ϱ_k (winter peak rate)	0.189 USD/kWh
ϱ_0 (winter off-peak rate)	0.088 USD/kWh
ϱ_s (winter standard rate)	0.096 USD/kWh
Maximum demand rate	9.039 USD/kVA

4.4 SIMULATION RESULTS AND DISCUSSION

Simulations are conducted, to evaluate the effectiveness of the proposed optimal energy management model, applied to the grid powered RTG crane's demand, equipped with a battery storage system and regenerative energy capabilities, for a full load cycle (as described in Section 2). Three main scenarios are simulated and discussed. These are:

- The grid powered RTG crane (Baseline).
- The grid powered RTG crane with a battery storage system, without energy recovery.
- The grid powered RTG crane with a battery storage system, with energy recovery through regenerative braking.

Concerning the battery's sizing: modern, advanced, and accurate metaheuristic or deterministic optimization methods have been successfully used, to solve optimal sizing problems of hybrid energy systems. Therefore, this work does not confront the optimal sizing of the proposed system. The main goal of this work is to minimize the operation cost linked to the use of the grid and maximizing the potential energy recovered through the regenerative braking, that occurs during the lowering phase.

The RTG crane used in this work is the Hybrid Power Pack manufactured by Konecranes, which includes a high-power lithium battery pack, with an autonomy of approximately 2 hours [40]. The methodology for sizing the battery storage system, is reported in Ref [68].

4.4.1. Baseline: RTG crane's demand supplied by the grid only (peak pricing period of the ToU)

The sole supply of the RTG crane's load demand by the grid, is considered as the baseline for comparison with the developed optimal energy management model applied to the proposed hybrid system.

As a sole energy source, Figure 4.3 shows that the grid operates in a load following manner and the load factor is low.

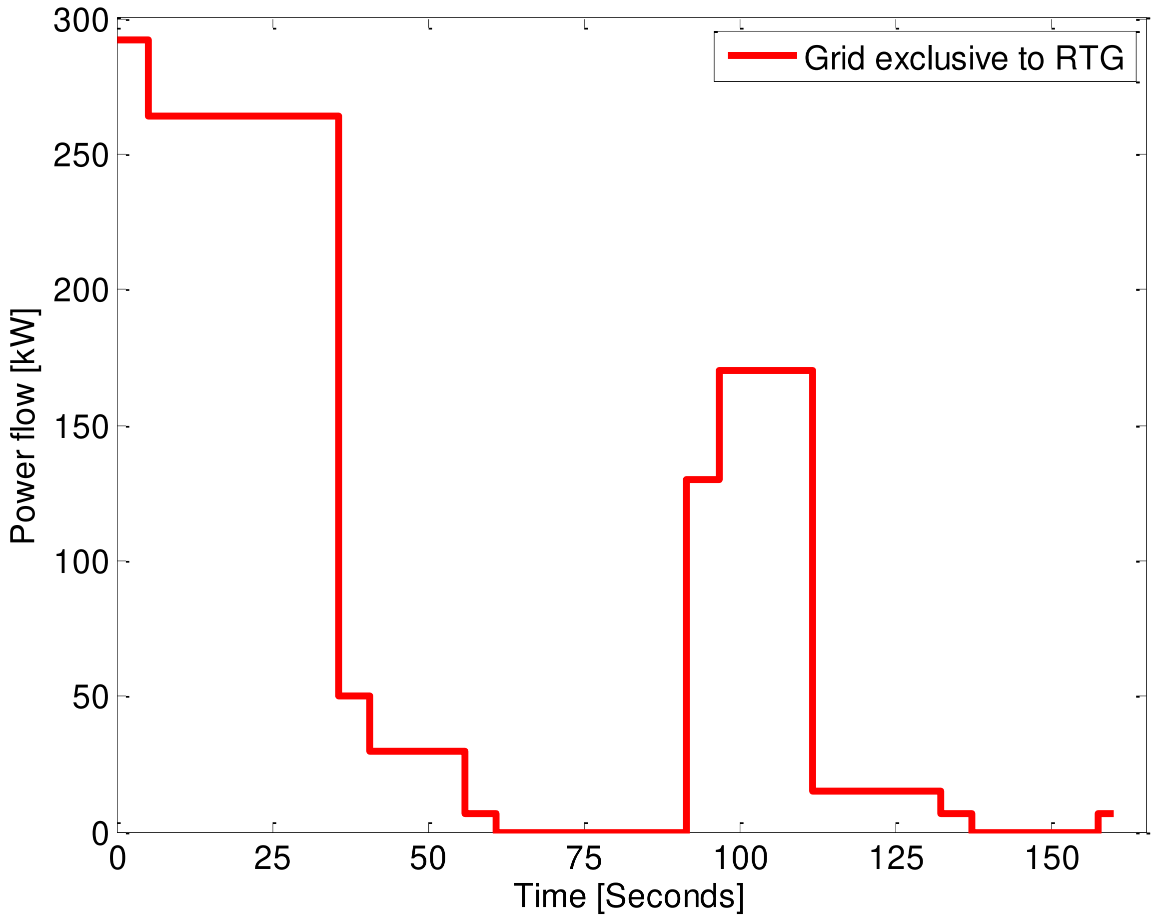

Figure 4.3: Baseline power profile (grid only)

4.4.2. The RTG crane's demand supplied by the grid and battery without energy recovery

In this case, the developed optimal energy management model is applied to the RTG crane, supplied by the grid and battery hybrid system. The role of the battery in this arrangement, is to supply the load demand, as well as to reduce the maximum demand charges and energy cost linked to the power supplied from the grid. Therefore, the RTG crane's load demand is supplied by the grid operating in conjunction with the battery storage in a hybrid system configuration. However, there is no energy recovery through the regenerative braking during the hoist down phase; the braking resistances are used to dissipate the generated energy into heat. This means that the battery may solely be recharged by the grid.

The powerflows in the system are managed using the developed optimization model. Figure 4.4 shows the operation strategies on the powerflows, while Figure 4.5 shows the corresponding SoC's dynamics, during the various operation phases.

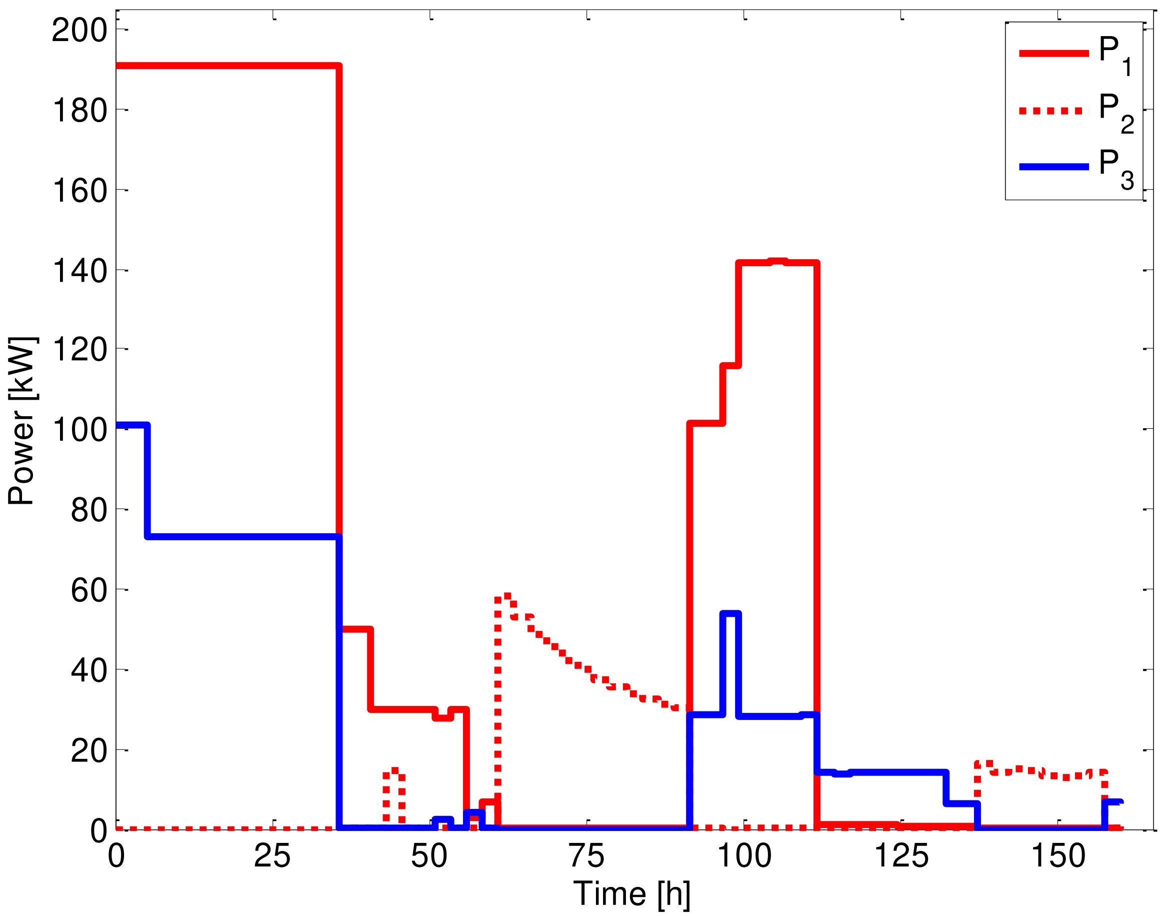

Figure 4.4: Hybrid Grid/Battery without energy recovery

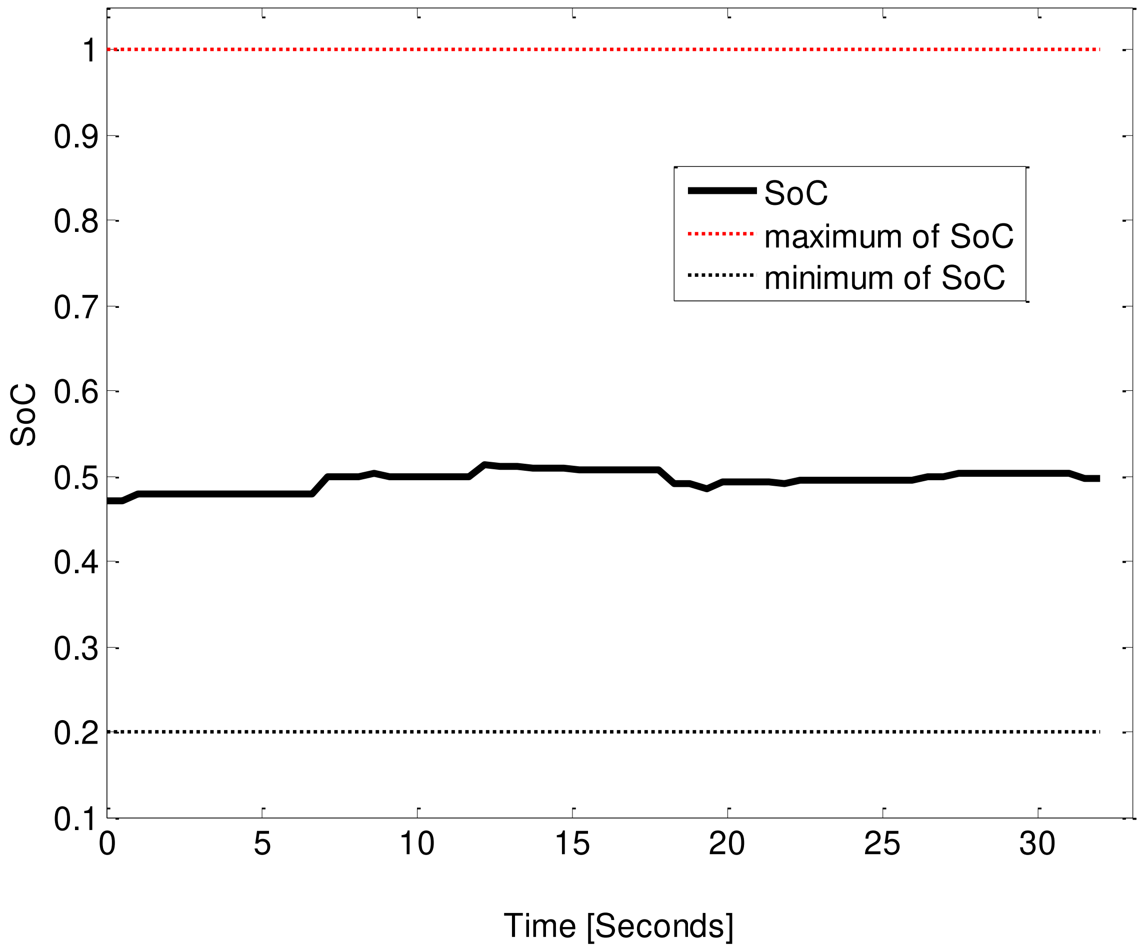

Figure 4.5: Dynamic of the SoC in the Hybrid Grid/Battery without energy recovery

4.4.2.1 Hoisting up phase

During the hoist up phase (at full load), Figure 4.4 shows that the load is supplied by the power from the grid, with a contribution of the power from the battery system.

4.4.2.2 Trolley left phase.

During this phase, the container is moved to the left using the trolley, which results in a lower load demand. Therefore, Figure 4.4 shows that the power required during this phase, is mainly supplied by the grid and is a small contribution of the battery to the load, occurring towards the end of this operating phase. It may further be noticed that the grid is further used to recharge the battery; the corresponding SoC of the battery shows a small increase, as shown in Figure 4.5.

4.4.2.3 Lowering load phase

During the hoist down phase (at full load), there is no power from the grid or from the battery to supply the load demand. It may be seen that, in Figure 4.4 the grid is used to recharge the battery, which is translated by a small increase in the corresponding SoC (Figure 4.5). It is usually at this stage, that the energy recovery through the regenerative braking system is achieved. However, in this case, it is assumed that there is no energy recovery, and the power is dissipated through the resistor brakes.

4.4.2.4 Hoisting up phase: No load

During this hoist up phase (at no load), Figure 4.4 shows that the load demand is supplied by the grid and the battery; the corresponding SoC decreases during this phase (Figure 4.5).

4.4.2.5 Trolley right phase: No load

During this phase, the trolley is being moved to the left (at no load) and the demand is principally met by the grid (Figure 4.4). The battery is neither charged nor discharged during this phase, as seen from the stationary SoC (Figure 4.5).

4.4.2.6 Hoisting down: No load

During this hoist down phase, Figure 4.4 shows that there is a lack of power from the grid to supply the load or to recharge the battery. Similarly, the battery is neither charged nor discharged during this phase, as seen from the stationary SoC (Figure 4.5).

4.4.3. The RTG crane's demand supplied by Grid/Battery with energy recovery

In this case, the RTG crane's load demand is supplied by the grid, operating in conjunction with the battery storage system. In addition, there is a possibility of energy recovery through the regenerative braking during the hoist down phase; this energy is converted and stored in the battery storage system. Therefore, the optimization model is applied to manage the power flows from the different sources, in addition to the power from the energy recovery system, to achieve the minimum operation cost and during a full handling cycle, taken as the optimization window.

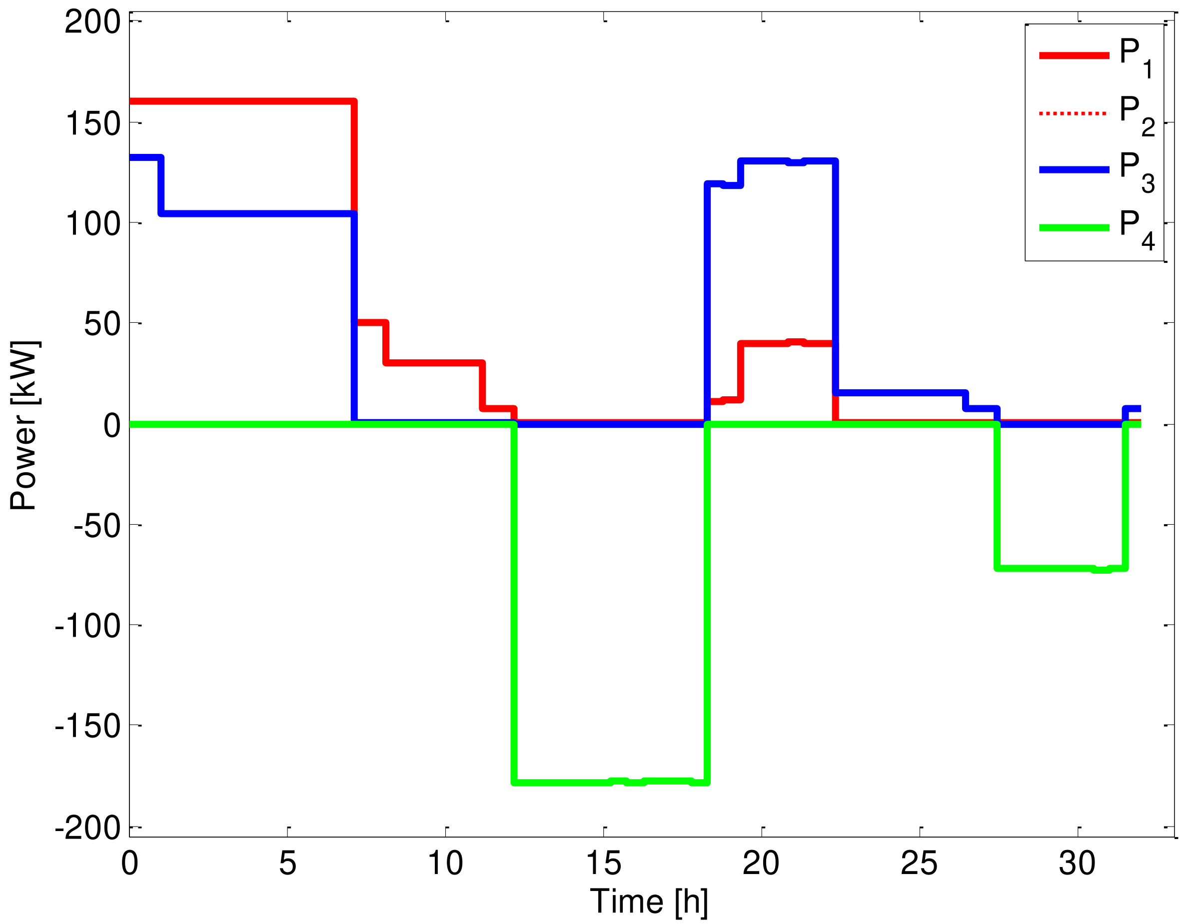

Figure 4.6: Hybrid Grid/Battery with energy recovery from the regenerative braking

The peak power demand is further reduced to 160 kW; corresponding to 45.2% reduction, compared to the baseline, where the grid is used alone to supply the RTG.

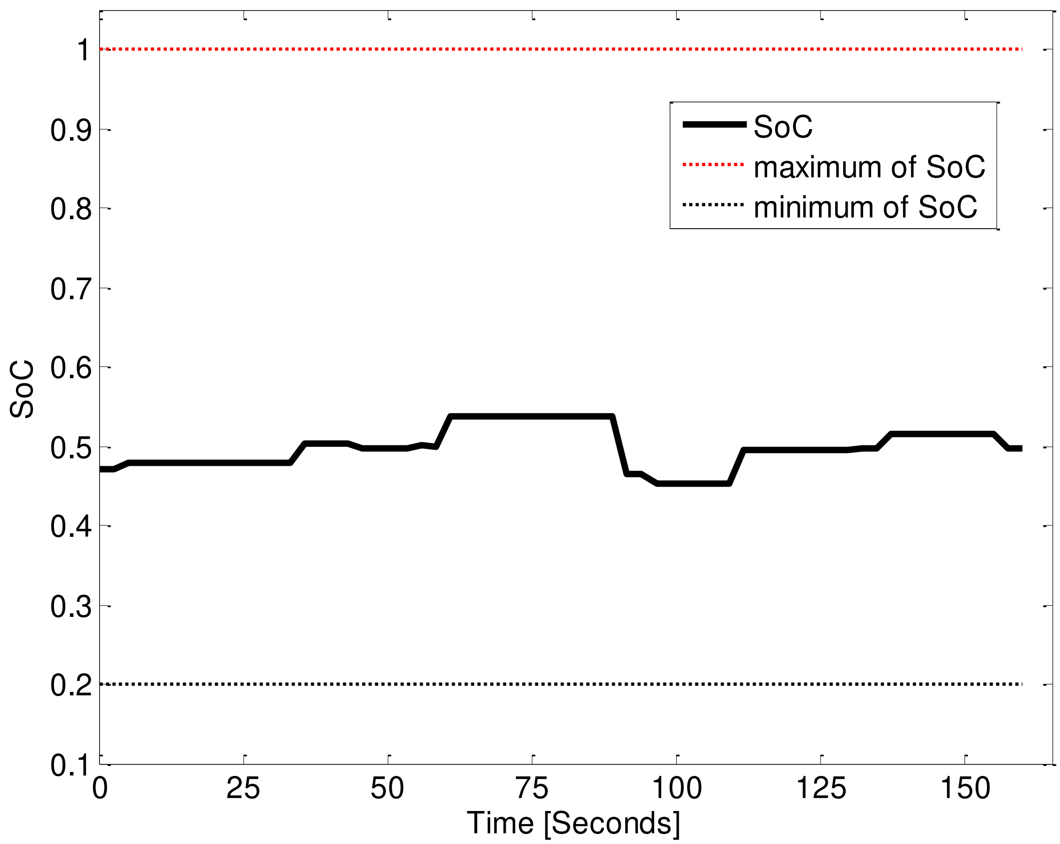

Figure 4.7: Dynamic of the SoC in the Hybrid Grid/Battery with energy recovery

4.4.3.1. Hoisting up phase

As in the previous case, Figure 4.6 shows that, during to hoist up phase, the load demand is met by the power from the grid, with a contribution of the power from the battery system.

4.4.3.2. Trolley left phase.

During this phase, where the loaded trolley is moved to the right, Figure 4.4 shows that the demand is principally met by the grid. The battery is not charged or discharged during this operating phase and the corresponding increase in the SoC, is shown on Figure 4.7.

4.4.3.3. Lowering load phase

During the hoist down phase, Figure 4.8 shows that there is a lack of power from the grid to supply the load demand or to recharge the battery. However, it may be seen that the energy recovery through the regenerative braking system takes place; this energy recovered is used to recharge the battery. An increase in the battery SoC is noticeable, from Figure 4.7.

4.4.3.4. Hoisting up phase: No load

During this hoist up phase, Figure 4.6 shows that the load demand is mainly supplied by the battery, with a small contribution of the power from the grid. The corresponding SoC decreases, as shown in Figure 4.7.

4.4.3.5. Trolley right phase: No load

During this phase, Figure 4.6 shows that the trolley is moved to the right (at no load) and the demand is exclusively met by the battery, while the grid power is not used. The corresponding SoC of the battery, is shown in Figure 4.7.

4.4.3.6. Hoisting down: No load

During this hoist down phase (at no load), Figure 4.6 shows that there is energy recovered through the regenerative braking, system and stored in the battery, which is translated by an increase in the SoC (Figure 4.7). Additionally, it may be clearly seen that the grid is not used (Figure 4.6).

4.5 ECONOMIC ANALYSIS

4.5.1. Results for the selected RTG handling cycle

The simulation results are further analysed, in terms of the economic performance of the optimally controlled grid powered RTG crane, with a battery storage system and energy recovery capabilities. The cumulative cost of the proposed optimally controlled system, versus the baseline, for a cycle during the off-peak pricing period of the ToU, are given in Figure 4.8, where the difference in cost may be noticed at the end of the considered simulation horizon.

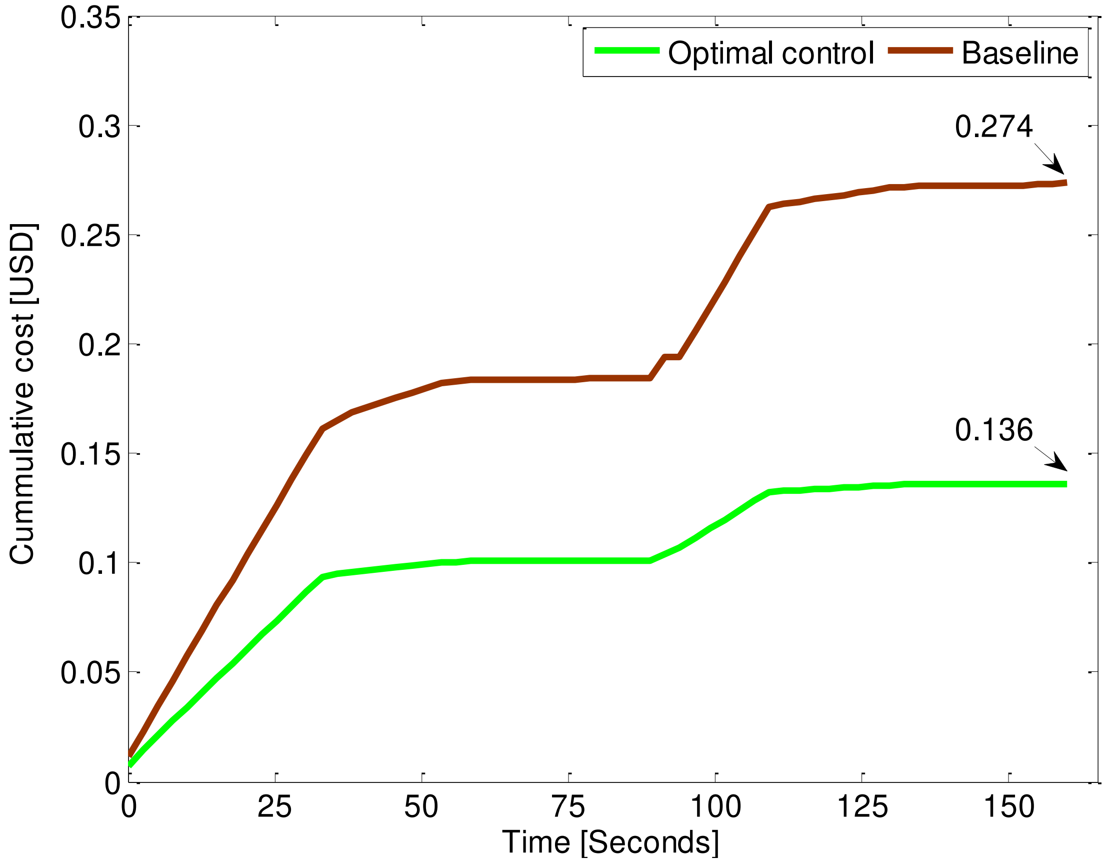

Figure 4.8: Cumulative ToU cost comparison between the Hybrid Grid/Battery with energy recovery and the baseline for the considered handling cycle

The same methodology may be followed for any full handling cycle, in any different pricing period.

Table 4.2 shows that a possible 50.36%, 60.6% and 64.4% cost reduction, per full handling cycle, is possible in off-peak standard and peak pricing periods, for the selected winter day. Table 4.2 further shows that the maximum demand charges, for a full load in any of the pricing period, is USD 2 639.39, when the baseline is considered. This may be reduced by 45.20%, to USD 1446.24, when the RTG crane is supplied by the optimally controlled hybrid system, with energy recovery.

Table 4.2: Cost comparison between the baseline and the optimal scheme for a winter day.

Supply options (Scenario)	**Off-peak ($)**	**Standard ($)**	**Peak ($)**	**Maximum demand charges ($)**
Baseline	0.274	0.467	1.028	2639.39
Hybrid system with energy recovery	0.136	0.184	0.368	1446.24
Savings (%)	*50.36*	*60.6*	*64.2*	*45.20*

4.5.2. Lifecycle analysis

Due to the intensive computation power required to perform the simulation, the analysis conducted in Section 4.5.1 was solely limited to one full load handling cycle of 160 seconds, where the operation cost was linked to the highest maximum demand charge, as well as the resultant energy cost in the peak ToU pricing period. However, given the stochastic nature of the weight to be handled in the various cycles; the energy used, energy recovered, as well as the length of the different cycles, will differ significantly. Therefore, there is a need to perform a lifecycle cost analysis, including all the different costs (initial, operation and maintenance, replacement), to better assess the economic benefits of the proposed system's savings, when compared to the baseline. The analysis is based on the worst operating case, where the RTG crane handles a full load of 40 T.

4.5.2.1. Annual cost analysis

As explained in Section 4.4, due to the computation power required to consider a daily optimisation horizon simultaneously, the simulations have been performed for each hour, in each pricing period separately and the results have been summed up to present the daily operation cost, achievable for the demand given in Figure 4.3. This is then extrapolated to present the yearly cumulative energy and maximum demand cost comparison between the proposed system, with energy recovery and the grid as baseline.

As discussed in Ref. [11], RTG cranes work continuously daily, up to 24 hours for 362 days a year and are only turned off for 3 days, for maintenance. Therefore, considering the daily operation cost computed, the annual cost may be calculated.

The daily cost is computed for each handling cycle, in all the various pricing periods for the low and high seasons, with the corresponding costs given under Section 4.3. This methodology is extended for the different months, to which the correspond maximum demand charge is added. In the worst case, with the highest considered load to handle, the maximum demand charges will be the same for all the months.

Table 4.3 presents the detailed cumulative yearly cost comparison between the electric RTG directly powered from the grid, with the optimally controlled hybrid grid/battery RTG crane, with energy recovery capabilities. The following may be noticed:

- The yearly energy cost based on the time of use has been reduced by 56.09%, from USD 77527.85 to USD 34037.94.

- The yearly maximum demand charge has been reduced by 45.2%, from USD 31672.68 to USD 17354.88.
- The proposed system achieved a reduction in the total annual electricity bill to 52.9%, from USD 109200.53 to USD 51392.82.

Table 4.3: Annual energy costs and maximum demand charges analysis

Supply option and pricing periods	**Grid cost per seasons (USD)**		**Year (USD)**
	Winter (days)	**Summer (days)**	
Off-peak	22.5*8*92*0.274 = 4537.44	22.5*8*270*0.2448 = 11897.22	16434.66
Standard	22.5*11*92*0.467 = 10633.59	22.5*11*270*0.3832 = 25607.34	36240.93
Peak	22.5*5*92*1.028 = 10639.8	22.5*5*270*0.4679 = 14212.46	24852.26
Maximum demand	2639.39*3 = 7918.17	2639.39*9 = 23754.51	31672.68
Total baseline	***33729***	***75471.53***	***109200.53***
Off-peak	22.5*8*92*0.136 = 2252.16	22.5*8*270*0.1047 = 5088.42	7340.58
Standard	22.5*11*92*0.184 = 4189.68	22.5*11*270*0.1642 = 10972.67	15162.35
Peak	22.5*5*92*0.368 = 3808.8	22.5*5*270*0.2379 = 7226.21	11535.01
Maximum demand	1446.24*3 = 4338.72	1446.24*9 = 13016.16	17354.88

Total proposed system	***14589.36***	***36803.46***	***51392.82***
Total savings	***19139.64***	***38668.07***	***57807.71***

4.5.2.2. Lifecycle cost analysis

The energy savings are further a function of the converters, as well as the battery storage system's size. Therefore, a lifecycle cost (LCC) analysis is conducted, to provide a better indication of the project cashflow over the system's operation lifetime, taken over 20 years. This may be computed as:

$$LCC = C_{I(i)} + C_{R(i)} + C_{OM(i)} + C_{EC(i)} - C_{S(i)}$$

(4.14)

Where: C_I, C_S, C_R, C_{OM} and C_{EC} are the initial cost, salvage cost, replacement cost, operation and maintenance costs, as well as energy cost respectively linked to each component of the system.

For simulation purposes, the yearly operation and maintenance cost is taken as 1% of the equipment initial cost; this is associated to an annual average inflation rate of 5.3% [69]. The bill of quantity for the additional equipment, to achieve the hybrid grid/Battery with energy recovery, is given in Table 4.4.

Table 4.4: Bill of quantity for the battery and inverter

Component	**Size**	**Price (USD)**	**Life(years)**
2 x Blue Nova Lithium Iron Battery 65kWh [72]	128 kWh	59 952.98	10

3 x ABB PVS 100KW Inverter Three Phase incl AC+DC Protection [73]	300 kW	30 221.88	20
Total capital		***90 174.86***	

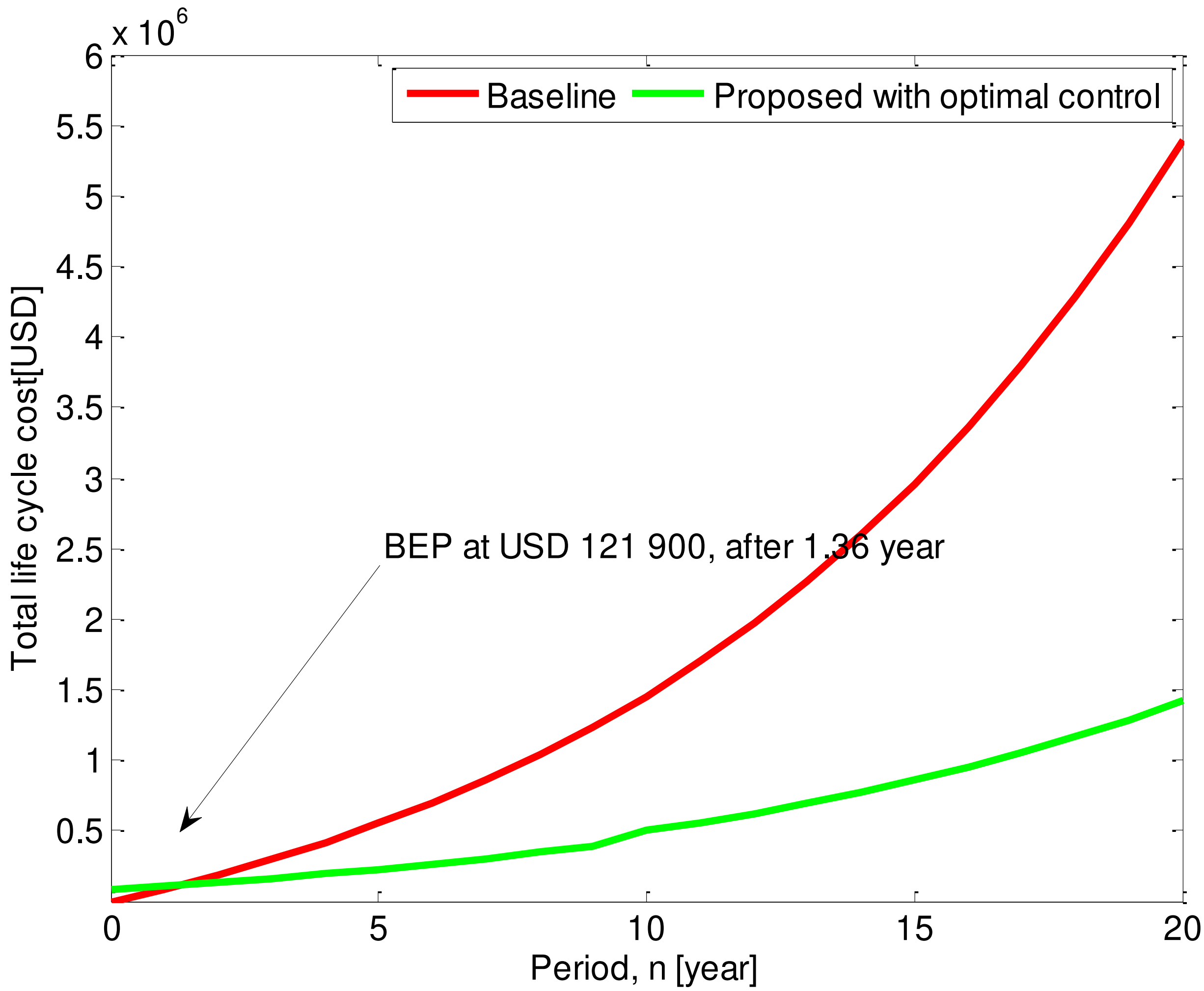

Figure. 4.9 The break-even point of the proposed optimally controlled hybrid grid/Battery

As compared to the baseline, Figure 4.9 shows that the break-even point of the proposed optimally controlled hybrid grid/Battery, with energy recovery, suppling the RTG crane, may take place after 1.36 year, corresponding to USD 121 900. For the 20 years' project lifetime, the computed lifecycle, in the case of the proposed optimally controlled grid/Battery with energy recovery is USD 1 425 000. However, when solely the baseline is considered, the projected lifecycle cost is USD 5 384 000. There is a potential cost saving of USD 3 950 000 corresponding to 73.53%

4.5.2.3. Payback Period

In addition to the LLC, a "true" payback period (PBP) analysis is conducted, to assess the economic performance of the system and discover the length of time it takes to recover the investment accumulated on the battery, as well as the bidirectional inverter from the operation cost saving, as compared to the baseline [71]. The true PBP may be computed as the quotient of the present worth of the total costs (PW_{TC}), to the yearly average of the present worth of the overall benefit ($PW_{TB\text{-}av}$).

$$"True"\ PBP = \frac{PW_{TC}}{PW_{TB-av}}$$

(4.15)

The PW_{TB} is computed as:

$$PW_{TB} = AB\left[\frac{(1+r)^n - 1}{r(1+r)^n}\right]$$

(4.16)

Where: AB is the yearly benefit and r is the rate.

Using the annual cost savings obtained in Section 4.5.2.1, the true payback period is computed, using the online tool available [73] and the results show that the simple payback period is 1.716 years. The true or discounted payback period is 1.978 years, and the cash flow return rate is 62.28% per year.

4.6 CONCLUSION

In this work, an optimal energy management model for the proposed system is developed, with the aim to reduce the ToU energy cost, as well as the maximum demand charges and maximize the recovery of energy through the regenerative braking, that takes place during the cargo lowering phase.

As a case study, a RTG crane operating in the Durban port, has been selected. The load profile, the grid charges, as well as of the battery storage system information, were used as input to the model developed. Simulations, for a complete full load RTG handling cycle, have been conducted to evaluate the techno-economic performances of the developed model used to optimally dispatch the power flow in the system, during the various phases of operation. Considering a 40 T full load, three main configurations have been simulated as energy sources for the RTG: namely grid alone, grid/Battery without energy recovery during the lowering phase, grid/Battery with energy recovery, during the lowering phase.

As compared to the baseline, the simulation results have shown that, using the proposed model, a possible 50.36%, 60.6% and 64.4% cost reduction, per full handing cycle, is possible in off-peak standard and peak pricing period, for the selected winter day. Table 2 further shows that the maximum demand charges, for a full load in any of the pricing period is USD 2 639.39, when the baseline is considered. This may be reduced by 45.20%, to USD 1446.24, when the RTG crane is supplied by the optimally controlled hybrid system, with energy recovery.

The yearly analysis has revealed that the break-even point of the proposed optimally controlled hybrid grid/Battery, with energy recovery, suppling the RTG crane, may take place after 1.36 years, corresponding to USD 121 900. For the 20 years' project lifetime, the computed lifecycle, in the case of the proposed optimally controlled grid/Battery with energy recovery, is USD 1 425 000. However, when solely the baseline is considered, the projected lifecycle cost is USD 5 384 000. There is a potential cost saving of USD 3 950 000, corresponding to 73.53%.

The result of the true payback period analysis has shown that the overall investment cost may be recovered in 1.716 years. Additionally, using the proposed system, the peak power demand on the grid has been reduced. This may assist in reducing the size of the inverter by more than 50% required, which may lower the initial cost of the system.

CHAPTER V: GENERAL CONCLUSION

5.1. SUMMARY AND CONCLUSION OF THE WORK

To increase their profitability and become environmentally friendly, seaports and rail terminals should reduce the energy costs and the CO_2 emission of their cargo handling equipment. Therefore, energy management strategies are put in place to achieve these goals. The aim of this work was the development of optimal energy management models of the proposed hybrid diesel/battery and hybrid grid/battery RTG cranes, respectively, to minimize the total electricity costs, supplying a RTG crane, enabled with energy recovery capabilities.

Therefore, Chapter II reviewed the available literature published on the efficiency improvement of RTG cranes, including the general operation and main components of a RTG crane, the energy monitoring of RTG cranes during their operations, the different energy storage systems used in retrofitting RTG cranes, as well as the various strategies and algorithms used for the optimal control and energy management of RTG cranes.

Chapter III developed an optimal energy management model for a RTG crane, supplied by a hybrid DG/battery system, with the aim to reduce the energy cost, by minimizing the amount of fuel consumed by the DG and maximizing the potential energy recovered through the regenerative braking that takes place during the lowering phase. The simulation results for a year of operation have revealed that 76.04% in operation costs may be potentially saved, using the proposed system. As compared to the DG alone, the break-even point of the proposed optimally controlled DG/Battery, with energy recovery, supplying the RTG crane, may take place after 1.1 years, corresponding to USD 113 900. The result of the true payback period analysis has shown that the overall investment cost may be recovered in 1.36 years. Additionally, using the proposed system, the peak power demand on the DG has been reduced. This may assist in reducing the size of the DG by more than 50%, which may lower the initial cost of the system.

Chapter IV developed an optimal energy management model for a hybrid grid/battery system, supplying an RTG crane enabled with energy recovery capabilities, with the aim to reduce the ToU energy cost, as well as the maximum demand charges and maximize the recovery of energy through the regenerative braking, that takes place during the cargo lowering phase. For the 20 years' project lifetime, the computed lifecycle, in the case of the proposed optimally controlled grid/Battery with energy recovery, is USD 1 425 000. However, when solely the baseline is considered, the projected lifecycle cost is USD 5 384 000. There is a potential cost saving of USD 3 950 000, corresponding to 73.53%. The result of the true payback period analysis has shown that the overall investment cost may be recovered in 1.716 years. Additionally, using the proposed system, the peak power demand on the grid has been reduced. This may assist in reducing the size of the inverter by more than 50% required, which may lower the initial cost of the system.

5.2. SUGGESTIONS FOR FURTHER RESEARCH

For further studies, the following aspects can be considered:

- Alternative renewable energy sources such as photovoltaic or wind energy conversion system, may be considered as a primary source of energy.

- The techno-economic impact of using energy storage systems, such as flywheel, fuel cell or supercapacitor should be studied.
- Closed loop optimal control approach should be studied, when working toward the implementation of the control method in real-time.
- Knowing that several RTG cranes operate simultaneously handling stochastic loads, studies should be extended to optimally manage their operation, considering the total maximum demand charges, as well as ToU charges for the considered harbour. This may include the "Peer to Peer" energy sharing concept between the suppliers and energy storages of the different hybrid RTG cranes operating in a harbour.

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APPENDICES

Appendix 1: OPTIMAL ENERGY MANAGEMENT MODEL OF A HYBRID DIESEL GENERATOR AND BATTERY SUPPLYING A RTG CRANE WITH ENERGY RECOVERY CAPABILITY

Main code

```
cycle=1;
division=32*cycle;
ts=1/2;
N=division/ts;
%time-of-use tariff
%-----------------------------------------------------------------------
```

```
%-----------------------------------------------------------------------

%Load Profile

PLoad_crane=[292*ones(1,1/ts),264*ones(1,1/ts),264*ones(1,1/ts),264*ones(1,1/ts),264*on
es(1,1/ts),264*ones(1,1/ts),264*ones(1,1/ts),50*ones(1,1/ts),30*ones(1,1/ts),30*ones(1,1/ts
),30*ones(1,1/ts),7*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),
0*ones(1,1/ts),0*ones(1,1/ts),130*ones(1,1/ts),170*ones(1,1/ts),170*ones(1,1/ts),170*ones(
1,1/ts),15*ones(1,1/ts),15*ones(1,1/ts),15*ones(1,1/ts),15*ones(1,1/ts),7*ones(1,1/ts),0*on
es(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),7*ones(1,1/ts)]';

%----------------------------------------------------------------------

P4_max=[0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones
(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,
1/ts),178*ones(1,1/ts),178*ones(1,1/ts),178*ones(1,1/ts),178*ones(1,1/ts),178*ones(1,1/ts),
178*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),
0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),75*ones(1,1/ts),75*ones(1,1/ts),
75*ones(1,1/ts),75*ones(1,1/ts),0*ones(1,1/ts)]';

eff_batchar=0.85;

eff_batdisch=0.9;

Cn=2000; % Nominal capacity of the battery in kWh

Y=(eff_batchar*ts)/(Cn);

Z=(ts/eff_batdisch)/Cn;

SoC_max=1;% maximum state of charge of battery

SoC_min=0.2;% maximum state of charge of battery

SoC_0=0.5*SoC_max; % Initial state of charge of battery

PDG_min=0;PDG_max=410; % in kW

P1_min=0;P1_max=410; % in kW
```

```
P2_min=0;P2_max=292; % in kW

P3_min=0;P3_max=292; % in kW

P4_min=0;

% in kW

%----------------------------------------------------------------------

%Objective function vector


 A1=[eye(N,N),eye(N,N),zeros(N,N),zeros(N,N)];

 A2=[zeros(N,N),-Y*tril(ones(N,N)),Z*tril(ones(N,N)),-Y*tril(ones(N,N))];

 A3=-A2;

 A=[A1;A2;A3];

 b1=PDG_max*ones(N,1);

 b2=(SoC_0-SoC_min)*ones(N,1);

 b3=(SoC_max-SoC_0)*ones(N,1);

 b=[b1;b2;b3];

 %Equality constraints

 Aeq=[eye(N,N),zeros(N,N),eye(N,N),zeros(N,N)];

 beq=PLoad_crane(1:N);

 %Boundary constraints

 lb=[P1_min*ones(N,1);P2_min*ones(N,1);P3_min*ones(N,1);P4_min*ones(N,1)];

 ub=[P1_max*ones(N,1);P2_max*ones(N,1);P3_max*ones(N,1);P4_max(1:N)];

 %----------------------------------------------------------------------

 %nonlinear Solver
```

```
options=optimset('Algorithm','interior-point');
 optnew=optimset(options,'MaxFunEvals',200000,'Tolx',1e-8);
x0=ub;
[x, fuel]=fmincon(@objective_PhiriDG,x0,A,b,Aeq,beq,lb,ub,@Phiri,optnew)
P1=x(1:N);
P2=x(N+1:2*N);
P3=x(2*N+1:3*N);
P4=x(3*N+1:4*N);
for i=1:N
    SoC(i)=SoC_0+Y*(P2(i)+P4(i))-Z*P3(i);
end
SoC=SoC(1:N);
%plots
%load profile
Figure (1)
stairs(linspace(0,division,N),PLoad_crane,':k')
hold on
ylabel('Power flow [kW]')
xlabel('Time [Seconds]')
legend('Load demand')
Figure (2)
plot(linspace(0,division,N),P1(1:N),'r','linewidth',1.5)
hold on
```

```
plot(linspace(0,division,N),P2(1:N),':r','linewidth',1.5)

hold on

plot(linspace(0,division,N),P3(1:N),'b','linewidth',1.5)

hold on

plot(linspace(0,division,N),P4(1:N),'g','linewidth',1.5)

ylabel('Power [kW]')

xlabel('Time [h]')

legend('P_1','P_2','P_3','P_4','maximum of P_D_G')

axis([0 division+1 0 0.55*max(PDG_max)]);

Figure (3)

stairs(linspace(0,division,N),P2(1:N),'k','linewidth',1.5)

hold on

stairs(linspace(0,division,N),PDG_max*ones(1,N),':r','linewidth',1.5)

ylabel('P_2 [kW]')

xlabel('Time [Seconds]')

legend('P_2','maximum of P_2')

axis([0 division+1 0 1.05*max(PDG_max)]);

Figure (4)

stairs(linspace(0,division,N),P3(1:N),'k','linewidth',1.5)

hold on

stairs(linspace(0,division,N),PDG_max*ones(1,N),':r','linewidth',1.5)

ylabel('P_3 [kW]')

xlabel('Time [Seconds]')
```

```
legend('P_3','maximum of P_3')

axis([0 division+1 0 1.05*max(PDG_max)]);

Figure (5)

stairs(linspace(0,division,N),P4(1:N),'k','linewidth',1.5)

hold on

stairs(linspace(0,division,N),PDG_max*ones(1,N),':r','linewidth',1.5)

ylabel('P_4 [kW]')

xlabel('Time [Seconds]')

legend('P_4','maximum of P_4')

axis([0 division+1 0 1.05*max(PDG_max)]);

Figure (6)

stairs(linspace(0,division,N),SoC(1:N),'k','linewidth',1.5)

hold on

stairs(linspace(0,division,N),SoC_max*ones(1,N),':r','linewidth',1.5)

hold on

stairs(linspace(0,division,N),SoC_min*ones(1,N),':k','linewidth',1.5)

ylabel('SoC')

axis([0 division+1 0.1 1.05*max(SoC_max)]);

xlabel('Time [Seconds]')

legend('SoC','maximum of SoC', 'minimum of SoC')
```

Objective function

```
function y=objective_PhiriDG(x)

cycle=1;

division=32*cycle;

ts=1/2;

N=division/ts;

fc=14;

a=0.0074;

b=0.233;

c=0.4200;

y=fc*(ts*(sum(a*(x(1:N).^2)+b*x(1:N)+c))+ts*(sum(a*(x(N+1:2*N).^2)+b*x(N+1:2*N)+c)
)-ts*(sum(x(3*N+1:4*N))));

end
```

Non-linear constraints

```
function [c,ceq]=Phiri(x)

format long

cycle=1;

division=32*cycle;

ts=1/2;

N=division/ts;

 for i=1:N

   ceq1=x(N+1:2*N).*x(2*N+1:3*N);
```

```
  ceq2=+x(3*N+1:4*N).*x(2*N+1:3*N);
  ceq3=x(1:N).*x(3*N+1:4*N);
  ceq4=x(2*N+1:3*N).*x(3*N+1:4*N);
end
c=[];
ceq=[ceq1(1:N),ceq2(1:N),ceq3(1:N),ceq4(1:N)]';
```

Appendix 2: OPTIMAL ENERGY MANAGEMENT OF A RTG CRANE SUPPLIED BY A HYBRID GRID/BATTERY WITH ENERGY RECOVERY CONSIDERING THE TIME OF USE AND MAXIMUM DEMAND CHARGES

```
cycle=1;
division=32*cycle;
ts=1/2;
N=division/ts;
%time-of-use tariff
%------------------------------------------------------------------------
%Commercial TOU
off_peak=0.6146; std=0.9642; peak=1.397;  % Rand/Kwh Summer Commercial TOU tariff
cm=[peak*ones(1,32/ts)]';
```

```
md=[138.58*ones(1,32/ts)]';

%-----------------------------------------------------------------------

%Load Profile

PLoad_crane=[292*ones(1,1/ts),264*ones(1,1/ts),264*ones(1,1/ts),264*ones(1,1/ts),264*ones(1,1/ts),264*ones(1,1/ts),264*ones(1,1/ts),50*ones(1,1/ts),30*ones(1,1/ts),30*ones(1,1/ts),30*ones(1,1/ts),7*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),130*ones(1,1/ts),170*ones(1,1/ts),170*ones(1,1/ts),170*ones(1,1/ts),15*ones(1,1/ts),15*ones(1,1/ts),15*ones(1,1/ts),15*ones(1,1/ts),7*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),7*ones(1,1/ts)]';

%----------------------------------------------------------------------

P4_max=[0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),178*ones(1,1/ts),178*ones(1,1/ts),178*ones(1,1/ts),178*ones(1,1/ts),178*ones(1,1/ts),178*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),0*ones(1,1/ts),75*ones(1,1/ts),75*ones(1,1/ts),75*ones(1,1/ts),75*ones(1,1/ts),0*ones(1,1/ts)]';

eff_batchar=0.85;

eff_batdisch=0.9;

Cn=3000; % Nominal capacity of the battery in kWh

Y=(eff_batchar*ts)/(Cn);

Z=(ts/eff_batdisch)/Cn;

SoC_max=1;% maximum state of charge of battery

SoC_min=0.2;% maximum state of charge of battery

SoC_0=0.5*SoC_max; % Initial state of charge of battery

PDG_min=0;PDG_max=410; % in kW
```

```
P1_min=0;P1_max=410; % in kW

P2_min=0;P2_max=292; % in kW

P3_min=0;P3_max=292; % in kW

P4_min=0;

% in kW

%------------------------------------------------------------------------

%Objective function vector

 A1=[eye(N,N),eye(N,N),zeros(N,N),zeros(N,N)];

 A2=[zeros(N,N),-Y*tril(ones(N,N)),Z*tril(ones(N,N)),-Y*tril(ones(N,N))];

 A3=-A2;

 A=[A1;A2;A3];

 b1=PDG_max*ones(N,1);

 b2=(SoC_0-SoC_min)*ones(N,1);

 b3=(SoC_max-SoC_0)*ones(N,1);

 b=[b1;b2;b3];

 %Equality constraints

 Aeq=[eye(N,N),zeros(N,N),eye(N,N),zeros(N,N)];

 beq=PLoad_crane(1:N);

  %Boundary constraints

 lb=[P1_min*ones(N,1);P2_min*ones(N,1);P3_min*ones(N,1);P4_min*ones(N,1)];

 ub=[P1_max*ones(N,1);P2_max*ones(N,1);P3_max*ones(N,1);P4_max(1:N)];

 x0=lb;

 %----------------------------------------------------------------------
```

```
%nonlinear Solver
f=@(x)ts*sum(cm(1:N).*(x(1:N)))+ts*sum(cm(1:N).*x(N+1:2*N))-
ts*sum(x(3*N+1:4*N))+max(md(1:N).*(x(1:N))+md(1:N).*x(N+1:2*N));
nlcon=@(x)ts*sum(x(N+1:2*N).*(x(2*N+1:3*N))+x(3*N+1:4*N).*x(2*N+1:3*N)+x(1:N).
*x(3*N+1:4*N)+x(2*N+1:3*N).*x(3*N+1:4*N));
nlrhs = [];
nle=0;
xtype='';
for (each=1:N)
    xtype=[xtype,'CCCC'];
end
MyOptions= optiset
('solver','auto','display','iter','maxiter',20000000,'maxtime',100000000,'maxnodes',1000000000
0)
Opt=opti('fun',f,'nlmix',nlcon,nlrhs,nle,'ineq',A,b,'eq',Aeq,beq,'bounds',lb',ub','xtype',xtype,'o
ptions',MyOptions);
[x,fval,exitflag,info]=solve(Opt,x0');
info ,x=x';
P1=x(1:N);
P2=x(N+1:2*N);
P3=x(2*N+1:3*N);
P4=x(3*N+1:4*N);
PT=x(1:N)+x(N+1:2*N);
for i=1:N
```

```
    SoC(i)=SoC_0+Y*(P2(i)+P4(i))-Z*P3(i);
end
SoC=SoC(1:N);
for k=1:N
RTG_SUMMER_ToU_only_cost(k)=5.22*ts*sum(P1(1:k)*cm(1:k)+P2(1:k)*cm(1:k))/2763
0;
BaseLine_COST_ToU_only_PLoad_crane(k)=0.927*ts*sum(PLoad_crane(1:k).*cm(1:k))/1
4900;
end
TotalCost_Optimal=RTG_SUMMER_ToU_only_cost(1:N)+max(PT(1:N)*md(1:N));
TotalCost_Baseline=
BaseLine_COST_ToU_only_PLoad_crane(1:N)+max(PLoad_crane(1:N)'*md(1:N));
Savings=(TotalCost_Baseline(N:N)-TotalCost_Optimal(N:N))
%plots
%load profile
Figure (1)
stairs(linspace(0,division,N),PLoad_crane,':k')
hold on
ylabel('Power flow [kW]')
xlabel('Time [Seconds]')
legend('Load demand')
Figure (2)
stairs(linspace(0,division,N),P1(1:N),'r','linewidth',1.5)
hold on
```

```
stairs(linspace(0,division,N),P2(1:N),':r','linewidth',1.5)

hold on

stairs(linspace(0,division,N),P3(1:N),'b','linewidth',1.5)

hold on

stairs(linspace(0,division,N),-P4(1:N),'g','linewidth',1.5)

ylabel('Power [kW]')

xlabel('Time [h]')

legend('P_1','P_2','P_3','P_4')

axis([0 division+1 -0.5*max(PDG_max) 0.5*max(PDG_max)]);

Figure (3)

stairs(linspace(0,division,N),P2(1:N),'k','linewidth',1.5)

hold on

stairs(linspace(0,division,N),PDG_max*ones(1,N),':r','linewidth',1.5)

ylabel('P_2 [kW]')

xlabel('Time [Seconds]')

legend('P_2','maximum of P_2')

axis([0 division+1 0 1.05*max(PDG_max)]);

Figure (4)

stairs(linspace(0,division,N),P3(1:N),'k','linewidth',1.5)

hold on

stairs(linspace(0,division,N),PDG_max*ones(1,N),':r','linewidth',1.5)

ylabel('P_3 [kW]')

xlabel('Time [Seconds]')
```

```
legend('P_3','maximum of P_3')

axis([0 division+1 0 1.05*max(PDG_max)]);

Figure (5)

stairs(linspace(0,division,N),P4(1:N),'k','linewidth',1.5)

hold on

stairs(linspace(0,division,N),PDG_max*ones(1,N),':r','linewidth',1.5)

ylabel('P_4 [kW]')

xlabel('Time [Seconds]')

legend('P_4','maximum of P_4')

axis([0 division+1 0 1.05*max(PDG_max)]);

Figure (6)

plot(linspace(0,division,N),SoC(1:N),'k','linewidth',1.5)

hold on

plot(linspace(0,division,N),SoC_max*ones(1,N),':r','linewidth',1.5)

hold on

plot(linspace(0,division,N),SoC_min*ones(1,N),':k','linewidth',1.5)

ylabel('SoC')

axis([0 division+1 0.1 1.05*max(SoC_max)]);

xlabel('Time [Seconds]')

legend('SoC','maximum of SoC', 'minimum of SoC')

Figure(7)

plot(linspace(0,division,N),BaseLine_COST_ToU_only_PLoad_crane(1:N),':b','linewidth',2,'
HandleVisibility','on');
```

```
hold on

xlabel('Time [h]')

ylabel('Cost [ZAR]')

plot(linspace(0,division,N),RTG_SUMMER_ToU_only_cost(1:N),'k','linewidth',1.5,'Handle
Visibility','on');

hold on

xlabel('Time [h]')

ylabel('Cost [ZAR]')

legend('Baseline Cost','Optimal Cost','orientation','horizontal');

title('ToU Cost only')

Figure(8)

plot(linspace(0,division,N),TotalCost_Baseline(1:N),':b','linewidth',2,'HandleVisibility','on');

xlabel('Time [h]')

ylabel('Cost [ZAR]')

hold on

plot(linspace(0,division,N),TotalCost_Optimal(1:N),'k','linewidth',1.5,'HandleVisibility','on');

hold on

xlabel('Time [h]')

ylabel('Cost [ZAR]')

legend('Baseline Cost','Optimal Cost','orientation','horizontal');

title('ToU and Maximum demand (Total Cost)')
```

Appendix 3: LIFECYCLE COST ANALYSIS: DG COMPARED TO PROPOSED OPTIMALLY CONTROLLED DG/BATTERY

Year	Cumulative Costs						Life Cycle Costs	
	Energy Costs		Operation and Maintenance		Replacement Cost		BASELINE	PROPOSED
0	0	0	0	0	0	0	-	90 174,86
1	91137,120	21 832,99	-	901,75	0	0	91 137,12	112 909,60
2	191387,952	45 849,29	-	1 848,58	0	0	191 387,95	137 872,73
3	301663,867	72 267,21	-	2 842,76	0	0	301 663,87	165 284,83
4	422967,374	101 326,93	-	3 886,65	0	0	422 967,37	195 388,43
5	556401,231	133 292,61	-	4 982,73	0	0	556 401,23	228 450,20
6	703178,474	168 454,87	-	6 133,62	0	0	703 178,47	264 763,34
7	864633,442	207 133,35	-	7 342,04	0	0	864 633,44	304 650,25
8	1042233,906	249 679,68	-	8 610,90	0	0	1 042 233,91	348 465,43
9	1237594,417	296 480,64	-	9 943,19	0	0	1 237 594,42	396 598,69
10	1452490,978	347 961,70	-	11 342,10	0	55332,82	1 452 490,98	504 811,47
11	1699622,024	404 590,86	-	12 810,95	0	55332,82	1 699 622,02	562 909,49
12	1971466,175	466 882,94	-	14 353,25	0	55332,82	1 971 466,17	626 743,87
13	2270494,740	535 404,23		15 972,66	0	55332,82	2 270 494,74	696 884,56

			-					
14	2599426,162	610 777,64	-	17 673,04	0	55332,82	2 599 426,16	773 958,36
15	2961250,727	693 688,40	-	19 458,44	0	55332,82	2 961 250,73	858 654,52
16	3359257,748	784 890,24	-	21 333,11	0	55332,82	3 359 257,75	951 731,03
17	3797065,470	885 212,25	-	23 301,51	0	55332,82	3 797 065,47	1 054 021,45
18	4278653,966	995 566,47	-	25 368,34	0	55332,82	4 278 653,97	1 166 442,49
19	4808401,310	1 116 956,11	-	27 538,50	0	55332,82	4 808 401,31	1 290 002,30
20	5391123,389	1 250 484,72	-	29 817,18	0	55332,82	5 391 123,39	1 425 809,58

Appendix 4: LIFECYCLE COST ANALYSIS: GRID COMPARED TO PROPOSED OPTIMALLY CONTROLLED GRID/BATTERY

Year	**Cumulative Costs**						**Life Cycle Costs**	
	Energy Costs		Operation and Maintenance		Replacement Cost		BASELINE	PROPOSED
0	0	0	0	0	0	0	-	90 174,86
1	109200,530	51 392,82	-	901,75	0	0	109 200,53	142 469,43
2	229321,113	107 924,92	-	1 848,58	0	0	229 321,11	199 948,37
3	361453,754	170 110,23	-	2 842,76	0	0	361 453,75	263 127,86
4	506799,660	238 514,08	-	3 886,65	0	0	506 799,66	332 575,59
5	666680,156	313 758,31	-	4 982,73	0	0	666 680,16	408 915,90
6	842548,701	396 526,96	-	6 133,62	0	0	842 548,70	492 835,43
7	1036004,101	487 572,47	-	7 342,04	0	0	1 036 004,10	585 089,38
8	1248805,042	587 722,54	-	8 610,90	0	0	1 248 805,04	686 508,29
9	1482886,076	697 887,61	-	9 943,19	0	0	1 482 886,08	798 005,66
10	1740375,213	819 069,19	-	11 342,10	0	55332,82	1 740 375,21	975 918,97
11	2036487,721	952 368,93	-	12 810,95	0	55332,82	2 036 487,72	1 110 687,56
12	2362211,480	1 098 998,65		14 353,25	0	55332,82	2 362 211,48	1 258 859,57

			-					
13	2720507,615	1 260 291,33	-	15 972,66	0	55332,82	2 720 507,62	1 421 771,67
14	3114633,364	1 437 713,28	-	17 673,04	0	55332,82	3 114 633,36	1 600 894,00
15	3548171,687	1 632 877,43	-	19 458,44	0	55332,82	3 548 171,69	1 797 843,55
16	4025063,843	1 847 558,00	-	21 333,11	0	55332,82	4 025 063,84	2 014 398,79
17	4549645,214	2 083 706,62	-	23 301,51	0	55332,82	4 549 645,21	2 252 515,81
18	5126684,722	2 343 470,10	-	25 368,34	0	55332,82	5 126 684,72	2 514 346,12
19	5761428,181	2 629 209,93	-	27 538,50	0	55332,82	5 761 428,18	2 802 256,11
20	6459645,986	2 943 523,74	-	29 817,18	0	55332,82	6 459 645,99	3 118 848,60