A survey of technical efficiency in crane systems using POET structure

SF Phiri¹, K Kusakana² and BP Numbi³

¹,³ Department of Electrical, Electronic and Computer Engineering
² Central University of Technology Bloemfontein, South Africa
Email: phirisf@gmail.com¹, kkusakana@cut.ac.za², numbi.papy@gmail.com³.

Abstract. Aiming at operating characteristic of the rubber tyre gantry crane (RTG), the present development aiming to propose an ESS (double power) energy saving system of RTG, which uses a battery pack as the main supply or control. The battery pack may supply all electric operations of RTG for a period of time, realizing the complete matching between the output power supply and the equipment control demands for the whole process to increase energy efficiency, achieving recovery and recycling for the RTG braking energy. Due to the challenge of demand side management, the RTG crane system will be reconsidered from the POET (performance, operation, equipment, and technology efficiency) outlook, showing the possibilities and would be a control of engineering approach for the efficiency of energy as well as demand side management. Once the storage system is put into operation, it would run the most efficient economical fuel consumption area, achieving the highest fuel efficiency.

1. Introduction
Presently, safety for the environment and savings of energy are the essential matters in a seaport. The container terminals are fast-growing and are challenged with the increase of fuel prices, therefore focusing on both operational costs’ reduction and the environment benefits, through a significant reduction of greenhouse gases and sound, would be valuable. Thus, by doing the research, the port terminal requests (advanced through by obtaining larger equipment, improvement of tracking and dispatching, and increasing productivity) and terminal encounters (use of fuel and discharges, costs saving) the countless energy-saving solutions have been prepared in the previous years for greener transportation. Rubber Tyred Gantry (RTG), possibly the world’s largest rubber tyred vehicle, are movable equipment used around the terminal, to load and unload containers onto ships or trucks. Predictable RTGs are driven by electric motors which are powered by sizeable on-board generation circles [1]. A few alternatives of RTG are diesel grid-connected electric, Genset-electric, and hybrid electric. A conventional diesel Genset-electric RTG uses a diesel-fuelled engine, to generate electricity, to power electric motors to lift the container, including the motive power to move the RTG along the container stack. An RTG diesel Genset used in the port procedure rated in a diesel engine, on average, is approximately 600 horsepower [2].

Currently, a change of both technologies and systems availability, for reducing fuel consumption and emissions may be recommended, improving the overall of RTG efficiency. Those technologies are flywheel energy storage, variable-speed generators, hybrid RTGs with regenerative breaking and super or ultra-capacitor technology, and electrified ‘zero-emission’ cranes [3]. Therefore, the energy efficiency of the RTG Crane components will be discussed below, based on their technological, performance, and operation.
1.1. Technologies of motors

![Figure 1](image1.png)

**Figure 1.** Energy consumption of different types of motors used in the RTG crane system

The container may be lifted by the electric motors and relocate the RTGs along with the container stack. When in the appropriate position, the container will be lowered to a controlled rate by the RTG. In a conventional RTG, when a container is lowered, the available energy would be wasted. In contrast, a hybrid RTG configuration captures the energy associated with reducing a container and stores it in an energy storage system. The power is released on a subsequent container lift – the net amount of electricity required by the diesel generator. The analyses of various motors used in the RTG crane system will be significant as to how multiple motors are being used to distribute energy.

Figure 2 below shows the RTG crane system with the hoisting motor, trolley, or gantry motors linked to a DC bus, powered by the primary energy source through a rectifier. When the motors request power (e.g. lifting a container), the DC bus voltage decreases, and when the motors regenerate power (e.g. lowering a container) it increases. The regenerated power is fed into the DC bus, permitting other motors to use part of the recovered energy. In contrast, all the extra energy dumped into the brake resistors which activate when the DC bus voltage reaches a threshold. 60% of energy is used on the hoisting motors, while 30% was used on the gantry motor. Therefore, the overall lifting energy ranges from 413.4 to 517.5 kWh, while the entire lowering power varies from 357.5 to 457.2 kWh on a typical day [4]. The same paper presents the investigation for RTG Cranes in energy usage. It may be determined that, generally, almost part of the consumed energy will be recoverable. Therefore, the power being recovered would be used to perform the next container lift to limit the peak demand. As a result of the primary energy source, the overall efficiency of the system increases as the need reduces.

The presentation indicates various situations, that shows the energy-saving possibilities carried out in port terminals about the recycled energy wasted [5]. The first situation presents the performance of two RTG cranes power through ESS connected to the DC bus. In the second situation, the use of an Active Front-End (AFE) converter is introduced, instead of the ESSs. The AFE converter being connected to the DC bus, which shifted the excess power back through the AFE converter, connected to the feeder substation via a three-phase AC cable.
Both circumstances have reached the expected energy saving concerning the energy produced by the hoist motor. The AFE plays an essential role in decreasing the primary energy demand of the terminal. Further, it decreases the potential of terminal shutdowns. Both exposed the ability of reused the energy generated by the hoist motor and, hence, shown the possibility of reducing the energy consumption in RTG and port terminals.

### 1.2. Motors as equipment

The AC variable frequency motors should be equipped with anti-condensation heaters. The motors of the same rating should be identical and interchangeable. All motors should have overload protection, which isolates phases with adjustable thermal/magnetic devices. The breakers and overload devices should send a signal via auxiliary contacts, with regards to their status and faults, to the safety logic and to the fault indication PC. The speed of these various motors has been discussed, as well as their standard maintenance [6]. Table 1 explains the different specifications of motors used in the RTG crane system.

A Variable Speed Drive (VSD), may supply the energy security by solely consuming the power required, compared to contactors and soft-starters for energy saving. This could be used as an energy alert component that would regularly check for the lift overload so that the crane may not lift the work when overloading is discovered. VSDs are estimated to save energy in the RTG system. The speed of a motor in an industrial application, improving the efficiency of the systems, and savings in energy consumption may be controlled by the use of VSD devices [7]. S. Khushiev and O. Ishnazarov, presented the applications overview of VDS in electrical motor energy savings and energy used. The principle operation of VSD is aligned with the attraction laws. Meaning, the electrical torque of a motor is proportional to the square motor speed, and the motor power is related to the cube of motor speed. In conclusion, VSDs applications on electrical motor have improved the system efficiency and saved the energy consumption, and as well as protecting the electrical motors from damage [8, 9].
Table 1. Specification of motors used in RTG crane system

| Gantry travel motors          | Trolley drive Motors                           | Hoist motor                             |
|------------------------------|-----------------------------------------------|-----------------------------------------|
| Four motors as a minimum, with max. power of 45 kW each | Motors with max. total power of 40 kW         | Motors with max. power of 200 kW        |
| Winding Insulation min. “Class F” | Winding insulation min. “Class F”           | Winding Insulation min. “Class F”       |
| Protection min. IP 56.        | Protection min. IP55.                         | Protection min. IP56.                   |
| Type of work S3 – 60%         | Type of work S3 – 60%                         | Type of work S3 – 60%                   |

2. Active level

RTGs use power to perform work against gravity, using a hoist motor to lift containers. Yet, while dropping that same motor, it acts as a generator, providing electrical braking. The power is naturally dissipated as heat through dump resistors via a fast-acting switch known as a chopper. The chopper is described as a static power electronics device, which is used to change fixed DC power to variable DC power; it may further increase or decrease the DC voltage at its opposite side and further known as a DC transformer [10]. The power supply switching-mode is an electronic power source that uses a switching regulator to control the conversion of electrical power in a highly efficient manner (thus lowering heat dissipation) [11].

Regenerative Energy: during the operation, the motors produce the regenerative energy created by the hoist, while decelerating and lowering. The regenerated power may be changed into heat using a braking resistor, conditioned and sent back to the source. This would be energy savings. An AC regenerative drive will reallocate that energy and would be wasted when converted to heat with a braking resistor, DC/DC converters are further known as Switching Regulators. The level of the voltage available from a DC source, such as a battery, solar cell, or a fuel cell, will be changed by the circuits to another DC level. It may either supply a DC load or be used as an intermediate voltage for an adjacent power electronic conversion, such as a DC/AC converter. The coupling of AC/DC converters allows for the use of high voltage DC (HV DC) transmission, which is approved in transmission lines throughout the world [12][13]. The devices of Choppers are IGBT, Power MOSFET, etc. (for lower power application) and SCR or Thyristor (for high power application). As the higher efficiency, smaller size, or lighter weight is required, switching regulators may be used as replacements for the linear regulators.

Chunhe Chang et al. [14] analysed the RTG crane energy flows relation in solving the existing problem that the RTG Crane consumes massive generating energy through resistance, produces plenty of heat, causes excessive fuel consumption, and exhaustion discharge, during operation. Firstly, it suggested that the structure and principle of RTG energy saving systems, as well as the topology and principle of the bi-directional DC/DC converter to be studied. They further proposed a voltage equalization method for RTG power-saving systems, an active voltage equalization method. It used the design of active voltage equalization circuit parameters and control strategies, after analysing a model for super-capacitor voltage equalization strategy. The analysis of the series connection of the super-capacitor’s module simulation came out. Therefore, most importantly, energy-saving improvement is confirmed. As their results, the simulation result confirmed that the active control circuit might be more useful for solving the problem of the partial over-voltage of the super-capacitor groups. This may further be applied on occasion for higher charging or discharging of currents. Therefore, it may be suggested to be used in the RTG energy-saving system. In [15] presented a Model Predictive Control (MPC) controller, to be used by an operator in network distribution, to control the energy systems on the low voltage network and further supply domestic customers. The MPC controller combines a deterministic forecast, intending to maximise the reduction of the peak for the distribution network. MPC aimed to
lower an application of voltage networks, which include high doubts in-demand applications, further decreasing the cost of operation and increasing the system’s efficiency. An optimisation scheme for an islanded micro-grid using an MPC strategy has been developed. The use of a multi-step MPC controller was carried out so as to control both the diesel power sources and renewable energy sources so that an ESS minimises the energy cost operation [16].

The stochastic prediction loads, with MPC models scenario of a microgrid system with Electric Vehicle (EV) integration, is presented in [17]. Moreover, they developed an advanced forecasting model based on the knowledge of EVs charging schedules, giving an awareness of when the electric vehicle requires charging. The MPC controller used the highest possible charging loads when there are unknown charging requests.

3. Technical level

To find the energy consumption levels of the various components of terminal equipment, it is essential to record the existing equipment and further the energy consumed by each type of equipment. Additionally, the output of each category should be defined.

An Energy Storage System (ESS), is an important tool for an ecosystem energy-efficient and benefits environment reduction concerns. ESS’s are more frequently applied to a varied range of demand-side applications. The ESS may further be valuable in energy cost reduction and avoiding the need to upgrade the distribution network. This may be done by fluctuating energy consumption from peak to valley periods peak demand [18]. Flywheels are required to store energy efficiency of 90%, unlike other storage systems, and hence, they discharge rates faster. [19, 20]. The less energy loss, meaning that if the same energy being stored in both a battery and a flywheel, and after a certain time, the lost energy, without saving energy in the battery, will be greater than the energy lost by the flywheel energy storage. Therefore, the flywheel energy storage system is recommended to be the power storage system of the future [21, 22].

The basic layout of the energy storage system for flywheel has been deliberated and further how the kinetic energy stored in a flywheel could be expressed [23, 24]. The super-capacitors may also be used as a storage device. It is currently being applied in many fields, such as peak power demand and regenerative braking. To reuse the RTG renewable energy, the super-capacitor may be associated with regenerative braking in a ‘hoist-down’ braking operation that contributes to energy recovery and the rapid energy consumption related to acceleration operations of a rubber tyred gantry crane (RTGC) [25]. Later, energy will be saved, which is conventionally lost by a brake [26].

The super-capacitors have two outstanding features that are; they have the energy density that is much larger than the conventional aluminium electrolytic capacitor and further has a more significant power density than that of the battery [27]. Then, this storage device may be applied as an energy buffer to the electric power system of a Crane system, which is explained for loading and unloading boxes in the container from a truck in the port, since it may power a load for longer than one with a low energy density.

Tan, Kai Hou and Fook Fah Yap [28, 29], defined the Flywheel Energy Storage System (FESS) as an energy regeneration system, for reducing peak power requirements on RTG cranes for up-load or unload container ships. The FESS usage was suggested, as the Port Operator may organise the undersized generators for new RTGs, as it would reduce the fuel consumption. They further investigated the energy amount and consumption of fuel, which may be in Rubber Tyred Gantry (RTG) cranes in container terminals to be reduced using software simulation. Therefore, a Variable Speed Generator is combined with the simulation-hybridized RTG. Their aim was to develop a hardware-in-the-loop simulator for a hybrid Rubber Tyred Gantry (RTG) crane, and also to optimize of the hybrid RTG crane design, in relation to cost performance. Their simulation results have been produced by using RTG crane and FESS mathematical models. Results revealed that the total 30% of energy savings was relative to conventional RTG. A hardware-in-loop system was introduced for validating the simulation results. The hardware components procured included a FESS, a Variable Frequency Drive (VFD), and brake resistors.

3.1. Technology efficiency
The development of a power management strategy (PMS) has been carried out for the control of storing energy in a system subjected to loads of random duration [30]. The costs associated with the energy consumption of specific systems were minimised, powered by the main energy source, and equipped with energy storage, assuming that the statistical distribution of load lengths is known. Holderbaum, William et al. [31] proposed a forecast model for a 24-hour three-phase active power for a single electrified RTG crane, using the Autoregressive integrated moving average exogenous variable (ARIMAX) and Artificial neural networks (ANN) methods. The analyses of the three-phase active power for locating the connection between the active power, containers gross weight, and the number of moves of an RTG crane throughout one hour. They were comparing the input matrix for the ANN and ARIMAX models. According to the MAPE results, the ANN is concluded to be more accurate.

Chunhe Chang et al. [32, 32] analysed the flows of energy relations of the RTG crane system. To solve the existing problem of a Rubber Tyred Gantry (RTG) Crane with consuming enormous generating/braking energy through resistance, produces plenty of heat, causes excessive fuel consumption, and exhaust emission during operation. Firstly, they suggested the structure and RTG energy-saving system principles and studied the principle topology of the bi-directional DC/DC converter. They proposed the method of a voltage equalization for an RTG power saving system, namely, the active voltage equalization method and design of active voltage equalization circuit parameters and control strategy were given, after analysing a super-capacitor voltage equalization strategy model. The series connection of super-capacitors module was analysed by performing the simulation. Therefore, the saving of energy improvement is mostly confirmed necessary. The theoretical analysis and simulation result shows that the active control circuit may be proved to be more efficient in solving the problem of the partial over-voltage of the super-capacitor groups. For the higher time of charging or discharging currents, this method may be applied. Therefore, it is recommended that the RTG energy saving system.

In regenerative Power Wasted, the heat is continually generated and dissipated through brake modules during RTG crane operation. Besides energy wasted, users have to spend more time maintaining the brake modules. DELTA industrial Automation has introduced the Delta’s AFE2000 Series active front end for RTG crane systems. The aim was the improvement of Power Factor, for collecting regenerative power in the original system. A power factor correction rectifier provided power to the DC BUS. Delta’s solution added an AFE2000 Series to the original system. Every time the system starts operating, the AFE2000 Series conducted a self-diagnosis. The diagnosis result generally transfers power to the DC BUS automatically, via the AFE200 Series, instead of the power factor correction rectifier. The AFE2000 Series notices and converts the heat generated into power during the operation, conducts reactive power compensation, and returns the regenerated power to the grid system for recycling. As a result, the AFE2000 series managed to reduce power consumption, and electricity fees for users improved the power factor and decreased the harmonic distortion [34].

3.2. Equipment efficiency (Battery as storage)

A battery may be used as a storage system to store energy using a battery technology so that it may be used at a later stage. Lithium-Ion batteries, valve-regulated lead-acid batteries, sodium nickel batteries, vanadium batteries, and liquid metal batteries, are technologies found in batteries [35, 36]. The RTG crane system is equipped with a Battery Management System (BMS) to maximize the life of the batteries, and further to regulate electricity flow to and from the battery pack [37]. The BMS confirms that battery design temperatures are not exceeded, and individual battery cells are recharged to unequal voltage. The RTG Crane system BMS measures and regulates the voltage of each individual battery and monitors the temperature of a set of three (3) batteries. The BMS will further show an indication when a battery fails and requires replacement. Zhao Nan et al. [38], investigated the energy storage systems feasibility of Hybrid Energy Storage System (HESS) implementation, to provide the power-train of an electrified port crane–RTGC and identifying the dynamic analysis of a typical RTGC, the requirement of energy and power rating of the crane power-train system are specified [39]. The traditional diesel Internal Combustion Engine (ICE) crane application was compared with the electric crane, particularly the battery-super-capacitor (SC) hybrid crane. It showed great potential for regenerative energy
recovery, which is associated with fuel costs reduction and emissions. They aimed to develop the measures for designing the battery alone and battery-super-capacitor HESS, which are shown to be different and independent of the optimization method chosen. System analysis would be completed by establishing a MATLAB/Simulink model for the RTGC power-train. Their results show the hybrid energy sources’ benefits to manage the significance for the design and improvement of port crane HESSs. They would influence marine goods transportation in terms of energy consumption and emissions.

4. Further improvements level
The present development discloses power energy saving for the system, composed of a motor, wheels, and storage system such as a battery pack, super-capacitor, and so forth. The performance of RTG crane systems requires improvement to ensure that they are reasonable, productive, and maintainable. The amount of energy consumed by the RTG Crane is shattered down as the amounts expended by the various components equipped used in the system. The system changed the power supply mode of traditional RTG, powered by the grid and storage system. Both the storage system and grid should support the RTG operations independently, forming the double-power energy saving system; to the equipment reliability, an energy storage system would be used as the secondary power source for RTG and the output power may be highly matched with the demanded power, reducing the reactive loss and increases the energy efficiency. Having observed that much energy is consumed as the container is lifted up, as when the container drops/brakes more energy is produced during regeneration and the energy is consumed in the form of heat when decelerating resistance, the feedback energy is produced, and the battery pack may be recovered back, which realizes cyclic utilization. The research should be carried out on how to solve the existing problem on the RTG system and how to use this energy in full [40, 41].

The advantages of improving energy recycling on the existing RTG has been discussed [42]. For further improvements on RTG Crane system, the comparison of RTGs and E-RTGs has been carried out to save energy and the savings could be up to 95% of diesel consumption reduction of greenhouse emissions and the operational costs may be reduced by up to 70%. The performance of various types of handling equipment is shown in Table 2.

The literature on the consumption of energy in container terminals is limited. Still, more effort has been carried out for the use of specific types of cargo handling equipment, from an operational perspective. The study indicated the reduction of braking energy and consumption of energy up to 60% by the -powered RTGs bus bar, equipped with online braking, identifying the energy consumption levels and profiles of various container types. The cost approach was recommended, making it possible to determine which operation area is consuming which amount of energy and establish a set of detailed indicators [44]. One example of reported findings is the impact of electric rubber tyred gantries on green port performance (Yang, Chang and Wei-Min, 2013).

| Item                  | RTG       | E-RTG     |
|-----------------------|-----------|-----------|
| Movement              | Average   | Average   |
| Security              | Average   | Average   |
| Operating system integration | Wireless transmission | Wireless transmission |
| Method                | System    | System    |
| Stability of signal   | Unstable  | Unstable  |
| Breakdown frequency   | Average   | Average   |

Table 2. The different types of control equipment and their performance [43]
Mechanical method       Hydraulic       Hydraulic  
Repair and maintenance time     Average       Average   
Energy source       Diesel       Diesel/Electric       
Maintenance cost     High       High       
Air pollution       Severe       Zero

Over the periods, several different energy storage methods have been planned, to capture and store energy, so that it may be fed back to the grid when it is most needed [45]. There are several energy storage technologies presented, and all come with their advantages and disadvantages, and not all energy storages operate equally well in all situations. In [46], it gave MPC real-time to optimise the power flow for the wind farm system, together with an ESS, to meet the demanding scheduling of the grid. They aimed to reduce the impact of the wind curtailment factor, to increase the ratio of generated wind power fed to the power grid and to maintain the power generation of the grid plan. Therefore, the MPC controller successfully followed the power of the electrical power grid system. In a different study, the MPC controller has been used to improve the energy dispatch ability for a large scale ESS located at wind power plants [47]. The simulation results have shown that an ESS with model predictive control (MPC), meet the power grid requirements by reducing the generation plan errors. Their work successfully shows an approximate 15% reduction of the generation plan error, due to the scheduling horizon’s impact on the generation plan error, where there are shorter scheduling horizons.

5. Conclusion
The development of the RTG Crane technology improved the efficiency, reliability, and safety of the system. Improved efficiency lowers the cost of running the crane, so the RTG should perform at the highest level, increasing safety and operational efficiency and further for maintenance. This would maintain the lifecycle value of the crane and assist in further reducing the total cost.

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