Energy Reports 7 (2021) 4769–4778

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Optimal energy management of a hybrid diesel generator and battery supplying a RTG crane with energy recovery capability

Kanzumba Kusakaka [a,*], Sibongile Florina Phiri [a], Bubele Papy Numbi [b]

[a] Department of Electrical, Electronic and Computer Engineering, Central University of Technology, Bloemfontein, South Africa
[b] Department of Electrical Engineering, Mangosuthu University of Technology, Durban, South Africa

ARTICLE INFO

Article history:
Received 21 April 2021
Received in revised form 17 July 2021
Accepted 26 July 2021
Available online xxxx

Keywords:
RTG crane
Diesel generator
Hybrid system
Energy recovery
Optimal operation

ABSTRACT

In this paper, an optimal energy management model for a RTG crane supplied by a hybrid diesel generator/battery system is developed. 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 tonnes RTG crane operating in South Africa has been selected. The demand profile, size of the diesel generator as well as of 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 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 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. The result of the true payback period analysis has shown that the overall investment cost may be recovered in 1.36 years. Additionally, it can be seen from the results that the peak power demand on the diesel generator has been reduced, this can assist in reducing the power rating and the initial cost of the diesel generator.

1. Intro.

Sea-ports and rail terminals use Rubber Tired Gantry (RTG) to organize container aisles, loading, moving cargo-containers and operate as the link between the cranes and the means of transportation by road, rail or sea connections (Naicker and Allopi, 2015).

RTGs' operation can be summarized in three essential movements (Yu et al., 2019):

- 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 h for 362 days a year continuously (Naicker and Allopi, 2015); this means a substantial amount of electrical energy is consumed. 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, diesel generators (DGs) are used as the preferred alternative power source. This said, most 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/h; which represents approximately 20% of diesel fuel emissions from cargo handling equipment at ports (Soukup, 2019).

Diesel powered RTGs use constant-speed diesel generators to supply the electrical power needed for the different handling operations performed by the cranes as well as by the auxiliary equipment such as lights and air conditioning used the operator's control house (Pietrosanti, 2019). 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 (Kusakana, 2018). Therefore, in instances where the

---

[*] Corresponding author.
E-mail addresses: kkusakana@cut.ac.za (K. Kusakaka), phirisf@cut.ac.za (S.F. Phiri), numbib@mut.ac.za (B.P. Numbi).

https://doi.org/10.1016/j.egyr.2021.07.074

RTG is idle or operating in a phase where little power is needed, the DG runs at a very low load factor which results in a very high specific fuel consumption, translated in an important amount of diesel fuel wasted and a significant quantity of pollutant gases are emitted (Knight et al., 2011).

Different 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, constant-speed DG run at an unnecessarily high speed when idling, resulting in high fuel consumption and excessive CO_2 emissions (Yang and Chang, 2013).
- The need for peak power on an RTG's diesel engine exists for only 4% of the total handling cycle's period (Antonelli et al., 2017).
- Due to the stochastic nature the containers' weight to be handled, diesel generator supplying RGT cranes often work with an output power below their rated capacity. Therefore, their specific fuel consumption is high like any DG operating at low load factor, which has a direct effect on the operation cost since more fuel is used (Phiri et al., 2018).
- The power from the lowering phase is dissipated as heat through resistor banks, used for braking purposes (Spengler and Wilmsmeier, 2019).

During the lowering phase, the hoisting motor is not performing any work because the lowering movement is being driven by the weight of the load, therefore the movement has the potential to produce electricity which a regenerated power close to 60% of the peak power supplied to the RTG crane by the DG. The power regeneration phase laps between 30 to 40% of a full handling cycle's duration (Phiri et al., 2020).

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 and can later be used to:

- Reduce the peak power demand on the DG during the subsequent RTG's hoisting and trolley moving phases,
- Supply the auxiliary equipment, allowing the DG to be turned off during idle and low demand periods.

From the available literature, different energy storage systems have already been studied and successfully used for the hybridization of RTG cranes, such as flywheel (Flynn et al., 2007; Tan and Fah, 2017), fuel cell (Corral-Vega et al., 2019a), supercapacitor (Corral-Vega et al., 2019a,b; Chang et al., 2010; Bolonne and Chandima, 2019a) and battery (Bolonne and Chandima, 2019a; Konecranes lifting businesses Power, 2021). The use of storage systems can result in a decrease of the fuel consumption, pollutant emission, operation cost, peak demand on the DG as well as in an increase of the DG's load factor (Kusakana, 2015b,a; Kusakana and Vermaak, 2013; Kusakana, 2016). However, the performance of the hybrid RTG system is not only based on the equipment or technology used. Therefore, given the variable operating conditions, the RTG crane with storage system, must be optimally controlled to achieved the lower energy cost while aiming for the maximum operation efficiency.

Optimal operation control is a powerful method that is proposed in the literature to find solutions to different energy management problems (Numbi and Malinga, 2017; Kusakana, 2017). Recently, few studies have been conducted and published on different control methods applied to the operation of hybrid DG/battery RTG cranes with battery storage systems.

In Ref. Alasali et al. (2019), a stochastic optimal management system using Genetic Algorithm (GA) for the control of a RTG crane with storage system has been presented. The stochastic optimal management system aimed to enhance the reliability as well as minimize the operation cost. The results showed that the optimal management system successfully decreases the operation cost as well as the peak power demand on the DG and performs better compared to other control methods such as set-point controller.

In Ref. Pietrosanti et al. (2020), a Fuzzy Logic Controller (FLC) compared to 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 performs 26% better as compared to the PI controller.

In Ref. Bolonne and Chandima (2019a), the authors proposed state machine control strategy to manage the power flow based on the RTG's demand. The simulation results have shown that 27% reduction in fuel consumption per handling cycle is achievable when comparing the proposed system with actual system having same variable speed DG and battery capacity as in the proposed system.

In Ref. Chen et al. (2019), a game theory based energy management method is developed for a hybrid DG/battery/supercapacitor, modelled as a multi-agent system, supplying a RTG crane. The simulation results showed that hybrid DG/battery/supercapacitor can adequately respond to the RTG's demand while reducing the fuel consumption.

In Ref. Hong-lei et al. (2018), a thermostat control strategy is used to switch between the "battery only" mode and the hybrid DG/battery mode when supplying a RTG crane. A PLC is used to manage the two modes based to the battery state of charge information received from the battery management system. When the battery state of charge is below 50%, the DG is switched ON and the hybrid mode is activated; when the SoC is above 80%, the DG is switched OFF and the system operated in DG only mode.

From the studies available in the literature, it can be seen that most control techniques applied to the energy management of hybrid DG/battery systems supplying RTG cranes, are based on "set-point"; and very few are based on "optimal power management". Hence, there is a need of further studies using optimal control approaches applied to the energy management of hybrid DG/battery system, supplying RTG cranes with the aim of decreasing the total cost of energy used as well as the amount of pollutant emitted. Therefore, 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 taking place during the lowering phase. As a case study, a RTG crane operating in South Africa has been selected. The load profile, size of the DG as well as of 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, DG/Battery with energy recovery during the lowering phase.

As compared to different researches currently available on the energy management of hybrid DG/Battery RTG, the key contributions of this work are:

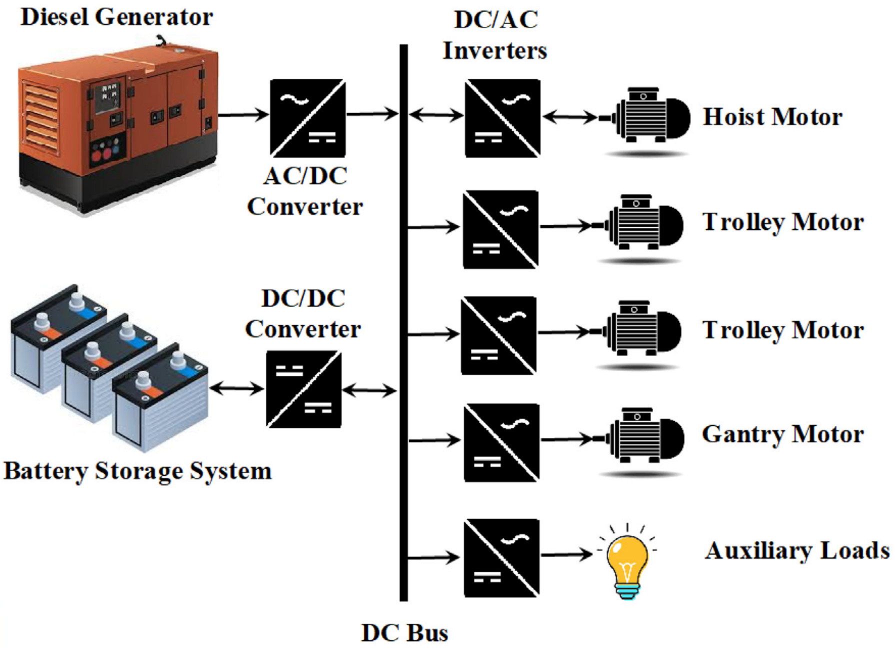

Fig. 1. RTG crane with its main electrical components.

- Most studies have used control techniques such as closed-loop PI controller, set-point control (SoC, power, voltage or frequency) to manage the operation of RTGs with hybrid DG/Battery. Studies focusing on power management systems were limited to the use of optimization algorithms such as Genetic Algorithm, Fuzzy Logic and Game-based controllers. However, this paper uses a deterministic nonlinear optimization approach to solve the power dispatch problem and minimize the energy cost resulting from operating the system.
- Available studies based on hybrid RTG cranes' energy management predominantly focus on diesel fuel savings, limiting their analysis on the energy cost for a cycle or a day. The current study goes beyond the cost saving to look at a lifecycle cost analysis, to assess the payback period and the breakeven point achieved when comparing the proposed optimally controlled system with the DG alone used as baseline.

The subsequent sections of this manuscript are organized as follows. A description of the system's components as well as the load demand is presented in Section 2. The proposed optimal power dispatch model is discussed in Section 3. Section 4 presents the simulation results and optimal power flow achieved during the simulated horizon and for the given operating conditions. The economic analysis is presented in Section 4.5. Conclusion, remarks and suggestion for future works are given in Section 5.

2. Hybrid RTG with DG and battery storage system description

Fig. 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 a AC/DC rectifier; and the gantry, hoist and trolley AC electric motors are fed from the DC bus through their respective DC/AC inverters.

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

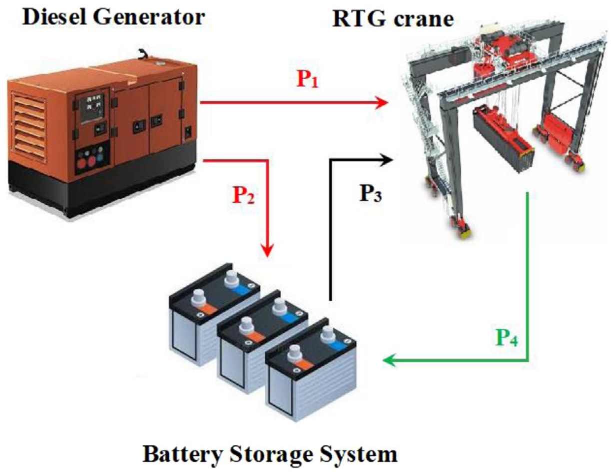

Fig. 2. Main powerflows (control variables).

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 a 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 is handling a load, while it does not during the second half cycle. Therefore, the load demand can either be positive during the hoist up, trolley left and right; or be negative during the lowering processed.

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

3.1. Proposed model's main powerflows

The different powerflows in the proposed system are shown on Fig. 2. It can be seen that the power from the DG can 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) can be used alone or in conjunction with the DG to supply the different motors. However, during the energy regenerative process, the battery is being 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, can be expressed by the following non-linear equation:

$$FC = aP_{DG}^2 + bP_{DG} + c \tag{1}$$

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

The cost is calculated by multiplying the fuel consumption by the price ($/L).

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 a RTG while handling containers. Additionally, the energy recovered through the regenerative process, during the lowering of containers, must be maximized. The objective function (OF) can be modelled as:

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

where j is the sampling interval under consideration with N the total of optimization intervals; Δt is the length of each sampling interval.

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

3.3. Load balance

From the operation given on Fig. 2, the load balance can be given as:

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

where P_L is the electrical demand resulting from the handling of container (kW). This means that for any selected sampling interval "j", the load can be supplied by either the DG or the battery; or operate in the regenerative braking mode.

3.4. Diesel generator power constraints

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

$$P_{1(j)} + P_2 \leq P_{DG}^{Rated} \tag{4}$$

3.5. Dynamics of the energy storage's SoC

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

$$SoC_{(j)} = SoC_{(0)} \times (1-\delta) + \frac{\Delta t}{E_n} \times \left(\eta_{ch} \times \sum_{i=1}^{j}(P_{2(j)} + P_{4(j)}) - \frac{\sum_{i=1}^{j} P_{3(j)}}{\eta_{disc}} \right) \tag{5}$$

With $SoC_{(j)}$ the SoC at the considered optimization sample; $SoC_{(0)}$ 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.

3.6. Variables limits

Each control variable, or power flow, can be modulated between a minimum and a maximum value according to the system's design specifications while following the manufacturers' design and operation specifications. These can be modelled as:

$$P_1^{\min} \leq P_{1(j)} \leq P_1^{\max} \tag{6}$$

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

$$P_2^{\min} \leq P_{2(j)} \leq P_2^{\max} \tag{7}$$

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.

$$P_3^{\min} \leq P_{3(j)} \leq P_3^{\max} \tag{8}$$

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

$$P_4^{\min} \leq P_{4(j)} \leq P_{4(j)}^{\max} \tag{9}$$

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 can be modelled as:

$$SoC^{\min} \leq SoC_{(j)} \leq SoC^{\max} \tag{10}$$

3.7. Restricted power flows

This restriction is applied to power flows that cannot happen concurrently in the same considered optimization sample. In the case of the battery, the charging and discharging processes cannot happen simultaneously. Using Fig. 2, this condition can be expressed as:

$$(P_{2(j)} + P_{4(j)}) \times P_{3(j)} = 0 \tag{11}$$

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

$$(P_{1(j)} + P_{3(j)}) \times P_{4(j)} = 0 \tag{12}$$

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 can be modelled as:

$$\sum_{j=1}^{N}(P_{2(j)}+P_{4(j)}-P_{3(j)})=0 \tag{13}$$

3.9. Processing steps of the developed energy management algorithm

The processing steps of the proposed energy management system, as depicted in Fig. 2, can be summarized 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 Fig. 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.

3.10. Solver selection

Due to the nature of 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 can be solved using "*fmincon*" in MATLAB (Alasali et al., 2016).

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 2). Three main scenario, 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 happening during the lowering phase.

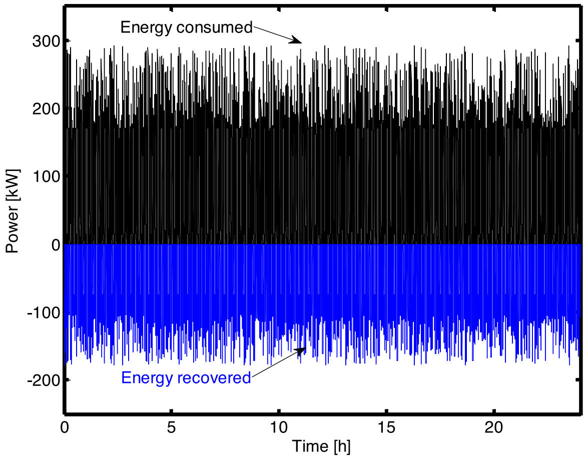

Fig. 3. Daily measured energy profile (used and recovered).

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 batteries pack with an autonomy of about 2 h (Konecranes lifting businesses Power, 2021). The methodology for sizing the DG and the battery storage system is reported in Ref. Kusakana and Vermaak (2014). The typical average power of a RTG crane is 24.8 kW. The storage system is expected to have an autonomy of 90 to 120 min when solely supplying the RTG operation. Therefore, the battery storage system with a capacity of 37.2 to 49.6 kWh can be proposed. However, to expand the battery lifespan, a state of charge usage is recommended as 0.3, yielding a battery storage system capacity of 124 to 165.3 kWh. For economic consideration, the batter capacity is selected as 128 kWh.

4.1. Load demand

Analyses on RTG cranes' energy usage as well as the approximate duration of a handling cycle have been analysed by few authors (Bolonne and Chandima, 2019a; Steenken et al., 2004; Papaioannou et al., 2017). 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 paper, the measured power profile is given in Fig. 3 with the energy consumed considered as positive, while the energy produced from the regenerative process is considered to be negative. Due to the stochastic nature of the containers' weight to be handled in different cycles, the energy used as well as recovered as well as the length of the different cycles differ significantly.

It has to 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. Additionally, the daily profile is made of 540 cycles with 64 sampling intervals per cycles and 4 variables to be optimized in each interval. Thus, the number of possible combinations for simulation is too high to compute. Therefore, to make the discussion clear and analyse the behaviour of the system in each handling phase, the simulation horizon has been shortened and focuses on a single cycle to emphasize 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 is taking up to 160 s as shown on

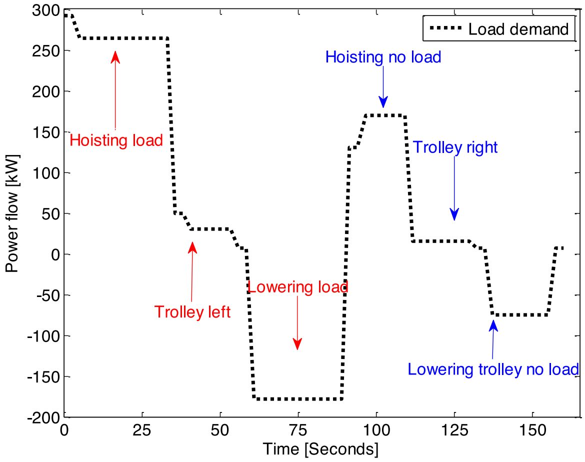

Fig. 4. 40T RTG crane typical cycle power profile (full load).

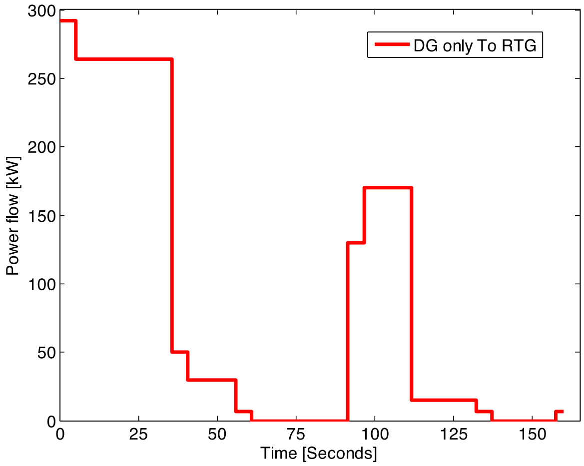

Fig. 5. Baseline power profile (DG only).

Table 1
Simulation parameters.

Parameter	Value
Sample interval	2.5 s
DG power rating	410 kW
a (Konecranes lifting businesses Power, 2021)	0.0074 (L/kWh^2)
b (Konecranes lifting businesses Power, 2021)	0.233 (L/kWh)
c (Konecranes lifting businesses Power, 2021)	0.4200 (L)
Diesel price	1.018 USD/L
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

Fig. 4. The peak demand during the hoist up phase is 292 kW with an average demand of 24.8 kW and 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 needed during all the handling phases are presented on Fig. 4. The main phases are hoisting up phase (takes around 35 s), trolley moving left phase (around 25 s), lowering load phase (around 30 s), hoisting up at no load (around 20 s), trolley moving right at no load (around 25 s), lowering trolley at no load (around 25 s).

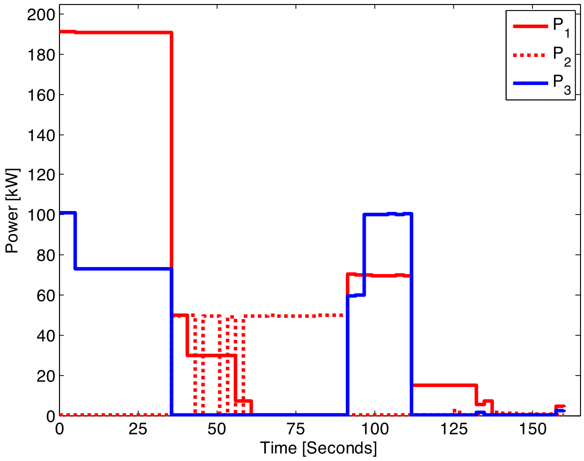

Fig. 6. Hybrid DG/battery without energy recovery.

The simulation parameters of the DG and battery as well as other inputs to the developed model are given on Table 1.

4.2. 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 sole energy source, Fig. 5 shows that the DG operates in a load following manner and the load factor is low.

4.3. 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 can only 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. Fig. 6 shows the operation strategies on the powerflows, while Fig. 7 shows the corresponding SoC's dynamics during the different operation phases.

4.3.1. Hoisting up phase

During the hoist up phase (at full load), Fig. 6 shows that the load is supplied by the power from the DG with a contribution of the power from the battery system.

4.3.2. Trolley left phase

During this phase, the container is moved to the left using the trolley which results in a lower load demand. Therefore, Fig. 6 shows that the power needed during this phase is exclusively supplied by the DG. It can also be noticed that the DG is also used

Table 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

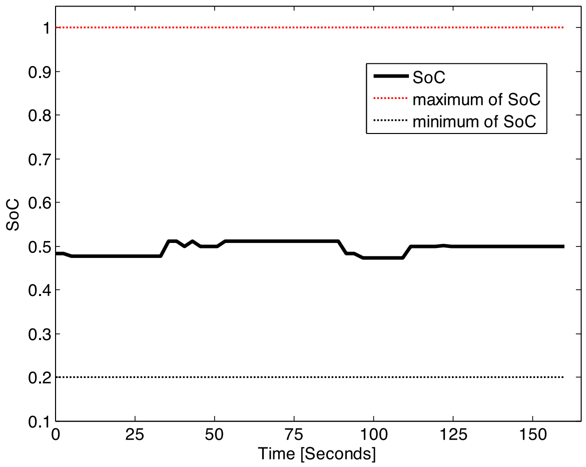

Fig. 7. Dynamic of the SoC in the hybrid DG/battery without energy recovery.

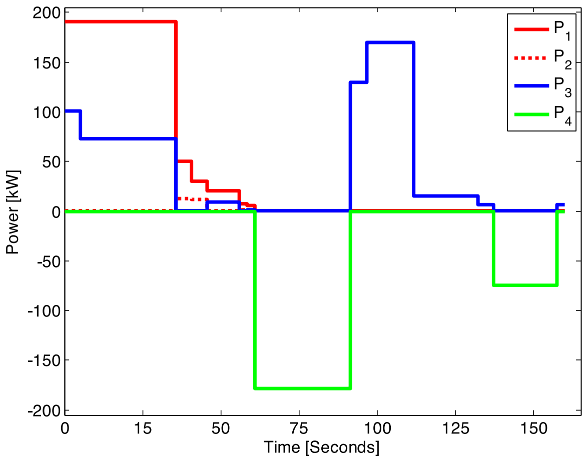

Fig. 8. Hybrid DG/battery with energy recovery from the regenerative braking.

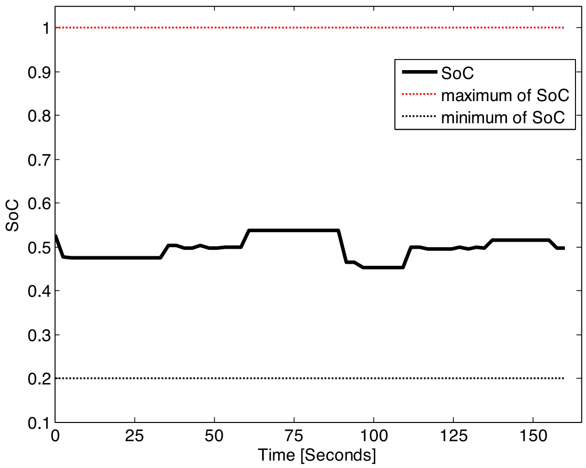

Fig. 9. Dynamic of the SoC in the hybrid DG/battery with energy recovery.

to recharge the battery; this increases the load factor on the DG during this phase. The corresponding SoC of the battery shown a small increase as shown on Fig. 7.

It can be seen that the peak power demand, in this phase, is now 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 can be reduced.

4.3.3. *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 can be seen that of Fig. 6 that the DG is used to recharge the battery which is translate by a small increase in the corresponding SoC (Fig. 7). It is normally 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.

4.3.4. *Hoisting up phase: No load*

During this hoist up phase (at no load), Fig. 6 shows that the load demand is supplied by the DG and the battery; the corresponding SoC is decreasing during this phase (Fig. 7).

4.3.5. *Trolley right phase: No load*

During this phase, the trolley is being moved to the right (at no load) and the demand is principally met by the DG (Fig. 6). The battery is neither charged or discharged during this phase as seen from the stationary SoC (Fig. 7).

4.3.6. *Hoisting down: No load*

During this hoist down phase, Fig. 6 shows that there is no power from the DG to supply the load or to recharge the battery. Similarly, the battery is neither charged or discharged during this phase as seen from the stationary SoC (Fig. 7).

4.4. *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 also reduced to 190 kW; corresponding to 35% reduction compared to the baseline.

4.4.1. *Hoisting up phase*

As for the previous case, Fig. 7 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.

4.4.2. Trolley left phase

During this phase where the loaded trolley is moved to the right, Fig. 7 shows that the demand is principally met by the DG, which also makes a very small contribution to the battery charging process. It can also be notices that at around, the battery is also supplying the with a small power contribution, which is linked to the SoC increase shown on Fig. 8.

4.4.3. Lowering load phase

During the hoist down phase, Fig. 7 shows that there is no power from the DG to supply the load demand or to recharge the battery. However, it can 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 Fig. 8.

4.4.4. Hoisting up phase: No load

During this hoist up phase, Fig. 7 shows that the load demand is exclusively supplied by the battery while the DG is not used. The corresponding SoC is decreasing during as shown on Fig. 8.

4.4.5. Trolley right phase: No load

During this phase, Fig. 7 shows that the trolley is being 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 on Fig. 8.

4.4.6. Hoisting down: No load

During this hoist down phase (at no load), Fig. 7 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 (Fig. 8). Additionally, it can be clearly seen that the DG is not used (Fig. 7).

4.5. Economic and environmental analysis

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 2 shows that 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 82.12% is achievable in the case the energy recovery is included.

The cumulative fuel consumption curves of the proposed optimally controlled system versus the baseline are given on Fig. 9 where the difference in fuel consumed can be noticed at the end of the considered simulation horizon.

It has to be mentioned that the 0.522 L fuel consumption, achieved using the baseline, is mainly dependent on the type of DG used and its specific fuel consumption parameters a, b and c as given in Table 1 (which were directly provided by the manufacturer Konecranes (Konecranes lifting businesses Power, 2021)). However, the 0.522 L diesel consumption per handling cycle is far from industrial practice. It is shown, in Ref. Konecranes lifting businesses Power (2021), that 25 moves of 20T container will consume 26 L of diesel fuel; that is, 1 container will need 1 L in average for industrial engine RTG. 25 moves of 20T container will consume 18 L diesel, that is, 1 container needs 0.72 L for hybrid RTG. In other words, 25 containers will need 95 kWh; that is, 1 container needs 3.8 kWh (1 L) for the selected RTG, which is in line with typical internal combustion engines' conversion efficiency .

Therefore, for simulation accuracy, the fuel consumption parameters must be checked to reflect the actual real performance of the DG used.

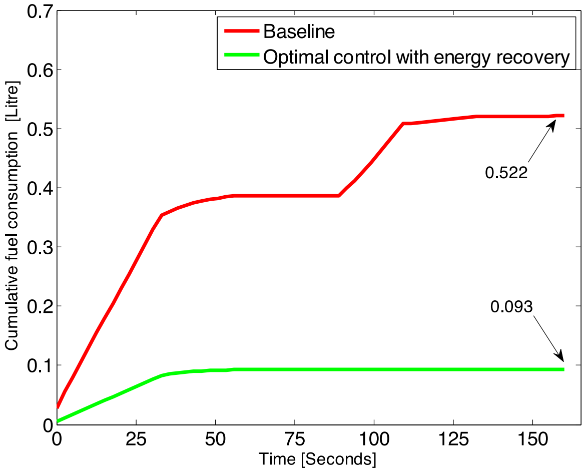

Fig. 10. Cumulative cost comparison between the hybrid DG/battery with energy recovery and the baseline for the considered handling cycle.

4.5.1. Lifecycle analysis

Due to the intensive computation power required to perform the simulation, the analysis conducted in Section 4.4 was limited to only one handling cycle of 160 s, 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 different costs (initial, operation and maintenance, replacement) to better assess the economic benefits of the proposed system' savings when compared to the baseline.

4.5.2. Annual cost analysis

As explained in Section 4, due to the computation power required to consider a daily optimization horizon at once, the simulations have been performed for each hour separately and the results have been summed to come up with the daily operation cost achievable for the demand given on Fig. 3. As an example, Fig. 10 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. Naicker and Allopi (2015), RTG cranes continuously work daily up to 24 h for 362 days a year and are only turned off 3 days for maintenance. Therefore, considering the daily operation cost computed, the annual cost can be calculated (Table 3).

4.5.3. Lifecycle cost analysis

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

$$LCC = C_{I(i)} + C_{R(i)} + C_{OM(i)} + C_{EC(i)} - C_{S(i)} \quad (14)$$

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 energy cost respectively linked to each 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% (Harrison

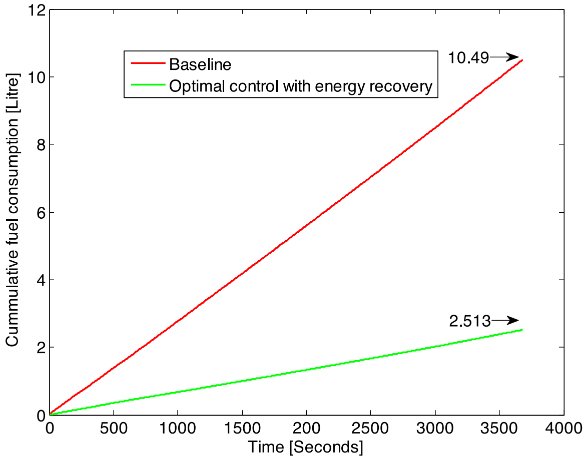

Fig. 11. Cumulative cost comparison between the hybrid DG/battery with energy recovery and the baseline for the hour of operation.

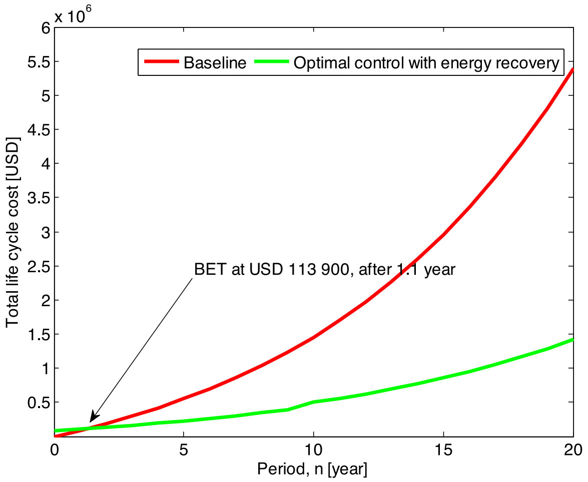

Fig. 12. Cumulative lifecycle cost and breakeven analysis.

et al., 2018). The bill of quantity for the additional equipment to achieve the hybrid DG/Battery with energy recovery is given on Table 4.

As compared to the baseline, Fig. 11 shows that the break-even point of the proposed optimally controlled DG/Battery, with energy recovery, suppling the RTG crane can take place after 1.1 year, corresponding to USD 113 900. For the 20 years' project life-time, the computed lifecycle in the case of the proposed optimally controlled DG/Battery with energy recovery is USD 1 426 000. However, when only 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% (see Fig. 12).

4.5.4. Payback period

In addition to the LLC, a "true" payback period (PBP) analysis is conducted to assess the economic performance of the system and found out how long 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 (Hohne et al., 2019). 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-av}).

$$\text{“True” } PBP = \frac{PW_{TC}}{PW_{TB-av}} \tag{15}$$

The PW_{TB} is computed as:

$$PW_{TB} = AB\left[\frac{(1+r)^n - 1}{r(1+r)^n}\right] \tag{16}$$

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

Using the annual cost savings obtained in Section 5.2.1, the true payback period is computed, using the online tool available from Ref. Kusakana (2020), and the results show that the simple payback period is 1.28 years, the true or discounted payback period is 1.360 year and the cash flow return rate is 77.24% per year.

5. Conclusion

In this work, an optimal energy management model for a 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 compared to the baseline, the daily simulation results have shown that using the proposed model, a 45.97% reduction is 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 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, 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 cost can 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, suppling the RTG crane can take place after 1.1 year, 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 can assist in reducing the size of the DG by more than 50% needed which can lower the initial cost of the system.

For further studies, the following aspects can be considered:

- Alternative renewable energy sources such as Photovoltaic or wind energy conversion system can be considered as 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.

CRediT authorship contribution statement

Kanzumba Kusakaka: Concept, Design, Analysis. **Sibongile Florina Phiri:** Writing. **Bubele Papy Numbi:** Revision of the manuscript.

Table 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

Table 4
Bill of quantity for the battery and inverter.

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

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Alasali, Feras, Haben, Stephen, Becerra, Victor, Holderbaum, William, 2016. Analysis of RTG crane load demand and short-term load forecasting. Int. J. Comput. Commun. Instrum. Eng. 3 (2), 448–454.

Alasali, Feras, Haben, Stephen, Holderbaum, William, 2019. Stochastic optimal energy management system for RTG cranes network using genetic algorithm and ensemble forecasts. J. Energy Storage 24, 100759.

Antonelli, Marco, Ceraolo, Massimo, Desideri, Umberto, Lutzemberger, Giovanni, Sani, Luca, 2017. Hybridization of rubber tired gantry (RTG) cranes. J. Energy Storage 12, 186–195.

Bolonne, Sheron R.A., Chandima, D.P., 2019a. Sizing an energy system for hybrid li-ion battery-supercapacitor RTG cranes based on state machine energy controller. IEEE Access 7, 71209–71220.

Chang, Chunhe, Yang, Jiangping, Cao, Pengju, Niu, Quanmin, Zhu, Zhongni, 2010. Study on supercapacitor energy saving system for rubber-tyred gantry crane. In: 2010 Asia-Pacific Power and Energy Engineering Conference. IEEE, pp. 1–6.

Chen, Dawei, Niu, Wangqiang, Gu, Wei, Schofield, Nigel, 2019. Game-based energy management method for hybrid RTG cranes. Energies 12 (18), 3589.

Corral-Vega, Pedro J., Fernández-Ramírez, Luis M., García-Triviño, Pablo, 2019b. Hybrid powertrain, energy management system and techno-economic assessment of rubber tyre gantry crane powered by diesel-electric generator and supercapacitor energy storage system. J. Power Sources 412, 311–320.

Corral-Vega, Pedro J., García-Triviño, Pablo, Fernández-Ramírez, Luis M., 2019a. Design, modelling, control and techno-economic evaluation of a fuel cell/supercapacitors powered container crane. Energy 186, 115863.

Flynn, M.M., McMullen, P., Solis, O., 2007. High-speed flywheel and motor drive operation for energy recovery in a mobile gantry crane. In: APEC 07-Twenty-Second Annual IEEE Applied Power Electronics Conference and Exposition. IEEE, pp. 1151–1157.

Harrison, I., Pietrosanti, S., Luque, A., Mayer, R., Holderbaum, W., 2018. Recording and analysing measurements from an RTG crane. Measurement 125, 284–293.

Hohne, P.A., Kusakana, K., Numbi, B.P., 2019. Optimal energy management and economic analysis of a grid-connected hybrid solar water heating system: A case of bloemfontein, South Africa. Sustain. Energy Technol. Assess. 31, 273–291.

Hong-lei, Wei, Wei, Gu, Jian-Xin, Chu, 2018. The dynamic power control technology for the high power lithium battery hybrid rubber-tired gantry (RTG) crane. IEEE Trans. Ind. Electron. 66 (1), 132–140.

Knight, C., Becerra, V., Holderbaum, W., Mayer, R., 2011. A consumption and emissions model of an RTG crane diesel generator. In: Proceedings of the TSBE EngD Conference. TSBE Centre, Whiteknights, UK, p. 5.

2021. Konecranes lifting businesses power options for RTGs let's think about power. available from: https://www.konecranes.com/en-za/equipment/container-h{and}ling-equipment/rubber-tired-gantry-cranes-0/power-options-for-rtgs/diesel-fuel-saver, accessed 14 2021.

Kusakana, K., 2015a. Minimum cost solution of isolated battery-integrated diesel generator hybrid systems. In: South African University Power and Energy Conference (SAUPEC 2015). pp. 141–147.

Kusakana, K., 2015b. Optimisation of battery-integrated diesel generator hybrid systems using an ON/OFF operating strategy. In: 2015 International Conference on the Domestic Use of Energy (DUE). IEEE, pp. 187–192.

Kusakana, Kanzumba, 2016. Energy dispatching of an isolated diesel-battery hybrid power system. In: 2016 IEEE International Conference on Industrial Technology (ICIT). IEEE, pp. 499–504.

Kusakana, Kanzumba, 2017. Energy management of a grid-connected hydrokinetic system under time of use tariff. Renew. Energy 101, 1325–1333.

Kusakana, Kanzumba, 2018. Hybrid DG-PV with groundwater pumped hydro storage for sustainable energy supply in arid areas. J. Energy Storage 18, 84–89.

Kusakana, Kanzumba, 2020. Optimal energy management of a grid-connected dual-tracking photovoltaic system with battery storage: Case of a microbrewery under demand response. Energy 212, 118782.

Kusakana, K., Vermaak, H.J., 2013. Hybrid diesel generator-battery systems for offgrid rural applications. In: 2013 IEEE International Conference on Industrial Technology (ICIT). IEEE, pp. 839–844.

Kusakana, Kanzumba, Vermaak, Herman Jacobus, 2014. Hybrid diesel generator/renewable energy system performance modeling. Renew. Energy 67, 97–102.

Naicker, Rowen, Allopi, Dhiren, 2015. Analysis of electric-rubber tyred gantries for a more green Durban Container Terminal. IOSR J. Eng. 5 (6), 25–28.

Numbi, B.P., Malinga, S.J., 2017. Optimal energy cost and economic analysis of a residential grid-interactive solar PV system-case of ethekwini municipality in South Africa. Appl. Energy 186, 28–45.

Papaioannou, Vicky, Pietrosanti, Stefano, Holderbaum, William, Becerra, Victor M., Mayer, Rayner, 2017. Analysis of energy usage for RTG cranes. Energy 125, 337–344.

Phiri, S.F., Kusakana, K., Numbi, B.P., 2018. Optimal energy control of a rubber tyre gantry with potential energy recovery. In: 2018 Open Innovations Conference (OI). IEEE, pp. 124–128.

Phiri, S.F., Kusakana, K., Numbi, B.P., 2020. A survey of technical efficiency in crane systems using POET structure. J. Phys. Conf. Ser. 1577 (1), 012037, IOP Publishing.

Pietrosanti, Stefano, 2019. Supervisory Control of Energy Storage in Rubber Tyred Gantry Cranes (PhD diss.). University of Reading.

Pietrosanti, Stefano, Alasali, Feras, Holderbaum, William, 2020. Power management system for RTG crane using fuzzy logic controller. Sustain. Energy Technol. Assess. 37, 100639.

Soukup, James Vincent, 2019. Air Quality, GHG, and Human Health Impacts Associated with Fuel Cell Electric Technologies in Port Applications (PhD diss.). UC Irvine.

Spengler, Thomas, Wilmsmeier, Gordon, 2019. Sustainable performance and benchmarking in container terminals—The energy dimension. In: Green Ports. Elsevier, pp. 125–154.

Steenken, Dirk, Voz, Stefan, Stahlbock, Robert, 2004. Container terminal operation and operations research-a classification and literature review. OR Spectrum 26 (1), 3–49.

Tan, Kai Hou, Fah, Yap Fook, 2017. Reducing fuel consumption using flywheel battery technology for rubber tyred gantry cranes in container terminals. J. Power Energy Eng. 5, 15–33.

Yang, Yi-Chih, Chang, Wei-Min, 2013. Impacts of electric rubber-tired gantries on green port performance. Res. Transp. Bus. Manage. 8, 67–76.

Yu, Dayong, Li, Dong, Sha, Mei, Zhang, Dali, 2019. Carbon-efficient deployment of electric rubber-tyred gantry cranes in container terminals with workload uncertainty. European J. Oper. Res. 275 (2), 552–569.