Battery & Charging Solutions in Ports and Terminals

A PEMA Information Paper

This information paper is intended to provide an overview of battery solutions for equipment used in Ports and Terminals such as Rubber Tyred Gantry Cranes, Straddle Carrier, and Automated Guided Vehicles. The content is intended to provide ports, terminals, and other interested parties with information on the state-of-the-art by way of practical advice on the selection and implementation of battery solutions both for new build equipment and for retrofit installations.

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INTRODUCTION

This information paper is intended to provide an overview of battery solutions for equipment such as Rubber Tyred Gantry Crane, Straddle Carrier, and Automated Guided Vehicles. These types of equipment handle cargo not only horizontally but also vertically. Regardless of the operational direction, regenerative energy results which can be utilized.

The intent of this document is to provide ports, terminals, and other interested parties with information on the state-of-the-art by way of practical advice on the selection and implementation of battery solutions both for new build equipment and for retrofit installations.

DOCUMENT PURPOSE

PEMA cannot advocate or suggest which solution or combination of solutions is the right choice for any particular facility. Therefore, the intent is to contribute to industry awareness of the possibilities now available, as well as highlighting the issues and options that ports and terminals should consider during the selection process.

ABOUT THIS DOCUMENT

This document is one of a series of Information Papers developed by the Environment Committee (EVC) of the Port Equipment Manufacturers Association (PEMA). The series is intended to inform readers about battery application on different equipment in ports & terminals and the benefits of utilizing battery technology in respect of fuel saving, flexible operation, reduced maintenance and environmental impact.

DISCLAIMER

This document does not constitute professional advice, nor is it an exhaustive summary of the information available on the subject matter to which it refers.

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1. EXECUTIVE SUMMARY

In the Port environment it is established that the main source of carbon dioxide emissions and energy consumption comes from container handling equipment (76%), Office building (21%), lighting equipment (2%) and others (1%) [Ref: Green Port in Blue Ocean: Optimization of Energy in Asian Ports].

Energy efficiency has emerged as a key point in the port industry because of different factors such as the adoption of stronger environmental regulations and the increasing pressure from the local commu- nity in the vicinity of ports. As sourcing operational data from port terminals can be difficult due to privacy constraints, studies on emissions and energy efficiency of these terminals are scarce. The following research example provides key information about the real energy consumption and CO_2 emissions at one such large container terminal in the Mediterranean area, located in Valencia, Spain. The results show that yard terminal tractors and Rubber Tyred Gantry cranes (RTGs) are the main emission sources, accounting for 68.1% of the terminal's total CO_2 emissions [Energy efficiency and CO_2 emissions of port container terminal equipment: Ref: Port of Valencia].

This paper addresses this topic primarily in the context of RTG's (Rubber Tyred Gantry Cranes).

Container handling equipment (Ship to Shore cranes, RTG's, Straddle carriers, AGV's, Reach stackers, Top loaders, and Tractors/Tugs) in a container terminal is required to receive, organise and dispatch containers. Increased electrifica- tion is common nowadays in the port sector and has proven to increase energy efficiency, reduce emissions and lower fuel consumption.

A variety of initiatives have been increasingly applied by ports in different countries, especially those countries with particular focus on the concept of the "green port". The green port concept aim is to achieve the goal of environmental health, ecological protection, optimized usage of energy resources, reduce energy consumption and minimize pollution. A further goal is to ensure harmony between the smooth operations of the container terminal and human health while fostering the sustainable development of the port. One of these initiatives is through the conversion of traditional RTG's through electrification to so-called ERTG's. This achieved through the utilization of Cable reel and Conductor rail technology and offers significant performance improvement compared to traditional diesel-engine powered RTG's with substantial energy savings being achieved.

In recent years, state-of-the-art green ports have adopted shore charging of vessels, rapid automated berthing, AGV (automated guided vehicle) with low emissions, and electric cranes operating in the terminal yard. In addition, alternative energy sources such as Wind and Solar have been introduced to replace or augment the network power source.

Apart from electrification, another practice is hybridization, namely adopting other energy sources to make full use of regenerative energy from the gravitational energy potential of lifted loads and during deceleration of horizontal drives. These solutions include Battery, Supercapacitor and Hydrogen Fuel Cell technologies and combinations of same. In this paper, only the battery solution which is both technically mature and commercially proven is discussed in the context of RTG cranes. The application on other port equipment as listed above is also gaining momentum using the same battery concept.

2. BATTERY TECHNOLOGY

Since 2008, the lithium-ion battery market has grown dramatically. To those not familiar with battery technology, the term 'lithium ion' is used generically for many products, however the detail of the associated chemistry utilized results in very different performance characteristics from batteries. The performance characteristics are summarized as, but not limited to, cost, lifetime, power capacity, energy density and reliability. Every chemical configuration is designed to be suitable for a specific application and therefore not all li-ion batteries are suitable for port applications. It is important therefore to understand that when selecting such systems that the design detail and quality of the battery will determine the quality of the total system.

Battery construction consists of an anode, cathode, separator, and electrolyte. These layers can be rolled into a cylindrical form, or in a pouch type or prismatic cell. Most li-ion batteries use a graphite carbon anode on a copper collector. Some batteries use a lithium titanate anode.

The cathode is the electrode that determines the common name for a battery.

Cathode materials	NCM	Lithium Nickel Cobalt Manganese Oxide
	LFP	Lithium Iron Phosphate
Anode materials	C	Graphite
	LTO	Lithium Titanate

Lithium/iron/phosphate cathode type batteries are mostly called LFP or LiFePO4. LFP batteries exhibit lower to moderate energy density but have a moderate cycle lifetime. Many variations of the NCM batteries exist, sometimes being called NCM. These batteries have medium to long cycle lifetime, reasonable power capability and higher energy density (>130 Wh/kg). NCM batteries basically can fall into two categories. One is called a 'power type' NCM battery, which is tolerant to high C (Coulomb) rate and suitable for power application, e.g. Acceleration and Hoisting up. Another type is the 'energy type' NCM battery suitable for long time operation at small C rate.

Generally speaking, NCM chemistry is versatile for multiple applications while maintaining thermal stability. Lithium/titanate/oxide (LTO) chemistries claim long cycle lifetime.

C-rate or Coulomb rate indicates the ratio of the used battery current (A) over the battery capacity (Ah). The Relationship between the amps and the Ah rating of the battery: C= A/Ah. Normal values are between 0.1 – 6. For example, 1C means it takes one hour to fully charge/discharge the battery, 0.5C means that it takes two hours to fully charge/discharge a battery and 2C means it takes 30min to fully charge/discharge battery. Since battery behavior is highly nonlinear, the C rate capability has to be defined for different durations, i.e. maximum pulse power, continuous 1-cycle power and continuous infinite power (RMS). Moreover, C rate is usually different for charge and for discharge. For most batteries with graphite anodes (e.g., li-ion batteries except LTO) the charge C rate capability is lower than the discharge C rate. The reason for this is that high charge rates lead to irreversible loss of cyclable lithium ions due to plating of metallic lithium on the surface of the anode.

When designing a battery solution for equipment for ports and terminals, a tradeoff between engineering requirements vs. cost must be considered.

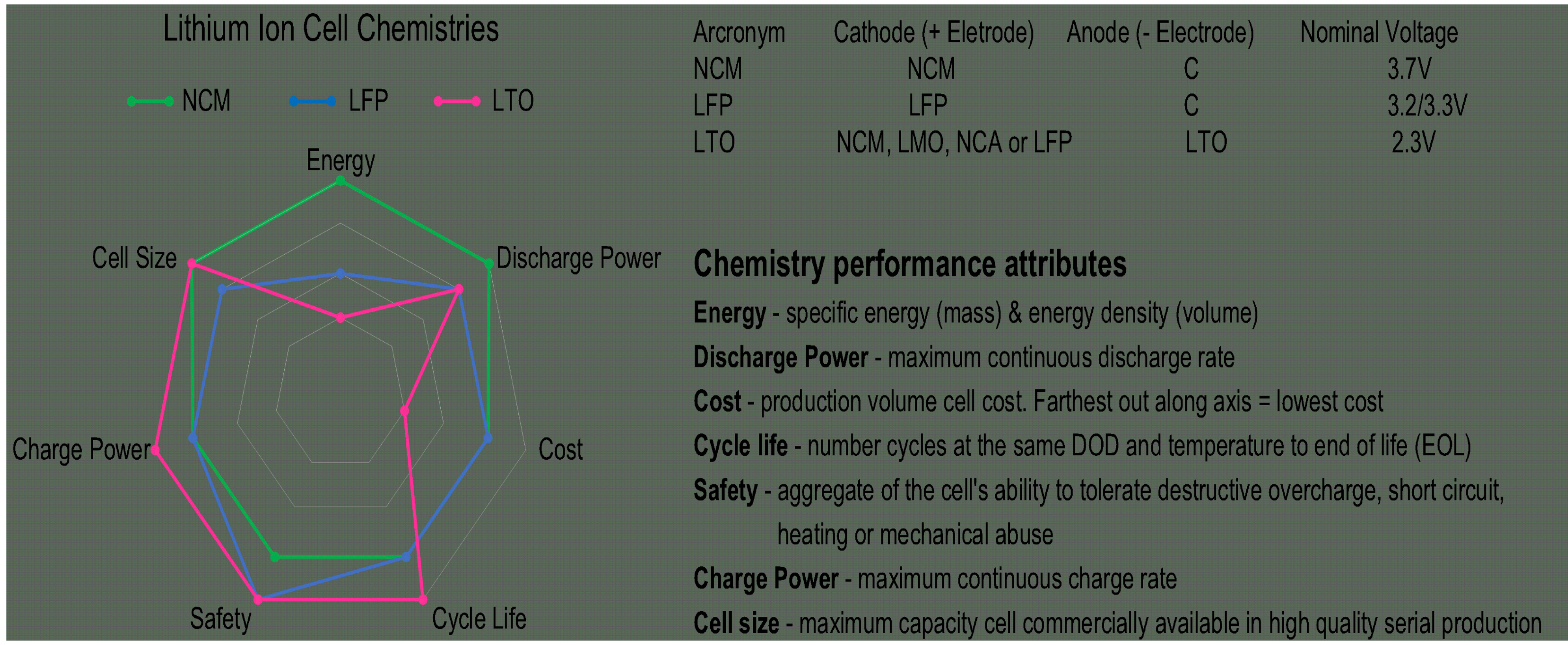


Figure 1

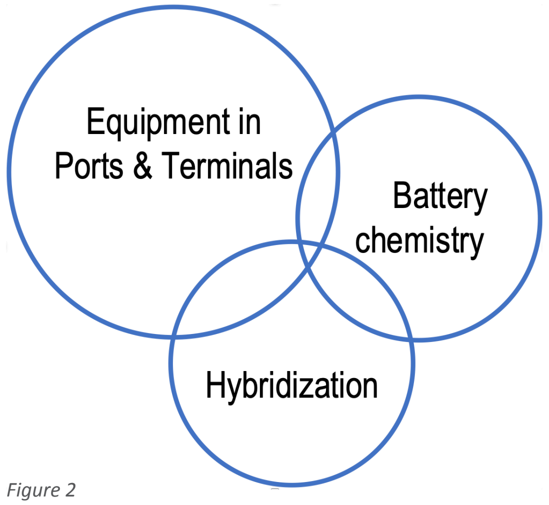


Figure 2

3. BATTERY APPLICATION ON PORT EQUIPMENT

3.1 REGENERATIVE ENERGY

A Conventional RTG crane utilises a diesel engine generator set as its energy source. It has low energy conversion efficiency, high energy consumption, high operating costs, with high emissions and noise pollution. This configuration of the conventional RTG crane is no longer compatible with the increasingly stringent global requirements for a green port.

One typical power system configuration of an RTG is as shown on below Fig 3. The main motor drive motions are hoist, trolley, and gantry. These drives are powered by the diesel generator set. The output of the genset is 3 phase AC power which is converted into DC power by a rectifier to form a common DC Bus. The DC bus voltage is connected to each of the drive inverters. Each inverter supplies power to the motors as variable frequency and voltage.

Hoisting motion is the vertical movement of the empty spreader or spreader with attached container. The Trolley is a movable device to which the spreader/container is attached, and which moves the container perpendicular to the container stack. Gantry motion is the horizontal operation of the RTG itself parallel to the container stack. When motors regenerate energy during lowering or during deceleration of horizontal movement, this regenerated energy flows back to the DC bus. When the DC bus voltage exceeds a pre-set upper limit, braking resistors are energized to consume this regenerative energy. The graph below Fig 3 shows the measured voltage and current of a hoist inverter on the DC bus side with rated container load and rated speed. During container hoisting, the voltage is 620V and current is 386A, resulting in an equivalent power demand of 239kW. During container lowering, the voltage is 622V and current is 282A, equivalent to a power demand of 175kW, or 73% of hoisting motor power demand. This measurement result is consistent with theoretical calculations and reflects the efficiency of the hoist system.

The graph also shows RTG energy flow during container lowering. Under such a scenario, both genset and hoist motor provide energy to RTG. The diesel supplies loads connected before the rectifier typically small (10 - 20 Kw) for secondary systems. The regenerated energy not consumed by the auxiliary power systems which are connected to the DC Bus inverter is dissipated by the braking resistance as heat.

Utilization of this Regenerative energy is a key element in any strategy to save energy and reduce emissions. A variety of solutions are available and in commercial use today. Battery technology is one such solution.

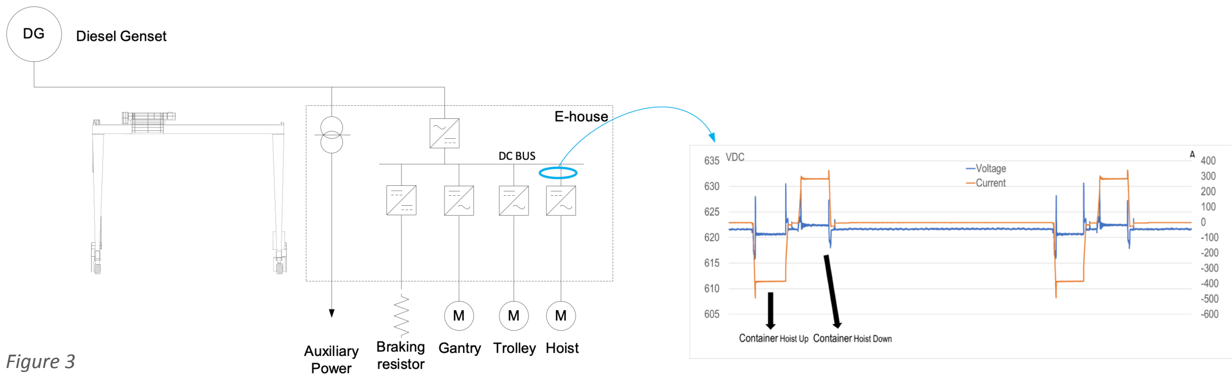


Figure 3

3.2 ENERGY CAPACITY DESIGN

The amount of battery energy capacity (kWh) required is of particular interest. Since battery capacity is directly related to the cost, this is a topic of consideration for the end user. As a crucial component in port equipment design the battery selection also affects other component selection. Therefore, the OEM, as the coordinator of all the components for the ports equipment, has to take this topic into consideration. In this paper, several considerations have been referenced during design and selection of battery energy capacity.

DIESEL GENERATOR SET

Combining a diesel genset with batteries in port equipment is a mature solution on the market. During most of the operational time, the battery discharges to provide power and the diesel genset is used to charge the battery. The Diesel genset power level shall be designed based on several factors, one of which is the startup frequency.

Diesel genset startup frequency is a combination of the battery system capacity and the diesel genset power level. When the battery system capacity is optimized, the diesel genset power level required is smaller, the startup frequency is lower and the cost of the diesel genset is lower. In a hybrid system with a high-capacity battery and small size of diesel genset, the genset will not turn on/off frequently. It should be noted that the diesel genset power level cannot be smaller than the minimum value which guarantees that the battery can be fully charged without interfering with the operational performance of the port equipment. When compared to conventional port equipment, the benefit of the hybrid system is reduced genset maintenance (reduced engine running hours) and less fuel consumption (i.e. engine runs at its optimal specific fuel oil consumption point - ref: Page 17).

BATTERY LIFE

There are two distinct, but inter-related factors that are used to measure battery life. I.e., Cycle life and Calendar life.

CYCLE LIFE

Cycle life is expressed in terms of the number of charge and discharge cycles that can be achieved as a function of the discharge level of the battery. Discharged level is known as its depth of discharge (DOD).

A battery needs to be dimensioned for the number of charge/recharge cycles it must perform in its lifetime. Increasing the number of cycles means that the DOD must be reduced to fulfil the required design lifetime. This means that the kWh rating of the battery selected must be higher to achieve the required lifetime. For a specific piece of ports equipment, this means that the higher the battery energy capacity, the longer the battery life. Fig 4 figure shows a typical example of cycle life DOD relationship at a temperature of 25°C.

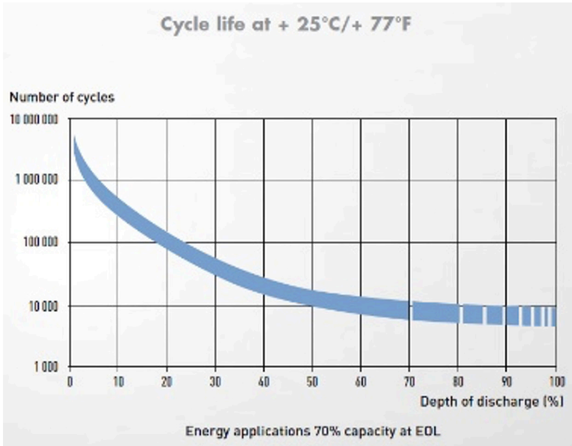


Figure 4

From the graph it will be noted that the relationship between cycle life and DOD is nonlinear, the cycle life being much longer with smaller DOD. Limiting the DOD therefore results in increased gain in lifetime energy. A battery system with double the capacity may provide up to three or four times the cycle life when utilized in the same application. It must be emphasized that these curves represent a very simplified case being extracted from a relatively small set of measurement data. Battery aging tests require long testing times and extensive resources while multiple factors such as temperature, charging technology and construction of the cells themselves as well as evolving technology have a major impact on the data samples

CALENDAR LIFE

Calendar life is defined as how long the battery might be expected to last in terms of years. This calendar aging has two main stress factors, the SOC (State of Charge) and the operating temperature.

In general terms, high SOC levels give shorter calendar life and low SOC gives less calendar aging. Figure 5 shows a calendar aging curve where cells have been utilized at different SOC and different temperatures. For most Li-ion batteries, lower SOC leads to extended calendar aging, i.e. worst aging occurs at 100% SOC. Since the chemical reactions at high SOC levels occur at higher rates and at higher temperatures, the calendar life deteriorates as aresult of the associated higher cell temperature.

Note: In this context it is critical that battery storage should comply with the manufacturer manual.

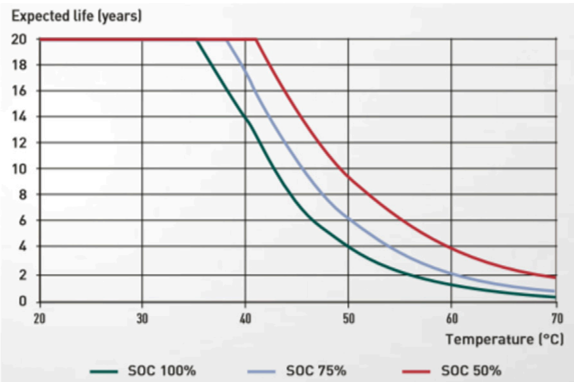


Figure 5

Considering Fgure 5, it is apparent that adequate cooling of the batteries is a necessity to ensure a good lifetime. Proper thermal design of the battery modules as well as the complete system is very important especially for high C-rate applications. Currently available mature cooling systems in the marketplace are either air-cooled or liquid- cooled systems. Both cooling systems have been evaluated and adopted by different suppliers on the basis of cost and technical suitability. Air-cooling is simpler, lighter and easier to maintain. However, due to the lower heat capacity of air, a much higher volumetric air flow rate is required to achieve a similar cooling performance as liquid-cooling. In essence, liquid-cooling is much more effective in removing substantial amounts of heat with relatively low flow rates.

3.3 SAFETY AND MAINTENANCE

All lithium-ion batteries have the intrinsic risk that in certain failure modes they produce flammable and explosive gases which when failure further escalates can produce extensive heat and ignite. Figure 6 below illustrates the battery safe operation region with respect to the cell voltage and battery temperature range. It also illustrates the failure modes that would occur when the safe window is exceeded.

Risks can be mitigated through correct engineering on the battery system level by considering all possible failure risks. Proper safety management implemented at cell, module, and system level is necessary. One of the primary tasks of the Battery Management System (BMS) is to ensure that the battery is always operated within the Safety Window.

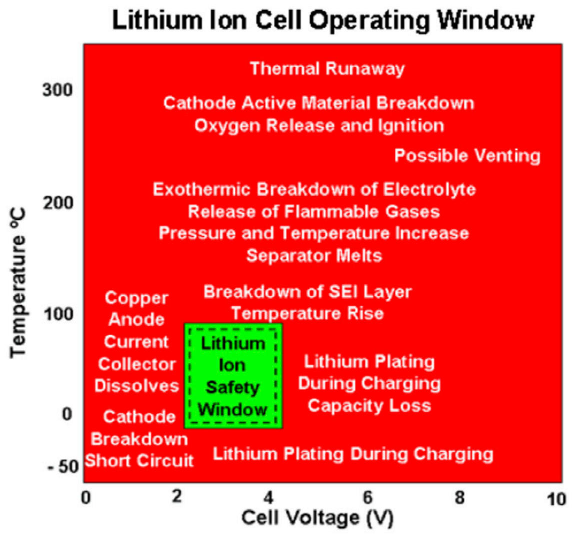


Figure 6

Battery systems which have been selected and are operated in port equipment can be considered as maintenance-free. The cooling system and protection system have been designed such that the battery system operates under optimal condition. As mentioned in the previous chapter, battery aging occurs even when it is not in use or in long-time storage. Spare batteries and especially spare battery modules must therefore be stored carefully with the proper SOC and temperature conditions. Considering this requirement, it is necessary to do regular maintenance inspections on spare modules and store these modules under specific warehouse conditions. It is therefore recommended that the battery supplier or equipment manufacturer keeps spare module in its suitably equipped worldwide branches in order to expedite delivery to end-customers should a module be damaged in a port/terminal.

3.4 STANDARDS

Battery safety related accidents have occurred worldwide over the years and safety standards have been implemented accordingly. Before deciding on the applicable standard for a battery installation consideration of the markets and or countries to which the battery will be sold as well as to the end-product in which the battery will be installed must be taken into account.

The Cell is the basic functional unit of any battery system, consisting of an assembly of electrodes, electrolyte, enclosure, terminals and usually separators. This cell construction is the source of electric energy obtained by direct conversion of chemical energy. Before assembling cells into a module, the battery supplier should clarify the certification requirements. For example, in the USA, UL1642 (safety testing of lithium battery) shall be followed. UL1642 is a general and authoritative standard covering primarily (non-rechargeable) and secondly (rechargeable) lithium batteries used as power sources in products.

A battery module is a block in which the single cells are assembled in a series and parallel connection configuration. The configuration is usually described by the letter sequence xSyP where x is the number of series connected cells and y is the number of parallel cells. To increase coulombic capacity (measured in Ah) and current capability the cells are connected in parallel.

Not only are there different standards for different chemistries and types but often, different markets or industries have specific standards which have to be complied with. Even though there is no specific standard defined for the port industry, it is suggested that battery suppliers follow the current most established standard which is IEC62619. This standard specifies the requirements and tests applicable for the safe operation of secondary lithium cells and batteries used in industrial applications including mobile applications, e.g. AGV, marine, forklift truck, and stationary applications.

When shipping lithium cells and/or battery modules, a UN38.3 certificate is mandatory. UN38.3 is a chapter of the "Recommendations on the transport of Dangerous Goods Manual of Tests and Criteria". UN38.3 requires a series of tests such as altitude simulation, thermal test, vibration, shock, external short-circuit etc. Similar to UN38.3, there is another IEC standard (IEC62281 safety of primary and secondary lithium cells and batteries during transport). The main difference between the standards is the number and status of samples. Currently UN38.3 is accepted and recognized worldwide.

3.5 REUSE

Engineering design considers different factors in order to prolong battery life. Regardless of the application a battery will however ultimately age. One indicator which reflects battery aging is capacity fade or degradation where its capacity declines over battery life. In EV, marine and ports industries, when the battery reaches the stage when it no longer can deliver an acceptable capacity, typically 70% - 80% of nameplate rating it is, referred to as its EOL (end of life). This is the criteria for battery replacement.

Even though battery capacity degrades, that does not mean that such a battery is no longer useful. Such batteries still have considerable value in that they can be reused in energy storage applications, either for household or industrial energy storage.

An EU-financed project is investigating how used batteries from the transport sector can be reused for energy storage in ports. The two-year project involves classification society DNV GL, the ports of Gothenburg and Kiel and several Stena companies – Stena Recycling, Batteryloop, Stena Rederi and Stena Line.

Stena will seek to utilize recycled lithium-ion batteries in port charging stations that will act as power banks which can provide fast charging of electric ferries in the future while reducing emissions. Quayside energy storage can also be used as an alternative power source for vessels when in port as an alternative to conventional shore power sources.

This project will be part-financed by INEA, the EU's Innovation and Networks Executive Agency. The reuse of Li-Ion batteries potentially offers an efficient and lower-cost development of energy storage solutions including meeting the charging requirements of hybrid-electric vessels. The reuse of batteries also offers an opportunity to deliver a cost-effective solution to the challenge of increasing supply capacity in regions where local electricity grid capacity might not be sufficient to support rapid increases in demand.

Figure 7

4. PORT EQUIPMENT USING BATTERY TECHNOLOGY

As outlined above there are currently several types of Port equipment using diesel generators as the prime mover which are being adapted to include the use of Battery Technology. These include RTG's, Straddle Carriers, Terminal tractors/Tugs, AGV's, Reach stackers, Top loaders, and Forklifts. Several configurations apply to each type of equipment.

RTG:
- Hybrid RTG (diesel engine and battery operated RTG)
- BE-RTG (full battery operated RTG)
- E-RTG (RTG Electrified with conductor rail or Cable Reel)
- FE-RTG (Electrified and Battery operated RTG)

AGV/Truck:
- Hybrid AGV (diesel engine and battery operated AGV)
- Full E-AGV (full battery operated AGV)
- Hybrid Truck (diesel engine and battery-operated Truck)
- Full E-Truck (full battery-operated Truck)

Similar basic battery technical principles and structures as used in RTG's also apply to AGVs and trucks. The batteries are smaller but the principles are almost the same. Hoisting howeverdoes not exist, so regeneration of energy is applicable during deceleration only. Operational average energy consumption and max peak power level being the main design criteria for battery system design.

Straddle Carrier:
- Hybrid Straddle Carrier (diesel engine and battery-operated Straddle Carrier)
- Full E-Straddle Carrier (full battery-operated Straddle Carrier)

A Straddle Carrier (SC) belongs to the yard crane family. In a SC container yard the quay crane performs loading/unloading the container between ship and ground. The SC moves the container between quayside and the container stack area where it performs loading /offloading /shuffling/stacking the container in the container stack area as well as servicing external trucks in a so called decoupled operation.

SC drive system configuration is similar to that of an RTG except that the SC does not have a trolley drive.

5. RTG'S WITH BATTERY OPTIONS

A Rubber Tyred Gantry crane (RTG) is a container stacking crane located in the yard. In all container terminals the quay crane(s) performs loading/unloading of the containers between ship the tranfer equipment i.e. SC, AGV or terminal tractor (Horizontal transport) which move the container between quayside and the container stack area. The RTG performs loading / unloading from the horizontal transport or road trucks as well as stacking and shuffling of container within the container stack.

5.1 HYBRID RTG (HYBRIDIZATION OF TRADITIONAL RTG AND BATTERY)

The Hybrid RTG, which utilizes both diesel Genset and battery, can use a smaller diesel engine thereby improving fuel efficiency, reducing emissions, and maintenance costs. A lithium battery system connected to the DC bus through a bi-directional DC/DC converter is utilized as the main energy source. The battery is defined as the main energy source because it supplies energy for the RTG most of time. The battery power is generated by a combination of diesel fuel and regenerative energy. The downsized diesel genset which is connected to the DC bus through a rectifier charges the battery. Figure 8 below figure shows one typical such system configuration and energy flow.

When the diesel genset is not running the batteries are the only source of energy for all RTG functions, e.g. hoisting, trolley motion, gantry travelling and other auxiliaries. In this mode the batteries also have the ability to fully absorb all regenerative energy.

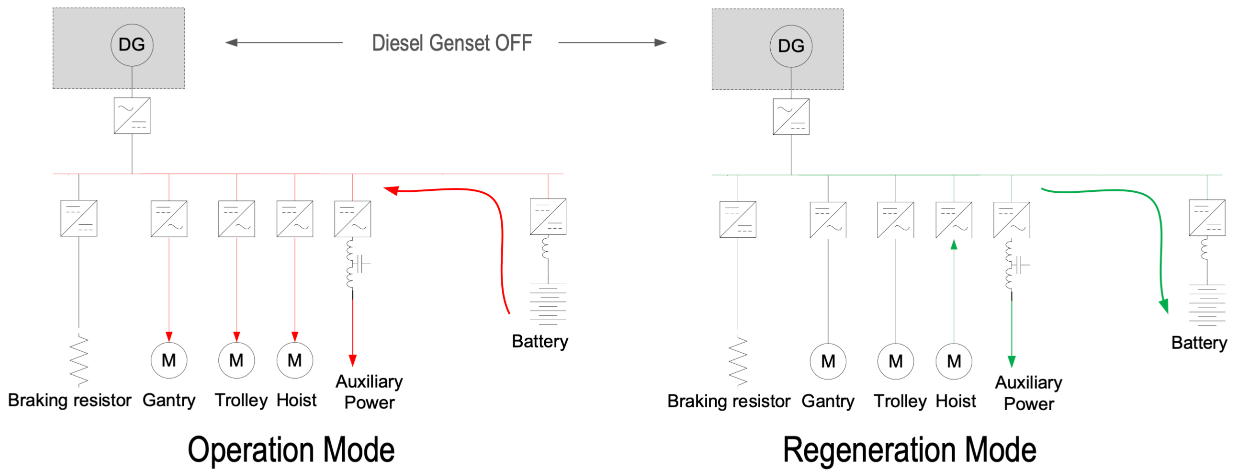


Figure 8

Even though all regenerative energy flows back to the battery bank for reuse, the consumed energy is still higher due to the efficiency ratio. As a consequence battery SOC (State of Charge) gradually decreases to its minimum limit. On reaching this level a command will automatically trigger which will start the diesel genset. The battery and diesel genset then work in parallel to supply energy for RTG functions. As described in chapter 2.1, regenerative energy is produced during container lowering motion. This is generally much higher than the auxiliary load demand and the battery is therefore re-charged during this phase in the cycle. After repeating this working cycle a number of times, the battery SOC increases to its maximum limit value which triggers another command to automatically switch off the diesel genset.

The result is that, the diesel genset is not always running as was the case with a traditional RTG. Less running time leads to less fuel usage and maintenance costs. With a hybrid RTG, the diesel genset running time can be reduced to 50% or even less. The actual running time required is a function of the coordination between the diesel genset and battery capacity.

Figure 10 illustrates battery SOC onsite measurement data. For each charge/discharge cycle (minimum SOC -> maximum SOC -> minimum SOC), the duty ratio varies as a function of the RTG operational requirements.

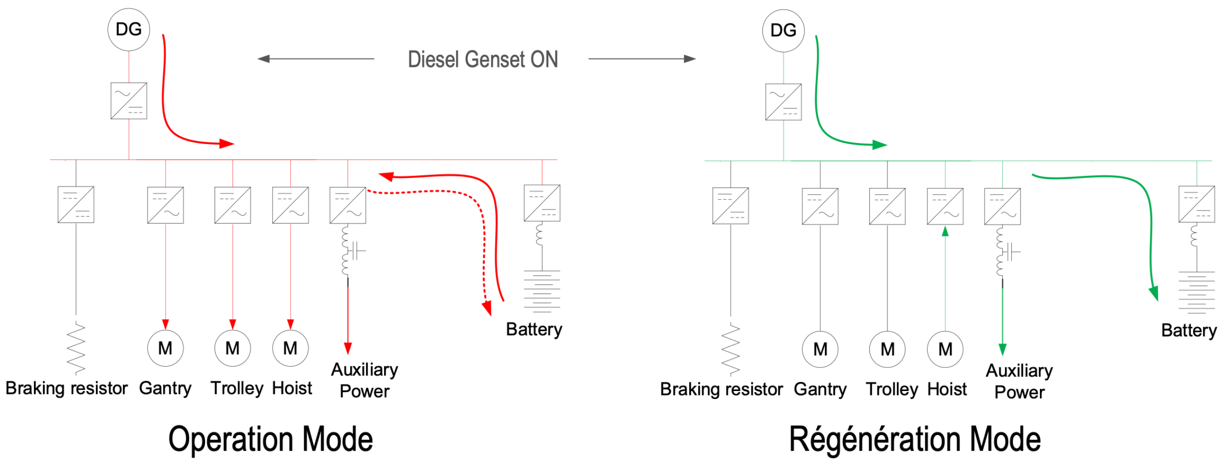


Figure 9

Figure 10

The reduction in the diesel genset running time results in considerable fuel saving this being the primary advantage of a hybrid RTG's. Reduced fuel consumption in turn results in lower emissions. The fuel saving therefore results from the combination of utilization of the regenerated energy the downsized diesel genset and the reduced genset operting time.

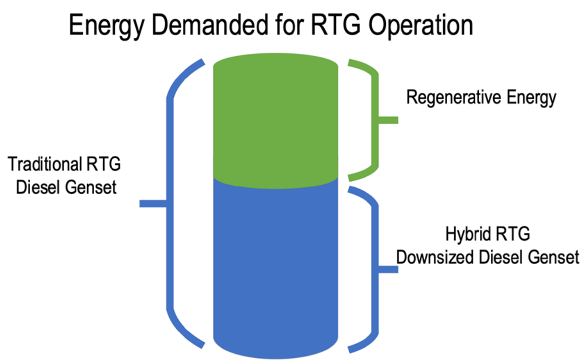


Figure 11

Analyzing the effect of the engine size on fuel consumption, the downsized diesel engine consumes less fuel per Kw output when compared to that of a traditional RTG due to the diesel engine's SFOC (specific fuel oil consumption) characteristic. Figure 12 is an example of a diesel genset SFOC characteristic which illustrated this effect. It highlights that the fuel consumption required to produce 1 kWh of energy is inversely proportional to the engine load. Therefore a smaller engine operating at the optimum point on the load curve maximises engine efficiency.

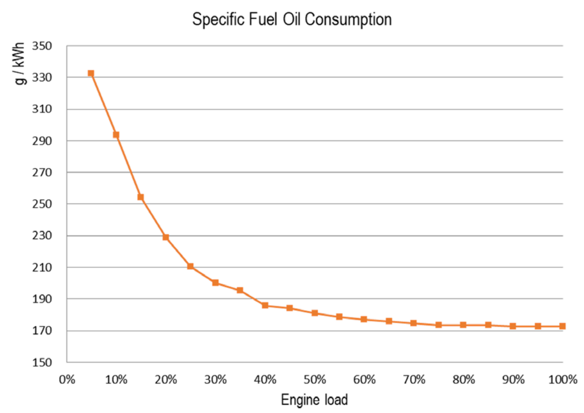


Figure 12

RTG cranes have a variable load profile. A typical RTG power demand increases from zero to approximately 400kW when accelerating a 40 Tonne container from standstill to rated speed typically within 2-3 seconds. The RTG c an return peak regenerative power from 250kW to 0kW during lowering and deceleration. RTG's have an average power demand of between 10kW and 30kW for auxiliary systems such as lighting, air-conditioning, control power and hydraulic systems.

A traditional RTG crane consists of a single diesel genset as the main energy source. In practice this generator is rated at more than 400kW in order to handle a 40 Tonnes heavy container at rated acceleration as well as the other drives and auxiliaries. This onboard diesel genset (DG) consists of an asynchronous generator which requires that engines with higher power ratings are selected to maintain engine stability at the high-power slew rates experienced during hoist acceleration/deceleration. In practice the average container weighs 10 – 20 Tonnes and opertional practices result in the average RTG power deman d being relatively low when compared with the diesel generator capacity. This results in the diesel generator operating in the low efficiency area of its performance characteristics most of the tim e. Therefore higher fuel consumption per Kw and higher emissions than when operating at its optimum speed and load result.

For hybrid RTG's, the downsized diesel genset is sized such that it runs at its optimal SFOC point. Several such systems have been installed in a variety of ports where hybrid RTGs have recorded typical fuel saving of higher than 60%.

Battery DC Bus Configuration Options

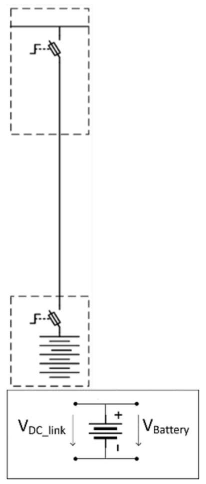
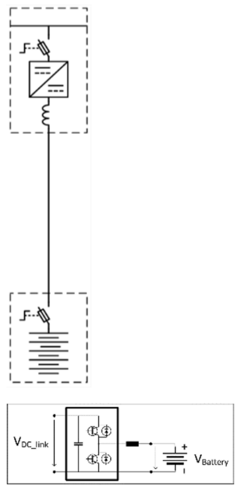
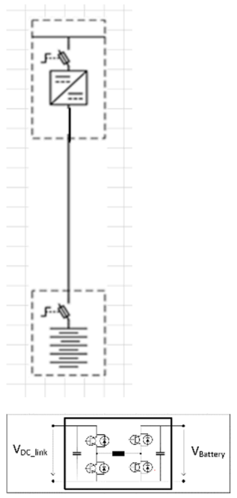
In addition to the typical configuration (with DC/ DC converter) as depicted inFig 9 above, other alternative drive configurations (i.e. direct connection to DC bus) are available which allow integration of batteries in RTG's.

The advantages/disadvantages of the various configurations are illustrated in the table below.

A directly connected battery results in increased system efficiency when compared to the battery connected via a DC/DC converter. This however is achieved at the expense of less control and more complex integration for the following reasons:

- The DC bus voltage reference must be manipulated to get the required output from the battery.
- Minimum DC voltage needs to be decided based on minimum SOC and maximum load current of the battery.
- Aging also affects the battery resistance, not only SOC. This will affect which SOC window is available at EOL.
- Use, limits, and profiles must be clearly defined and communicated to customer.

Buck (Step down) and Buck-Boost (Step up/ down) Converters as illustrated are switch mode power supplies using semi-conductor technology to achieve voltage regulation.

	Direct connection	DC/DC Converter	DC/DC Converter
System Connection Method	Direct 	Buck converter 	Buck-boost converter 
Response	Good	Instant	Instant
Autonomy	Partial	Full	Full
Battery design	$V_{Battery} = V_{DC\_link}$	$V_{Battery} < V_{DC\_link}$	$V_{Battery}$ independent of V_{DC_link}
Functionality	Limited	Full	Full
Converter Size	None	∝ Peak power	∝ Peak power
Main advantage	Efficiency	Controllability	Controllability

5.2 FULL ERTG (FE-RTG) (HYBRIDIZATION OF ERTG AND BATTERY

Since 2006, port and terminal operators have initiated the implementation of RTG electrification. One of the key challenges has been to maintain the flexibility of RTG cranes in container yard operations while at the same time reducing the dependency on fuel oil. Today the market offers several proven and advanced solutions to convert RTGs to so-called 'ERTG's which utilise either Conductor rail or Cable Reel technology.

5.2.1 CONDUCTOR RAILS

One preferred technology in many applications is the use of conductor rail, also known as bus bar or conduct bar. The first example where conductor rails were used for RTG electrification was in China in 2007. The basic concept of having a supported conductor rail system installed along the full length of a container block has not changed since then. Today, around 75% of all converted and newly supplied ERTG systems are electrified by conductor rails.

Conductor rails have proved over many decades to be a reliable means of providing energy to moving equipment, both indoors and outdoors, even in harsh environmental conditions. There are currently two main conductor rail connection technologies used to electrify RTGs using conductor rails, namely 'Plug-In' and 'Drive-In' types. With both systems conductor rails are installed parallel to the container block. The technical difference is in the connection method used between the fixed conductor rail and the mobile RTG.

The main challenges for the conductor rail system include:

- When connected there is a mechanical link between the E-RTG and the fixed structure which requires the installation of safety devices to avoid accidental impacts
- The installation of the rail support structure in the yard fixes the layout of the terminal making it more difficult to re-configure in the case of future expansion or should operational changes be required.
- The Plug-In technology still retains the need to unplug/plug when changing blocks. (This problem has been overcome with the Drive-In variant)

Figure 13 Typical Conductor Rail Installation

5.2.1.1 PLUG-IN SOLUTION

The concept of an E-RTG with a plug connection is relatively simply. Electrical energy is provided through a conductor rail system running alongside the container block. The support structure of the conductor rails also includes a running track for a collector trolley.

The trolley which holds the current collectors for 3-phase and earth connection is pulled by a towing rope/arm attached to the travelling RTG. The connection between the RTG and the rail system is managed by a cable and plug.

Plug-In systems are now well-proven as practical, safe, and reliable, with several hundred installations worldwide. However the disadvantage is the connection and disconnection time required when transferring between container blocks. This process can take in excess of tens of minutes and requires that either the driver climbs down to perform this task by himself or the deployment of additional manpower resources on the ground. Depending on the operation of a terminal and the frequency of block transfers required this could be a significant time factor.

5.2.1.2 DRIVE-IN SOLUTION

Drive-In systems also operate using an elevated conductor rail system as described in 5.2.1.1. In this case the collector trolley which is attached to the RTG with an articulated arm is allowed to leave the rail at each end of the block through special drive-in/out zones at the end of the blocks. A series of sensors with associated interlocking logic for functionality and safety are an integral part of the installation.

Recent developments allow the change-over process to be managed by the driver directly from the cabin, the process taking less than one minute to perform. The Drive-In solution offers the full benefit of a conductor rail powered RTG however without impacting the flexibility of RTGs to move between blocks.

5.2.2 CABLE REELING DRUM SOLUTION

An alternative technology is the use of a Cable reeling drum with trailing cable. This requires the installation of protection guides or a support structure for the trailing cable on the terminal as well as a plug/socket/switch for connection purposes.

Cable reels in various spool designs and sizes have become standard for STS and RMG cranes in container terminals worldwide. Cables, typically medium voltage designs, are wound onto large spools to enable linear travel along the RTG travel path. Spooling devices and cable protection systems guarantee safe operation. The application of cable reels on RTGs, which are designed to run not only in linear but in all possible directions, presents some special challenges both for the technology deployed and in terms of operational practicalities.

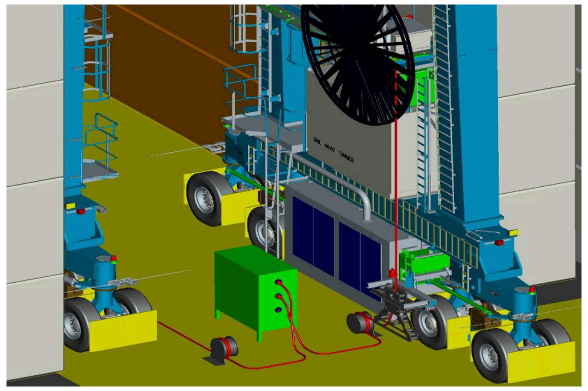


Figure14 Typical Cable Reeling Drum Installation on an RTG

Where the operation of an RTG can be limited mainly to linear travel and allocated to a particular container block, the use of cables reels can be managed quite well. It becomes more difficult when the operation requires frequent block changes as there is the requirement to unplug and plug, a procedure that can cause significant delays. Development is ongoing on automated plug/unplug solutions which when available will reduce the required time for the unplug/plug process.

There are also technical requirements that need to be considered for RTG crane modification in order to accommodate a Cable Reel and its associated components. The position of the cable reel on the RTG needs to be defined according to the design of the machine giving due consideration to the RTG structural design. The reel itself and the additional supports and mounting platforms which have to be installed result in significant extra weight. Many new build RTG cranes have either cable reels pre-installed or are prepared for later fitting of cable reeling systems.

Using cable reels for RTG electrification means that major structural site work is either not required or minimal in nature, in contrast to the conductor rails execution. Many terminal operators view this as a significant benefit. As the retrofitting of a cable reel on existing RTGs can be a significant project, the decision on the type of solution (reels or rails) is mainly driven by operational considerations and requirements

With both the conductor rail and cable reel solutionsa, a seperate energy source is required to effect block transfer. An auxiliary diesel generator or a battery systen may be employed for this operation.

Some challenges for cable reel implementation on RTGs can include:

- Significant additional weight and possibly mechanical modifications on the RTG
- The need to unplug and plug in again to change aisles
- Cable alignment between RTG and container stack and additional cable protection required to avoid damage
- Additional measures have to be taken if a number of RTGs are to operate in one block.

5.2.3 BENEFITS OF ELECTRIFICATION

Electrification of RTG cranes offers significant performance improvement when compared with traditional diesel generator RTG's by way of energy savings. In addition, the change from diesel genset to electricity has the added benefit of reducing the operating noise level by in excess of 50% depending on the configuration. Electrification of RTG's will meet not just local site CO_2 emission reduction targets but will also contribute to annual country specific electricity induced CO_2 emission requirements. This is defined as less than 1.5 Tonnes of CO_2 per MWh as is the requirement for all European countries [Ref: Green Port in Blue Ocean: Optimization of Energy in Asian Ports].

Drive system configurations where the input rectifier is replaced by an AFE (active front end) are also employed on E RTG's allowing energy regeneration to the network during lowering and deceleration. In such a configuration the braking resistor is no longer required and additional energy savings accrue.

The ERTG benefits are described above however there are still challenges for the ERTG installation. As mentioned earlier for example in the case of the conductor rail system, the installation of the rail support in the yard fixes the layout of the terminal making it more difficult facilitate operational changes when an RTG has to operate on several container stacks or blocks. In this instance batteries are integrated into the ERTG to improve operational mobility by permitting stack transfer using the on-board battery system. The result is the so-called FE-RTG (Full ERTG) which can be used with both Conductor rail and Cable Reel executions.

Below diagram Fig.15 shows the system configuration and energy flow in the case of the FE-RTG. The FE-RTG is powered by either conductor rail or cable reel while operating within the container stacks. When it comes to the block changes, the RTG gantry system and auxiliaries are powered by the battery system. Seamless changing from one container stack to another is thus possible and flexible and optimised with the provision of the auto feed-in/plug options. The time required for generator set warmup does not apply nor does the concern for diesel fuel re-fill and associated issues. The Battery system design allows for a gantry travel distance of greater than 1km.

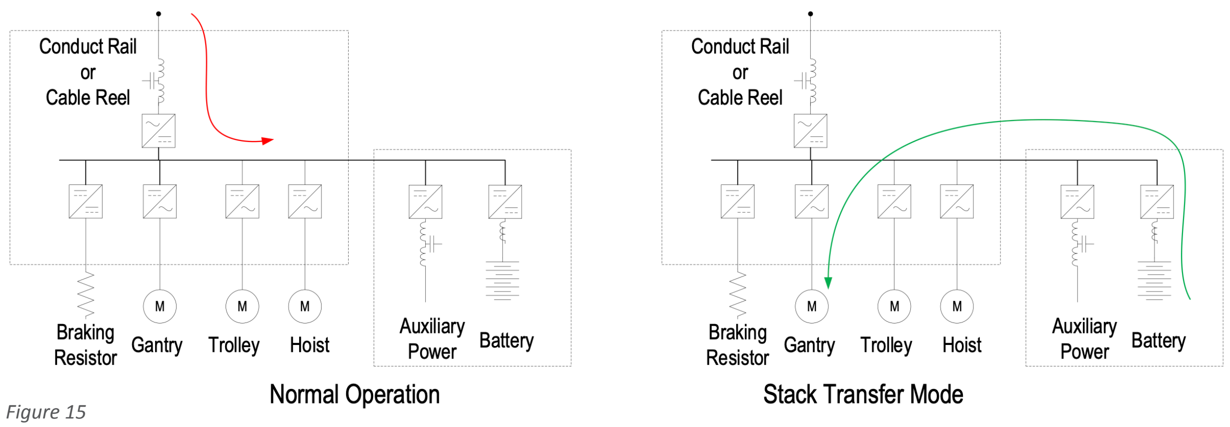


Figure 15

5.3 BATTERY OPERATED RTG (BE-RTG)

As an alternative to the FE-RTG electrification can be achieved by using batteries only or the so called BE-RTG (Battery Electric RTG). The battery system is selected as the only energy supply source. Since regenerative energy is never enough to keep the RTG running contin- uously, the battery needs to be re-charged after a certain period of energy usage. When the battery system is fully charged from the charging station it can continuously feed power for all crane operations for up to 10 hours. During this period, the battery supplies energy for all the motions and absorbs the regenerative energy. When the SOC decreases to a designated minimum limit, the RTG needs to drive to a charging station. This charging point is connected to the existing port AC electrical grid power network via a dedicated high-speed charging system. Recharging time is a function of battery size, C rate and charging station configuration and rating.

The Battery operated RTG configuration therefore achieves zero emissions during operation.

The required number of batteries supporting RTG operation hours results in the battery capacity being sized at around 500kWh. Typically, the nominal RTG power demand is approx. 400kW during hoisting of a 40tonne container. Based on the formula for C rate calculation the theoretical discharging C rate is less than 1. This is a typical energy-type application where NCM chemistry cell technology is the most suitable for BE-RTG application. The rate of battery discharge and resultant operational time between charging on a BE-RTG is a function of the type of operation: i.e.

Number of cycles,
Loading or unloading pattern, Container weight, Ambient temperature, Acceleration/Deceleration times, Day/ Nighttime operation, Gantry cycles, etc.

A typical average energy demand of an RTG when regeneration is taken into considered is 35-50 kWh/Hr on the basis of a handling rate of 15-20 Containers/hour. This results in up to 10 hours operation using the battery installation. Figure 16 illustrates a typical BE-RTG SOC discharge/ charge graph based on operating/charging time (as reference only).

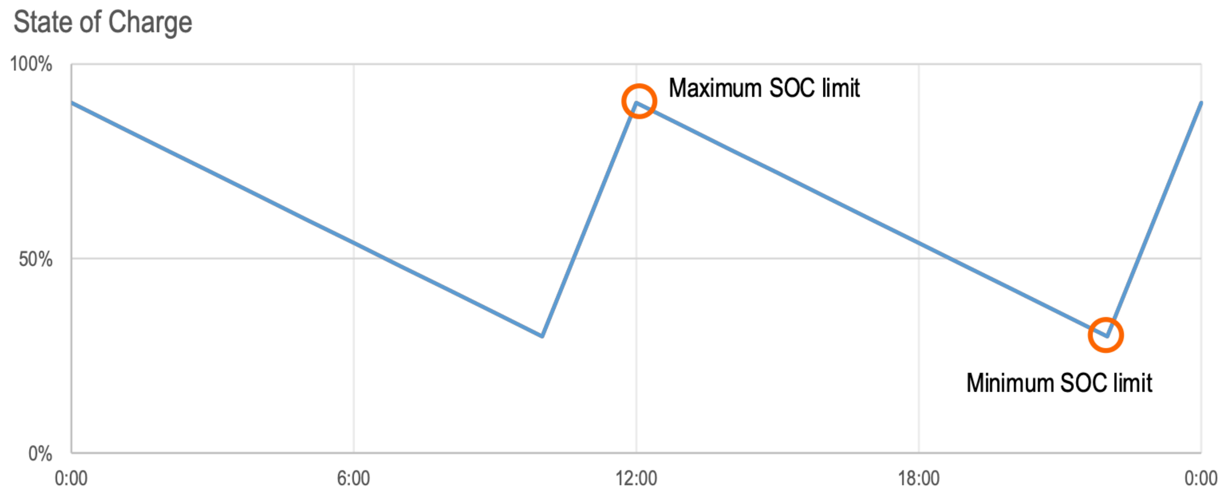


Figure 16

Below table is a summary of the diferences between the various RTG types for reference.

	Full speed diesel genset RTG	Variable speed diesel genset RTG	Hybrid RTG	FE-RTG	BE-RTG
Operational mobility	Very good	Very Good	Very good	Good	Very good
Qty. of RTG per block	No limit	No limit	No limit	Limited	No limit
Length of container block	No limit	No limit	No limit	Limited / No limit	No limit
Energy saving	Poor	Good	Very good	Very good	Very good
Maintenance expenditure	High	Good	Good	Very good	Very good
Environmental impact	Bad	Good	Good	Very good	Very good

5.4 CHARGING REQUIREMENTS/ BATTERY MANAGEMENT SYSTEM

Charging station(s) can be either an AC or DC power source depending on port infrastructure. Charging station(s) can also be installed in the ground at strategic locations throughout the terminal to allow for battery malfunction.

As mentioned above, the battery capacity of the BE-RTG is around 500kWh. Depending on the operating voltage specification there may be a requirement to have several battery packs connected in parallel. Therefore, a critical issue is the BMS (battery management system) control scheme. The management system not only monitors battery status but the BMS master unit's main function is to optimally control individual packs. For example, should pack1 triggers a fault, then the BMS master unit sends a command to disconnect pack1. In this case the other packs are not affected and continue working. Temperature monitoring and charge/discharge Rates and balancing are an integral part of all BM systems.

When RTG drives to the charging station the BMS master unit also controls the pack connection sequence. Packs will attempt to connect starting with the one with the lowest SOC. The BMS will dynamically evaluate the condition of the other packs and will connect when appropriate. For example, in a 2 packs battery system having the SOC's distributed as shown in Fig 16 below should a charging command be issued while no current is flowing and no pack is connected, Pack1 will connect first, and the other pack will each connect when the connected pack approach their SOC.

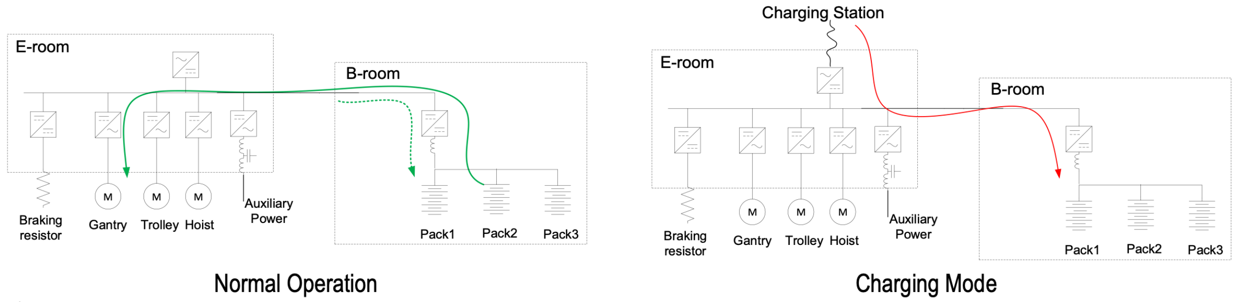


Figure 17

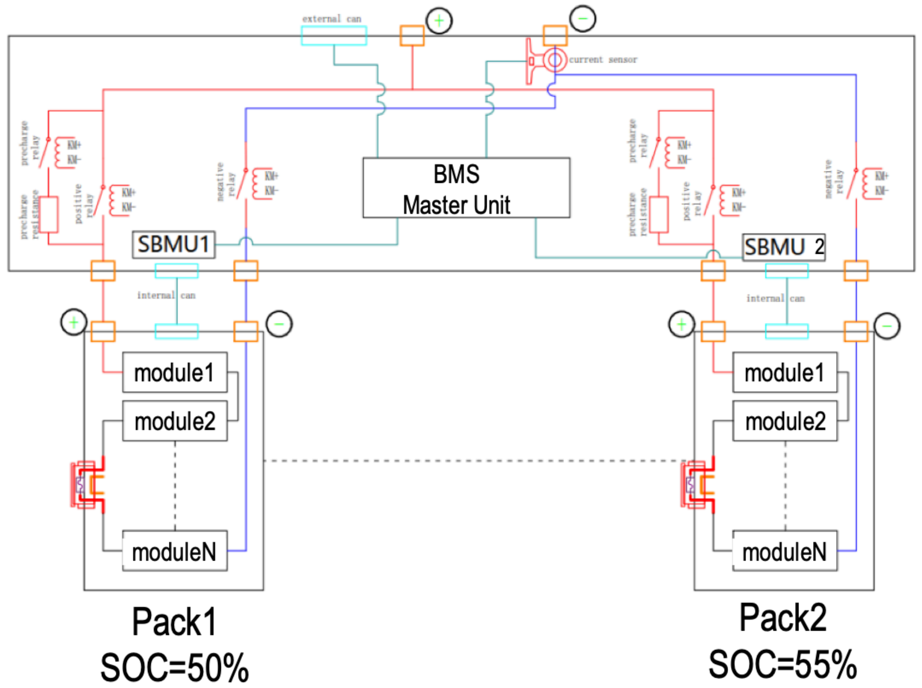


Figure 18 BMS Schematic Diagram

6. CHARGING SOLUTIONS

6.1 STATIONARY CHARGING (-RTG, AGV, STRADDLE, TRUCK,) / NON-OPERATION CHARGING)

RTG's equipped with batteries can have both AC and DC charging power connection options. Therefore, it is possible to charge the battery through either an AC or DC supply connection point in the terminal. The operation principle of the battery equipped RTG is when the RTG drives to the charging area, the battery is charged by taking energy from utility grid of the port. The RTG is powered by the battery when the RTG operates in the container yard.

One of the main challenges of charging station design is the sizing of the charging capacity. The design has to consider the equipment operation schedules, the effect on the utility grid and battery charging ability. If the equipment has a tight time schedule and requires a short charging time there is a requirement for high-power charging capability. The charging station is also regulated by power supply safety regulations and there are requirements in respect of voltage quality such as the permissible total harmonic distortion (THD), rapid voltage changes and flicker. Connection plugs and procedures must also comply with the relevant regulations.

The topology of a charging station can be either AC or DC and can be located either on the RTG or on the terminal. When making the decision as to which topology is the best for the application, five practical issues as listed in this chapter need to be considered:

- **Maintenance and flexibility**

Maintenance will be much easier if all the charging equipment can be installed on the terminal between RTG and charging power source.

- **Weight and volume**

Weight and volume of the charging system is an important factor if the charging station is partially installed on the equipment. For example if the AC/DC rectifier is installed inside the E-house AC plugs/sockets are required for connecting the AC/DC rectifier with the port power station. With the advent of suitable DC plugs the possibility of locating the AC/DC rectifier inside the site charging station is now available whereby batteries are charged via the DC bus directly.

- **DC voltage controllability**

In the case where the battery is connected to the RTG DC bus through a DC/DC converter, a charging system with fixed DC voltage can be selected since the DC/DC converter can match the two voltages. If the battery is connected directly to the RTG DC bus, then the charging station must have a regulated DC voltage such that the voltage of the charging station can match the DC bus voltage and optimally adjust battery charging rate.

- **Cost**

Installation cost is one of the main considerations when designing the charging station. The RTG fleet size can be the key deciding factor for either installing the AC/DC conversion on the RTG or inside the site charging station. Where multiple RTGs are operating on a terminal it is generally more economical to install the AC/DC converter inside the charging station on the terminal.

In this case only one AC/DC unit needs to be installed with multiple DC outlets fed from a common DC Bus in the charging station. The fact that DC plug technology is more expensive than its AC equivalent must be considered in the cost evaluation.

- **Quantity of charging stations**

Currently and regardless of whether the battery chemistry is NMC, LTO or LFP, battery charging C rate can be higher than 1. This means the charging time can less than 1 hour. Charging time can in practice be as little as 30 min as in most cases the DOD rarely reaches 100%.

Charging time is not dependent on the quantity of charging points but rather the rating and capacity of the charging DC/DC convertor, the connection cable cross section and the plug rating. These components have to accommodate the required charging current and can be a practical limiting factor in the charging time achievable.

Charging station number is dependent on the charging station power rating. If for example the power rating is limited and the port equipment has to be charged one by one the charging station ratio is typically 3 for every 10 pieces of container handling equipment.

6.2 INDUCTIVE CHARGING

Inductive Charging is gaining in popularity for mobile equipment. It is currently utilized in the Transport sector particularly for busses and AGVs. Inductive charging is based on the principle of electromagnetic induction as applied to virtually all electric generation, transmission and other electrical and electronic devices. As is the case with a transformer an alternating electric current in the primary circuit produces an alternating electromagnetic field. By the law of electromagnetic induction this field induced an alternating current in an adjacent secondary circuit. Unlike the classical transformer configuration, where the primary and secondary parts are closely coupled by a shared iron or ferrite core, inductive charging consists of separate primary and secondary parts. The primary and secondary parts are therefore no longer coupled via a fixed core. The primary part is 'stretched' to a long conductor loop which is installed in the ground. The secondary part is wound around an open ferromagnetic core installed on a bus or AGV which moves with the vehicle. Using the principle of electromagnetic induction the secondary part draws power from the magnetic field of the 'stretched' primary part and thus supplies the power to battery.

This inductive charging system can be used and designed in different configurations by the various suppliers on market. The principle of operation is same however, and most configurations are similar in cocept. Below Fig 19 and Fig 20 illustrates a typical inductive charging system configuration with the main components described for supplying power to mobile transport units, e.g. Bus, AGV etc.

Primary part (Power supply module & charging mat) The function of primary part is to generate a magnetic alternating field. The frequency of the alternating field created around the primary part is a critical factor for the functioning and efficiency of an inductive charging system. While the standard AC electrical supply network operates at 50/60 Hz, inductive charging system work typically at a frequency of 20,000 Hz, or some 400 times higher and even more. Using this higher frequency makes it possible to transfer power effectively over a large air gap.

Secondary part (Power pickup & charging electronics)
The function of secondary part is to extract power from the magnetic field and supply this power to the battery. The charging system electronic control and conversion technology is adapted to control the power supply for the battery charging process on the vehicle.

A major advantage of an inductive charging system is contactless energy transfer. Since there is no mechanical contact a barrier-free environment can be achieved which makes the application of such a system in the area of people very attractive in terms of safety.

On-going research in this field is extensive and as Inductive energy transfer is independent of the dynamics it is expected that it will ultimately become established in the market as a continuous power supply as well as being used for opportunity charging.

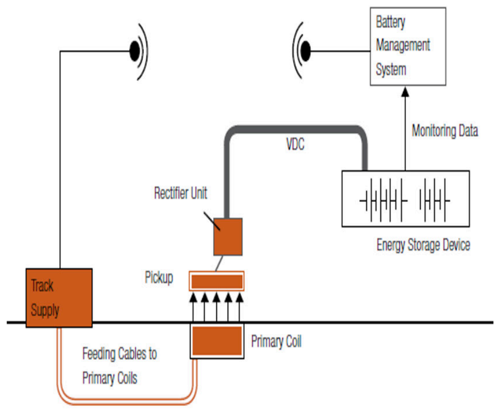


Figure 19

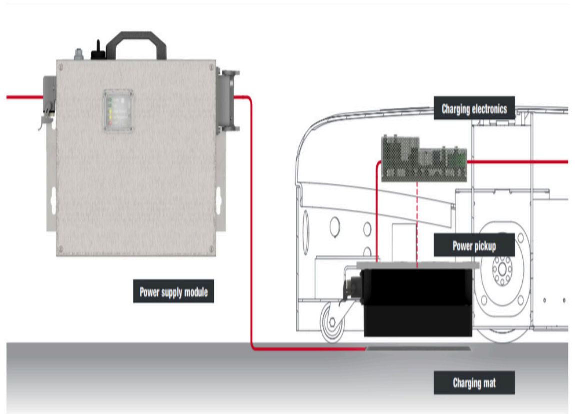


Figure 20

ABOUT THE AUTHORS AND PEMA

ABOUT THE AUTHORS

This paper was prepared by Neal Liu of Conductix with contributions from Kalmar, Kone, Liebherr and other PEMA members.

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Founded in late 2004, PEMA's mission is to provide a forum and public voice for the global port equipment and technology sectors, reflecting their critical role in enabling safe, secure, sustainable and productive ports, and thereby supporting world maritime trade.

Chief among the aims of the Association is to provide a forum for the exchange of views on trends in the design, manufacture and operation of port equipment and technology worldwide.

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