# Automation and electric drives
## A powerful union for sustainable container terminal design

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# Chapter 5
# Automation and Electric Drives

## A Powerful Union for Sustainable Container Terminal Design

**Joan C. Rijsenbrij and Armin Wieschemann**

**Abstract** Despite a reduced annual growth in trade volumes, major shipping lines continue to invest in ULCVs (*U*ltra *L*arge *C*ontainer *V*essels with 20,000+ TEU). For efficiency reasons shipping lines operate in alliances and joint services, to maintain attractive shipping services to shippers/consignees and to benefit from economies of scale and enlarged buying power. Parallel to this, the complexity of logistics is growing and the society and port authorities put stronger demands on environmental control and sustainable designs. These developments influence terminal designs and terminal operations, which have to deal with much larger vessel call sizes, longer container dwell times, and frequent changes in handling volumes from varying alliance policies and shipping services. A growing amount of container terminals have recognized (partly) automation as an appropriate tool for cost control and performance improvement, required by the powerful shipping alliances. The application of state-of-the-art electric drive technologies will support an increased use of renewable energy and long-term cost reductions.

## 5.1 Introduction

Over the last years there has been a moderate growth in yearly port handling volumes, reaching towards about 700 million TEU handlings in 2017. A major part of this volume ($>34\%$) is handled by Chinese ports and when looking to the developments in other Asian ports, there is a clear shift in volume towards the Asian region (see Fang et al. 2013). Contrary to the moderate growth in port handlings, the world container vessel fleet capacity has increased considerably to over 20 million

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TEU. An impressive part of the fleet is realized by vessels larger than 10,000 TEU capacity, with already more than 50 vessels in the range of 18,000–21,000 TEU (mid July 2017; see Alphaliner 2017). In order to fully benefit from economies of scale, the shipping lines increasingly operate in global alliances (e.g. 2M, Ocean Alliance, THE Alliance), very helpful to optimize their worldwide shipping services and to increase their buying power not only for supplies and bunkers but for terminal services as well. This has caused noticeable reductions in terminal handling rates and at the same time the enlarged vessels have resulted in larger operational peaks and more idle time for the terminals' waterside operations. In addition, shipping lines and inland transportation companies require terminals to realize increased handling performances and predictable, limited turnaround times (see Merk et al. 2015).

Parallel to this, the complexity of logistics is growing. The dominance from shippers and consignees deteriorate landside stochastics as a result of last-minute changes and unknown (inter-)modal connections. Moreover there is a growing influence from customs regulations and security requirements, larger volumes of container checking with X-ray and recently the demands from the International Convention for *S*afety *O*f *L*ife *A*t *S*ea (SOLAS) that shipping documents must include a *V*erified *G*ross *M*ass (VGM); see IMO Secretary-General (2016).

And finally, governments, port authorities, and the society put stronger demands on environmental control and sustainable designs. Habitats around port developments should not be influenced and pollution from sound and exhaust gases is increasingly restricted and the use of renewable energy from hydro, wind, and solar power is stimulated or even subsidized. The use of casual labor is diminishing and port operators are required to provide good working conditions, appropriate training, and labor contracts with well described regulations.

In this rapidly changing environment terminal operators are challenged to design or modify their terminals for the expected volume growth in the next decades. Many terminals have recognized (partly) automation as an appropriate tool for cost control and performance improvement. The application of state-of-the-art electric drive technologies will help to design sustainable automated terminals that can meet the future demands from a caring society.

## 5.2 Changed Demands in Terminal Design

After the year 2000 the larger terminals were confronted with the introduction of container vessels carrying more than 10,000 TEU. In the 1990s, an overall berth productivity of 100 moves/hour/vessel served with 4–5 *S*hip-*T*o-*S*hore (STS) cranes used to be a good service to shipping lines. However, after the arrival of 14,000 TEU vessels and nowadays up to 21,000 TEU vessels, the shipping lines require a berth productivity of 175–250 cont. moves/hour/vessel with 6–8 STS cranes, still seldom met by terminals and thus a real challenge for an automated transportation system connecting so many STS cranes per vessel and the (large) stacking yard.

Not only a proper scheduling and dispatch for all the transport vehicles, but also the dynamic logistics, caused by the reversing push (discharge operation) and pull (loading) processes, require an intelligent control system for the horizontal transport system between STS cranes and stacking yard (see Rijsenbrij 2008). Regardless smart interfaces and well-defined priority rules, the required berth performance for *U*ltra *L*arge *C*ontainer *V*essels (ULCV) results in a highly intensified traffic density at the apron. The example elaborated in the below presented case study shows the impact of ULCVs on apron traffic density, labor demand, and idle time for waterside operations (simplified comparison with equal yearly volume) (Table 5.1).

The demand for increased berth performance from large shipping lines and alliances is often combined with guaranteed berthing, which is even worse for the terminal's quay wall utilization. Shipping lines introduced ULCVs to get cost savings in their operations; however, for terminal operators the handling of ULCVs causes inefficiencies and more complex (and thus more costly) logistics.

Other demand changes can be recognized at the landside of the terminal. There the inland transportation operators (road, rail, and barges) demand guaranteed service times and pre-planned service slots. This must be realized independently from the workload at the terminal waterside resulting in additional equipment/systems for the terminals' landside service.

Beside the handling systems at terminal water- and landside, one of the most important terminal design components is the stacking yard, both the size and type (handling equipment, interchange areas, stacking height, and modular design) as well as the possibilities for future expansion. Many years of planning experience show that over the years the dwell time of containers has not been reduced; to the contrary, in many large terminals average dwell times longer than 5 days are rather common. The arrival of very large container vessels has resulted in 1.5–2 times larger call sizes and due to the reduced call frequency and limited inland transportation capacity this has increased the dwell time. Another phenomenon in that respect is the demand for cost reduction in the overall logistic chain, resulting in lowering (or even avoiding) warehousing and regional distribution centers. Shippers and consignees try to avoid warehousing by delivering containers directly after packing and through the collection of import boxes just in time for their logistics. Also the delays from incorrect CSI (*C*ontainer *S*ecurity *I*nitiative from U.S. Customs Service) information or missing VGM documents cause transit elongations. The mentioned changes in container logistics could be detrimental for the container dwell time at terminals and will increase the area demand and even (unpaid!) housekeeping.

Design changes can be triggered as well by the demand to cope with changing annual throughputs due to carrier policy to divert volumes for commercial (cost) reasons. Noticeable volume shifts have been occurred between terminals in Hong Kong, Singapore, Port Klang, North-West European ports, USA East Coast, etc. In those cases terminals want (and have!) to adjust stack capacity, handling capacity, and related labor demand.

Parallel to the above terminal design influences, terminals have to implement many features forthcoming from increased environmental awareness (pollution

**Table 5.1** Case study: impact of ULCVs on apron traffic density, berth utilization, and labor demand

The ongoing drive for Economies of Scale has resulted in ULCVs operated by shipping lines. In 2016 more than 25% of the world's container vessel fleet consists of vessels with >10,000 TEU capacity (see Wadey 2016). Unfortunately, the application of ULCVs in an almost stable trade environment influenced terminal operations in a number of areas: berth utilization, labor utilization, more equipment, and more traffic density at the apron. These are the consequences from the shipping lines' requirement for much higher performance figures, when handling their ULCVs. In a case study the impact of ULCVs on the above issues was analyzed and in particular the transportation traffic between the STS cranes and the stacking yard, hence this traffic density is an important topic, when realizing automated transport systems.

For the case study a liner service calling at a terminal was projected; however, with two alternative vessel sizes: one service with 8000 TEU vessels and another with 18,000 TEU vessels. Both services, equal in yearly terminal throughput, realized approx. 1 million TEU and for that volume the terminal guaranteed a 500 meter berth length throughout the year. The service with 8000 TEU vessels resulted in 4 vessel calls per week, each call 3000 cont. moves (equals 3000 × 1.6 = 4800 TEU) and the service with ULCVs had 2 calls per week, each 6000 cont. moves. As vessels never arrive exactly on a labor shift change a 15% labor idle time was considered. The results per vessel type are presented in the table: The study showed: when shipping lines apply vessel sizes with capacity ranges of 16,000–20,000 TEU (instead of 6000–9000 TEU), the traffic density of transport vehicles at the apron will increase by 50%–60% and during performance peaks even by 60%–85%.

In addition, the requirement for increased berth performance (to maintain an almost equal time in port for the ULCVs) will decrease berth utilization by 35%. Moreover for the terminal operator, ULCVs cause less demand for waterside labor shifts, however with much higher peaks. This is unattractive when aiming for well-motivated employees with fixed labor contracts and work rosters (casual labor is less attractive for automated operations).

| Vessel size (TEU) | 8000 | 18,000 |
|---|---|---|
| Vessel length (m) | 340 | 400 |
| Required additional berth length for mooring (m) | 25 | 25 |
| Berth length guaranteed for shipping line during the year (m) | 500 | 500 |
| Number of vessel calls per week | 4 | 2 |
| Call size (total moves for discharge and loading) | 3000 | 6000 |
| Yearly throughput (in TEU with TEU-factor = 1.6) realized in this liner service | 998,400 | 998,400 |
| Number of cranes assigned to vessel during vessel operation | 4–5 | 7–8 |
| Average operational crane productivity (cont. moves/hour/crane) | 26–29 | 26–34 |
| Required average berth productivity (cont. moves/hour) | 125 | 225 |
| Assumed extra time at berth for berthing and un-berthing (hour) | 3 | 4 |

| | | |
|---|---|---|
| Vessel operating time (hour) | 24 | 26.7 |
| Total vessel berth time during one call (hour) | 27 | 30.7 |
| Average traffic density (transport cycles/hour per required meter berth length during a call) | 0.34 | 0.53 |
| Peak traffic density (all cranes operating at hourly maximum of their operational productivity) | 0.40 | 0.64 |
| Berth occupation from all vessel calls (berth-meter * hours) | 2,049,840 | 1,356,940 |
| Available berth-meter * hours (500 m 8760 h/year) | 4,380,000 | 4,380,000 |
| Berth utilization (%) | 47 | 31 |
| Gross number of crane operating hours required during one call, including 15% idle time | 138 | 246 |
| Required yearly waterside labor shifts (8-h) when all cranes operate simultaneously | 718 | 400 |
| Theoretical available waterside labor shifts during the year (365 days) | 1095 | 1095 |
| Labor utilization (required versus theoretically possible in %)[a] | 65.6 | 36.5 |
| Assumed extra time at berth for berthing and un-berthing (hour) | 3 | 4 |
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[a] Assuming that labor is available three shifts per day over the whole year

control, provisions for cold-ironing, use of renewable energy, etc.) and demands for safety and security (cameras, entrance control, training). On top of that comes the rapidly growing demand for data communication, both internally (control of automated systems, work orders, *F*ailure *M*ode and *D*efects *A*nalysis (FMDA), etc.) and externally (process info to shipping lines and shippers, tracking and tracing, Customs, port authorities, governmental bodies, etc.). The realization of secure data exchange (especially for radio data communication) will be a challenge for large terminals.

## 5.3 State-of-the Art in Terminal Automation

Over the last 25 years, automation has entered the operations of container terminals and today almost 30 terminals have installed automated handling and/or transportation of containers with centralized control systems and combined with some kind of automated gate control and features for automated container ID and X-ray inspection. The most elaborated automation has been installed in terminals at Hamburg (HHLA *C*ontainer *T*erminal *A*ltenwerder – CTA), Long Beach (*L*ong *B*each *C*ontainer *T*erminal – LBCT), and Rotterdam (ECT Delta Terminal, Euromax Terminal, *APM T*erminals Maasvlakte II – APMT and *R*otterdam *W*orld *G*ateway – RWG), where both the stacking and waterside transportation is fully automated and the landside delivery/receipt to the road is done remotely controlled. Even the transportation to the railhead could be automated (APMT with *A*utomated *G*uided *V*ehicles designed as active Lift-AGVs). Also in China the first fully automated container terminals have been installed. The first one has been put into operation at Xiamen in May 2013 (Xiamen Yuanhai Container Terminal). There as well the proven concept of AGVs for the transportation on the apron, connecting the STS cranes with *A*utomated *S*tacking *C*ranes (ASC) in the yard, has been selected as an effective terminal handling concept.

Notwithstanding the large benefits from cost savings and reliable, well-planned operations, the implementation of automation in terminals developed rather slowly. Some terminals even decided to take a risk-avoiding approach and selected a partly automated concept, limited to an automated stacking yard and a control system for the scheduling of manually operated transportation equipment between the STS cranes and the stack area, for example, using 1-over-1 straddle carriers (also referred to as *Sprinter*) at the Virginia International Gateway terminal (Portsmouth) or common 1-over-3 *S*traddle *C*arriers (SC) at the HHLA *C*ontainer *T*erminal *B*urchardkai (CTB) in Hamburg.

Overall, the automated stacking of containers is widely accepted as beneficial for terminals and a majority of automated stacking yards are realized with *R*ail-*M*ounted *G*antry (RMG) cranes in an end-to-end configuration (perpendicular to quay wall), safely separating waterside and landside operations by stacking modules perpendicular to the quay wall (see Rijsenbrij and Wieschemann 2006). Almost all of these automated operations have been installed at new, greenfield terminal areas, mostly comprising 60 hectares or more. Typical examples in this regard are CTA and the terminal DP World London Gateway at the mouth of the river Thames (UK), see Fig. 5.1.

In the Middle-East and Asia the configuration of automated stacking yards is often a parallel layout arrangement where manually driven vehicles realize the interchange of containers alongside the stacking modules, which are operated with cantilever RMG cranes, allowing a remote-controlled interchange (see Fig. 5.2 with terminals at the ports of Dubai (left), Pusan (middle), and Kaohsiung (right)).

More than a decade ago, one terminal operator in Australia (Patrick Container Terminals) installed an automated SC operation at the port of Brisbane which looked promising for the modification of existing SC terminals. So far, automation of SC terminals is limited, e.g. Patrick's Sydney terminal at Port Botany, DP World's West Swanson Terminal (Melbourne), and POAL's container terminal at Auckland (New Zealand). A different SC automation concept is shown at terminals in Los Angeles (TraPac) and Melbourne (VICT), where automated SCs (for transport only) are applied in combination with automated RMGs. An advantage of automated SCs could be the possibility to apply them rather easy in existing, mid-size SC terminals, although special measures will be required to safely separate manual and automated operations. However the infrastructural modifications to convert a manually operated SC terminal into an automated SC terminal will be much lower than a conversion from SC operations into an automated RMG operation. The CTB

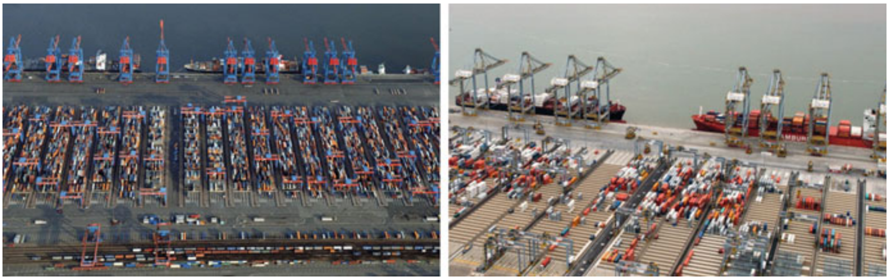


**Fig. 5.1** Automated stacking in end-to-end arrangement – CTA (left) and London Gateway (right)

**Fig. 5.2** Automated stacking in a parallel arrangement

at the port of Hamburg is a good example for the conversion from pure manual SC operations to automated RMG crane operations in the yard, still using manual SCs at the water- and landside for container transport between yard and STS cranes or railhead, respectively.

The issue of converting existing manual handling systems will get more attention in the future as an increasing number of terminal operators have recognized the advantages of automation and are considering installing an automated handling system in their existing facilities. Today terminal operators see the following drivers for automation:

- more logistic control, supporting priority-based scheduling, and last-minute changes;
- more predictable and reliable operations, less dependency of operator's skills;
- cost reductions, repetitive service quality, and less damages (accidents);
- less liability for injuries, reduced sickness percentage, and less vulnerability to labor shortages.

Some additional remarks on the above summary of advantages should be made:

1. Many ports face extremely high land costs (e.g. Shanghai or Singapore) and even when labor costs are low, this scarcity of land is a major reason for automation. Automated handling systems provide more storage capacity per hectare (certainly valid for end-loaded ASC concepts) and this characteristic of high area utilization is an increasing demand in concessions (lease contracts) from port authorities, looking for more throughput per hectare. As a result, such (automated) high-density stacking systems will enable Port Authorities to increase their income per hectare of port area.
2. Human beings and labor unions demand more flexible working schedules. This will complicate the design of shift systems covering the 24/7 demand in ports. The application of automation will give room for more flexible work rosters and will support an increased participation for lower management in the daily operational decision-making. Moreover, automation supports the avoidance of monotonous jobs and allows the upgrading of employee's satisfaction resulting in less sickness and more motivated employees.
3. In many areas of the world terminal operators cannot find enough qualified personnel to run manual equipment. Moreover the training of personnel is a major effort which must partly be realized during real time operations, impacting productivity and a higher chance on damages. The continuous turnover in personnel may result in a training effort of sometimes more than 100 training hours per operational job per year (includes operator to be skilled, instructor and equipment resulting in several hundreds of dollars per training hour).
4. Automated operations are less vulnerable for extreme climate conditions (both warm and cold/windy conditions) and save energy for comfort conditions in manned equipment. Requirements for lighting are much lower, again a cost saving.

5. In general, automation includes less downtimes and less maintenance, because automated equipment is uniform and orderly operated and independent from driver's behavior. Moreover in icy or snow conditions, automated equipment can be better controlled resulting in less accidents and continuing service.

The developments up till now have learned that especially for fully automated terminals the integration of automated equipment and all kinds of related subsystems into one efficient, terminal handling system is a real challenge. Various types of equipment must be efficiently controlled by means of equipment control systems integrated in the terminal's operations control system. On top of that large amounts of data from RFID systems, container weighing, gate control systems, equipment status and condition monitoring, remote operations (such as STS crane operations, landside ASC operations, X-ray activities) must be processed. Process information must be made available for operator's decisions (and manually controlled equipment) through standardized human interfaces and menu-driven graphical user interfaces.

At the start of terminal automation, operators themselves arranged the integration of all these various subsystems. Recent terminal automation projects have emphasized the need for a well-structured, timely integration of all components and subsystems. Extensive testing and training with emulation tools showed their benefit for a successful go-live of automated terminals.

This integration process of a growing number of features requires well-defined interfaces and protocols; more and more an expert activity. Therefore terminal operators are increasingly interested to acquire complete systems with guaranteed performances. For that reason, system suppliers may offer a total automated terminal handling system, including the installation and commissioning of all components necessary for the entire functionality.

## 5.4 Approach for Successful Implementation of Terminal Automation Projects

In the design of an automated terminal a large variety of equipment, control systems, data communication, priority rules, etc., has to be combined into one reliable handling system, capable of performing all handling functionalities, even under peak conditions. A variety of equipment, control systems, IT software and hardware, labor organization, etc., has to be selected and combined into one efficient system, often resulting in a number of feasible solutions for a terminal system.

### *5.4.1 Concept Assessment*

Alternative concept solutions should be analyzed and assessed on a multitude of topics, such as the potential to grow stepwise with the projected terminal throughput development and the requirements for sufficient service, provided by stacking capacity and ample handling productivity at waterside and landside. The assessment should not be limited to the initial investment (i.e. the capital expenditures) but should include the mid- and long-term operational expenditures (someday inflation will rise again) and more qualitative criteria such as the complexity of applied technology (proven or new), required maintenance skills, and earlier experiences with computer-controlled operations.

### *5.4.2 Concept Selection and Integration*

The selection process should not be a “battle between concepts”; to the contrary, right from the start of the conceptual design a systems approach should be taken. In other words, terminal operators should try to minimize their “nice-to-have’s” and should try to recognize critical interfaces in an early stage of the terminal design process. That will help to determine which type(s) of tests and commissioning efforts will be required to get a controlled integration. Moreover this will support a proper specification of the required functionalities, necessary when purchasing large subsystems from key system suppliers (which avoid the often occurring extra costs due to underestimated interface definitions). Lessons learned from terminal automation projects during the last decade have emphasized the need for a well-structured, timely integration of all components and subsystems. Extensive testing and training with emulation tools are necessary to meet start-up dates successfully.

## 5.5 Developments in Electric Drive Technologies

During the last decade many port authorities and governmental bodies have put increasing demands on terminals to install more sustainable and environmentally friendly technologies, such as the Long Beach and Hamburg Port Authorities to name a few (see Meier and Wegner 2015). Parallel to this general trend, terminals face growing uncertainties about energy sources and their cost. This has caused a search for alternative drives, not only for cranes but also for mobile equipment used for stacking and container transportation at terminals.

### *5.5.1 Technology Use of Terminals from Adjacent Industries*

Especially for (automated) stacking operations there is a clear tendency to shift towards electrically supplied RMG cranes and also *R*ubber-*T*yred *G*antry (RTG) cranes (so far with diesel-electric drives) are increasingly connected to the public grid through bus bar systems or cable reels with flexible cables, see Naicker and

Allopi (2015) for a rough technology overview. For RTGs with their relatively high idle (but stand-by) time, the primary advantage is an emission free drive system with reduced energy cost and less maintenance.

Nowadays manually operated and automated RMGs, as well as some RTGs are electrically supplied using medium voltage supply cables at the same time benefitting from the possibility of high-speed data transmission (see Naicker and Allopi 2015). Supply cables with fiber optics allow for high-density data communication up to 10 Gbit/s; via the conductors of the bus bar system transmission rates of about 100 Mbit/s are feasible. This is especially an advantage when applying remotely controlled operations which require a fast data transfer to remote visual displays, e.g., for RTGs serving in a (partly) automated stacking system. The application of sensors, cameras, and laser systems for automated motions, remote (video-controlled) handling and safety systems (to avoid collisions and trigger emergency stops when people or equipment enter the operational area around the RTG) need reliable, undisturbed, data transmission. Often, the available Wi-Fi systems cannot fulfill these demands.

However, it is not that easy for rubber-tired equipment, running over the terminal without predetermined tracks (e.g. *T*erminal *T*ractors (TT), AGVs, SCs, reach stackers, and empty handlers). For many years that mobile equipment was powered by a diesel engine connected to an automatic gear reducer as the standard drivetrain with a power take-off to a hydraulic system, powering lifting, and steering. However for SCs (in the late 1970s) and AGVs (in the new millennium), diesel-electric drivetrains proved to be an improvement with regard to energy consumption, speed control, reliability, and maintenance cost. Also RTGs were in general designed with diesel-electric drives for all functions (see Fig. 5.3).

During the last decade energy efficiency, emission control, and a concern about fuel cost resulted in the application of new technologies from adjacent industries, such as:

- Energy recuperation during vehicle braking or load lowering through the use of energy storage systems. For instance, batteries and super-caps in RTGs and TTs (very few) and hydraulic pressure vessels (in some mobile cranes).
- Electric drivetrains supplied from on-board batteries to be charged when remaining in the vehicle or through battery exchange. A proven technology for electric

**Fig. 5.3** Rubber-tired terminal equipment: RTG (left), SC (middle), AGV (right)

forklift trucks and vehicles at airports and warehouses and recently AGVs and a few TTs;

- Combustion engines fueled with less costly and/or less polluting fuels. CNG (*C*ompressed *N*atural *G*as) and LNG (*L*iquefied *N*atural *G*as) engines have been developed for public transport (busses, road trucks) and these engines have some advantages. This concerns their lower $CO_2$ production per mega Joule of fuel (compared to regular diesel engines). However, recent (legal) requirements for diesel engines have resulted in matching characteristics from state-of-the-art diesel engines. The better efficiency of diesel engines partly compensates their higher $CO_2$ emission, inherent for diesel fuel. Overall the $CO_2$ emission of CNG/LNG engines is around 15% lower than for diesel engines, a moderate advantage.
- Hybrid drives, compiled of a combustion engine, a generator, a transmission, a smaller energy storage device, and an electric motor. The energy storage (battery, super-caps, etc.) can be charged by the on-board generator and/or by recuperated (braking/lowering) energy or even by an external energy source. There is a large variety of hybrid concepts with either parallel or serial arrangements of combustion engine, energy storage device, and electric motor. However, the enlarged number of components and the more complex control units influence reliability and still the remaining emissions cannot match the more favorable figures of full-electric drivetrains. So far hybrid drives are not very attractive for mobile terminal equipment.

### 5.5.2 Evaluation and Selection of Drivetrains

The selection of an appropriate drivetrain for terminal equipment is a complex process for terminal management. Obviously they want to support societal demands to be assessed from pollution figures measurable from the WTW (*W*ell-*T*o-*W*heel) or less correct the TTW (*T*ank-*T*o-*W*heel) pollution figures. On top of the well-known exhaust gases (like $NO_x$), the $CO_2$ emission from energy sources, applicable for mobile equipment, is becoming more important.

Terminal economics are equally (or even more) important and that is determined by fuel consumption per operating hour, fuel cost, maintenance cost, availability and cost of provisions for fuel storage, fuel supply, and safety measures. In general, a full-electric drivetrain offers by far the best energy efficiency and lowest maintenance cost; however, when the selection is, nevertheless, made for a combustion engine, the modern diesel engine is still attractive due to its rather high efficiency and the high energy content of diesel fuel. Nowadays equipment designs should be eco-efficient: This also includes the reduction or avoidance of the use of fossil energy (see Rijsenbrij and Wieschemann 2011). Considering terminal system suppliers, such as Konecranes, the experience with diesel-electric drivetrains, applied in AGV transportation systems, triggered research aimed at even more environmentally friendly AGVs. Many alternatives were analyzed, including some hybrid drivetrain concepts and full-electric drivetrains, supplied with either Lead-Acid or Li-Ion batteries. The advantages of full-electric drivetrains are illustrated in Fig. 5.4, which clearly shows their simplicity when removing the diesel-generator and connected AC/DC converter.

Another major improvement is the much better energy efficiency of full-electric drivetrains, obtained by avoidance of the unfavorable energy conversion in a combustion engine. Figure 5.5 shows the energy efficiency for a Lead-Acid battery energy supply.

Compared with a diesel-electric drivetrain, the overall efficiency is more than two times better, a real contribution to better eco-efficiency (see Fig. 5.6). On top of that, a battery-supplied AGV shows zero energy consumption during operational stand-still periods (e.g. waiting for jobs in a buffer or when receiving a load under a crane).

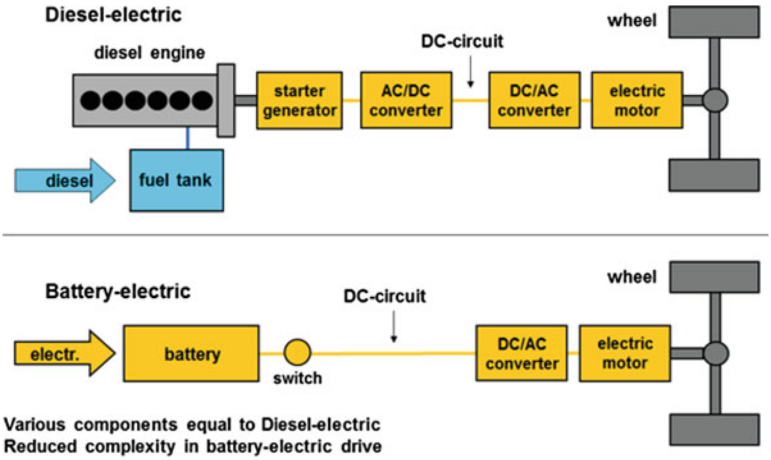


**Fig. 5.4** Diesel-electric and battery drivetrain schematic

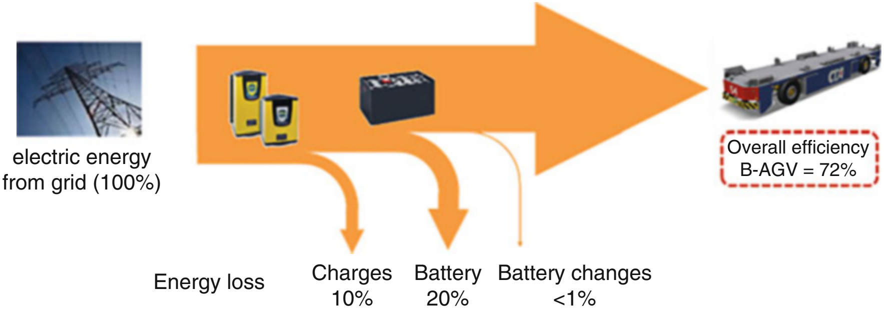
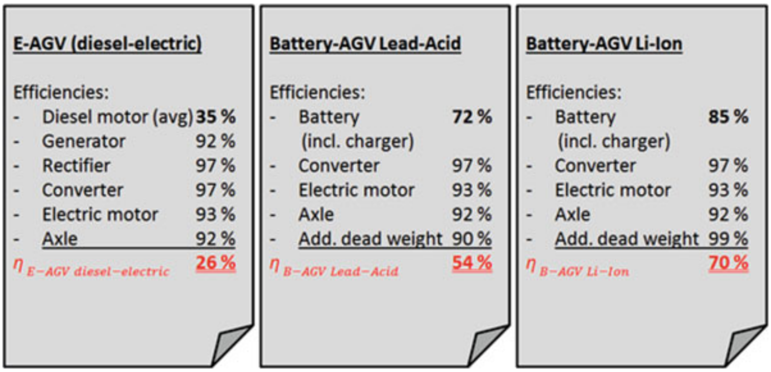


**Fig. 5.5** Energy transfer efficiency for battery drivetrain



**E-AGV (diesel-electric)**

Efficiencies:

| | | |
|---|---|---|
| - | Diesel motor (avg) | **35 %** |
| - | Generator | 92 % |
| - | Rectifier | 97 % |
| - | Converter | 97 % |
| - | Electric motor | 93 % |
| - | Axle | 92 % |
| | $\eta_{E-AGV\ diesel-electric}$ | 26 % |

**Battery-AGV Lead-Acid**

Efficiencies:

| | | |
|---|---|---|
| - | Battery (incl. charger) | **72 %** |
| - | Converter | 97 % |
| - | Electric motor | 93 % |
| - | Axle | 92 % |
| - | Add. dead weight | 90 % |
| | $\eta_{B-AGV\ Lead-Acid}$ | 54 % |

**Battery-AGV Li-Ion**

Efficiencies:

| | | |
|---|---|---|
| - | Battery (incl. charger) | **85 %** |
| - | Converter | 97 % |
| - | Electric motor | 93 % |
| - | Axle | 92 % |
| - | Add. dead weight | 99 % |
| | $\eta_{B-AGV\ Li-Ion}$ | 70 % |

**Fig. 5.6** Overall drivetrain efficiency

The availability of (large) Li-Ion batteries for industrial mobile equipment will further increase the eco-efficiency. The present Lead-Acid battery drivetrains realize a 72% efficiency which will further increase to over 85% when applying Li-Ion batteries.

The intensive utilization of AGVs with a maximum gross vehicle weight of 100 tons (compared to 1.8 tons for a luxury road car) necessitates a Lead-Acid battery capacity of gross 360 kWh, allowing 18–20 operating hours (280 kWh net) and after that period, the battery has to be charged or exchanged with a fully charged one. For reasons of economics and proven design, today the Lead-Acid battery offers a good feasible concept and at present there are more than 200 Battery-AGVs operational worldwide, all of them with recyclable Lead-Acid batteries. The required large battery capacity for AGVs, applied in container terminals, could not be met economically with Li-Ion batteries so far. Nevertheless, the technology and economics of Li-Ion batteries have considerably advanced over the last years and therefore this battery type can become a good alternative for day-to-day operations in the near future (as of mid-2017) although the possibilities for recycling are still of some concern.

During the last decade various types of Li-Ion batteries have been developed for the automotive industry (cars and city buses), both for hybrid and full-electric drivetrains. Advantages such as a high energy density, low weight, better energy transfer efficiency, lower maintenance, increased lifetime, and the ability for fast charging are attractive for automotive applications. However, this type of batteries is much more complex and requires higher investment than the proven Lead-Acid batteries. For safe operation, Li-Ion batteries need a sophisticated battery management system and may need an additional cooling/heating system (climatic conditions). Today there is only little long-term experience, especially in the rough port environments. A proper charging of Li-Ion batteries still requires 1–2 h. This outage for charging might be acceptable for private cars and city buses, but for the 24/7 continuous terminal operations outages on this level are problematic and require either a surplus of equipment or a battery exchange facility (see Sect. 5.5.3).

Figure 5.7 shows the AGV demand of Lead-Acid battery capacity, compared to the Li-Ion batteries applied in automotive electric vehicles for the year 2015.

The high eco-efficiency of battery-supplied drives also results in a considerable decrease in *G*reen*H*ouse *G*ases (GHG). Compared with a diesel-electric drive, the full-electric drive reduces the $CO_2$ emission by 50% (see Wieschemann 2014). The WTW results are shown in Fig. 5.8 and this figure is based on the actual energy sources used in German power plants. Obviously a full-electric drivetrain will be zero-emission in case of solar, hydro, or wind turbine power generation.

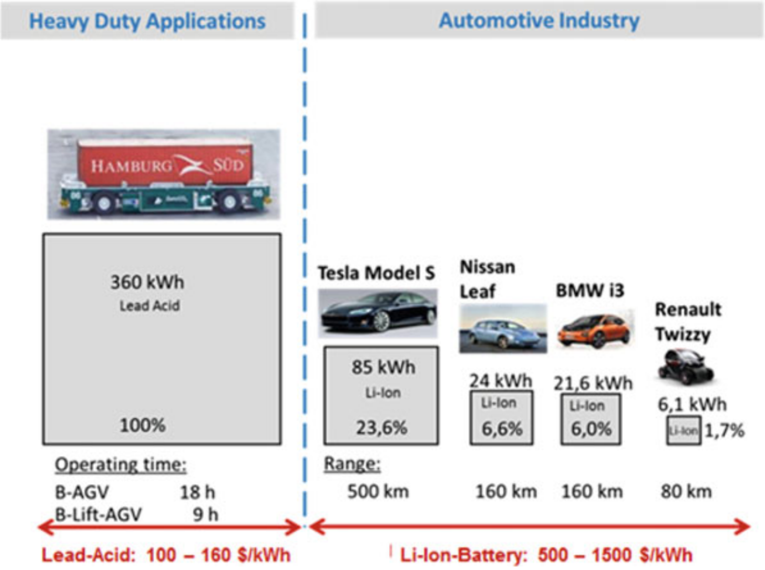


**Fig. 5.7** Comparison of battery capacity demand (2015)

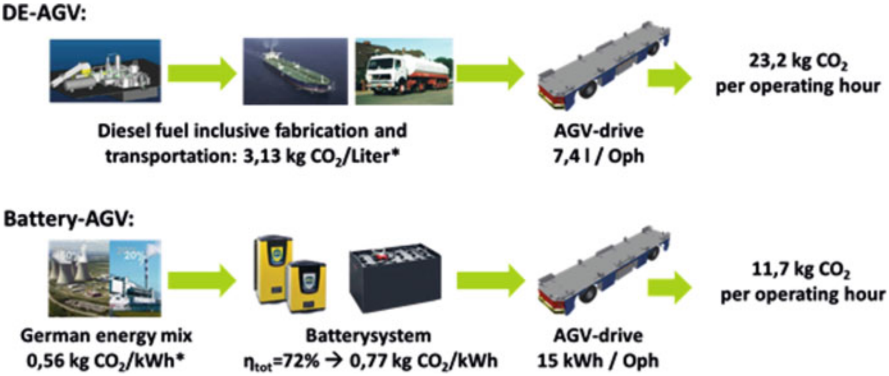


**Fig. 5.8** AGV well-to-wheel GHG production for *D*iesel-*E*lectric (DE) and battery drivetrain

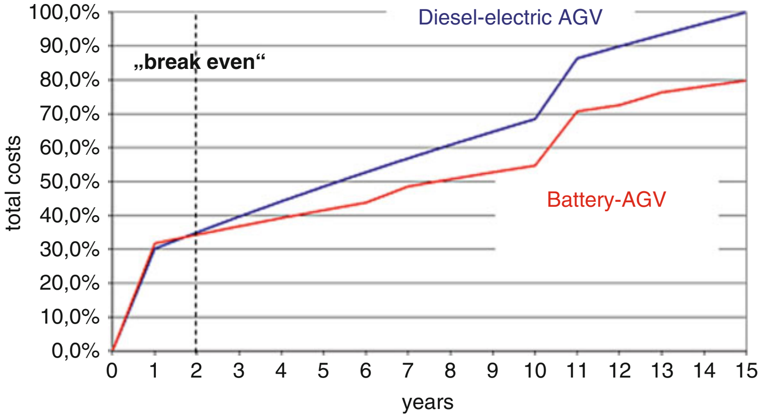


**Fig. 5.9** TCO results for diesel-electric and battery-AGV (for the years 2010 to 2025)

When selecting battery type and charging method, it is recommended to analyze the *T*otal *C*ost of *O*wnership (TCO) with an NPV (*N*et *P*resent *V*alue) approach for the various alternatives. The TCO approach is increasingly used for purchasing, covering all costs during the lifetime of an investment (see also Ellram and Siferd 1993). The analysis should cover AGV and battery(ies), the charging method and charging provisions, the planned outage algorithms, the installed transformer capacities, and resulting peak loads at the grid.

During the last 5 years the TCO analysis for the comparison of diesel-electric and fully battery-supplied AGVs clearly showed a much better TCO result for the battery types. Reduced energy cost and much lower maintenance cost highly compensate the slightly larger initial investment (see Fig. 5.9).

The future will enlarge the favorable TCO results for battery-supplied vehicles; these will be forthcoming from the reduced battery cost and performance improvements driven by the automotive industry and the forecast that the gap between electric energy cost and diesel fuel cost will further enlarge as a result of the world's massive energy transfer from fossil fuels towards renewable energy sources. Nowadays energy from wind turbines is already competitive with coal or gas-fired power stations.

### 5.5.3 Alternatives for AGV Battery Charging During Terminal Operations

To support a continuous terminal operation, it is necessary to timely realize a battery recharge which should be cost-attractive and ideally should have no impact on the terminal's logistic performance. The charging time for batteries does require an outage of the battery for hours, e.g. 6–8 h for Lead-Acid batteries and

1–2 h for Li-Ion batteries, applied in heavy-duty transport vehicles. For Li-Ion batteries a too short recharging time with high power will decrease the lifetime (measured in load cycles). Daytime operations like warehousing do not suffer from such recharging times, as they are executed during evening/night. However, the continuous operations in container terminals require a 24 h uptime of equipment and then there are three possibilities (see Fig. 5.10):

1. Battery exchange
   In this option, the terminal has to realize a central BES (*B*attery *E*xchange and charging *S*tation incl. storage function for batteries), preferably with automated processes for battery exchange into and out of the equipment as well as for battery storing and retrieving from the storage area. Due to the ratio equipment investment/battery investment in case of Lead-Acid batteries, until 2017, this solution proved to be the more economic one for container terminals as can be seen in four terminals, recently installed with battery-supplied AGVs (see also Fig. 5.11).
2. Opportunity charging
   In this case the battery (staying in the equipment) has to be charged during normal operation processes. As waiting times during operations will be short, the amounts of energy that can be charged will be small and for that reason many chargers have to be installed at terminal positions where AGVs stop during

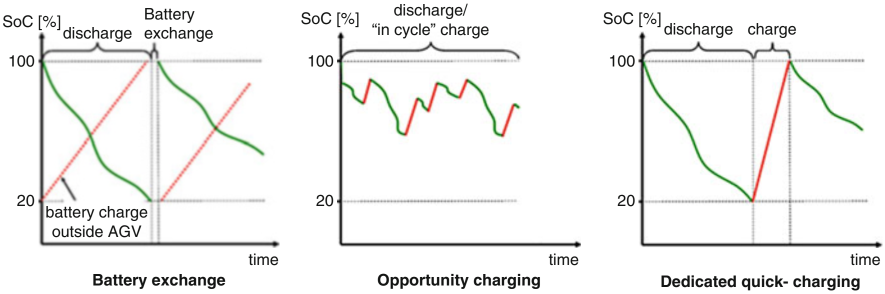


**Fig. 5.10** Schematic of alternative battery charging methods

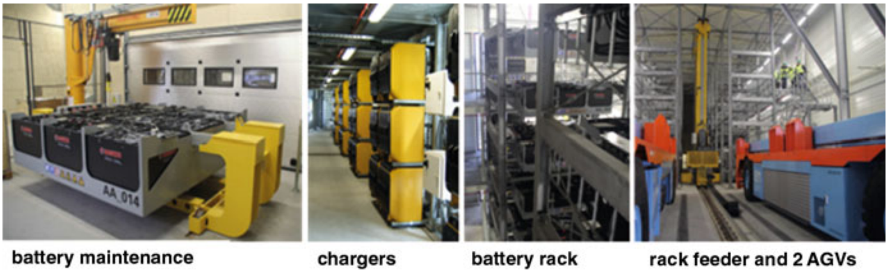


**Fig. 5.11** Details of automated BES at Rotterdam Maasvlakte container terminals

their transportation cycles. Obviously, vehicle operations and battery charging processes have to be aligned and thus a high number of battery chargers is required, resulting in a low utilization of chargers and a relatively high investment in charging equipment and power supply distribution to these chargers.

3. Dedicated quick-charging
   At a limited number of locations, the terminal will install quick-charge provisions and purchase more equipment, to exchange equipment in case of a discharged battery. This will definitely result in more investments (5–10%, depending on battery type and size) and some additional area for equipment parking and connections to the electric charging provisions. Obviously, the major part of the additional investment (in extra equipment) is balanced through delayed replacement investments resulting from an elongated equipment lifetime (hence the same workload is distributed over more equipment).

For an effective *BES implementation*, the logistical characteristics of automated container terminals must allow the integration between logistic control and battery recharge/exchange management systems. Practical experiences at the abovementioned terminals show that the actual vehicle outage of 5 min for battery exchange has no influence on the transportation performance of an AGV fleet. Using BES, the fluctuating utilization of the AGV fleet and the installed battery capacity even allows the (future) application of smart grid technology. This enables to benefit from low electrical energy cost during low periods (e.g. night time) or during wind turbine or solar surplus periods when the energy cannot be distributed to the end users. Spot prices for energy often decrease to 50% or less than the normal prices; however, in order to benefit from such situations it is necessary to be connected and known as a potential user. That means that benefits from smart grid technology can only be used when batteries are stored in a BES with some flexibility in charging demands. The design of an automated BES requires a systems approach between logistics, infrastructure, and economics, covering battery storage capacity, electrical supply (transformer) power, maintenance facility, ventilation, and fire-detection provisions (see Fig. 5.11). The design should have some flexibility to adapt to new battery technologies that will come in the next decades. Nowadays Lead-Acid technology is proven in some major terminals and the electric supply from the grid allows a long-term cost control and the potential of applying green energy when the power utility purchases solar, hydro, or wind energy. In that case terminal transport will be a real zero-emission system.

*Opportunity charging* for waterside transportation with AGVs so far is not recommended. The short waiting times during the AGV transport cycles and the large variety of locations to be connected by the AGVs would require many charging points, spread over the entire apron area; very difficult in that dense traffic area. This will result in an extensive electric supply network with related (safety) switchgear, all to be designed for the large power demand when an AGV has to be supplied with as much as possible energy in the short parking periods. Beside of the large investment for these connection points also the maintenance of the outdoor connections (direct contact or inductive) in an automated operational area will need a (costly) attention. Possibly in the coming decades, the automotive industry may trigger cost-attractive developments for opportunity charging with induction; up till now this method is not feasible for waterside AGV operations.

*Quick-charge* provisions for container terminals are under development and are promising. Nevertheless, it should be considered that AGVs require battery sizes up to 5 times larger than the currently largest car battery (see Fig. 5.7). This size influences battery design (hot spots) and charging control equipment, which also requires five times more power (impacting infrastructure and high peaks in electric supply, causing extra charges from the energy supplier).

Today, the technology developed by the automotive industry for the quick-charging of public transport vehicles can be applied to terminal equipment. Such quick-charge provisions can be realized either through a direct connection with receptacle or pantograph or in the future with inductive power, although the latter method is neither feasible nor cost-attractive for port operations. When required operationally, quick-charging will allow a fast (short) energy supply; not necessarily until the fully charged battery status.

Recently, such a quick-charging technology has been applied e.g. by Konecranes for AGVs in an automated terminal. In the near future, 25 Li-Ion battery-powered AGVs and six *A*utomated *Q*uick-*C*hargers (AQC, see Fig. 5.12) will come into operation at the automated CTA in Hamburg entailing a new concept for battery-powered mobile equipment in day-to-day operations of related facilities. A TCO analysis for this case was carried out and it was learned that the reduced battery cost of the next-generation Li-Ion batteries and the improved AQC design outperformed the current concept of Lead-Acid batteries and BESs.

In the future, it can be expected that the TCO results for battery-powered vehicles will become even more favorable. The choice between Lead-Acid batteries and BESs or Li-Ion batteries and AQCs depends upon many variables. Case-by-case,

**Fig. 5.12** Li-Ion battery-AGV at an AQC at CTA, Hamburg

TCO analyses will need to be carried out. Both concepts are viable and valuable in transferring operations away from fossil fuels towards renewable energy sources.

## 5.6 Short-term Developments in Terminal Automation

In the coming 3–5 years the efforts to install new automated terminals or to modify existing (manual) terminals will increase, especially because of the growing pressure in terms of cost and performance being transferred from container liner shipping to the terminal business. Many operators will select available proven concepts, but of course with improvements on earlier detected shortcomings in system components. Parallel to this evolution in existing concepts new developments can be expected, partly driven by new demands from operators, interested to automate manually controlled operations and improve service and utilization of their present-day handling concepts. The introduction of new technologies from adjacent industries will also trigger a further development of automated handling systems. Some indications of such developments are already recognizable, for example the "Internet of Things," sensors and software for autonomous driving, obstacle recognition systems, etc.

The majority of worldwide installed stacking systems operate with RTGs, stacking concepts that require TTs/trailers and road haulers to pick up or deliver a container in the stacking area. The interchange of containers between trailer (internal or external) needs a lot of (human) attention to guarantee a safe operation. The simplicity and flexibility of the RTGs is very attractive; however, when it comes to operating costs, labor cost represents a growing part especially for container delivery operations where the idle time share can exceed 50%. For that reason terminals tend to apply remote control for the handshake which requires a lot of sensors, cameras, and safety provisions both at the RTGs and the order control systems. So far data transfer with radio data communication systems could not fulfill all demands for a fail-safe (semi-)automation of RTG operations. However, the developments in electric supplied RTGs will enable a further automation of the RTG stacking yards; safety and productivity will be key topics.

During the last decade the exchange of data between equipment and control centers has increased tremendously (FMDA, Remote Control, Order Control, safety, security, etc.). Moreover there are all kinds of organizations active in or around terminals, also using wireless data transfer in the public domain (WLAN, Internet). This is a concern, not only the available capacity but also the risk of cyber-crime and this issue should get much more attention, especially when terminals plan remote-controlled and/or automated operations. When terminals require safe, reliable, and high-speed data communication then a private band might be a good investment.

The "Internet of Things" is a technology that will bring new applications to the terminals. Addressable, network capable, components will allow online condition monitoring, fault management, and self-acting service planning. The industry in particular is developing all kinds of new applications that might become of interest to terminals as well. Terminal stakeholders (e.g. shipping lines, customs, tax departments, inland transportation companies, security authorities) may also ask for new functionalities to be installed in steadily growing interconnected networks with all the risks of reliability, data integrity, and management of such large scale IT systems. Terminals will increasingly be confronted with the question: is there a positive trade-off between the benefits of new "Internet of Things-gadgets" and the growing complexity, maintenance cost, and cyber risks of these systems and applications.

In a number of ports the authorities are encouraging container terminals and shippers/consignees to reduce road transportation, as trucking still has an environmental impact. Moreover truckers complain about waiting times and traffic jams in port areas and that has resulted in satellite terminals at distances of tens or even hundreds of kilometers from major ports. Daily shuttle services by trains or barges connect these satellite terminals (often managed by deep-sea terminal operators or shipping line), avoid empty trips for truckers, and can reduce the dwell time of containers at the deep-sea ports, supporting these terminals to realize more throughput per hectare. Examples are the *Alameda Corridor*, connecting Los Angeles/Long Beach with a few large *Inland Container Transfer Facilities* managed by the large railroad companies; other examples are some satellite terminals in Belgium, The Netherlands, and Germany (see e.g. Port of Rotterdam Authority 2017). This type of satellite terminals and connecting shuttle services is likely to expand in the future. The high-density, terminal controlled transportation is very attractive for automation and the application of electric drives. Trains are easy to supply with electric power and also barges are changing over from direct diesel drives towards electric drivelines with generator sets powered by environmentally friendly energy sources. LNG is attractive for shuttle barges (fixed supply stations can be realized) and when distances are limited to some tens of kilometers even battery supply is feasible.

Such shuttles can be supported with automated transport to railheads and barge loading/discharging sites and even automated inter-terminal transport in large port areas will be feasible in the future. When doing so, a really low emission transport can be made available to the society.

## 5.7 Conclusions

Automation in container terminals has been established over the last 25 years. Port Authorities and container terminal operators, driven by the need to reduce costs and reduce their carbon footprint, are increasingly turning to automated container handling systems and electric drive technology.

The container handling industry is increasingly focusing on electric drive technology in order to reduce costs, reduce carbon footprint and emissions, and improve sustainability. The trend is definitely towards the installation of automated handling systems and the application of electric drives; this will be enabled by the following topics:

- Li-Ion or other composite batteries will be further developed and will become attractive for large industrial vehicles as well. The developments of Li-Ion batteries are promising (with their potential of short recharging times and enlarged capacity) but still, the selection of type and size should be based on a proper TCO analysis.
- Increasing fossil fuel prices (from scarcity and tax measures) and directives for reductions in greenhouse gases and emissions (exhaust, sound) will further encourage the application of full-electric, battery-supplied drives. Today's technology allows a truly zero-emission operation when the energy provider supplies green energy (hydro, solar, and wind power).
- Electric supply enables a safe and reliable, high-density data transfer to equipment, a requirement for complex logistic control systems, remotely controlled operations and equipment monitoring associated with FMDA.
- The attainable cost savings, the potential performance, the better area utilization, and the availability of proven technology will encourage terminal operators to apply automation. Electric drives are a must for such automated systems and on top of that will result in decreased operating cost and do support the demands from society for sustainability and environmental control.
- Terminal operators are increasingly interested to acquire complete systems with guaranteed performances. That will encourage system suppliers for terminal equipment to offer a total transportation/handling system, including installation and commissioning of all components necessary for the entire terminal functionality.

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