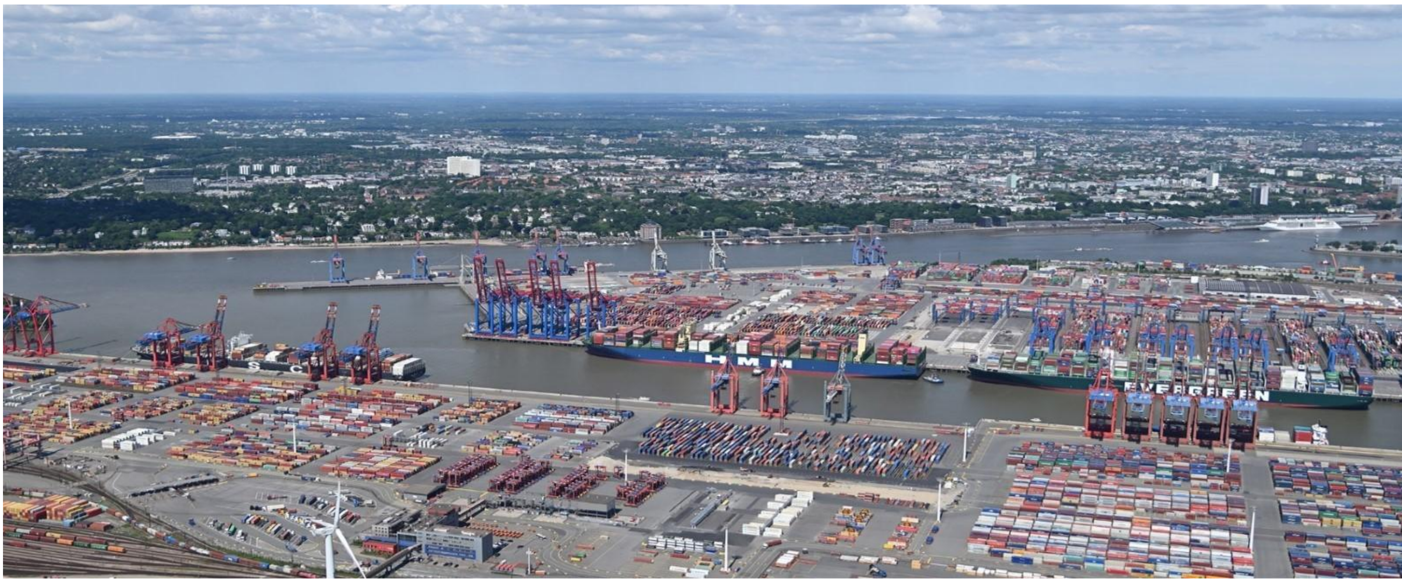
BLUE
SUPPLY
CHAINS



Demonstrated electrification process of port operations in Gdynia Container Terminal and Port of Skagen

Deliverable 2.1

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List of Abbreviation

ARTG	Automated Rubber-Tired Gantry crane
BSC	Blue Supply Chains project
CAPEX	Capital Expenditures
CEF	Connecting Europe Facility
CO_2	carbon dioxide
e.g.	For Example
eRS	electric-propelled reach-stacker
eRTG	electric-propelled Rubber-Tired Gantry crane
GCT	Gdynia Container Terminal
GHG	Greenhouse Gases
HVO	Hydrotreated Vegetable Oil
kW	Kilowatt (1000 W)
kWh	kilowatt -hour
LNG	Liquefied Natural Gas
MGO	Marine Gas Oil
MW	Megawatt (1000 kV)
MVA	Mega Volt Amperes
NO_x	Nitrogen Oxides
OPEX	Operational Expenditures
OPS	On-shore Power Supply (cold-ironing)
PM	Particular Matters
PPA	Power Purchase Agreement
RCeRTG	Remote-controlled Electric Rubber-tired Gantry Crane
RS	Reach-Stacker
RTG	Rubber-Tired Gantry crane
SEP	Specific Certificates of Qualification
SO_x	Sulphur Oxides
STS	Ship-to-shore Gantry Crane
SETS	Scandinavian Electric Transport System
TEU	Twenty Foot Equivalent Unit
TOS	Terminal Operation System

BLUE SUPPLY CHAINS PROJECT

This report is part of the Blue Supply Chains (BSC) project. BSC supports port authorities and port operators to decarbonise port operations by advancing electrification, providing alternative fuels strategies, and setting up green transport chains.

Ports are essential for global trade and prosperity, but at the same time contribute to the emission of pollutants through freight traffic and port activities. Ports can be an important factor in achieving European and national climate goals and will also play an important role in the storage and onward transport of alternative fuels in the future.

The "Blue Supply Chains" project supports port authorities and port operators in implementing long-term measures to decarbonize port locations.

The project follows different approaches supporting decarbonization in ports:

- Evaluation and piloting of measures for the further electrification of handling equipment.
- Strategies for providing, handling, and storing alternative fuel.
- Promotion of more environmentally friendly transport chains in the hinterland, with a focus on the development of combined transport.
- The project runs from January 2023 to December 2025 under the leadership of Hafen Hamburg Marketing. It received funding from the Interreg Baltic Sea Region Programme 2021-2027.

More information and documentation:

https://interreg-baltic.eu/project/bluesupplychains

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Demonstrated electrification process of port operations: process documentation for the technical retrofitting of a gantry crane in Gdynia Container Terminal

1. Reducing Energy Consumption and Electrifying Rubbered Gantry Cranes: A Significant Challenge for Maritime Transport

Ports serve as crucial nodes within the global transportation network, handling over 90% of global freight moving by containers. Container terminals are integral components of the international supply chain, playing a vital role in regional economies. The efficiency and environmental performance of these terminals are directly related to their ability to adapt to emerging challenges. One of the most commonly used pieces of cargo handling equipment (CHE) in container terminals is the rubber-tyred gantry (RTG) crane. These cranes are essential for yard operations, managing the handling and transfer of containers. Historically, diesel-powered RTGs (dRTGs) have dominated the sector. However, the increasing focus on environmental sustainability and stricter regulations highlight the significant challenges associated with the energy consumption and emissions of this equipment within the broader maritime transport system.

The combustion of diesel fuel by dRTGs during operation leads to significant air pollution and a large volume of carbon emissions. These emissions are a major concern as container ports are large energy users and are often located near population centers. According to one study focusing on a terminal in Valencia, Spain, RTGs and yard tractors were identified as the primary sources of CO2 emissions, accounting for 68.1% of the terminal's total CO2 emissions in 2011. The high operating costs, pollution, and noise associated with dRTGs are significant drivers for change [Martinez-Moya, 2019].

Electrifying port equipment, particularly gantry cranes, has emerged as a key strategy to mitigate these environmental and economic issues. This involves replacing or retrofitting existing diesel RTGs with electric RTGs (eRTGs) or hybrid diesel-electric RTGs (hRTGs). ERTGs are powered via electric cables, drawing electricity from the grid, while hRTGs can operate on either diesel or electric power using systems like cable reels or conductor rails. Some equipment suppliers also offer hybrid solutions with energy storage systems such as super-capacitors, lithium batteries, or flywheels.

The benefits of electrification and improving energy efficiency in gantry cranes are substantial, making this effort critically important for the sustainability of maritime transport. Environmentally, switching from diesel to electric power can lead to a significant reduction in pollutant emissions, estimated at 60%-80%. Energy consumption can be reduced by 10%-30%, and noise and exhaust emissions can decrease by up to 40%. Specific data from one terminal showed that eRTGs consumed 54.9% less energy equivalent per TEU compared to dRTGs. Life cycle assessment studies have also indicated over a 70% reduction in CO2 equivalent emissions for electric RTGs compared to conventional ones, though this is dependent on the power grid mix. Savings of 32,600 liters of diesel fuel per crane per year can translate to savings of 81 tonnes of CO2 emissions per crane per year. Across a large port with many RTGs, the total CO2 savings can be thousands of tonnes annually. Implementing a carbon emission tax policy has also been shown to be an effective measure to reduce carbon emissions [Martinez-Moya, 2019], [Ding, Yi, 2021], [Papaioannou, Vicky, 2017].

From an economic perspective, electrification promises to reduce operating costs by 50%-70%. Energy costs specifically can be greatly reduced. For example, eRTGs consumed energy at a lower cost per TEU ($0.384/TEU) compared to dRTGs ($1.295/TEU), leading to a 29.7% reduction in total energy costs in one study. Globally, the implementation of diesel-electric retrofitting on RTGs could save approximately $685 million in energy costs annually, based on 2017 global container throughput figures. Payback periods for the investment in electrification can be relatively long but are offset by energy cost savings. Furthermore, improving the energy efficiency of existing diesel RTGs, such as by replacing oversized engines, can reduce fuel consumption, lower emissions, and lead to significant annual savings per unit while maintaining operational performance [Ding, Yi, 2021].

Despite the clear benefits, electrifying gantry cranes presents significant challenges. One major hurdle is the substantial initial investment required for retrofitting or purchasing new electric cranes and modifying the terminal infrastructure (depot modification). These costs can be high, requiring careful financial planning.

Maintaining operational efficiency and satisfying container handling requirements during the transition is also critical. Investment decisions must be made under the premise of ensuring that the terminal yard container handling capability is met. A trade-off is needed between implementing investment decisions and maintaining appropriate operating capacity. This requires developing detailed deployment plans and purchase/retrofit strategies that consider the distinct characteristics of different types of RTGs, including purchase cost, retrofit cost, operation capability, energy consumption, and emissions.

A significant challenge also lies in effectively managing the energy demands and recovery potential of gantry cranes. RTGs are energy-intensive, particularly the hoist motor used for lifting containers, which can account for a large portion of total energy consumption. A considerable amount of energy is consumed during the lifting phase, but energy is regenerated when containers are lowered due to regenerative braking. This regenerated energy can be fed back into the system. However, in conventional diesel RTGs, this potentially recoverable energy is often dissipated in dump resistors instead of being stored or reused. Sources suggest that around half of the energy consumed is potentially recoverable. Capturing and reusing this energy using storage systems is key to improving overall efficiency and reducing reliance on the primary power source, but it adds complexity and cost.

The environmental benefit of electric RTGs is also contingent on the power source. The CO2 emission factor for electricity varies significantly by region. If the electricity is generated from sources with high carbon footprints (e.g., coal power plants), the overall environmental benefit compared to efficient diesel operations might be reduced, although studies still show significant CO2 reductions even with current grid mixes. Life cycle assessments of electric equipment also need to consider the environmental impact of battery production and disposal.

Successfully implementing electrification requires integrated planning that goes beyond simple equipment replacement. It involves optimizing both investment decisions (what to purchase or retrofit, and when) and operational management (how to deploy and schedule the diverse fleet of dRTGs, eRTGs, and hRTGs) simultaneously. This integrated approach is relatively new in research, making decision-making complex. Integer programming models and advanced computational methods are being developed to help decision-makers determine optimal investment timing and deployment strategies to meet operational demands and emissions reduction targets. Considering battery technology choices, sizing, degradation, and charging strategies also adds layers of complexity, particularly for hybrid or battery-assisted systems.

Furthermore, the drive for electrification is heavily influenced by external factors such as green port initiatives, environmental regulations, and carbon emission policies. Navigating the evolving policy landscape and potentially leveraging government subsidies or carbon tax incentives are part of the challenge and the opportunity.

In conclusion, reducing the energy consumption of gantry cranes and electrifying them represents a significant, multi-faceted challenge for maritime transport. It is driven by the urgent need to mitigate the substantial environmental impact and high operating costs of conventional diesel equipment in ports, which are critical links in the global supply chain. While electrification offers considerable benefits in terms of emissions reduction and economic savings, its successful implementation requires significant capital investment, careful integrated planning of assets and operations, effective management of energy recovery, consideration of the power grid's carbon footprint, and adaptation to policy drivers. Addressing these challenges through technological advancements, sophisticated planning models, and supportive policies is crucial for enabling ports to achieve their sustainability goals and contribute to a greener maritime transport ecosystem.

2. Strategies for Reducing Energy Consumption in Container Terminal Rubbered Gantry Cranes

Container terminals are critical components of the global supply chain and significant energy consumers within the maritime transport ecosystem. Among the various types of cargo handling equipment (CHE) used in these terminals, rubber-tyred gantry (RTG) cranes are particularly prevalent, frequently accounting for a large portion of a terminal's energy consumption and carbon emissions. Traditionally powered by diesel engines (dRTGs), these cranes contribute significantly to air pollution and greenhouse gas emissions. Addressing the energy intensity of gantry cranes is therefore a key challenge and a focus for "green port initiatives". The sources identify several primary strategies and approaches for reducing the energy consumption of gantry cranes, primarily centered around electrification, improving operational efficiency, and implementing energy recovery systems.

One of the most significant and frequently discussed methods is the electrification of RTG cranes. This involves transitioning from conventional diesel-powered RTGs (dRTGs) to electric RTGs (eRTGs) or hybrid diesel-electric RTGs (hRTGs). ERTGs typically draw power directly from the electricity grid via cable reels or conductor rails, while hRTGs combine diesel power with electric power, often utilizing energy storage systems. This transition directly reduces or eliminates the consumption of diesel fuel, which is a major source of carbon emissions and air pollutants in ports. Studies have shown that electrifying RTGs can lead to a significant reduction in energy consumption, estimated at 10%-30%. Specific data presented from a terminal in Shanghai indicated that eRTGs consumed approximately 2.28 kWh of electricity per TEU, equivalent to 0.834 kgce, which was 54.9% less energy equivalent per TEU compared to dRTGs that consumed about 1.27 kg of diesel per TEU (equivalent to 1.851 kgce). This energy reduction also translates into substantial decreases in energy costs, with one study showing a 9.7% reduction in total energy costs for eRTGs compared to dRTGs. Globally, implementing diesel-electric retrofitting on RTGs could save approximately $685 million annually in energy costs, based on 2017 container throughput figures. Furthermore, electrification promises to reduce pollutant emissions by 60%-80% and noise and exhaust emissions by up to 40% [Ding, Yi, 2021].

Electrification can occur through purchasing new eRTGs or hRTGs or by retrofitting existing dRTGs. Retrofitting dRTGs to become eRTGs is mentioned as a key focus driven by green port initiatives. While the initial investment in retrofitting or purchasing new electric cranes and modifying terminal infrastructure can be substantia, the long-term energy cost savings contribute to relatively long payback periods. For instance, a case study showed an investment for a 25% emission reduction target (involving depot modification, purchasing new eRTGs, and retrofitting dRTGs) leading to a 40% energy cost reduction with an estimated payback period of around 15 years [Ding, Yi, 2021].

Beyond full electrification, another crucial way to reduce energy consumption is through improving the energy efficiency of the cranes themselves and optimizing their operation. Conventional diesel RTGs, as highlighted in a study of a terminal in Valencia, often suffer from low energy performance. Problems identified include operating outside the optimum working point for a large percentage of the time (around 95%) and being equipped with oversized generators that provide more power than needed for yard operations, thereby increasing fuel consumption and carbon emissions. A direct solution implemented in this case was to replace the existing oversized engines with less powerful ones. This modification resulted in improved energy efficiency by reducing fuel consumption (e.g., saving 6.06 liters per hour), leading to significant annual savings per unit (estimated at €41,000) and crucially, maintaining the operational performance of the RTGs. This demonstrates that targeted technical modifications to existing diesel equipment can yield substantial energy savings [Martinez-Moya, 2019].

Operational management also plays a role in reducing energy consumption. While less studied in detail in the sources compared to technological solutions, existing research has addressed the operational management of yard cranes (YCs/RTGs) with objectives such as minimizing energy consumption or considering CO2 emissions in deployment and scheduling. The sources note that few studies have addressed operational management in a "green manner" or explicitly considered the distinct energy consumption characteristics of different types of RTGs (dRTGs, eRTGs, hRTGs) in deployment problems. However, the concept that optimizing how cranes are used and managed can reduce overall energy burn is present. For example, the frequency of container movements (interval between lifts) directly impacts energy consumption, with shorter intervals leading to higher energy use due to reduced idle times. The duration of lifts, influenced by container stack height, also affects hoist motor power requirements. Understanding and potentially influencing these operational parameters could contribute to energy efficiency, alongside investment decisions.

A third major avenue for energy consumption reduction, particularly relevant for both diesel and electric RTGs, is energy recovery and storage. Container handling involves lifting and lowering heavy loads. When a container is lowered, potential energy is converted into kinetic energy, and through regenerative braking, this energy can be converted back into electrical energy. Studies have shown that a considerable amount of energy is potentially recoverable during RTG operations. Analysis of RTG energy usage revealed that on average, about half of the energy consumed is potentially recoverable. The greatest portion of this recoverable energy comes from the hoist motor when lowering containers, acting as a generator. For a typical operation day, the average percentage of recoverable hoist energy roughly ranges from 70% to 80%. In conventional diesel-powered RTGs, this valuable regenerated energy is typically dissipated as heat in dump resistors instead of being captured and reused. Implementing energy storage systems (such as batteries, super-capacitors, or flywheels) allows this regenerated energy to be stored locally on the crane. Storing this energy at the point of use means it can be utilized for subsequent lifting operations or to limit peak power demand. This reduces the load on the primary power source (diesel generator or electricity grid) and increases the overall efficiency of the system. The potential energy savings from recovery are significant; recovering the potential amount of energy from a typical RTG in Port of Felixstowe could reach 78.25 MWh per year, translating to savings of 32,600 liters of fuel and 81 tonnes of CO_2 per crane per year for diesel RTGs. Implementing optimal operation control and power management systems is necessary to effectively manage the energy demands and the recovery potential from regenerative braking in cranes equipped with storage systems [Papaioannou, Vicky, 2017].

These approaches, driven by environmental regulations, green port initiatives, and economic incentives, are crucial for reducing the environmental footprint and operating costs of container terminals, contributing to the broader sustainability goals of maritime transport. Implementing these solutions effectively often requires significant investment and integrated planning across equipment procurement, retrofitting, infrastructure modification, and operational management.

3. Energy Characteristics of Rubbered Gantry Cranes: Drive Utilization and Energy Recovery Potential

Rubber-Tyred Gantry (RTG) cranes are indispensable pieces of cargo handling equipment (CHE) in modern container terminals, playing a crucial role in managing container stacks within the yard. Traditionally, these cranes have been powered by internal combustion diesel engines (dRTGs). The operation of these heavy machines is inherently energy-intensive, making them significant energy consumers within a port and major contributors to air pollution and carbon emissions. Understanding the energy usage patterns of RTGs, including how their drives are utilized and the potential for energy recovery, is critical for improving their efficiency and reducing their environmental impact.

From an energy perspective, the operational profile of an RTG crane is characterized by distinct modes and varying power demands. An RTG crane typically operates in three main modes: working, idle, and switched off. Analyses of RTG crane activity show that they are often not actively engaged in moving containers for a significant portion of the time. For example, data from the Port of Felixstowe indicated that a typical RTG crane was only active about 50% of the time, with the remaining time spent either in idle mode waiting for a task or switched off (fig. 1). The idle mode occurs when the crane is switched on but not performing a task, such as waiting for a truck or during operator breaks. In this mode, although not performing heavy work, the crane still consumes energy to maintain systems.

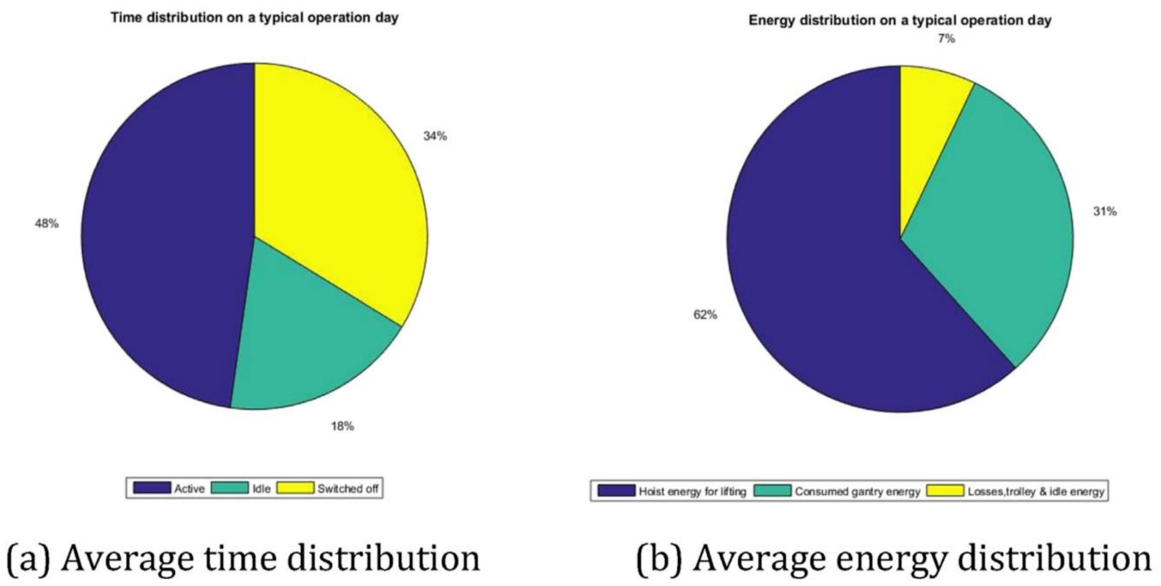


Fig. 1. Distribution of crane activity on a typical day of operation for an RTG crane in port of Felixstowe (http://dx.doi.org/10.1016/j.energy.2017.02.122)

The "working" mode is where the most substantial energy is consumed, corresponding to the core functions of lifting, lowering, and moving containers. The main movements involved are hoisting (vertical movement of the spreader and container), gantry (longitudinal movement along the yard block), and trolley (lateral movement across the block). Energy consumption is correlated with the crane's activity level. Key factors influencing energy demand during working mode include the container weight, the duration of lifts (which depends on stacking height), and the intervals between lifts (indicating frequency of movement) fig. 2, 3.

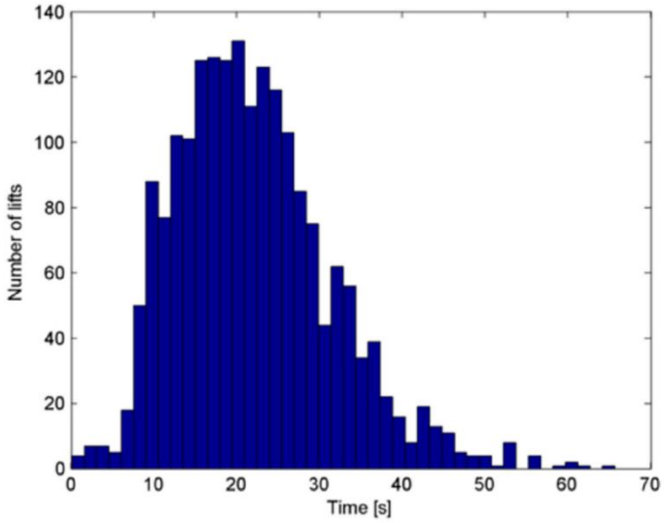


Fig. 2. Histogram of the number of lifts with the measured duration, data collected over a period of 4 days (http://dx.doi.org/10.1016/j.energy.2017.02.122)

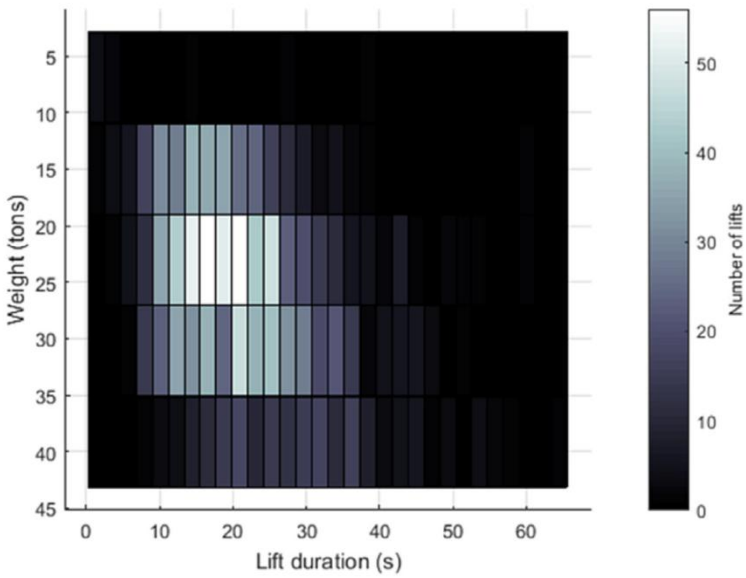


Fig. 3. Distribution of lift durations. The brightness increases with the number of lift durations with the specified mass. (http://dx.doi.org/10.1016/j.energy.2017.02.122)

Within the working cycle, the hoist motor is the highest-rated electrical machine and the primary energy consumer, especially during the lifting phase. Lifting a container requires significant power, with peak demands potentially reaching up to 400 kW for masses up to 52 tons (container plus spreader) lifted for durations up to 65 seconds. The speed of lifting is also influenced by container weight, with heavier containers lifted at a slower pace (table 1). On a typical operation day, approximately 60% of the energy used during active time is consumed by the hoist motor for raising containers. The gantry motor, responsible for longitudinal movement, accounts for about 30% of the energy usage during active time, while the trolley motor, idle energy, and losses make up the remaining 10%. The total electric power required by the RTG crane includes steady load power and dynamic power, with dynamic power being the main element influencing drive motor power, dependent on acceleration. The load demand itself is highly non-linear and does not vary significantly with seasons (Fig. 4) [Papaioannou, Vicky, 2017].

Table 1. Statistical information on container weight, duration of intervals between lifts and duration of lifts. Data collected over a period of 4 days (http://dx.doi.org/10.1016/j.energy.2017.02.122)

	Container weight	Intervals	Lift duration
Maximum value	32.3 tons	298.5 s	65.6 s
Minimum value	1.2 tons	4.5 s	1.0 s
Average value	16.3 tons	83.0 s	22.1 s
Median value	15.3 tons	58.0 s	21.0 s

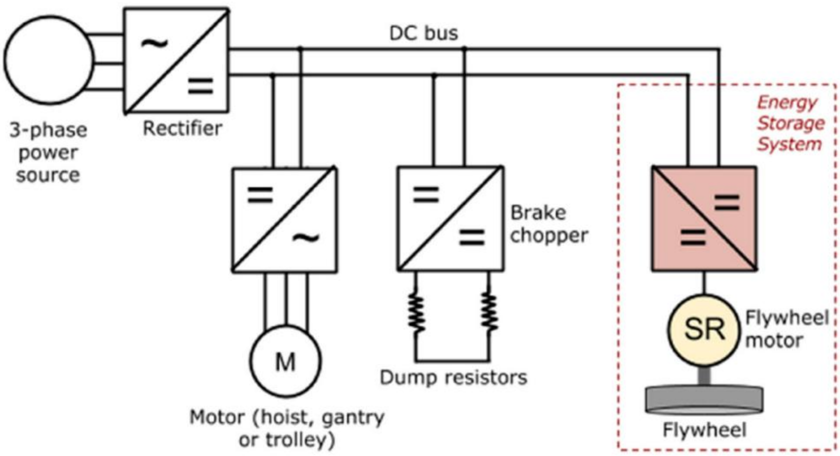


Fig. 4. Diagram of the main electric elements of an RTG crane with the addition of an energy storage system. (http://dx.doi.org/10.1016/j.energy.2017.02.122)

A particularly important characteristic from an energy perspective is the significant potential for energy recovery, especially during the lowering of containers. When a container is lowered, the hoist motor acts as a generator, producing energy. In conventional diesel-powered RTGs, this regenerated energy is often dissipated as heat using dump resistors. However, electric and hybrid-electric RTG systems can capture and utilize this energy. On average, about half of the total energy consumed by an RTG crane is potentially recoverable. The greatest amount of this recoverable energy comes from the hoist motor when lowering containers. Data indicates that for a typical operation day, between 84% and 89% of the hoist energy is potentially recoverable, while for lower activity days, this range is between 67% and 84%. On average, the percentage of recoverable hoist energy roughly ranges from 70% to 80%. The gantry motors also generate some recoverable energy when braking, but this amount is much smaller, ranging only from 2.6% to 5% of gantry energy (Table 2) [Papaioannou, Vicky].

Table 2. Percentage of recoverable Energy (http://dx.doi.org/10.1016/j.energy.2017.02.122)

No of test	1	2	3	4	5	6	7	8
Hoist Energy %	89.0	86.5	83.8	84.1	84.3	72.6	67.1	84.2
Gantry Energy %	5.06	4.09	4.47	4.30	2.68	2.80	3.54	2.87
Total Energy %	57.1	50.1	57.7	51.9	50.8	54.0	49.8	30.2

The ability to recover this energy is a key factor in improving the overall energy efficiency of the crane. If the recovered energy is stored, for example, in energy storage systems like batteries, super-capacitors, or flywheels, it can be used to power subsequent lifting operations or to limit peak demand from the primary energy source (either the grid or a diesel generator). Storing energy from a typical RTG's potential energy recovery could lead to considerable fuel savings for diesel cranes and reduce grid dependency for electric ones, increasing the overall efficiency of the system. The average total recoverable energy (including both hoist and gantry) for a typical operation day was calculated to be approximately 313 kWh in one analysis. For terminals with large fleets, the cumulative potential for energy recovery and efficiency gains is substantial.

In summary, the energy profile of an RTG crane involves intermittent, high-power demand during lifting operations, primarily driven by the hoist motor, interspersed with idle periods. Crucially, the lowering phase presents a significant opportunity for energy regeneration. The high proportion of potentially recoverable energy, estimated at around 50% of total consumption, primarily from the hoist function, is a defining energy characteristic of RTG operation. While energy is also lost through friction and internal motor/converter inefficiencies, which are not recoverable in the same way, the potential for capturing regenerative energy is considerable and directly influences the attractiveness of electric or hybrid drive systems incorporating energy storage. Effective utilization of the drive systems and implementation of energy recovery mechanisms are key to optimizing energy consumption and reducing the environmental footprint of gantry cranes in container terminals [Papaioannou, Vicky, 2017].

4. Power Supply Systems for Electric RTGs

Electric RTG cranes are widely used in container terminals for stacking and moving containers. The shift from diesel-powered to electric-powered RTGs is driven by environmental regulations, operational efficiency, and long-term cost savings. Several power supply systems are currently used, each with its own advantages and limitations.

RTG cranes are generally powered by electric motors. However, they can be powered in several ways:

- using a diesel generator (dRTG) with a power of 400 - 600 kW
- using direct electric power (eRTG) - mains power supply
- hybrid solutions (hRTG), e.g. a combination of a diesel generator with a battery tank or a combination of a battery tank with frequent charging

In the case of mains power supply (eRTG), the following variants can be distinguished:

- power supply via high voltage cable (6 - 20 kV)
- power supply via low voltage cable (400 - 690 V)
- power supply via low voltage busbars (400 - 690 V)

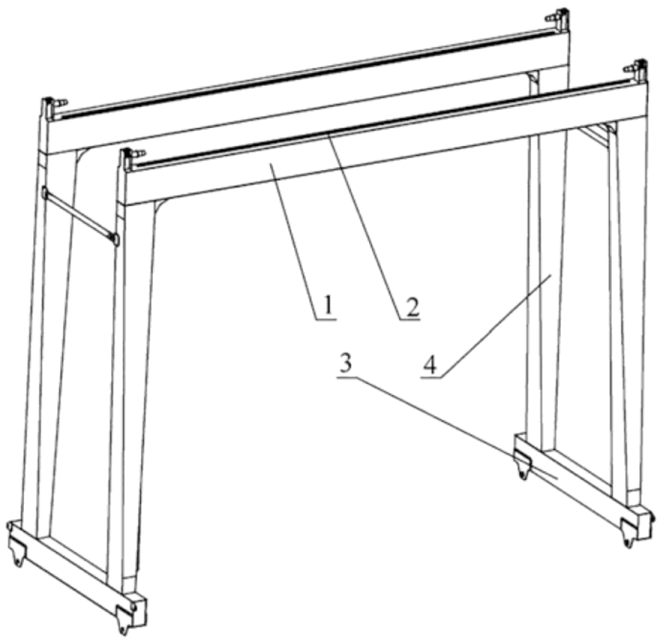


Fig. 5. Main structure. 1 Mainbeam; 2trolleytrack; 3 saddlebeam; 4 doorleg [Handbook of Port Machinery, 2024]

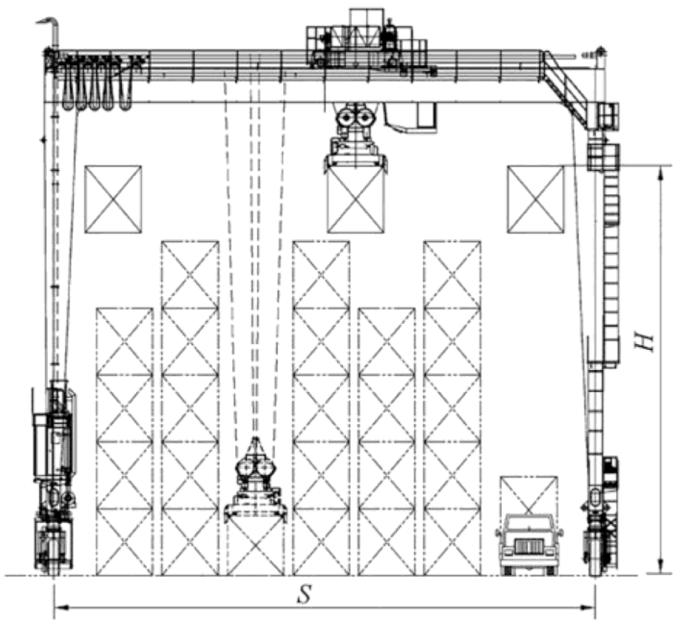


Fig. 6. Span and spatial arrangement of the RTG [Handbook of Port Machinery, 2024]

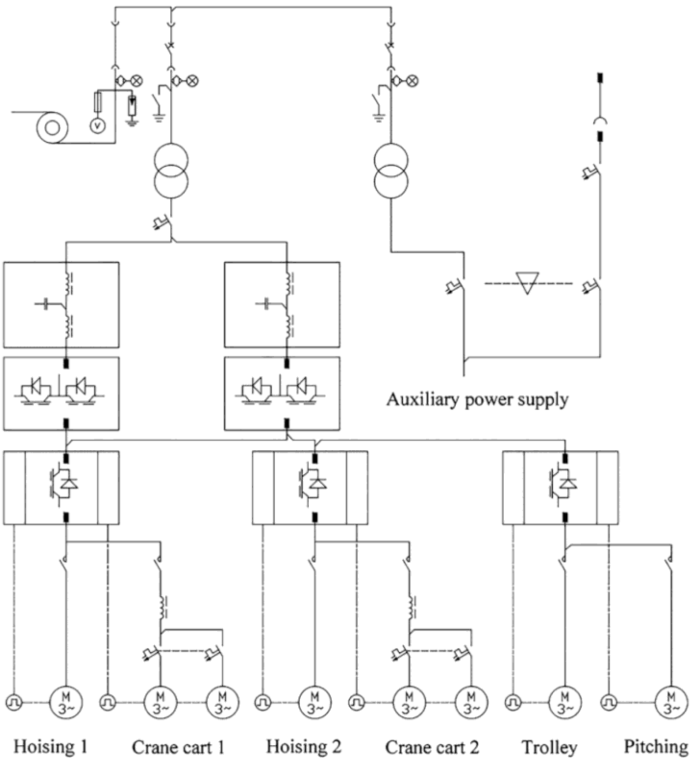


Fig. 7. Typical drive system of the quayside container crane [Handbook of Port Machinery, 2024]

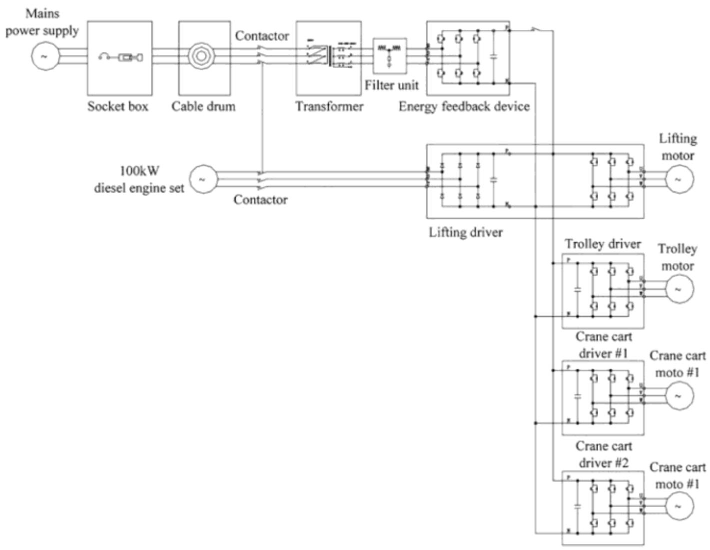


Fig. 8. Electrical schematic diagram of RTG with mains power supply [Handbook of Port Machinery, 2024]

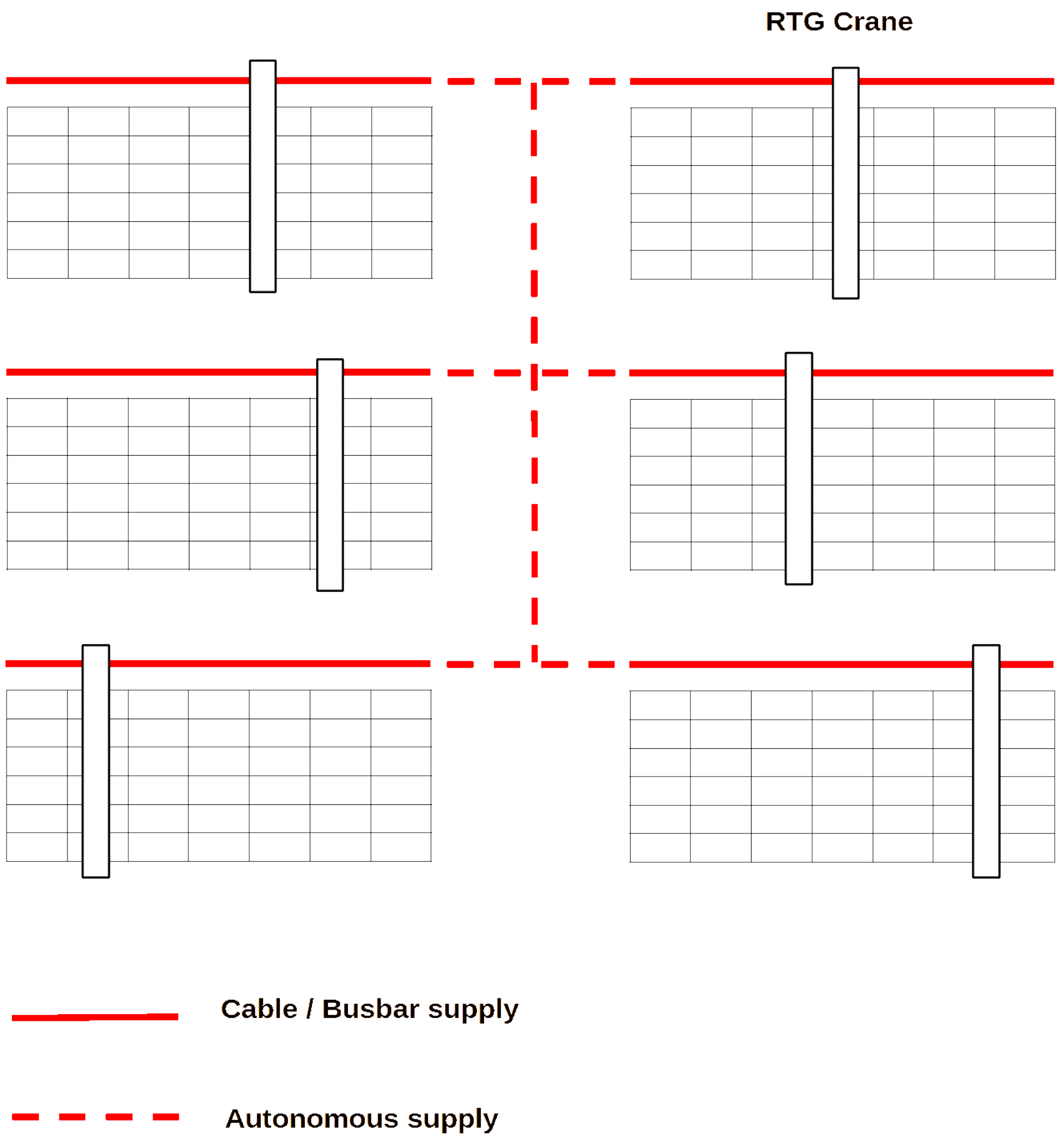


Fig. 9. Supply system on container yard

It should be remembered that in the case of mains power supply, it is also necessary to equip RTG cranes with an additional power source, because it is not possible to install power cables or busbars throughout the entire area of the container terminal. (fig. 9) The power source for autonomous driving can be a combustion generator or electrochemical batteries.

A. Diesel-Powered RTG (DRTG)

Traditional system still used in many ports, where the crane is powered by a diesel generator on board.

Fig. 10. Diesel generator set [Handbook of Port Machinery, 2024]

Advantages:

- High operational **flexibility** and **mobility**.
- Does **not require external power infrastructure**.
- Easy to deploy in **existing terminals**.

Disadvantages:

- **High fuel consumption** and **CO_2 emissions**.
- Significant **noise pollution**.
- **High maintenance costs** due to engine wear.
- Poor performance in terms of **sustainability goals**.

Trend:

- Gradual **phase-out** in favor of greener alternatives.

B. Cable Reel RTG (CR-RTG)

Connected to the electrical grid via a medium-voltage or low-voltage cable wound on a reel.

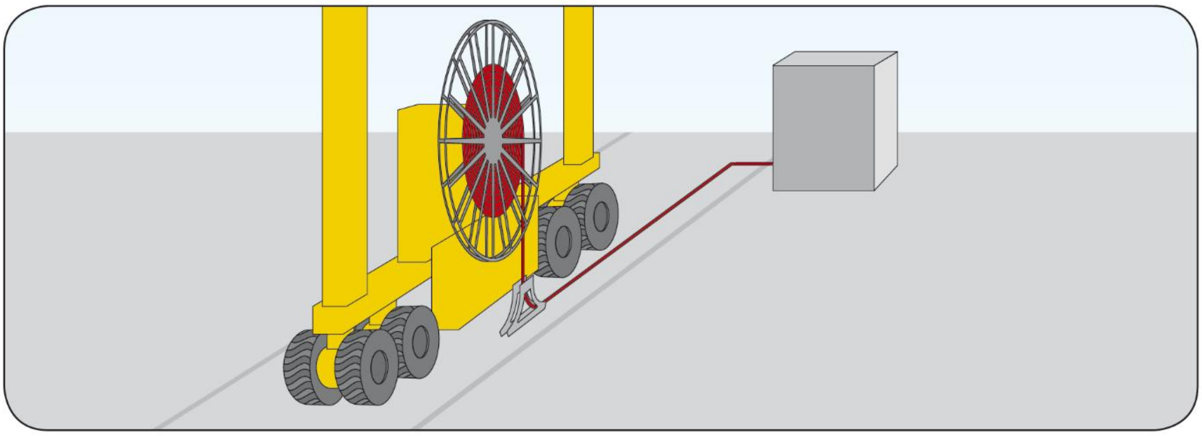


Fig. 11. Scheme of Cable Reel RTG supply system [Conductix wampfler information materials]

Fig. 12. Composition I of RTG power supply system with mains power supply[Handbook of Port Machinery, 2024]

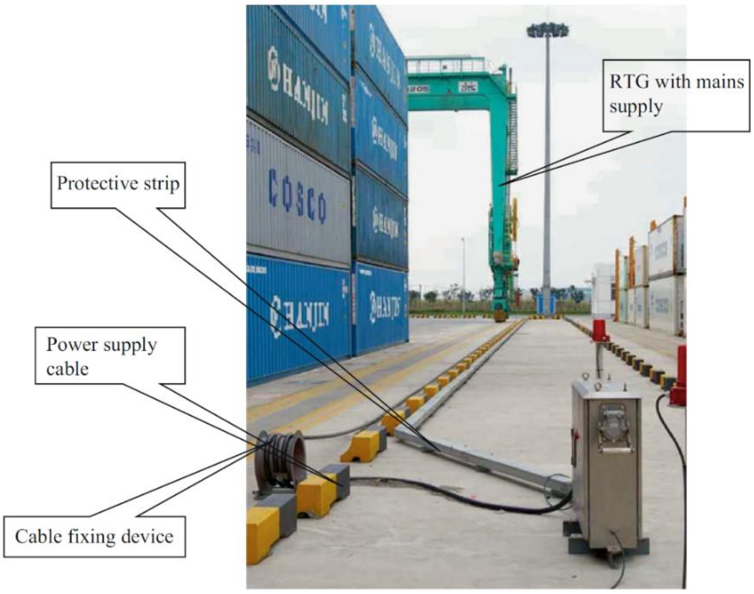


Fig. 13. Composition II of RTG power supply system with mains power supply [Handbook of Port Machinery, 2024]

Fig. 14. Power supply cable ground fixing device [Handbook of Port Machinery, 2024]

Advantages:

- **Zero local emissions** and **low noise**.
- **Lower operational costs** compared to diesel.
- Possibility of **regenerative braking** (energy recovery).
- Relatively simple retrofitting in some layouts.

Disadvantages:

- **Limited mobility** — movement restricted by cable length.
- Risk of **mechanical failures** in cable reeling system.
- **Cable management** can be complex and requires maintenance.

Trend:

- Still in use, especially in **compact yards** or where crane movement is predictable.

C. Conductor Bar RTG (Busbar RTG)

Uses fixed conductor rails (busbars) along the travel path, with a collector arm (pantograph or contact shoes) mounted on the crane.

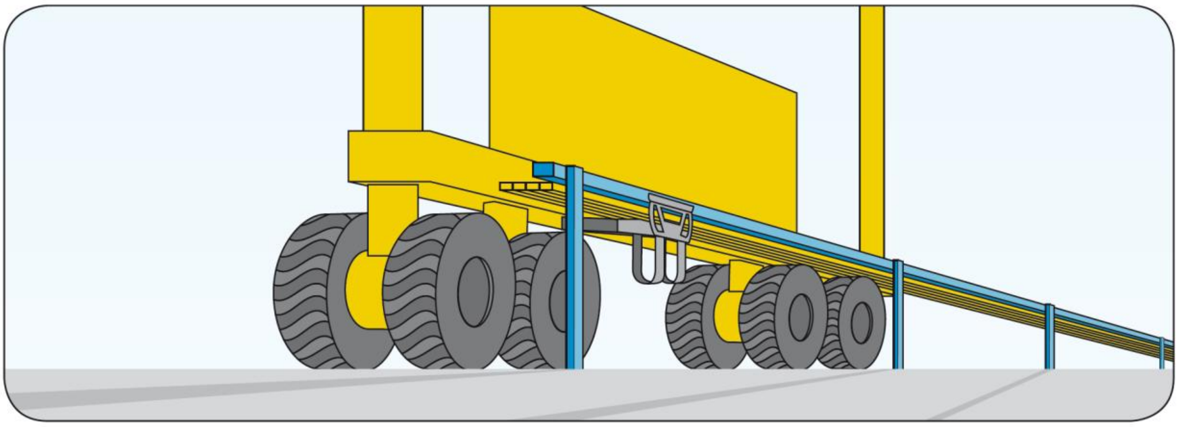


Fig. 15. Scheme of Conductor Bar RTG supply system [Conductix wampfler information materials]

Fig.16. Example of Conductor Bar RTG supply system [Conductix wampfler information materials]

Fig. 17 .Example of Conductor Bar RTG supply system [Conductix wampfler information materials]

Advantages:

- **Continuous power supply** without reeling mechanisms.
- **Low maintenance** and **low failure rates**.
- Very **clean and quiet operation**.
- Allows **energy recovery** during operation.

Disadvantages:

- **High initial investment** for infrastructure (busbars, safety systems).
- **Limited flexibility** — cranes can operate only along equipped tracks.
- Difficult to implement in **older terminals** without major modifications.

Trend:

- Gaining popularity in **newly developed or modernized terminals** prioritizing long-term efficiency.

D. Battery-Powered RTG (B-RTG)

Equipped with onboard batteries (usually lithium-ion) to power electric motors. Can be plug-in charged or charged during operation (opportunity charging).

Fig. 18. Battery system in RTG crane [Conductix wampfler information materials]

Fig. 19. Battery system of RTG crane [Conductix wampfler information materials]

Advantages:

- **High operational flexibility** — can operate anywhere in the yard.
- **Zero emissions** at the point of use.
- **Low noise**, suitable for urban ports.
- Ideal for **decarbonization goals** and ESG compliance.

Disadvantages:

- **Limited operational time** per charge.
- Requires **charging infrastructure** and **charging time** planning.
- **Battery degradation** over time and potential for high replacement cost.
- **Initial capital cost** can be high.

Trend:

- Strong upward trend in **green ports** and **electrification initiatives**.
- Increasing use of **hybrid systems** (battery + small diesel generator) to extend range.

E. Hybrid RTG (H-RTG)

Combines a small diesel generator with a battery system, offering more flexibility than purely battery-powered systems.

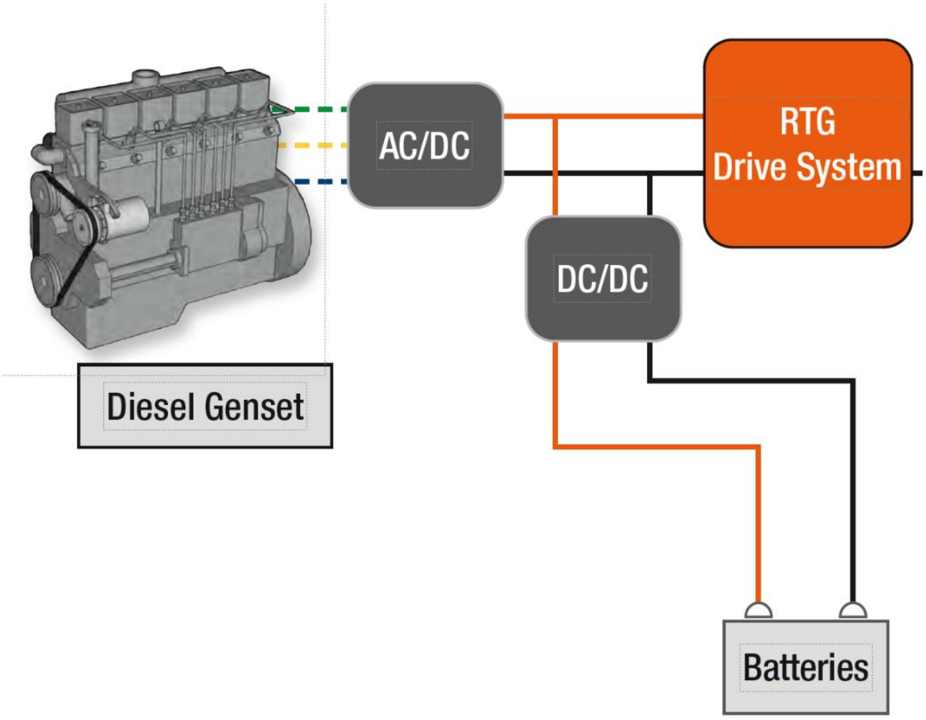


Fig. 20. Hybrid supply system of RTG crane (Conductix wampfler information materials)

Advantages:

- Reduced fuel use compared to traditional DRTG.
- Smaller engine = **less noise and emissions**.
- Operates even when batteries are depleted.
- **No external infrastructure** required.

Disadvantages:

- Still emits CO_2 (though less).
- More **complex system architecture** and maintenance.
- Dependent on **fuel availability** and **engine performance**.

Trend:

- Transitional technology in ports **moving away from diesel** but not yet ready for full electrification.

Current Trends in RTG Power Systems

- **Electrification and decarbonization** are major global trends in port operations.
- **Battery-powered and busbar-connected RTGs** are increasingly adopted in modern, sustainable terminals.
- **Hybrid RTGs** serve as an interim solution in ports unable to fully transition to electric infrastructure.
- **Automation and energy recovery systems** (e.g., regenerative braking) are being integrated into electric RTGs to improve energy efficiency.

Table 3. Comparison of supply system of RTG cranes

System	Emissions	Flexibility	Eco-Friendly	Infrastructure Cost	Operating Cost
Diesel RTG	High	Very High	❌	Low	High
Cable Reel RTG	Zero (local)	Low	✅✅	Medium	Low
Busbar RTG	Zero (local)	Medium	✅✅	High	Very Low
Battery RTG	Zero (local)	High	✅✅	Medium	Low
Hybrid RTG	Low	High	✅	Low	Medium

5. The Attractiveness of Electrifying of RTG's (Retrofitting) in Container Terminals

Container terminals are vital hubs in the global trade network, facilitating the movement of vast quantities of goods. However, their intensive operations, particularly involving heavy machinery like rubber-tyred gantry (RTG) cranes, contribute significantly to energy consumption and environmental impact. Traditionally, RTG cranes have been powered by diesel engines (dRTGs). These dRTGs are significant energy consumers, major sources of air pollution, and contributors to greenhouse gas emissions in ports. Addressing the environmental footprint and operating costs associated with these cranes is a key objective for container terminals, driven in large part by global "green port initiatives". One of the most compelling strategies to achieve these goals is the electrification of gantry cranes, often involving the retrofitting of existing diesel units. The attractiveness of this transition stems from a combination of significant environmental, economic, and operational benefits, as detailed in the sources.

1. Significant Environmental Benefits

A primary driver for electrifying RTGs is the substantial reduction in environmental pollution. Diesel combustion in dRTGs is a major source of air pollutants and greenhouse gases. Electrifying these cranes directly reduces or eliminates reliance on diesel fuel, leading to considerable environmental improvements.

- CO2 Emissions Reduction: Electrifying diesel-powered RTGs is confirmed to be effective in curbing CO2 emissions. Studies show a potential reduction in CO2 emissions by 60%-80% with the use of electric RTGs compared to diesel-powered ones. Data from a terminal in Shanghai demonstrated that eRTGs consumed energy equivalent to 0.834 kgce per TEU, which was 54.9% less energy equivalent per TEU than dRTGs, which consumed about 1.27 kg of diesel per TEU (equivalent to 1.851 kgce). The implementation of diesel-electric retrofitting on RTGs is stated to not only reduce terminal emissions considerably but may also save up to around $685 million annually in energy costs globally, based on 2017 container throughput figures. Lifecycle assessment (LCA) studies also confirm significant differences in GHG emissions between conventional and electric RTGs in the "use" phase, showing over 70% of CO2 eq. reduction for electric RTGs, although this is dependent on the power grid mix used for electricity generation. Implementing carbon emission tax policies can effectively promote the retrofit of RTGs, thereby reducing the port's carbon emissions. The higher the ratio of blocks retrofitted to electric-driven cranes, the fewer carbon emissions caused by the port under the same planning horizon [Martinez-Moya, 2019], [Ding, Yi].
- Air Pollution Reduction: Beyond CO2, dRTGs contribute to other forms of air pollution. The use of electrical RTGs compared to diesel-powered ones may reduce pollutant emissions by 60%-80%. According to [Chen and Zeng, 2021] , the degree of air pollution caused by RTGs in Ningbo Port is second only to that of ships. Switching to electric operation mitigates this problem.
- Noise Reduction: Diesel engines are inherently noisy. Electrically powered cranes operate significantly more quietly. Electrification promises to reduce noise and exhaust emissions by up

to 40%. This improves the working environment for terminal staff and reduces noise impact on surrounding communities.

- Alignment with Green Initiatives: The transition is strongly driven by "green port initiatives". Adopting electric technology promotes the use of clean energy for port equipment and is conducive to improving the reputation and competitive position of the port.

2. Substantial Economic Advantages

While the environmental benefits are a primary driver, the economic case for electrification, particularly retrofitting, is also strong, especially in the long term.

- Reduced Operating Costs: The sources highlight that these technologies promise to reduce operating costs, with one source stating a potential reduction of 50%-70% and another specifically mentioning 50%.
- Lower Energy Consumption and Costs: Electrification leads to reduced energy consumption, estimated at 10%-30%. As noted earlier, actual data shows even higher savings, with eRTGs consuming 54.9% less energy equivalent per TEU than dRTGs. This translates directly into reduced energy costs. A case study showed a 29.7% reduction in total energy costs for eRTGs compared to dRTGs. Overall, retrofitting can lead to a "greatly reduced" energy cost. The cost per TEU for electricity is significantly lower than for diesel ($0.384/TEU vs $1.295/TEU in one example) [Ding, Yi, 2021].
- Fuel Cost Savings: For hybrid systems or where diesel is still used for movement, fuel consumption is reduced. Electrification via cable reels for eRTGs means they are powered by electric cables instead of diesel engines. Diesel costs are eliminated entirely for purely electric operation. Even replacing oversized diesel engines with less powerful ones in existing dRTGs resulted in saving 6.06 l/h of fuel, demonstrating the potential for fuel reduction within the diesel fleet, but electrification goes much further [Martínez-Moya, 2019].
- Potential Maintenance Cost Savings: Electrically driven systems often have fewer moving parts subject to wear and tear compared to diesel engines. One source indicates that using electrical compared to diesel-powered RTGs may reduce maintenance costs by approximately 30% [Kanzumba Kusakana 2021].
- Long-term Lifecycle Savings: While initial investment costs for retrofitting and infrastructure modifications can be substantial, the long-term energy and operational cost savings can provide a return on investment. A case study estimated a payback period of around 15 years for an investment targeting a 25% emission reduction which involved purchasing new eRTGs and

retrofitting dRTGs. A lifecycle analysis of an optimally controlled hybrid grid/battery system with energy recovery for an RTG showed a potential cost saving of 73.53% over 20 years compared to a baseline grid-only system, with a break-even point after 1.36 years [Kanzumba Kusakana, 2021].

3. Technological Advancement and Integration with Energy Recovery

The technology for electrifying RTGs is available and evolving, including solutions for retrofitting existing cranes.

- Availability of Technologies: Electric-driven RTGs (eRTGs) and hybrid diesel-electric RTGs (hRTGs) are available on the market. Retrofitting of dRTGs into hRTGs or eRTGs was introduced in 2006. Various solutions exist for providing electric power, such as cable reels and conductor rails using plug-in or drive-in systems.
- Retrofitting Existing Fleet: The ability to retrofit existing dRTGs is a key aspect, driven by green port initiatives. This allows terminals to upgrade their current assets rather than needing to replace the entire fleet with new cranes, which can be a significant investment. Retrofitting involves adapting the existing diesel cranes to operate electrically.
- Integration with Energy Recovery: Container cranes generate significant amounts of recoverable energy, particularly from the hoist motor during lowering operations. On average, about half of the energy consumed by an RTG is potentially recoverable. In conventional diesel RTGs, this energy is often dissipated as heat. Electric and hybrid electric systems are much better positioned to capture and utilize this regenerated energy, often employing energy storage systems like batteries, super-capacitors, or flywheels. Storing this energy reduces the net energy drawn from the primary source (grid or diesel generator) and increases overall efficiency. Recovering potential energy from a typical RTG could save considerable fuel and CO2 per year for diesel cranes, and reduce grid dependency for electric ones. Optimal energy management systems are key to effectively utilizing this recovered energy.

4. Challenges to Consider

While highly attractive, the transition to electric RTGs, especially through retrofitting, does present challenges. The initial investment for retrofitting and necessary depot modifications or terminal infrastructure adaptations can be substantial. The operational flexibility of electric and hybrid RTGs might be reduced compared to diesel ones, particularly for movements between zones, often requiring turning off electric power and relying on internal buffers or auxiliary power sources. The operating capacity of eRTGs and hRTGs might also be perceived as lower than dRTGs, though improvements are being made. Furthermore, the actual environmental benefit in terms of CO_2 emissions is dependent on the carbon intensity of the electricity grid mix.

Despite these challenges, the significant environmental gains, substantial long-term economic savings, and the availability of mature retrofitting technologies make the electrification of gantry cranes a highly attractive solution for container terminals aiming to improve sustainability and operational efficiency. The move from polluting and costly diesel power to cleaner, more energy-efficient electric systems aligns with global environmental goals and offers compelling financial benefits through reduced energy consumption, lower operating costs, and the potential for energy recovery. As green port initiatives gain momentum and energy costs fluctuate, the case for electrifying RTGs, including through the retrofitting of existing fleets, becomes increasingly persuasive as a strategy for a more sustainable and economically viable future for container terminal operations.

In summary, reducing the energy consumption of gantry cranes in container terminals is being pursued through multiple, often complementary, strategies:

- Electrification and Fuel Switching: Replacing diesel cranes with electric or hybrid models to reduce reliance on fossil fuels and lower direct emissions.
- Energy Efficiency Improvements: Optimizing the performance of existing equipment, such as replacing oversized engines in diesel RTGs, and potentially improving operational planning and scheduling.
- Energy Recovery and Storage: Capturing energy generated during container lowering using regenerative braking and storing it for later use, thereby reducing the net energy drawn from the primary source.

5. Case study: MSC Terminal Valencia (MSCTV) conversion

A significant terminal within the Port of Valencia – which is Spain's largest port and the fifth busiest container port in Europe handling over 4.2 million TEUs annually – undertook a pioneering project to convert its existing Konecranes Rubber Tyre Gantry (RTG) cranes to fully electric operation. This conversion involved a busbar retrofit *("Konecranes boosts sustainability, safety and efficiency for MSC terminal VLC with Spain's first RTG busbar retrofit". Poniżej tego znajduje się podtytuł: "MSC TERMINAL VALENCIA CASE STUDY")*

This project marked Spain's first RTG busbar retrofit, aiming to enhance sustainability, safety, and efficiency. In addition to retrofitting existing cranes, MSCTV also acquired new Konecranes RTGs that were supplied as fully busbar ready. A busbar system as a method where power is supplied to the RTG by a low electrified fence that provides physical contact. This system allows for the electric operation of the RTGs.

The conversion involved retrofitting existing Konecranes RTGs with the busbar system. New RTGs purchased by MSCTV were already equipped to be busbar ready. This project was undertaken in collaboration with Konecranes, who supplied the technology for the conversion.

Benefits Achieved

The conversion to the busbar system at MSCTV resulted in significant benefits:

- CO2 Emissions Reduction: the busbar retrofit provides a CO2 emissions reduction of approximately 20%. This aligns with MSCTV's focus on using 'clean' equipment to reduce its environmental impact and work harmoniously with local communities.
- Reduced Noise: As mentioned above, the operation is quieter, contributing to a less noisy environment.
- Reduced Maintenance: The system requires less maintenance.
- Higher Productivity and Reliability: The RTGs operate at higher levels of productivity and reliability with the busbar system. Eliminating the need for refuelling means RTGs can spend more time shifting containers, contributing to increased productivity.

These factors lead to better results compared to other brands. Operators have provided good feedback on the comfort of the cabin and the value of having such a stable spreader when lifting and moving containers. Konecranes RTGs are designed to be industry benchmarks for safety and reliability, incorporating features like an intelligent steel structure, Active Load Control (ALC) technology, and 'smart cabins' to provide market-leading safety and productivity benefits.

The busbar retrofit at MSCTV, executed with Konecranes, transformed the RTG operations to fully electric, resulting in significant environmental benefits like a 20% CO2 reduction, reduced noise, lower maintenance, and increased productivity and reliability by eliminating refuelling. The project also included valuable safety enhancements like trailer lift prevention and auto-steering. The success was facilitated by the shared pioneering mindset of MSCTV and Konecranes, including the collaborative development of simple solutions like the 'single push button' system, and a strong service partnership with dedicated daily support.

6. Conversion process

The conversion process will be described using the example of the conversion of the RTG crane power supply in the port of Gdynia. Currently, Gdynia Container Terminal (GCT) operates seven Rubber-Tyred Gantry (RTG) cranes, which are powered by diesel generators. This fleet consists of two different models: four IMCC/GPC cranes, manufactured in 2005 and operating at 3Phase 400V AC 50Hz, and three ZPMC cranes, manufactured in 2008 and operating at 3Phase 440V AC 50Hz. Cranes appear structurally and mechanically suitable for the planned upgrades. However, it should be noted that the cranes are not new, and several issues were observed that may affect the overall upgrade timeline and implementation. Rectification of these identified faults falls outside the scope of this contract and is typically the responsibility of the port authority or its designated maintenance contractors. Key issues include: outstanding faults and faulty equipment in general, obsolete components within the drive and PLC systems (some of which are no longer supported or have limited availability), and a non-functioning Uninterruptible Power Supply (UPS) system. It is recommended that GCT conducts a comprehensive assessment of the overall technical condition of all cranes, as the findings from the two assessed cranes may not fully represent the condition of the remaining five.

The conversion is being carried out primarily to enhance the efficiency, sustainability, and safety of container handling operations at the port. The main objective is environmental impact reduction by significantly lowering reliance on diesel engines, which will reduce emissions and noise pollution. The project involves transitioning from diesel generator-powered systems to a more sustainable, efficient electrical power supply delivered via flexible cable connections from 15 kV yard-based outlets. The modernization also aims to improve the operational efficiency of the cranes by upgrading their power systems, control systems, and overall machinery, which is expected to lead to increased productivity, faster container handling, and reduced downtime. In the long term, electrification will ensure energy efficiency through better energy management and the utilization of cleaner power sources. Furthermore, modernizing port equipment helps in compliance with increasingly stringent environmental and safety regulations, both local and international. Finally, the project aims to increase the safety and reliability of the cranes, reducing the risk of malfunctions and accidents, and also serves as a futureproofing investment by integrating advanced technologies that can be further upgraded, ensuring the terminal's long-term competitiveness in the global shipping industry. In summary, the purpose of the modernization and electrification of RTG cranes in GCT is to improve operational performance, reduce environmental impact, enhance safety, and comply with evolving regulatory standards, ultimately contributing to the terminal's growth and sustainability.

The conversion of the power source involves changing the energy flow in the RTG crane. The main power source is the 15 kV power grid, while the combustion generator acts as an additional - emergency power supply, mainly in the event of autonomous (network-free) driving.

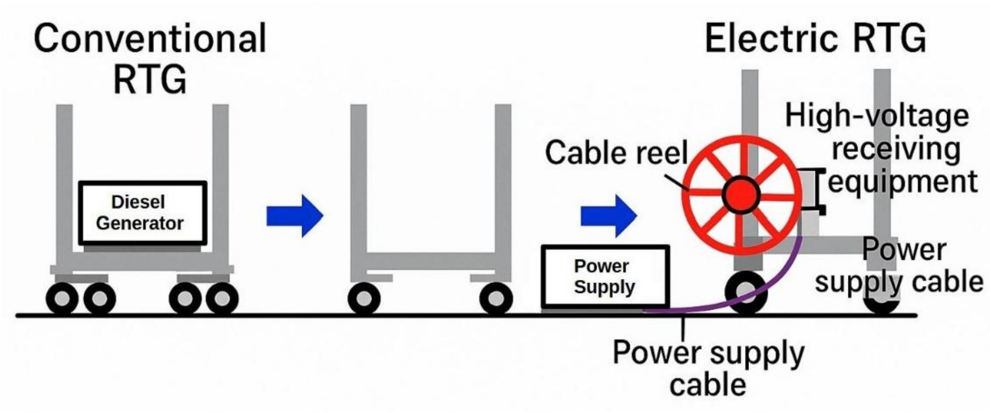


Fig. 21. Simplified procedure of conversion

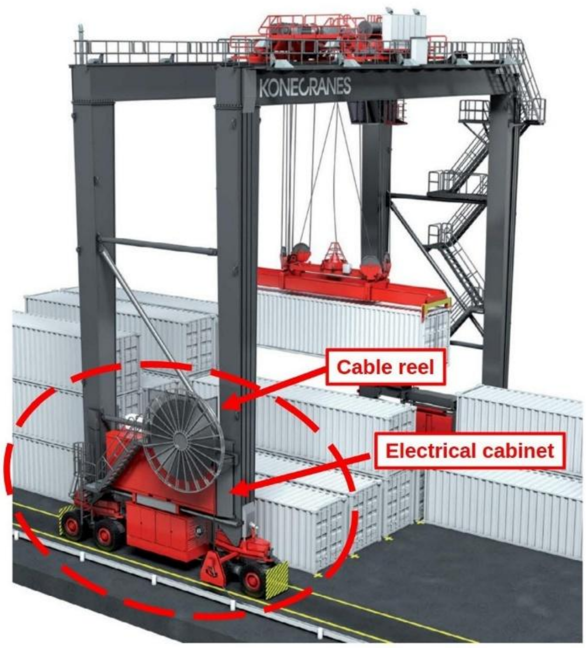


Fig. 22. The main elements of conversion [Based on Konecranes materials]

The main element of the conversion is the replacement of the high-power diesel generator with a cable power supply and additional emergency power supply with a lower-power generator. This involves the installation of a 15 kV power cable with a reel and a transformer. RTG cranes are connected to the container terminal's power grid at so-called Connecting points. Power points are connected to the power grid supplied by the transformer station.

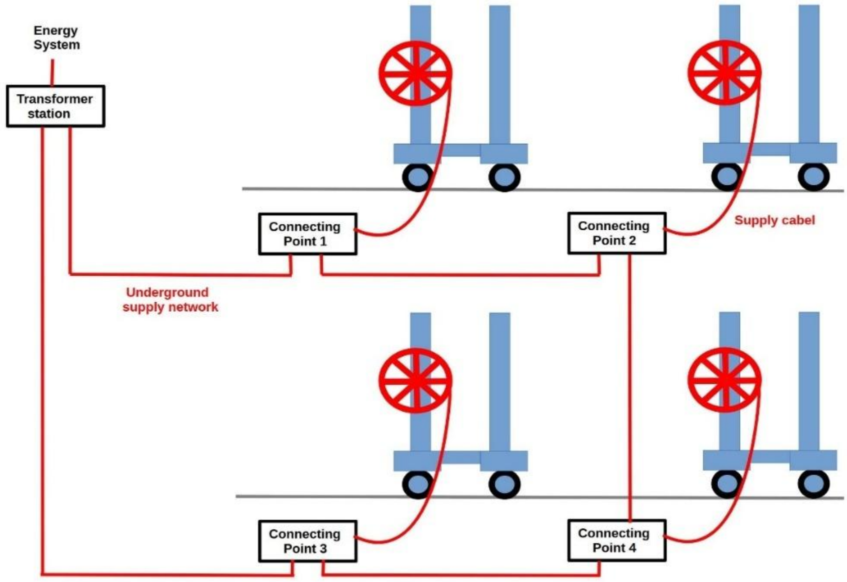


Fig. 23. Simplified scheme of RTG crane supply system

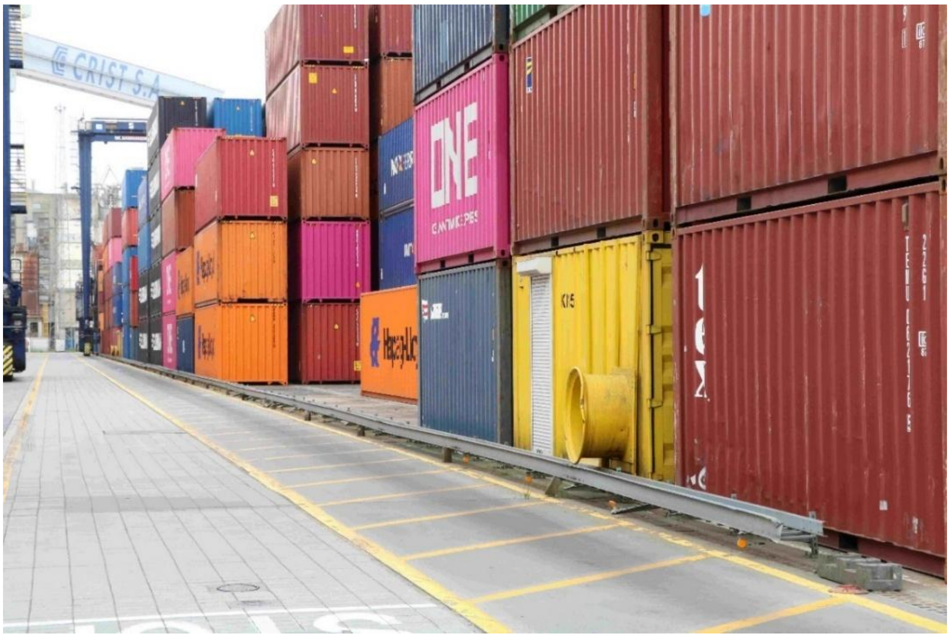


Fig. 24. Installed guide for 15 kV cable with 15 kV switchboard (yellow container)

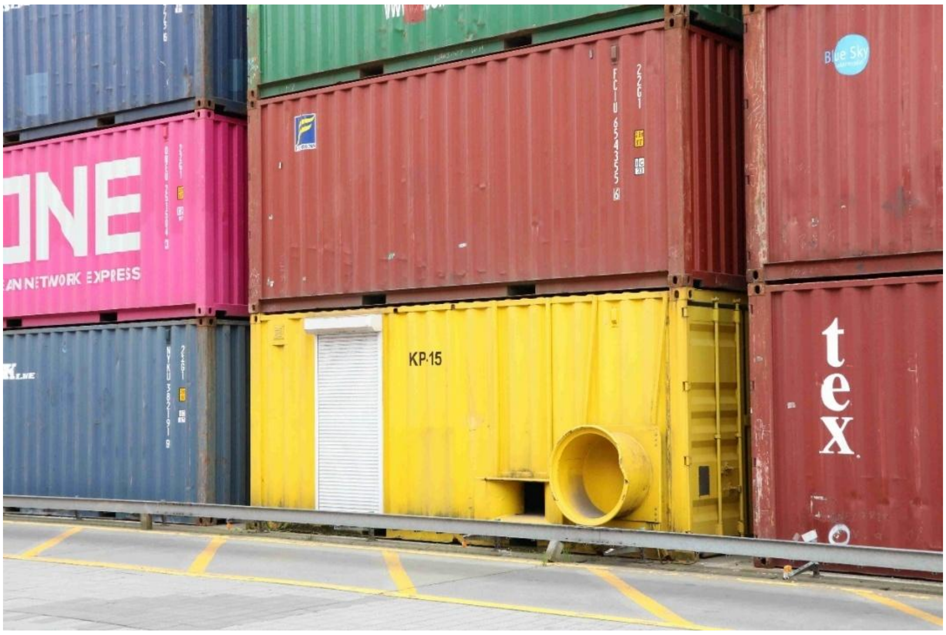


Fig. 25. 15 kV switchboard (yellow container)

Fig. 26. Diesel generator unit in the RTG crane, which will be removed during the conversion. In its place, new electrical equipment will be installed

Fig. 27. View of the entire RTG crane with the visible diesel generator unit (to be replaced) in the foreground

The conversion process involves several key stages, which are illustrated in figure 28. Figure 29 shows the energy flow diagram in the RTG crane after conversion. Two power sources are visible: the 15 kV network as the main one and the diesel generator as the additional one. In addition, the power supply block for own needs is a separate part.

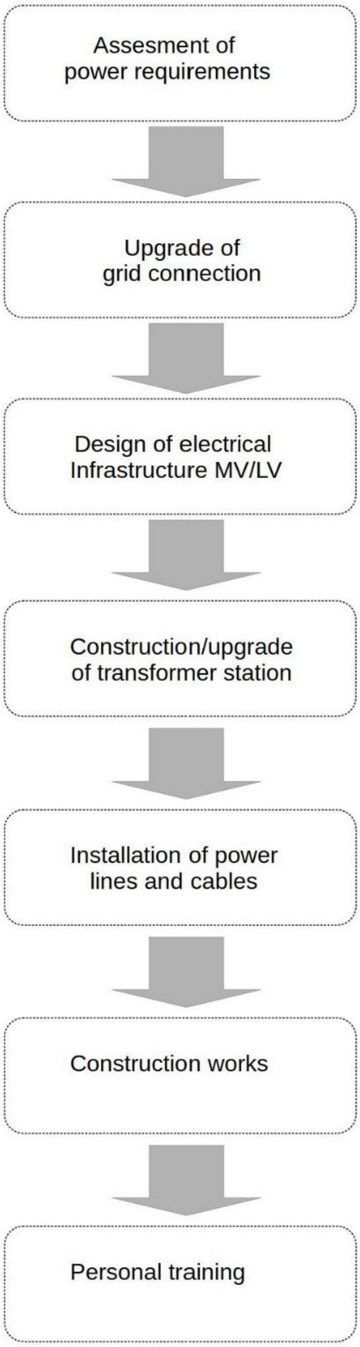


Fig. 28. The main steps of conversion

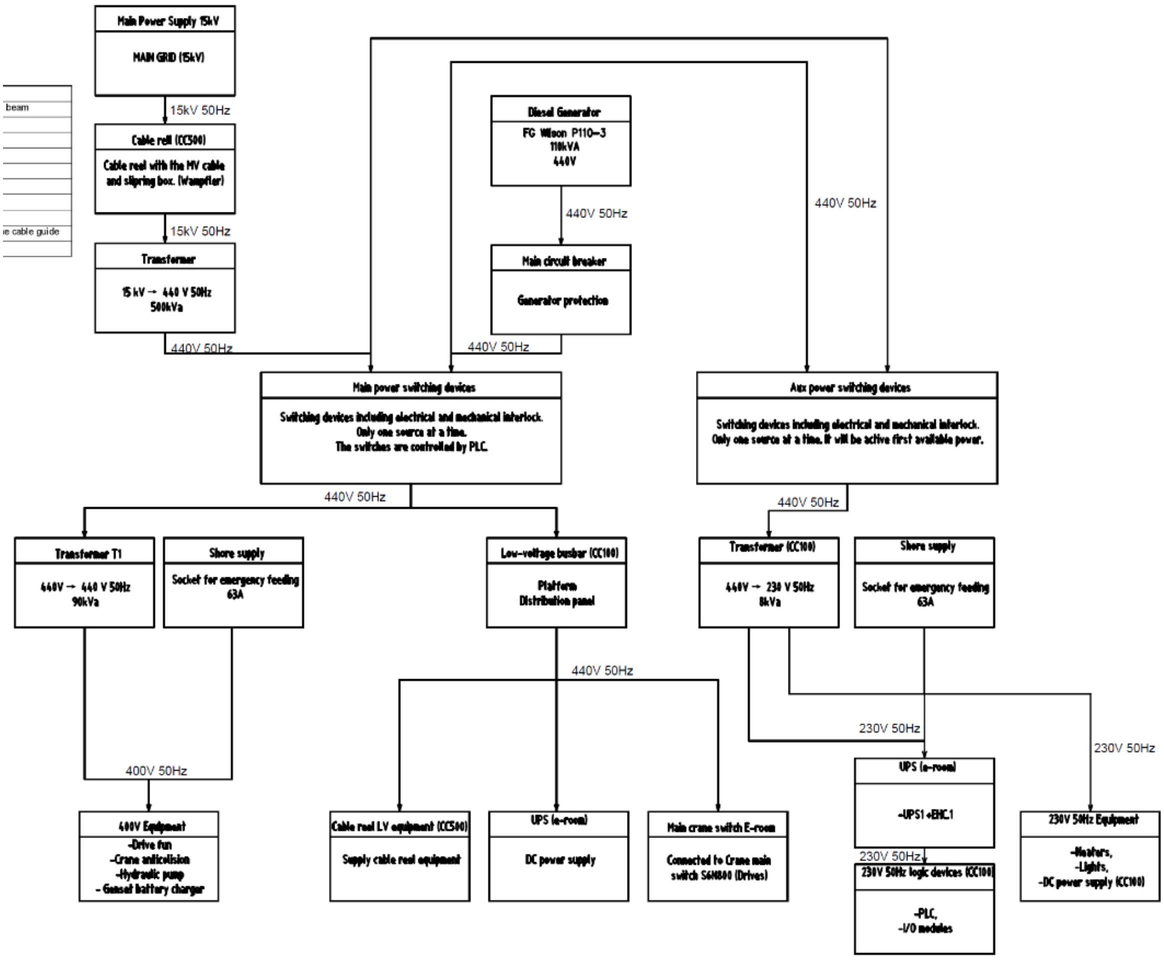


Fig. 29. Energy flow scheme (source: ALATAS)

The conversion involves the removal of the existing high-power generator and replacing it with a new power source. Figure 30. illustrates the main components of the container crane that must be replaced during the conversion The main components of the RTG crane power supply system which will should be installed during conversion are as follows:

1. Primary Power Supply
   - Source: 15 kV / 50 Hz network
   - Function: Supplies the main electrical power to the crane during normal operation.
2. Cable Reel
   - Type: High-voltage cable reel with slip ring
   - Function: Transfers high-voltage power from the supply to the crane via a flexible cable system.

3. Main transformer
   - Input/Output: 15 kV to Low Voltage (LV)
   - Function: Steeps down input high voltage
3. Transformer TR1
   - Input/Output: 440 V to 400 V
   - Function: Reduces input voltage from 440V to 400V to power auxiliary drives. The need for its use results from the use of an unusual voltage of 440 V in the crane.
6. Transformer T2
   - Input/Output: 440 V to 230 V
   - Function: Converts and conditions power for auxiliary and controll systems.
4. Low-Voltage Switchgear (IESCM)
   - Components:
     - Platform distribution panel
     - Cable reel with slip ring supply
     - UPS for control systems
     - DC power supply
   - Function: Distributes low-voltage power to various crane subsystems and ensures control system reliability.
8. Diesel Generator (FG Wilson P110-3)
   - Role: Emergency power source
   - Function: Ensures crane operation during main power failure and autonomous drive

Table 4. The main elements which need to be removed or added.

Replacement of Diesel Generator System	The primary change involves removing the diesel generator and its associated components, including the fuel tank. The structural analysis confirms a significant weight reduction after replacing the old system with the new electrified components.
High voltage Cable Reel System	A motor cable reel drum and a dedicated cable guiding system are installed to manage the flexible cable connection from the yard power outlet. High voltage slip ring current collectors, rated for 15 kV, are necessary to transfer power from the static cable reel to the rotating crane structure.

Medium Voltage (MV) Transformers	MV transformers are installed to step down the 15 kV incoming power to the operational voltage required by each crane type. A 500 kVA transformer is proposed, based on detailed power calculations considering worst-case loads and a 20% safety margin
Backup Generator	A backup generator, is included to provide auxiliary power in case of HV power loss. It is used for essential functions like lowering a hanging load (with empty spreader), powering auxiliary systems (control, heating, cooling, lighting), and moving the crane to a service area.
New AC Distribution Panel	A new panel is designed to manage the switch-over between the HV cable reel supply and the backup generator, and to distribute AC power to platform consumers like the cable reel drive, 24VDC power supply, lighting, heating, cooling, and power outlets

.

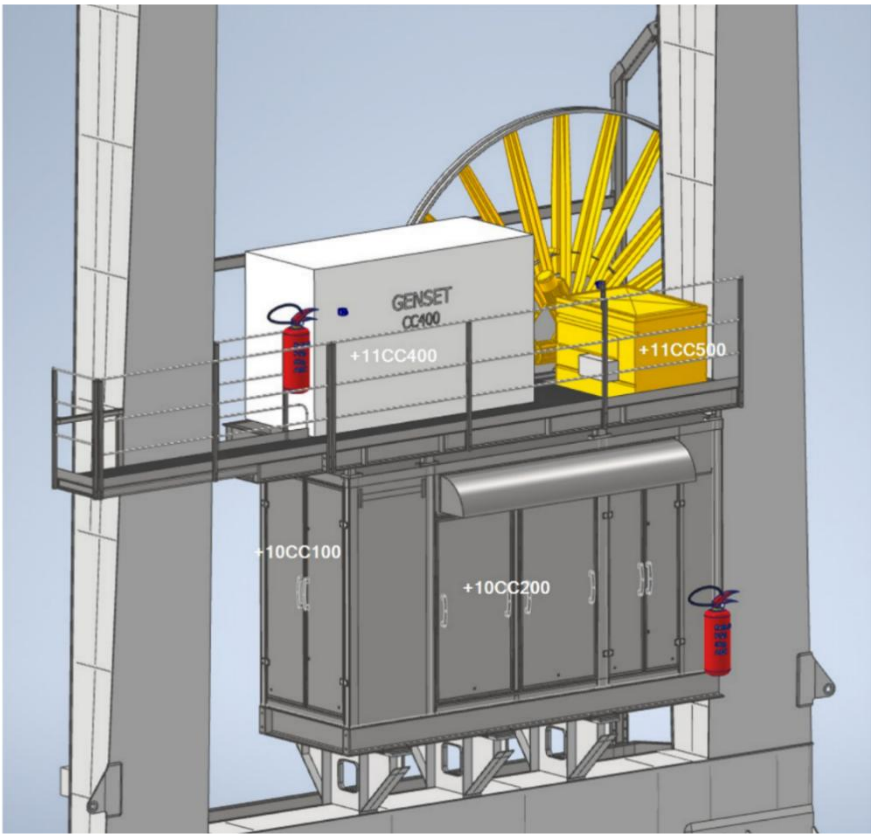


Fig. 30. Overview drawing of the main components involved in the conversion.

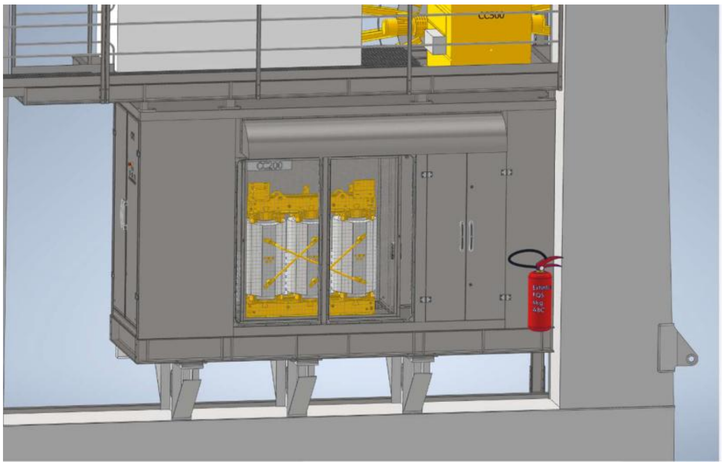


Fig. 31. Placement of the main transformer (Source: ALATAS)

7. RTGs electrification process

Prefeasibility

Conversion of the power source requires preparatory activities, which primarily include the selection of an appropriate power supply system and an energy audit to assess the investments needed in the port energy system. It requires the following steps:

- The process begins with an on-site assessment of the existing cranes to evaluate their general condition and suitability for electrification. This includes visiting at least one crane of each type and a reference crane already electrified.
- The electrification of RTG container cranes is associated with the need to provide an appropriate power supply. This entails the need to verify the power of the current power connection to the power grid and also to build an appropriate energy infrastructure.
- The first stage is to take stock of the current port energy system and, above all, determine the connection capacity of the energy supplier.
- Power Demand Assessment is the second step. A comprehensive study must be conducted to determine the total electrical load required by the RTG cranes. The results will inform system sizing and upstream grid requirements.
- If the current electrical connection does not meet the new load requirements, the terminal must apply for an increase in contracted power with the local utility provider. This process involves

submitting technical data, negotiating new terms, and potentially reinforcing external grid infrastructure.

Power assessment demand

The purpose of the energy analysis is to estimate the power required to power container cranes in order to verify the efficiency of the current power source.

Key Factors Influencing Energy Demand

- Rated power of the crane (typically 150–250 kW per electric RTG)
- Operating hours per day
- Load factor (average operating power vs rated power)
- Operational cycle (lifting, trolley movement, gantry travel)
- Efficiency of electrical systems
- Use of regenerative braking systems

Basic formula for energy demand of a single crane

The daily energy demand (*E*) for one crane can be estimated as:

$$E = P_{rated}\, k_{load}\, T\, \eta$$

where:

E - - energy demand [kWh]

P_{rated} - rated power of crane [kW]

k_{load} - Load Factor, typically 0.6 to 0.9

T – operating hours, crane working hours per day

η - overall system efficiency (usually 0.85–0.95)

Scaling for Multiple Cranes

For a terminal operating multiple RTGs:

$$E_{total} = E_{single} N$$

N – number of cranes

Additional Considerations

- Regenerative energy recovery can reduce net energy consumption by 20–30%
- seasonal and operational variations should be accounted for using historical data
- Demand profiles can be used for peak load analysis and infrastructure sizing
- Integration with energy storage or renewable sources (e.g., solar) may influence demand

Total Connection Power Calculation for Multiple RTG Cranes

1. Determine the Rated Power of One RTG Crane

The rated power depends on the crane type:

- Diesel RTG: Engine rating typically 300–600 kW (not relevant for electric supply).
- Electric RTG (e-RTG): Rated electrical power usually between 150–250 kW.

2. Calculate the Total Connection Power

$$P_{total} = N\, P_{single\_RTG} k_{div} k_{load}$$

k_{div} - Not all cranes operate at full load simultaneously. A diversity (or simultaneity) factor reflects the realistic maximum concurrent usage. Typical values range from 0.6 to 0.8.

k_{load} - The load factor reflects the average operating load versus peak capacity. RTGs typically run at 60–90% of full power.

Table. 5. Exemplary calculations

Parameter	Value
Rated Power per RTG	200 kW
Number of RTGs	10
Diversity Factor	0.7
Load Factor	0.8
Total Connection Power	1.12 MW
With 10% Safety Margin	1.23 W

Design

The commencement of the crane conversion must be preceded by the preparation of documentation that meets both technical and legal requirements. An essential element is the agreement of this documentation with both the user and the relevant offices. This documentation is the basis for the performance of construction works. It consists of several steps:

- Technical Documentation Preparation: Detailed technical documentation for the modernization project, covering the proposed solution and system components, is prepared.
- Client Approval: Upon receiving approval from client, the preliminary design phase concludes.
- Detailed Design Phase: The detailed design phase commences after client approval. This phase involves further refining and finalizing technical specifications, installation procedures, and integration strategies necessary for successful implementation.
- Coordination and Approval: A critical step is the coordination and subsequent approval of the project documentation by the Transport Technical Supervision (TDT – Transportowy Dozór Techniczny). This involves ensuring the design meets TDT regulations regarding electrical and mechanical safety, load factors, anti-collision systems, and alternative energy integration.

Electrical calculations of the crane

The purpose of the calculations is to dimension the electrical installation elements of the crane.

Transformer Power Calculations

- The primary goal of these calculations is to determine the optimal power rating for the new main power transformer.
- This involves summing up the electrical loads of the main hoist, trolley, crane travel motors, and other auxiliary systems, considering a worst-case operational scenario (main hoist + trolley + other devices).

Auxiliary Power (Backup Generator) Calculations

- These calculations focus on determining the necessary power for the new diesel generator.
- The purpose of the backup generator is to ensure essential crane functionality (such as moving an empty spreader to a safe position, and powering control, heating, cooling, and lighting systems) during main power outages or when moving the crane between container stacks.

Mechanical Load Calculations for the Platform and Container (Structural Analysis)

A set of calculations needs to be performed to assess the structural integrity of the redesigned platform and container where the new electrical components (cable reel, transformer, generator, control cabinets) will be mounted. These calculations ensure the modified structure can safely support the new loads and withstand operational forces. Calculations must be performed for the installed parts, it means:

- cable drum
- generator module
- control cabinet
- transformer module

Checking the applied load force

The calculations include:

- calculation of the dynamic horizontal force

$$F_h = m \cdot a_h$$

m – weight

a_h - horizontal acceleration of 0.3 m/s²

Since this force acts on the entire structure, we take half of this value for each of the two beams

$$F_{h,beam} = F_h/2$$

Updated bending moment value:

$$M = \frac{F_{h,beam} \cdot L}{4}$$

M_r - Cable drum weight

$$\sigma = \frac{M_r}{W_X}$$

W_X – Strength indicator

Shear force:

$$\tau = \frac{F_{h,beam}}{A}$$

A - Cross-sectional area

Reduced stress according to von Mises

$$\sigma_{V\,M} = \sqrt{\sigma^2 + \tau^2}$$

This value should be compared with the maximum strength of the material.

FEM 100 class, 2 million cycles - 100 MPa limit

Note: these are examples of calculations, specific values may vary depending on the shape of the structure.

Fatigue Verification:

Detailed fatigue analysis conducted in accordance with standards like FEM 1.001 and PN-EN 1993-1-9. This included calculating stresses in bolts (M20, class 8.8) due to dynamic acceleration of various components (cable reel, transformer, genset, control cabinet) and confirming that these stresses are below fatigue limits, particularly for pre-stressed, non-slip connections. The analysis also should consider wind forces on the cable reel.

Bolt calculations for main components

The purpose is to verify the load-bearing capacity of the bolts.

- ✓ The design load-bearing capacities of the bolts must be verified in accordance with EC3
- ✓ Checking the interaction of shear and tensile forces according to EN 1993-8-1.
- ✓ Interaction check of bolts
- ✓ Fatigue verification within EN 1993-1-9

Bolts - applicable standards

- ✓ EN 13001-3-1- (General strength criteria for cranes)
- ✓ Refers to PN-EN 1993-1-9 for fatigue design of steel.
- ✓ Requires fatigue verification of connections subjected to cyclic loading, especially when slip prevention is not ensured.
- ✓ ISO 8686-1:2012- Specifies load spectral groups for cranes (L1-L4) and stress range factors.
- ✓ For bolted connections, the ISO standard refers to fatigue categories specified in the EN standards.

- ✓ FEM 1.001- (Principles for the design of lifting equipment)
- ✓ Recommended fatigue category 125 MPa

S–N curve for fatigue category 125 MPa (standard for non-slip bolted connections)
Applies to:

- ✓ M20 bolts, class 8.8
- ✓ Prestressed bolts, no slip expected
- ✓ S355 steel
- ✓ Welded elements (if connected with bolts), normal quality

The calculations should assume a scenario in which the load is not distributed evenly (e.g. due to assembly imperfections or local deformations), which is typical practice in the verification of bolted connections in crane and overhead crane structures.

When calculating bolted connections for a cable reel, assume a wind speed of 30 m/s.

Buckling Check

This analysis ensures the stability of structural elements (e.g., vertical supports, stiffened panels, L/C-profiles) against buckling. The results confirmed the design is safe against local buckling.

The different heights that affect the effective width due to possible interaction with bending must be taken into account.

To reflect engineering conservatism in real conditions, a reduction factor based on the aspect ratio is usually used. Correction for actual aspect ratio

Modal Analysis

This analysis determines the natural vibration frequencies of the container and generator frame to confirm they are above the critical 20 Hz threshold (as per EN 13001-3-1, §5.7.5.2) to avoid resonance during operation.

Calculations using simulation methods

To verify the results, it is recommended to perform additional computer calculations. Figure 32 shows an example illustration of calculations performed using the Finite Element Method.

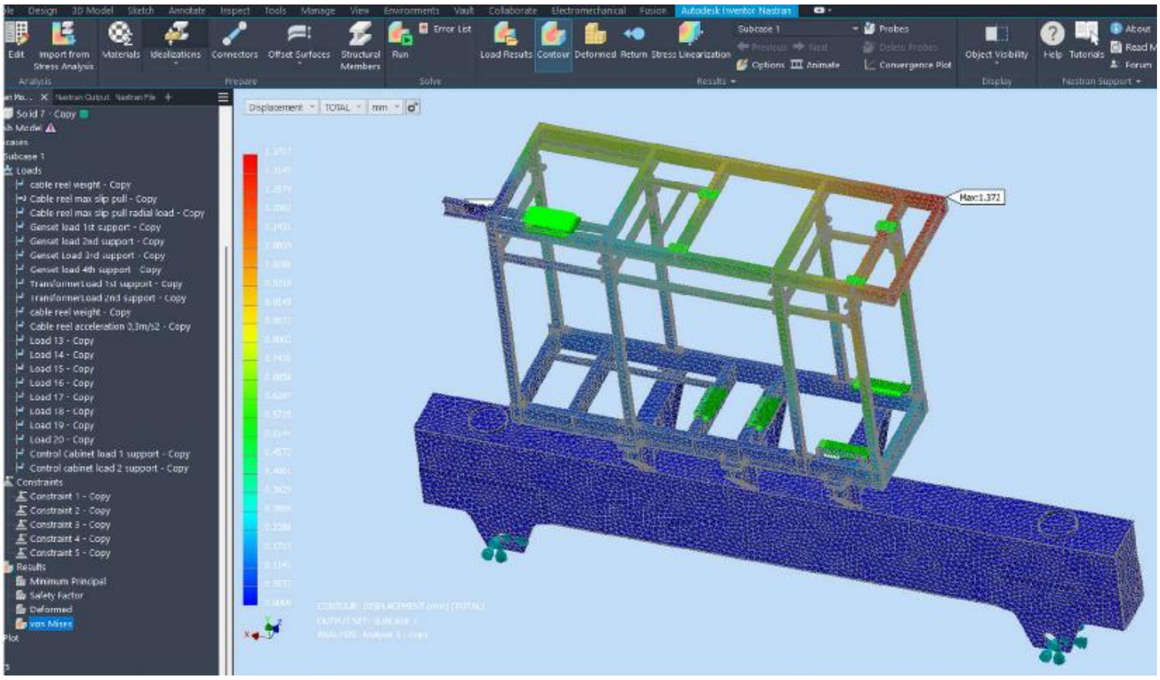


Fig. 32. An example of mechanical calculation by Finite Element Method (Source: ALATAS)

Electrical calculation process

Calculation of maximum load power – MV transformer power selection

To determine the maximum load power of single crane, it is necessary to sum up the power consumption of all crane drive systems, in particular:

- Main Hoist + Gantry inverter
- Trolley travel
- Gantry travel
- Hoist

The power of the supply MV transformer *S* can be determined as:

$$S = \frac{P_{overall}}{k} \text{ [kVA]}$$

Where

$P_{overall}$ - maximum load power [kW]

k - power factor (typical 0,6)

Based on the power thus determined, a transformer with the closest standard power should be selected.

Switchgear selection

For the electrification of Rubber-Tyred Gantry (RTG) cranes, which are typically large industrial systems that require robust and reliable electrical distribution, the switchgear must be selected to provide both operational efficiency and safety. Supply transformer will typically serve as the primary power source for the RTG cranes, and the choice of switchgear will depend on the system's voltage levels (400V-IMCC and 440V-ZPMC) and the specific electrical needs of the cranes.

Key Factors for Selecting Switchgear for RTG Electrification:

- Voltage Rating: RTG cranes typically operate at low voltages like 400V or 440V.
- Current Handling: The switchgear must handle the current drawn by the RTG cranes. The full-load current for a 500 kVA transformer can be calculated as follows:
  - For a 400V system

$$I_{full\ load} = \frac{S * 1000}{\sqrt{3} \times 400}\ [A]$$

  - For a 440V system

$$I_{full\ load} = \frac{S * 1000}{\sqrt{3} \times 440}\ [A]$$

- Short-Circuit Protection: The switchgear should have a high short-circuit rating to protect against fault conditions during crane operations, which may include high inrush currents during motor starts.
- Durability and Reliability: RTG cranes operate in harsh environments, so the switchgear must be durable and reliable to ensure continuous operation.

Based on this data, you should select the appropriate switchboard.

Calculation of Short – Circuit protection

Short-circuit current calculation is essential for the safe design and operation of 15 kV medium-voltage (MV) switchgear. It ensures the correct sizing of electrical equipment and the coordination of protection systems.

Basic Steps of simplified Short-Circuit Current Calculation

Step 1: Gather System Data

Collect electrical parameters, such as:

- nominal system voltage (e.g., 15 kV)
- Short-circuit power at the fault location (provided by utility or estimated)
- Impedances of transformers, cables, lines, and generators

Step 2: Calculate the Equivalent system Impedance

The system is reduced to an equivalent impedance

$$Z_{system} = \frac{U_n^2}{S_k}$$

Where:

- U_n: nominal voltage [V]
- S_k: short-circuit system power [VA]

Step 3. Determine Cable or Line Impedance to the Fault Location:

Use manufacturer data or typical impedance values per km.

Step 4. Calculate Total Impedance at Fault Location:

$Z_{total} = Z_{system} + Z_{cable}$

$$Z_{total} = Z_{system} + Z_{cable}$$

Step 5. Calculate Three-phase Short-circuit Current:

$$I_k = \frac{U_n}{\sqrt{3} \times Z_{total}}$$

tool for MV/LV short-circuit calculations

Practical Tips

- Always verify short-circuit power values with the grid operator or utility.
- Transformer impedance values (e.g., 6% impedance for a 15 kV/0.4 kV unit) must be taken from datasheets or standards.

- For more detailed studies, use sequence networks (positive, negative, and zero sequence) especially for asymmetrical faults.
- Consider minimum and maximum short-circuit currents for proper relay coordination.

Examples of electrical documentation

Figure 33 shows a general diagram of the basic components that must be installed during the conversion. Figure 34. shows a detailed single-line diagram of the power supply components that must be installed as part of the conversion. Figure 35 shows a simplified diagram of the additional control system that will be installed to operate the new devices.

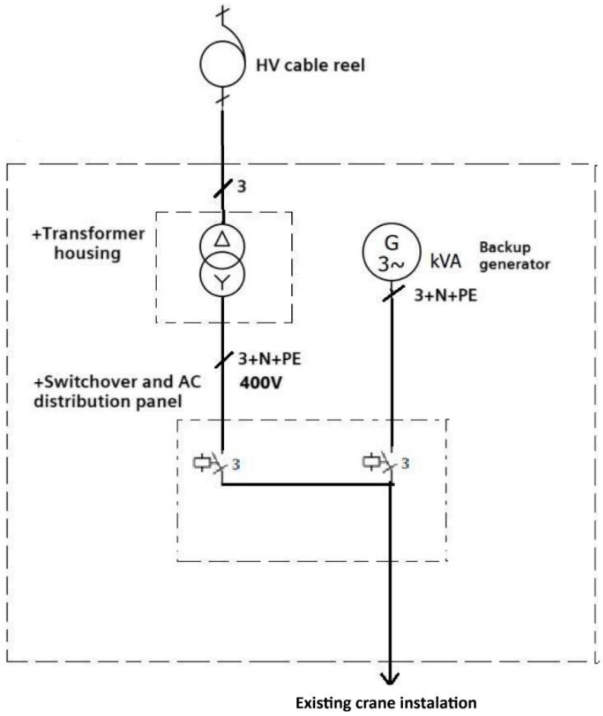


Fig. 33. Schematic diagram of the electrical power supply module required for installation in place of the existing combustion generator (Source: ALATAS)

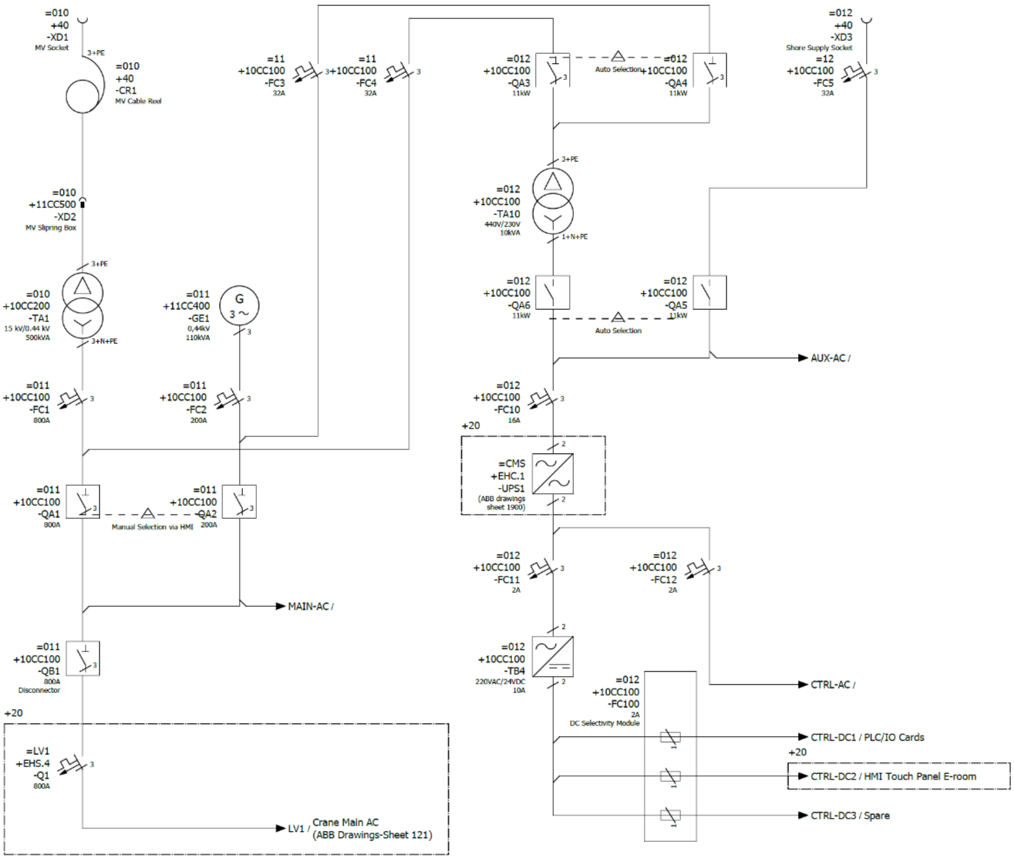


Fig. 34. Single-line diagram of the section of the electrical installation subject to conversion. (Source: ALATAS)

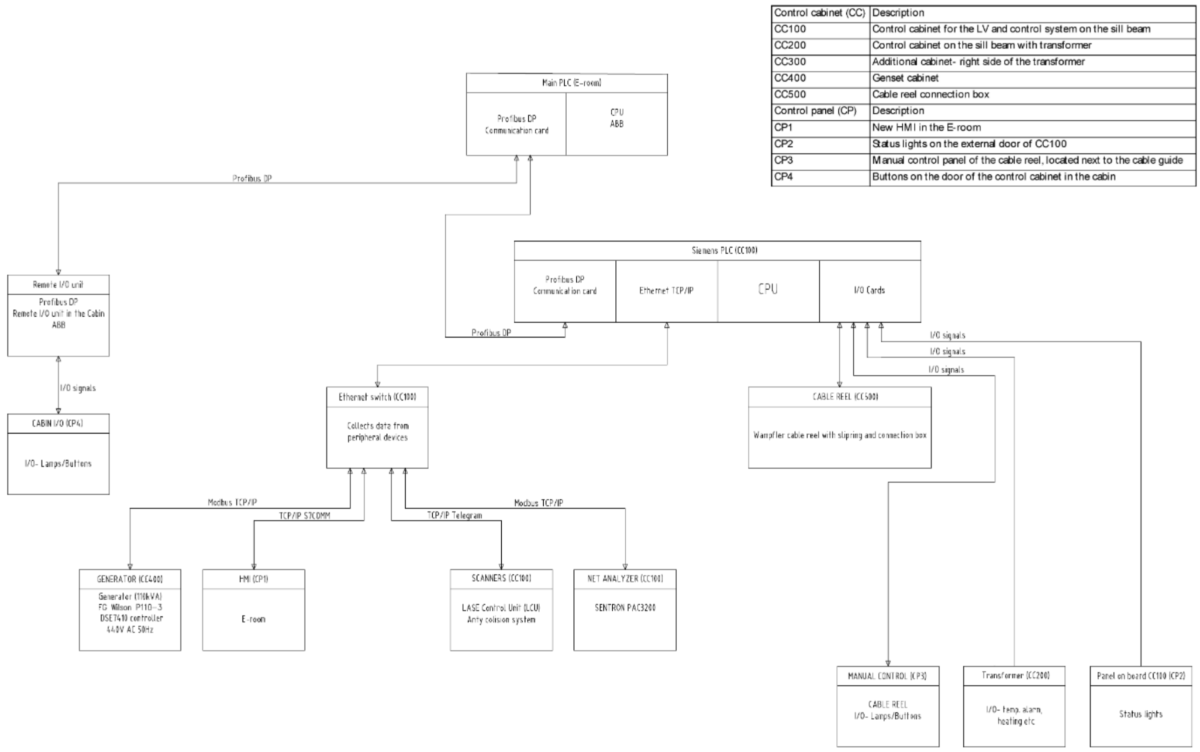
The power supply is supplied by 15 kV CR1 to the MV TA1 transformer. The main protection of the QA1 crane is located on the low voltage side behind the transformer. Due to the considerable length of the cable connecting the main MV transformer and the container with the drive system, it was decided to use two overcurrent protections (circuit breakers) - QA1 and QB1 - at the beginning and end of the cable. The GE1 diesel generator is used for power supply during autonomous driving, which is protected by the QA2 circuit breaker. The QA1 and QA2 circuit breakers have an interlock that prevents simultaneous switching on of both power sources. The crane drive system is powered from the QB1 switch.

Additional devices (auxiliaries) are powered by QA3 and QA4 switches and TA10 transformer. The TA10 transformer reduces the voltage of 440 V to 230 V, which is used to power additional devices. In addition, it is possible to provide additional emergency power supply from the 400 V AC connection using the

FC5 connector. To ensure the reliability of the power supply, the UPS1 UPS system was used. Some devices are powered by direct voltage. The TB4 rectifier is used to generate it.

Adaptation of control system

Existing control systems will be modified to accommodate the new power source. Software logic related to powering the crane with a diesel generator will be removed. A new communication block will be added to the crane PLC. A new PLC and HMI will be installed to manage the power control functions. The new PLC will communicate with the existing crane PLC to ensure seamless integration. Safety logic and diagnostics will be updated to meet standards.



Control cabinet (CC)	Description
CC100	Control cabinet for the LV and control system on the sill beam
CC200	Control cabinet on the sill beam with transformer
CC300	Additional cabinet- right side of the transformer
CC400	Genset cabinet
CC500	Cable reel connection box
Control panel (CP)	Description
CP1	New HMI in the E-room
CP2	Status lights on the external door of CC100
CP3	Manual control panel of the cable reel, located next to the cable guide
CP4	Buttons on the door of the control cabinet in the cabin

Fig. 35. Diagram of the necessary adaptation of the crane control system. (Source: ALATAS)

The new control system for the devices added during the RTG crane conversion must be integrated with the existing, older crane control system as follows (Fig. 35) :

1. Main Communication Channel: PROFIBUS The local PLC (Programmable Logic Controller) located in the new CC100 control cabinet will communicate with the main crane control system's existing PLC via the PROFIBUS fieldbus. This deterministic, high-speed protocol ensures reliable transmission of

control commands and information exchange between the two PLCs, providing seamless integration of the new power system with the existing PLC.

2. Distributed Control Architecture: The system utilizes a distributed control architecture, where a new Siemens PLC is added specifically for the new electrification components, minimizing interference with the existing ABB-based crane automation system.

3. Data Acquisition and Subsystem Monitoring: The new PLC in CC100 will aggregate and process operational data from all new systems and auxiliary subsystems.

4. Communication Layers and Peripherals:

- Local I/O: Digital and analog signals from field devices are received by I/O expansion modules directly connected to the new PLC, handling status monitoring and control of connected subsystems like circuit breakers, switches, and sensors.
- Peripheral Communication: Communication with intelligent subsystems (network analyzer, LASE anti-collision system, HMI, generator controller) uses standard fieldbus interfaces such as Modbus TCP, S7COMM TCP/IP, and Telegram TCP/IP, allowing real-time data exchange and control logic execution.

5. Re-use of Existing Infrastructure:

- Operator Cabin Signals: Signals for the operator cabin, such as power status indication, fault indicators, and reset buttons, will be implemented using available, pre-existing unused inputs/outputs in the current installation. This minimizes physical modifications and leverages existing wiring infrastructure for reliable transmission of control and status data to the PLC.
- Low Voltage (440V) Connection: Existing low-voltage cables and protections in the main switchgear remain unchanged. The new low-voltage switchgear (CC100 panel) is strategically located to align with existing power cable termination points, facilitating seamless integration with the new power distribution system.
- Medium Voltage (15kV) Connection: The 15kV medium voltage (MV) cable will be routed to the system via the CC500 slip ring enclosure. From there, the MV cable will be routed without intermediate connection points through dedicated cable trays to the CC200 container housing the transformer. Inside the container, the MV cable will terminate directly at the transformer's primary terminals, eliminating auxiliary connectors and improving system reliability. Standard mechanical fastening systems will secure the cable during crane movements.

- Communication and Control Cabling: All newly installed communication and control cables will be routed in existing cable trays and channels wherever technically feasible to maximize integration with the original crane infrastructure. Where existing routes are insufficient, new dedicated cable routes will be built with emphasis on safety, accessibility, and ergonomics, ensuring clear layout and protection from mechanical damage or external exposure. Power and control cables will be separated to avoid electromagnetic interference where possible. All new cables will be clearly numbered and permanently marked at both ends for efficient maintenance and to reduce human error.

6. Safety Integration:

- Emergency Stop (E-STOP) System: New E-STOP buttons will be installed at critical points (upper platform near generator and CC500 cabinet, CC100 container door, manual cable reel control panel, local generator E-STOP). These new E-STOPs, except for the local generator button, will be connected in series with the existing E-STOP line and integrated with the current safety relay system of the crane.

- Interlocks: PLC and electrical interlocks prevent simultaneous activation of both power sources (15kV grid and generator), ensuring safe switching. Before activating a power source, the PLC verifies no active alarms, closed cabinet doors, and available voltage before the main 440V contactor.

- UPS System: The UPS (Uninterruptible Power Supply) ensures continuous power to 24V DC control logic circuits (PLC, communication modules, safety interlocks, diagnostic interfaces) even before main power activation, crucial for system readiness and safe startup. The UPS can be powered and charged from both the 15kV grid (via transformers) and the generator, with automatic power source selection for battery charging even when the control system is off.

- MV Plug Presence Sensor: A dummy socket with a plug presence sensor on the crane ensures that the MV cable is safely coiled and disconnected from the grid when the crane moves on generator power, preventing damage.

This comprehensive integration ensures that the modernized electrical system enhances safety, reliability, and environmental performance while maintaining compatibility with the existing ZPMC RTG crane infrastructure.

Technical standards

The documentation for the RTG crane electrification project specifies adherence to numerous standards and norms across various engineering disciplines to ensure the safety, reliability, and functionality of the modernized system. These standards cover electrical installations, mechanical and structural design:

- 15011:2021-05- Gantry cranes and overhead cranes
- PN-EN IEC 60204- Safety of machinery
- PN-HD IEC 60364- Low voltage electrical installations.
- EN 954-1:1996– Safety of machinery
- EN 292- Safety of machinery
- EN 60439- European standard for low-voltage switchgear
- EN 50081-1,2 – Electromagnetic compatibility (EMC)
- IEC 60529 – IP protection degrees of enclosures of electrical and electronic devices
- PN-EN 287-1:2004- Welding standard
- EN 13135- design of mechanical elements of cranes (lifting equipment)

The approval of a modified crane for operation also requires carrying out tests according to the standards presented in Table 6.

Table 6. List of standards for crane testing

1	Acceptance tests of LV installations ≤ 1 kV	PN-HD 60364-6:2016-07	Complete acceptance test scenario: PE/PEN continuity, insulation resistance, short-circuit loop impedance, RCD tests, phase sequence.
2	Equipment for testing protection against electric shock	EN IEC 61557	Metrological requirements for insulation resistance meters (-2), short-circuit loop meters (-3), RCD meters (-6), and phase sequence indicators (-7).
3	Testing of differential circuit breakers/relays	EN 61008-1:2012 EN 61009-1:2012	Definitions of tripping currents and times, compliance criteria to record results.

4	MV dielectric tests (AC 1 min/ VLF 0.1 Hz)	EN 60060-1:2011 EN IEC 60060- 2:2025	AC and VLF test methods and assessment of measurement uncertainty for devices > 1 kV.
5	Insulation resistance / VLF of MV cables 6-30 kV	EN 60502-2:2014	Acceptance tests of extruded insulated cables (resistance, VLF, PD).
6	Power transformers 15 / 0.44 kV	EN IEC 60076-1:2021-01 EN 60076-11:2020- 12	Measurement of the ratio, winding resistance, voltage tests of HV windings.
7	Groundings >1 kV	EN 50522:2022	Design and resistance measurements of grounding systems of stations and transformers.
8	Power installations > 1 kV AC	EN IEC 61936- 1:2022-04	General design and acceptance requirements for high-voltage stations and switchboards.

Execution

The conversion should take about one month. The exact time of the works depends on:

- ✓ availability of components and the construction team,
- ✓ weather conditions (if the works are carried out outside),
- ✓ any structural modifications,
- ✓ accessibility of the crane (whether it can be taken out of service for the entire time).

Broadly speaking, the following stages of reconstruction can be distinguished:

Pre-Conversion Activities

- ✓ Site preparation and crane positioning in the designated maintenance area.
- ✓ Lockout/tagout of all power sources.
- ✓ Verification of documentation and safety compliance.

Dismantling of Existing Diesel System, removal of:

- ✓ Diesel engine and alternator
- ✓ Exhaust and ventilation systems
- ✓ Fuel tank, piping, and sensors
- ✓ Generator housing and control panel

Installation of Electric Power System

- ✓ Cable Reel System
- ✓ Medium Voltage Transformer (15 kV / 440 V, 500 kVA)
- ✓ Control system

Auxiliary Generator Installation

- ✓ Mounting of 110 kVA diesel genset on upper platform
- ✓ Fuel line routing and installation of refueling interface
- ✓ Integration with PLC for automatic/manual operation

Electrical Integration

- ✓ Connection of transformer output to crane's main power bus
- ✓ Routing and labeling of all new cables
- ✓ Installation of UPS support for PLC and safety systems

Safety and Monitoring Systems, installation of:

- ✓ Emergency stop buttons (E-STOP)
- ✓ LASE 3D anti-collision system
- ✓ Safety interlocks for power switching
- ✓ Cable reel monitoring sensors

Commencement

After completing the works related to the reconstruction of the crane, technical acceptance by the appropriate authorities supervising the operation of lifting equipment is necessary. In the case of Poland, this is TDT (Transport Technical Supervision). Transportowy Dozór Techniczny (TDT) operates as a specialized authority responsible for technical supervision in the field of transport. TDT plays a crucial role in the conversion of Rubber-Tired Gantry (RTG) cranes from diesel to electric power, ensuring technical supervision, approval, inspection, and compliance with regulations.

TDT is responsible for overseeing the technical aspects of the conversion process. This includes ensuring that the conversion meets all safety and technical standards. TDT's technical supervision ensures that the converted RTG cranes operate efficiently and safely, minimizing the risk of accidents and malfunctions.

Approval

Before the conversion process can begin, TDT must approve the plans and technical documentation for the conversion. This involves a thorough review of the proposed modifications to ensure they comply with all relevant regulations and standards. TDT's approval is a critical step in the conversion process, as it ensures that the modifications will not compromise the safety or performance of the RTG cranes.

Inspection

TDT conducts inspections at various stages of the conversion process to ensure that the work is being carried out in accordance with the approved plans and specifications. These inspections help to identify any potential issues early on, allowing them to be addressed before they become major problems. TDT's inspections are essential for maintaining the quality and safety of the converted RTG cranes.

Compliance

TDT ensures that the converted RTG cranes comply with all relevant regulations and standards. This includes both national and international regulations governing the operation of RTG cranes. TDT's compliance checks help to ensure that the converted cranes can operate legally and safely in their intended environment. Compliance with these regulations is essential for minimizing the environmental impact of the converted RTG cranes and ensuring their long-term viability.

Conclusion

The role of Transportowy Dozór Techniczny (TDT) in the conversion of RTG cranes from diesel to electric power is critical for ensuring the safety, efficiency, and compliance of the converted cranes. Through its technical supervision, approval, inspection, and compliance responsibilities, TDT helps to ensure that the conversion process is carried out to the highest standards, minimizing risks and maximizing benefits.

The stages of technical acceptance can be summarized as follows:

A. Preparation of documentation

- The necessary technical documentation should be prepared, which will include in particular::
    - Technical drawings
    - Electrical schematics
    - Risk assessment
    - Compliance with applicable standards (e.g., PN-EN, ISO)

B. Approval by TDT

- The documentation must be submitted to TDT for approval. TDT reviews the documentation and may request additional information or modifications.

C. Inspection and Certification

- Pre-Commissioning Inspection: TDT inspects the crane post-installation but before operation.
- Functional Testing: TDT may witness operational tests to verify safety and compliance.
- Issuance of Updated Certificate: If compliant, TDT issues a revised certificate of conformity for the modified crane.

8. Benefits from conversion

The existing, widely used internal combustion engine requires daily checks of oil and coolant levels, fuel level and alarm indicators. Weekly inspections, air filter and exhaust system integrity checks and monthly battery charge and fluid tightness checks. At specified intervals (e.g. every 250 or 500 operating hours) the engine requires oil change, filter replacement (fuel, oil and air), inspection or replacement of V-belts and inspection of fasteners and vibration isolators. All these activities make this system a very demanding service. The existing diesel system provides the crane with full mobility and operational independence but introduces several challenges. It is a solution that requires constant maintenance and service with many potential mechanical failures. The system contributes to environmental pollution through CO_2 and particulate emissions. It also requires logistical effort related to refuelling, generating significant acoustic noise and heat during operation. Many systems such as lubrication, cooling, and fuel supply pose the risk of system leaks, which can have an impact on the environment. Furthermore, the significant mass of the generator system – including the engine, generator, fuel load – significantly increases the dead load on the crane structure, affecting its dynamic performance and increasing wear on mechanical components. In summary, while the diesel generator system remains functional and integral to the ongoing operation of the crane, it is becoming obsolete in the context of modern, low-emission, electrically powered terminal equipment. Replacing the power system will eliminate these disadvantages.

9. SWOT Analysis to identify Potential Problems and Expected Challenges

SWOT analysis of RTG electrification [Gutowski, 2025]

The strategic analysis method used to determine the significance of electrification of seven RTG gantry cranes at Gdynia Container Terminal is SWOT analysis. It allowed for distinguishing strengths and weaknesses resulting from the modernization of these machines and also presented potential opportunities and threats for the Gdynia container terminal in the future. In order to achieve better clarity of the issues discussed, a division was also made into external and internal factors, as well as those that are positive or negative for the discussed terminal.

Strengths of RTG electrification in GCT [Gutowski, 2025]

- ✓ Reduction of carbon dioxide emissions into the environment (estimated reduction of such emissions by as much as 45%)
- ✓ Reducing your carbon footprint
- ✓ Improving air quality both in the port areas and in the entire region
- ✓ Noise reduction in the GCT terminal area resulting from the operation of electric engines, rather than diesel engines, which are characterized by greater operational smoothness
- ✓ Reducing vibrations thanks to the use of electric drives
- ✓ Lower energy cots
- ✓ A more economically advantageous solution for modernizing existing cranes compared to purchasing new machines
- ✓ Compliance of the electrification process with all decarbonization regulations
- ✓ Reducing the weight of individual components
- ✓ and mechanisms of the new drive system, thus reducing the weight of the entire cranes
- ✓ Lower operating and maintenance costs of cranes due to fewer structural elements
- ✓ The use of an auxiliary generator allows for continuous operation even in the event of a power cut or power outage
- ✓ Increased operational efficiency
- ✓ Improving the safety mechanisms in cranes and overall
- ✓ Improving operational safety

The electrification of RTG gantry cranes at the Gdynia container terminal brings a number of significant operational, environmental, and economic benefits. The use of electric drives allows for a significant reduction in carbon dioxide emissions and other harmful substances, which directly contributes to a significant reduction in the carbon footprint of the entire terminal. In addition, the reduction of noise and vibrations from operating engines contributes to the improvement of the quality of the working environment for staff, as well as to the improvement of living conditions both in the entire city and in the Gdynia port area. The modernization of existing machines turns out to be a more economically advantageous choice in relation to the purchase of new units. The use of a new, electric drive system in the form of a cable drum reduces the weight of the cranes and reduces the number of structural elements, which translates into easier technical maintenance. It is worth emphasizing that the entire process is compliant with decarbonization regulations, which strengthens GCT's position as a modern and sustainable terminal.

Weaknesses of RTG electrification in GCT [Gutowski, 2025]

- ✓ The retrofit process was carried out over a period of time
- ✓ Possible interruptions and downtime in terminal operations resulting from the commencement of modernization works
- ✓ The need to use more technically advanced electrical power systems that require specialist service knowledge
- ✓ The need to train staff in new technologies
- ✓ Dependence on a local electricity supplier
- ✓ The need for significant modernization of infrastructure within the storage yard
- ✓ Large initial financial outlay
- ✓ The need for intervention by the crane operator when reconnecting cables when changing the container block

Despite the numerous benefits of implementing the described solution, it also has several limitations. One of the main shortcomings is the extended nature of the modernization works, which may cause disruptions in the current transshipment activities of the terminal. Modernization of the storage yard infrastructure is also required, which includes the transformation of power supply systems using sockets placed between the container blocks. The initial high financial outlays borne by the terminal also include the preparation of the retrofit project itself and the purchase of all the required components for changing the power supply of the cranes. In the case of rather rare but still possible failures and faults, the use of technologically advanced power supply systems increases the level of complexity of the operation and servicing of machines, requiring specialist technical knowledge and appropriate training of personnel who are ready for the occurrence of unforeseen situations.

Opportunities resulting from the electrification of RTG for GCT [Gutowski, 2025]

- ✓ Possibility of installing a battery-powered power supply in the future thanks to early electrification
- ✓ Increasing the competitiveness of the GCT container terminal in the long term
- ✓ Carrying out the electrification process of cranes as an incentive to electrify all transshipment devices in the terminal equipment
- ✓ Striving through electrification to fit into the idea of "green ports"
- ✓ Electrification of RTG cranes as part of a broader terminal operator strategy including the installation of an OPS system at GCT
- ✓ Improving the image of the GCT terminal as an enterprise in the eyes of contractors and investors through the implementation of green technologies
- ✓ Improving the image and reputation of the entire network of port terminals of the international operator Hutchison
- ✓ Possibility to implement energy recovery systems

Thanks to the modernization of the cranes, the GCT container terminal has a clear potential for further development towards emission-free technologies. The electrification of the machines at this transshipment terminal may become an incentive for a broader modernization, including the electrification and automation of the entire transshipment equipment of the terminal. This approach aims to maintain a constant and established position in the global concept of "green ports", which promotes pro-ecological activities aimed at reducing greenhouse gas emissions in maritime transport. From an image perspective, the implementation of green technologies contributes significantly to the perception of the GCT terminal as a modern and responsible enterprise among entities cooperating with this transshipment point. Through the ongoing process of striving for decarbonization at this location, Gdynia Container Terminal has the opportunity to compete with other container transshipment terminals belonging to the network of the entire Hutchison operator.

Risks of electrification of *the electrification of RTG for GCT [Gutowski, 2025]*

- ✓ Modernization of existing old cranes may contribute to unplanned failures resulting from the previous long operating time of two types of cranes
- ✓ Rapid advances in marine propulsion technologies (e.g. hydrogen) may make electrification solutions uncompetitive after a certain period of time
- ✓ Ongoing competitive pressure from container terminals in the Baltic countries
- ✓ Threats to terminal employees resulting from electrical system failures, i.e. electric shock, fire
- ✓ The need to obtain a number of consents may contribute to extending the duration of the entire process
- ✓ Fluctuations in electricity prices
- ✓ Cybersecurity threats involved with new automated systems found in modernized cranes

The right thing to do when analysing the feasibility of electrification is to take into account the potential threats and risks that this process may entail. An unforeseen consequence is the uncertainty regarding the service life of the modernised cranes, whose operating time at the time of electrification will be around twenty years. Another significant risk factor is the dynamic development of technology in the maritime transport industry and, among others, the progress in the use of alternative fuels in transshipment equipment, such as hydrogen. This may result in the applied electrification solutions being uncompetitive or technologically outdated in the near future. Due to the multitude of container terminals in the Baltic Sea basin, the GCT container terminal is subject to constant pressure from neighbouring entities to implement low- and zero-emission innovations, and any delays or problems resulting from the modernisation may weaken its competitive position. An important aspect is the procedural and formal barriers related to the need to obtain many permits and documents allowing for modernization in accordance with the regulations and laws in force in the country, which can significantly extend the project implementation time if the bodies responsible for the documentation find various inconsistencies. It is also necessary to take into account the instability of electricity prices, a phenomenon that currently occurs on a very large scale. Its constant fluctuations can affect the economic profitability of operating modernized cranes in the future and also eliminate potential savings resulting from electrification.

Conversion of power supply for RTG cranes is a relatively simple procedure. However, since it concerns a device that is already in use, at least several years old, and not a new one, it carries several risks:

1. Power Supply Compatibility
    - Mismatch between crane electrical requirements and grid voltage/frequency.
    - Inadequate power capacity at the terminal.
2. Control System Integration
    - Software incompatibility between new electrical systems and existing crane PLCs.
    - Delays in signal communication or safety interlocks.
3. Grounding and Safety
    - Improper grounding leads to electrical hazards.
    - Incomplete emergencies stop or isolation systems.
4. Environmental and Operational Constraints
    - Weatherproofing issues for outdoor electrical components.
    - Limited crane mobility due to cable length or routing.
5. Regulatory Delays
    - Incomplete documentation for TDT approval.
    - Missed inspection deadlines or non-compliance with Polish standards.

Table. 7. Summary of major risks

Electrical Risks	High Voltage (electric shock, arc flash), Improper Grounding (equipment damage), Cable Reel Failure (power loss)
Mechanical Risks	Heavy Lifting (crane failure), RTG Structural Overload (stress damage), Moving Parts (operator injury)
Operational & Safety Risks	Power Supply Failure (downtime), Anti-Collision System Failure (collision), Fire Hazard

During the preparation of the RTG crane conversion concept for the container terminal in Gdynia, the following specific threats were defined:

- Condition of Existing Cranes: The initial assessment revealed outstanding faults, faulty equipment, and obsolete components in the drive and PLC systems on the existing cranes. While addressing these is outside the project's scope, they could negatively affect operational continuity and pose challenges during the upgrade process if not rectified by the client beforehand. The condition of the remaining cranes needs a comprehensive assessment.

- Structural Integrity Verification: Although preliminary structural analysis for cable reel mounting and the converted generator platform shows feasibility, detailed design with FEA simulations is required. For IMCC cranes, specific actions like 3D scanning, material testing, and NDT inspections of welds are recommended due to less documentation and fatigue life calculations nearing the 2 million cycle threshold.
- PLC Communication: Clarifying the communication interface with the cable reel supplier is necessary, particularly regarding whether the cable reel has its own PLC (preferable option) and the communication protocol (Profibus or TCP/IP). The IMCC crane's lack of an Ethernet interface requires either adding a card or ensuring the LASE control unit supports Profibus communication.
- HMI/CMS Modifications: The lack of source code for the existing HMI software for both crane types is a significant challenge, strongly suggesting the option of installing a new HMI touch panel for the new equipment.
- Existing Panel Space and Wiring: The existing E-room panels are described as very populated, presenting space constraints for mounting new circuit breakers or potentially increasing the capacity of the auxiliary transformer for the ZPMC.

In summary, the electrification project involves a well-defined process of assessment, design, approval, installation, and integration. It requires replacing the old diesel system with complex new electrical and mechanical components. While deemed feasible overall, potential issues related to the condition of the existing cranes, structural verification needs, electrical and software integration complexities, panel space limitations, and ensuring robust safety system implementation must be carefully managed during the detailed design and execution phases.

This preliminary design demonstrates the feasibility of upgrading the RTGs to fully electrified units in compliance with standards and regulations, contributing to improved efficiency, sustainability, and safety. The detailed design phase, following GCT's approval, will address these points further.

10. Lessons learnt from the RTGs' electrification process in Gdynia Container Terminal

Ports are pivotal global transportation hubs, facilitating the movement of over 90% of containerized freight and serving as critical links in international supply chains. Within these vital operations, rubber-tyred gantry (RTG) cranes are indispensable for managing container handling and yard operations. Historically, diesel-powered RTGs (dRTGs) have dominated the sector, but their operation is associated with significant environmental and economic drawbacks. The combustion of diesel fuel leads to substantial air pollution and a large volume of carbon emissions, with RTGs and yard tractors identified as major contributors to CO2 emissions in container terminals. High operating costs, pollution, and noise generated by dRTGs are compelling drivers for change. Consequently, electrifying port equipment, particularly gantry cranes, has emerged as a key strategy to mitigate these environmental and economic issues. This involves either replacing dRTGs with electric RTGs (eRTGs) or hybrid diesel-electric RTGs (hRTGs) or retrofitting existing diesel units. ERTGs draw power from the electricity grid via cables, while hRTGs combine diesel and electric power, often utilizing energy storage systems like super-capacitors, lithium batteries, or flywheels.

The benefits of electrifying and improving energy efficiency in gantry cranes are substantial and critically important for maritime transport sustainability. Environmentally, switching to electric power can lead to a significant reduction in pollutant emissions, estimated at 60% to 80%, alongside a 10% to 30% reduction in energy consumption, and up to a 40% decrease in noise and exhaust emissions.

Despite the clear advantages, electrifying gantry cranes, especially through retrofitting, presents significant challenges. A primary hurdle is the substantial initial investment required for new electric cranes, retrofitting, and necessary terminal infrastructure modifications. Maintaining operational efficiency and container handling capabilities during the transition is also critical, requiring careful financial planning and detailed deployment strategies. The conversion necessitates a thorough energy analysis and the design of appropriate electrical infrastructure. This includes verifying existing power connection capacities and potentially upgrading them, as well as designing the internal power distribution network. Specific challenges for GCT include power supply compatibility (mismatch between crane requirements and grid voltage), control system integration (software incompatibility, communication delays), grounding and safety concerns, environmental and operational constraints (weatherproofing, limited mobility), and regulatory delays (documentation, compliance). More specifically, issues like the condition of existing cranes requiring prior rectification, structural integrity verification with advanced simulations for older models, clarifying PLC communication interfaces, the need for new HMI touch panels due to a lack of source code for existing HMI software, and space constraints within existing E-room panels present significant hurdles that must be managed during detailed design and execution

In summary, the electrification of gantry cranes represents a significant, multi-faceted challenge for maritime transport, driven by the urgent need to mitigate the substantial environmental impact and high operating costs of conventional diesel equipment in ports. While electrification offers considerable benefits in terms of emissions reduction, economic savings, and enhanced operational efficiency, its successful implementation demands significant capital investment, careful integrated planning of assets and operations, effective management of energy recovery, consideration of the power grid's carbon footprint, and adaptation to evolving policy drivers. Addressing these challenges through technological advancements, sophisticated planning models, and supportive policies is paramount for enabling ports to achieve their sustainability goals and contribute to a greener maritime transport ecosystem. The ongoing projects and detailed energy analyses demonstrate the feasibility and necessity of this transition for a more sustainable and economically viable future for container terminal operations

Demonstrated electrification process of port operations: An installed onshore power supply system fully in operation in the Port of Skagen

This report documents the implementation of an Onshore Power Supply (OPS) system at the Port of Skagen, Denmark's largest fishing port.

Developed as part of the Interreg Baltic Sea Region project Blue Supply Chains, the OPS system enables large pelagic vessels to switch from diesel generators to shore power during unloading operations, reducing CO_2 and emissions in the port.

The initiative was driven by Skagen's goal of becoming carbon-neutral by 2030. Rather than waiting for vessels to be OPS-ready, the port chose to invest first and encouraged retrofitting among shipowners. The installation was completed in spring 2025 and tested successfully with the vessel Lingbank as the first user, with more vessels expected to follow. Initial user experience, documented during this test run, confirmed the technical feasibility and ease of the connection process.

Technically, the system includes an OPS unit with a capacity of up to 1,673 kVA, semi-automated cable management, and compatibility with multiple voltage and frequency levels. Electricity is supplied to the users at a fixed price and is certified as CO_2-free, aligning with both regulatory expectations and the environmental goals of the maritime sector.

The report serves as a step-by-step implementation manual. It documents the decision-making process, the tendering procedure, the system design and configuration, and the role of stakeholder involvement. To guide both the investment and its evaluation, the Port of Skagen introduced a set of Key Performance Indicators (KPIs) on system use, economic feasibility, and environmental impact. These provide a transparent framework for measuring success and serve as blueprints for other ports considering similar investments.

The project illustrates how ports can lead the green transition by combining strategic vision, stakeholder collaboration, and funding from multiple EU and national sources. The report also provides guidance for other port authorities by distilling Skagen's experience into a practical roadmap and transferability manual. This roadmap outlines the economic and technical feasibility of OPS, highlights lessons learned and supports the roll-out of OPS solutions in other fishing and landing ports across the Baltic and North Sea regions.

The Port of Skagen's experience offers valuable insights and practical tools for other ports aiming to reduce emissions, modernize their operations, and accelerate the maritime green transition.

1. Introduction

Onshore power supply in operation in the Port of Skagen

This report constitutes Deliverable 2 of the Blue Supply Chains project and builds directly upon the foundation established in Deliverable 1, which focused on the strategic role of port authorities in planning and preparing for green port operations. While the first report cantered on the pre-implementation phase—mapping stakeholder needs, identifying technical solutions, and assessing transferability—this second deliverable shifts attention to actual implementation and early-stage testing of green technologies, with a particular emphasis on Onshore Power Supply (OPS).

Deliverable 2 presents the first concrete results from the pilot activities, including technical deployment, stakeholder engagement, and preliminary experiences from the Port of Skagen. The OPS system developed at the port has just been commissioned and represents a significant step toward achieving climate-neutral operations. The facility is now operational and capable of supporting power-intensive activities such as the pumping and cooling of pelagic fish, but the system is still in its early phase. Further testing and fine-tuning will be carried out in the coming months, especially as additional vessels are prepared to receive shore power. At present, only one vessel has completed the necessary retrofitting to utilize the new OPS infrastructure.

This report also explores the broader implications of this implementation—technically, environmentally, and economically—and serves as a documentation of progress within the Interreg Baltic Sea Region project Blue Supply Chains, which aims to support ports in decarbonizing operations through electrification, alternative fuels, and green logistics.

Produced in close collaboration between the Port of Skagen, GEMBA Seafood Consulting and the University of Gdansk, the report reflects data and developments up to June 2025 and is intended to guide both local implementation and broader knowledge transfer to other ports across the region.

Methodology for Calculations and Assessments

The economic and technical feasibility of the OPS installation in Skagen was assessed through a structured process documented in *Deliverable 1.1 – Role of Port Authorities in Green Port Operation Activities* (sections 4.1.3 and 4.1.4).

The assessment combined technical capacity analysis, environmental impact calculations, and operational cost comparisons, using the following approach:

1. **Data Collection** – Energy demand profiles for pelagic vessels during unloading were collected through interviews with vessel operators and port stakeholders. Technical specifications were provided by equipment suppliers. Local electricity pricing and diesel fuel costs came from the Port of Skagen's contracts and market averages.

2. **Technical Feasibility** – OPS capacity was matched against measured and estimated peak loads, ensuring compliance with IEC/IEEE 80005-3 and compatibility with multiple voltages/frequencies.

3. **Environmental Impact** – CO_2 reductions were calculated using standard emission factors (2.68 kg CO_2/litre diesel). Additional pollutants (NO_x, SO_x, PM) were assessed qualitatively.
4. **Economic Assessment** – OPS electricity costs (fixed price) were compared to diesel-generated electricity costs, including fuel and basic maintenance. This ensured the OPS solution met operational needs, delivered measurable environmental benefits, and remained economically viable. Full details are available in *Deliverable 1.1*.

2. Implementation of the OPS system in the Port of Skagen

This chapter presents the Skagen OPS implementation in narrative form, describing the process from decision-making through design, procurement, installation, testing, and early operations.

Pre-Implementation Status of the Port of Skagen

Prior to the implementation of the new OPS system, the Port of Skagen had already positioned itself as a key actor in Denmark's transition toward greener port operations. As Denmark's largest fishing port, it serves a wide range of vessels—particularly large pelagic trawlers engaged in high-volume landings of herring, mackerel, sprat, blue whiting and sandeel. These operations are energy-intensive, requiring continuous onboard cooling and pumping systems.

The port was already equipped with a basic OPS infrastructure, primarily serving vessels in idle mode ("hotel load"), covering lighting, communications, and minimal onboard functions. However, the growing demand for decarbonization—combined with upcoming regulatory pressure and increased sustainability expectations from seafood buyers—created a clear motivation to expand shore power capabilities to include active operations such as unloading catch.

In particular, the large-scale pelagic fishery segment demonstrated a significant energy footprint during landing operations, typically powered by diesel generators. This created not only high CO_2 emissions but also considerable NO_x and particulate pollution, affecting both local air quality and the port's climate impact. The demand for a more sustainable solution grew steadily in dialogue with key stakeholders, including shipowners, processing companies, and local authorities.

Drivers and Decision-Making Process

The decision to invest in an OPS system at the Port of Skagen was shaped by a combination of environmental, operational, and strategic drivers. At the heart of the initiative lies the port's strong commitment to becoming CO_2-neutral by 2030, with electrification of quay operations identified early on as a central pillar of that strategy. To support this ambition, several analyses were carried out—including cost-benefit assessments, technical feasibility studies, and CO_2 reduction estimates. These were consolidated in a dedicated cost-benefit OPS tool, which played a role in the decision-making process.

The cost–benefit tool combines technical, environmental, and economic assumptions into a single framework, allowing the port to model the impact of OPS under different usage and price scenarios. On the technical side, it accounts for the expected number of port calls, hours at quay, and electricity demand per vessel. On the environmental side, it translates fuel consumption into CO_2, NO_x, and SO_x emissions, and compares OPS-related emissions with equivalent reference points (e.g. lorry transport or Danish grid averages). On the economic side, it integrates electricity purchase and sales prices, maintenance, construction costs, depreciation, and interest rates to calculate breakeven points, annual results, and sensitivity to market conditions. Together, these elements provide a transparent way of balancing 'use,' 'pricing,' and 'greening' as the key KPIs of the OPS system. The tool has been central in demonstrating both the economic and technical feasibility of the OPS solution and can serve as a blueprint for other ports considering similar investments.

As such, the tool was developed for the Green Supply Chain but proved valuable and is hence included in this description and for other ports to learn from in order to implement an OPS solution. Below is an abstract from the tool that illustrates the layout, and calculations. The numbers in the illustration are arbitrary and not directly related to the Skagen Case.

Cost benefit OPS

Port calls and power demand							
Calls pr. year	10	of hours	24	of kW demand	80	kWh	19.200
Calls pr. year	7	of hours	10	of kW demand	200	kWh	14.000
Calls pr. year	2	of hours	2	of kW demand	300	kWh	1.200
Calls pr. year	12	of hours	20	of kW demand	2000	kWh	480.000
Total calls	31	Avg. hrs at quay	14	Avg. kW demand	645	Total kWh	514.400

Total calls	31	Pr. year
Hours at quay	434	Pr. year
Demanded electricity	514.400	kWh pr. year
Shore power loss	76.440	kWh pr. year
Electricity bought	590.840	kWh pr. year

Environmental assumptions		
Generator consumption, fuel	200	g/kWh
Fuel consumption in port	102.880	kg fuel
CO2 in fuel	3,2	kg CO2/kg fuel
CO2 emission	329.216	kg CO2/year
NOx in fuel	68	g/kg fuel
NOx emission	6.996	kg NOx/year
SOx in fuel	5	g/kg fuel
SOx emission	514	kg SOx/year

Reference points		
CO2 emission from lorry 34 - 40t	675	g/km
Corresponding emission lorry 34 - 40t	487.727	km
Avg. DK power production CO2 emission	142	g CO2/kWh
If power produced by avg. power grid	83.899	kg CO2 pr. year

Economic assumptions			
Electricity price purchase	0,75	DKK/kWh	
Electricity mark-up	47%	DKK/kWh	
Elctricity price sold	1,60	DKK/kWh	
CMS rent	0,13	DKK/kWh	
Maintenance costs	37.000	DKK/år	
Construction costs	4.133.600	DKK	
Interest rate	4,00	%	
Depreciation time	20	year	
Linear to zero	206.680	DKK/year	
Financial result			
Costs:	Purchase of electricity	kr.	-443.130
	Maintanence	kr.	-37.000
	Total	**kr.**	**-480.130**
Revenue:	CMS fee	kr.	66.872
	Electricity sales	kr.	823.040
	Total	**kr.**	**889.912**
Gross income		**kr.**	**409.782**
Depreciation		kr.	-206.680
Operating income (EBIT)		**kr.**	**203.102**
Interest rates year 1		kr.	-165.344
Annual result		**kr.**	**37.758**

Many of the quantitative insights are reflected in Blue Supply Chains Deliverable 1 (Role of port authorities in green port operation activities), which provides detailed modelling of energy consumption, emissions reductions, and the potential impact of OPS deployment. However, what ultimately tipped the balance was not just the numbers, but the strategic vision of the Port of Skagen to be a front runner in the green transition within the maritime sector.

Throughout the process, there were ongoing discussions around the classic “hen and egg” dilemma: should the port wait for vessels to be OPS-ready, or should it take the lead by investing in infrastructure first? The port chose the latter—to show the way. With this investment, the Port of Skagen sends a strong signal to industry and its stakeholders: shore power for unloading the catch is no longer a distant ambition, but a real, operational alternative that supports a greener, more modern port.

This approach has helped break the deadlock and encouraged shipowners to begin vessel retrofitting, some of them supported by co-funding from the European Maritime, Fisheries and Aquaculture Fund (EHFAF). By delivering a working OPS solution that is designed specifically around the needs of the pelagic fleet, the port created the conditions for uptake, rather than waiting for it to emerge on its own.

Methodology for introducing OPS in the Port of Skagen for pelagic trawlers

Phase 1: Identify the high emissions generated by pelagic trawlers during unloading in Skagen.

Phase 2: Recognize OPS technology as a potential solution.

Phase 3: Develop a cost-benefit tool to calculate different cost scenarios and technology models. Several analyses were carried out to confirm the economic sustainability of the investment. The tool also defined a set of KPIs to measure success.

Phase 4: The Board of the Port of Skagen, as part of its CO_2-neutrality commitment, approved the OPS investment.

Phase 5: System configuration, tendering, and design were managed as an integrated process. As a frontrunner, the port accepted a “trial and error” approach, especially in relation to technological decisions.

Phase 6: Implementation and construction of the OPS system in the port.

Phase 7: Testing and onboarding of users. Each vessel’s first connection must be supervised by port staff and electricians until the crew can manage the plug-in independently.

Phase 8: Normal system operation.

These phases form the basis for the step-by-step roadmap for transferability to other ports, presented in Chapter 9.

While each phase was important, special attention should be given to Phase 5: System configuration. The Skagen experience demonstrates that OPS is not a "one-size-fits-all" solution. Careful configuration, based on the actual needs of expected users, is essential to ensure future adoption.

Guiding criteria for the system configuration included:

- **Technical feasibility:** The solution supports multiple voltage and frequency levels (400V/440V/690V, 50Hz/60Hz), making it compatible with a range of vessel types and future expansions.
- **Environmental impact:** The OPS unit enables a direct reduction in CO_2 and other pollutants from auxiliary engine use during high-energy unloading operations.
- **Economic rationale:** While not necessarily the cheapest energy option in the short term, OPS contributes to long-term efficiency, reduced maintenance, and regulatory readiness.
- **Stakeholder integration:** The final design was refined through close dialogue with local shipowners and fish processing companies, ensuring it fit within real-world quay-side workflows and space limitations.

The tendering procedure was done with three selected bidders and potential suppliers of the OPS system. The selected bidders were found via search on internet and knowledge about the sector. The bidders should have previous experience in establishing OPS systems and technical ability to adjust proposals and equipment in accordance with the system configuration and design. Based on this the tendering procedure was done.

An outcome of the tendering procedure and the project is to understand the importance of design and equipment ability to serve the customers in an easy and flexible way. The easy handling of cables and power systems is decisive for the success of a plug-in strategy in daily life at operational vessel and port level. An important technical decision was the inclusion of a semi-automated cable management system (CMS) with extended reach, allowing fast, safe, and flexible connection to vessels of varying lengths and mooring positions.

To guide both the investment decision and later evaluation of the OPS system, the Port of Skagen worked from a set of Key Performance Indicators (KPIs). These KPIs ensured that the project could be assessed not only on technical implementation, but also on its economic viability and environmental impact.

The important KPIs in the project were 'use', pricing', and 'greening'.

Use: A central KPI was the expected uptake of the system, measured in the number of calls and hours connected. This reflects the technical utility of the OPS system and shows the level of stakeholder engagement. In practice, “use” is both a technical and social indicator: if vessels connect frequently, it means the system is trusted, practical, and integrated into daily port operations. At Skagen, stakeholder involvement was therefore closely linked to this KPI, and it was secured through meetings with representatives from the pelagic fleet.

Pricing: Another key KPI was the economic viability of investment. A breakeven calculation of six years was made, which—compared to a depreciation horizon of 20 years—demonstrated financial feasibility. The calculations also showed that interest rates are a dominant factor in shaping economic outcomes. As rates have shifted recently, the expected breakeven point may in fact be lowered, improving the long-term business case. This KPI highlights the importance of clear economic assumptions and sensitivity testing in investment decisions.

Greening: The third KPI focused on quantifiable reductions in CO_2, NO_x, and SO_x emissions. These indicators provide a concrete demonstration of the environmental benefits achieved and help document the green outcome of the project. For Skagen, this KPI was not only important locally but also for aligning with national and EU climate goals, as well as for communicating results transparently to stakeholders and funding bodies.

Having defined KPIs is important in Skagen’s decision-making process because they provided a common reference point for balancing environmental ambitions with operational and financial realities. For other ports, the value of such KPIs lies in their transferability: they represent measurable, comparable benchmarks that can guide decision-making in diverse contexts. Whether a port is at an early planning stage or already implementing OPS, KPIs such as use, pricing, and greening allow ports to evaluate performance, communicate progress, and justify investments to both local stakeholders and external funders.

In sum, the Port of Skagen made a strategic choice to lead—not wait—and in doing so has laid the foundation for both immediate emission reductions and a broader transformation across the fishing and port logistics sectors.

3. Status of Implementation

The OPS at the Port of Skagen was commissioned on May 14, 2025 (first test, full load three cables, 920 Amps 631 kw), and the system is now technically operational and available for use by vessels equipped to receive shore power. Final technical tests have been completed, and ongoing fine-tuning and performance monitoring will continue throughout the second half of 2025, ensuring stability, safety, and efficiency under real operating conditions. Following are the milestones at the Port of Skagen during the implementation as a guideline for other Port Authorities:

Milestone I:

The system has already been tested successfully with one retrofitted vessel, HM379 Lingbank, which completed mooring and established a shore power connection at the quay adjacent to FF Skagen's fishmeal facility. This marked a significant milestone, demonstrating that the system can deliver high-capacity power to vessels during energy-intensive landing operations.

Milestone II:

Next milestone is two vessels expected to be OPS ready by the end of 2025. HG265 Asbjørn is expected to be retrofitted and ready for OPS connection in the coming months (late summer early fall 2025). Both vessels are part of the national project "Strøm til den pelagiske flåde" (EN:"Power to the Pelagic Fleet"), which aims to eliminate emissions from pelagic fishing vessels while in port. This project is co-financed through Denmark's share of the European Maritime, Fisheries and Aquaculture Fund (EHFAF), which supports both vessel-side retrofitting and port-side OPS infrastructure.

Milestone III:

Milestone number three concerns the involvement of the entire Danish pelagic fleet, comprising around 10 vessels, which is expected to take place during 2026–2027. The transition will happen gradually, as vessels begin equipping themselves with OPS-compatible technology. Two vessels from the Danish fleet are expected to be ready by late 2025 or early 2026, while additional vessels will be retrofitted in the following years. Looking further ahead, it is anticipated that newly built vessels will be designed to be OPS-ready from the outset, ensuring that the entire fleet can make full use of the system over time.

Milestone IV:

Milestone number four is the involvement of the Norwegian, Swedish, Faroese, and UK pelagic vessels landing in the Port of Skagen, expected to take place between 2026 and 2030. Within this group, some vessels already have a significant share of their landings in Skagen and are therefore the most likely to be among the first to invest in OPS compatibility. Others, with only occasional landings in Skagen each year, may be slower to adopt OPS technology unless the business case strengthens. If additional OPS facilities are introduced in ports in e.g. Norway or elsewhere, this could create further incentives for retrofitting.

Financing of the OPS Project

The full OPS setup at Skagen has been realized through a combination of four funding sources:

- OPS Infrastructure (power unit and transformer connection)
    - Funded by the Interreg Baltic Sea Region project Blue Supply Chains
    - Covers the actual OPS system and its integration into the port's grid.

- Cable Management System (CMS)
    - Funded by the Interreg North Sea Region project Green Supply Chains
    - Covers the semi-automated system used to deploy 45 meters of cable for flexible vessel connection.

- Vessel Access to Shore Power (electrical interface and onboard adaptation)
    - Funded by the Danish/EU program Grøn Omstilling i Fiskeriet (Green Transition in Fisheries) under EHFAF
    - Enables onboard compatibility with OPS standards, allowing vessels to receive and manage shore power.

- Co-funding by the Port of Skagen
    - As none of the above sources covered 100% of costs, the Port of Skagen has provided the remaining financing to make the system fully operational.

This layered funding structure reflects both the complexity and ambition of the project: integrating multiple technologies, infrastructure elements, and stakeholders across port and vessel environments. It also underscores the Port of Skagen's strategic decision to lead the transition, not just through planning, but by committing significant local investment to make OPS a reality.

4. Visual Documentation of the OPS Implementation

The following section provides a visual overview of the OPS at the Port of Skagen, illustrating the process from infrastructure development to operational use. The series of images begins with an overview of the OPS installation site and follows the project through key stages: the construction of the transformer and cabling system, the deployment of the CMS, the handling and connection of the cables aboard Lingbank, and finally, the onboard control and power intake procedures. Together, these images offer a practical illustration of how shore power is now being realized in everyday port operations.

The port of Skagen with an indication of where the pelagic center in Skagen is located and where the OPS for unloading of pelagic fish is placed.

A sea-side perspective of the two quays used for landing pelagic fish—FF Skagen and Scandic Pelagic—both now connected to the OPS system.

Construction work - cable trenching and routing.

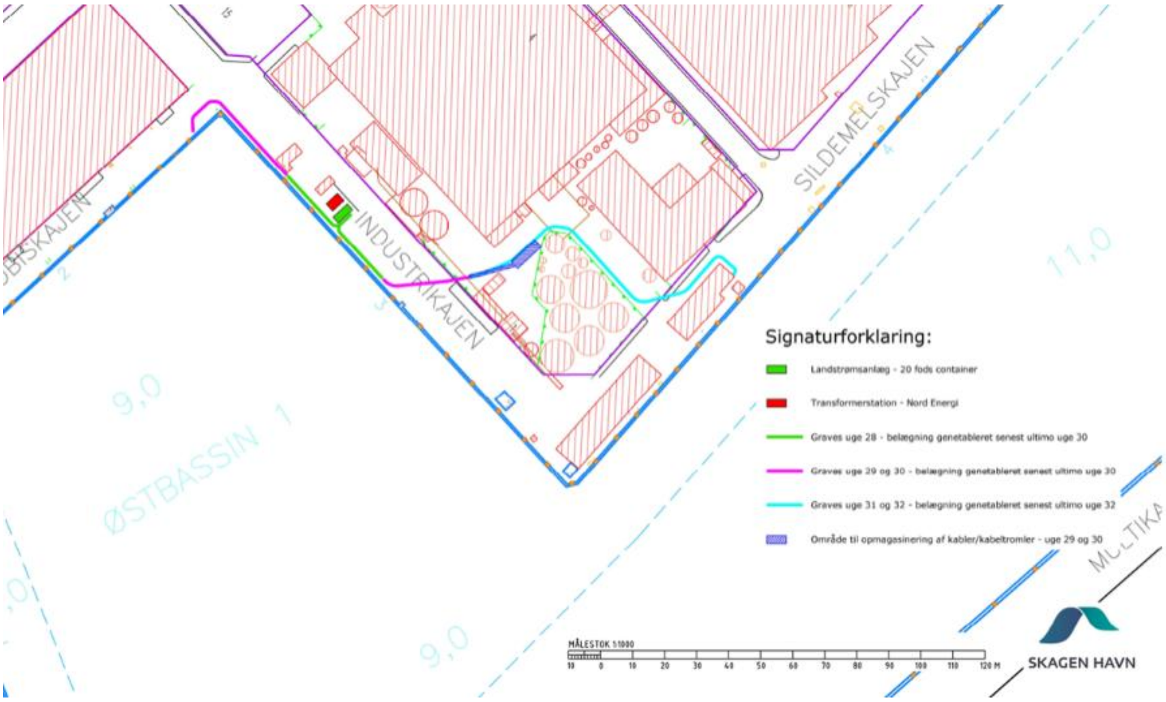


Diagram indicating the location of the OPS unit (green square), the transformer (red square) and underground cable routing to the two pelagic quays where the CMS units can be deployed.

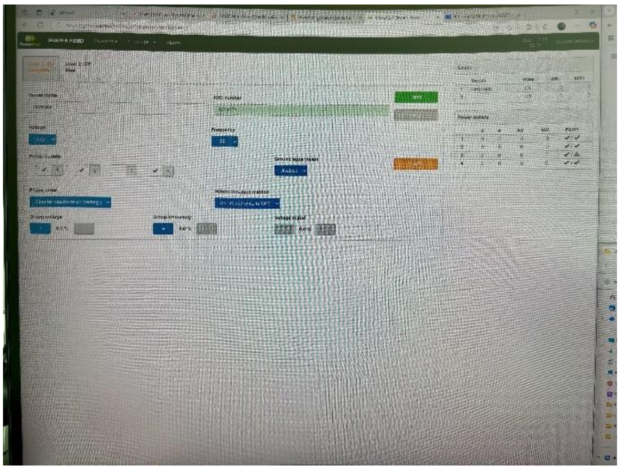
The operation of the OPS system is structured for reliability, safety, and simplicity, with clearly defined roles between port personnel and vessel crew.

The process is as follows:

1. **Advance notification**
   The vessel informs the Port of Skagen in advance if it intends to use OPS during its stay. This enables the port to allocate staff and equipment.
2. **CMS transport and setup**
   Port staff transport the CMS to the designated quay. The CMS is moved into position using standard port equipment.
3. **Cable handling and shore connection**
   Port staff:
   - Lay out the cables from the CMS.
   - Connect the CMS to the shore-side power outlet.
   - Prepare the system for vessel-side connection.
4. **Vessel connection**
   The vessel's technical staff connects the cables to the vessel's OPS inlet.
   - Depending on the vessel's energy needs, 1 to 4 cables are connected.
   - The technical staff selects the required voltage and frequency via an online interface integrated into the OPS control system.
5. **Power supply during unloading**
   Once connected, the vessel draws power continuously throughout the entire unloading operation, which typically lasts between 10 and 30 hours.
   - The cables remain connected for the entire operation, supplying energy for all onboard systems, and the vessels' main engines and generators can be turned off.
   - When the unloading process is complete, the vessel's technical staff disconnects the cables and places them back on the quayside.
6. **Post-use handling and billing**
   - Port staff retrieve the cables to the CMS and disconnect from the shore side connection point.
   - Energy consumption is measured automatically, and billing is handled via a digital metering and invoicing system (e.g., Tallykey).

To ensure safe and smooth operation, the vessel's technical personnel receive a brief hands-on introduction during their first use. The setup is designed to be intuitive and robust—as foolproof as possible—with integrated safety mechanisms and minimal room for error.

	The shore power station at the Port of Skagen The OPS unit and transformer station, which together convert and distribute certified green electricity to the connected vessels.
	The OPS unit from the other side is adjacent to the transformer station that can be seen to the left in the picture.
	Cable Management System (CMS) at the quay The CMS is in place at the landing quay. This semi-automated unit holds 45 meters of cable and connects the vessel to shore power, regardless of vessel size or exact mooring position. Each Zinus unit has two cables and the port of Skagen has two units and hence a total of four cables.

	Connection in Progress – Lingbank Port staff and crew manage the connection of shore power to the vessel HM379 Lingbank during one of the first full-scale OPS operations. The hatch where the cables are coming in has been established for an easy loading of the cables. The connection box at Lingbank is dimensioned to three cables, which reflects its maximum power demand. The largest vessels in the Danish fleet can handle four cables.
	Power Monitoring Onboard The vessel's engineer has access to a digital monitoring system that allows real-time tracking and configuration of the power load. The system can be viewed both onboard and via a secure online connection from shore. Through this interface, the voltage and frequency are selected. For cybersecurity reasons, the system can only be accessed through this dedicated online platform.

	Power Monitoring Onboard The vessel's chief engineer in his control room where power usage is monitored and configuration of power intake via the online interface, is made.
	The two vessels Asbjørn and Lingbank that are the first two Danish vessels that are ready for OPS – here during fishing operations in the sea.

5. Tendering procedure and implementation timeline

The tendering and procurement of the OPS system at the Port of Skagen followed an invitation-based tender procedure. Four suppliers were invited to submit bids. The port received two valid offers:

- One offer was financially significantly outside scope and deemed unfit.
- The other offer was subject to further negotiations, as the initial price proposal exceeded the allocated budget.

The following timeline governed the bidding process:

Procurement Step	**Date**
Deadline for submitting questions	14 December 2023, 12:00 (CET)
Deadline for submitting bids	22 December 2023, 12:00 (CET)
Intended contract award date	12 January 2024
Actual contract award date	**May 2024**

The delay in awarding the contract was due to a combination of further technical clarifications, internal negotiations, and the need to present a revised offer to the port's board of directors. The original bid was over budget and required cost adjustments before final approval could be granted.

Implementation Timeline and Key Milestones

The implementation was delayed due to unforeseen issues:

Milestone	**Planned Date**	**Actual Date**	**Remarks**
Contract award	January 2024	May 2024	Delayed due to price negotiations and board-level approval
Start of construction (breaking ground)	Week 28, 2024	Week 28, 2024	Work started as planned
Cable trenching and routing	Aug–Sep 2024	Delayed 3–4 months	Encountered soil contamination near FF Skagen; halted progress
Revised cable routing	–	Sep–Dec 2024	Cable plan had to be redesigned due to practical site constraints
Completion of system installation	February 2025	May 2025	~3-month delay
First vessel OPS test (Lingbank)	Q1 2025 (planned)	Mid-May 2025	Successful test and connection
Commissioning and fine-tuning	Spring 2025	Ongoing	System operational; additional tests expected during H2 2025

As of mid-2025 works in the area near FF Skagen remain incomplete, with an open trench and unresolved cleanup of contaminated soil, but it doesn’t affect the functionality of the OPS.

6. Technical solution of the OPS system in port of Skagen

The OPS system implemented at the Port of Skagen represents a tailored, high-capacity infrastructure designed specifically to support energy-intensive unloading operations from large pelagic vessels. Initially a mobile containerized systems was envisioned, but the final solution is a fixed installation with two power outlets where the CMS can be connected, strategically designed to serve the two pelagic landing points.

System Architecture and Location

At the core of the OPS setup is a dedicated transformer station, newly constructed to support the required power capacity and ensure stable grid integration. Located on port premises, this transformer station feeds into a fixed OPS unit positioned nearby, housing the core power conversion and control systems. From this central OPS unit, two cable lines have been laid to:

- **FF Skagen landing point** – servicing vessels delivering fish for fishmeal processing.
- **Scandic Pelagic landing point** – servicing vessels delivering fish for human consumption processing.

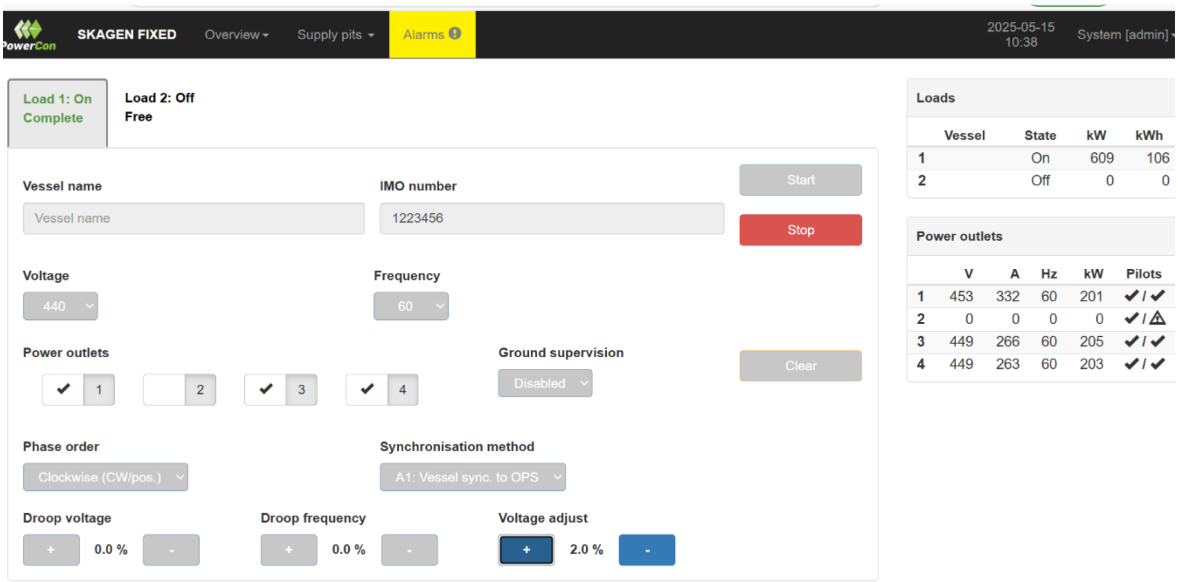
Each of these two landing locations is equipped with a quay-side connection box which is where the CMS is connected at one end and the vessel in the other.

Power and Connectivity Specifications

The OPS system was initially designed with a capacity of 850 kW but was later upgraded to meet higher power demands from the pelagic fleet. It can now deliver up to 1,673 kVA at 690 V / 60 Hz and 1,400 A, equivalent to approximately 1,506 kW of usable power (based on a 0.9 power factor). The system is limited by the transformer's capacity, which allows a maximum of 2,000 A at 400 V / 50 Hz, corresponding to 1,386 kVA or about 1,247 kW.

Feature	**Specification**
Total Power Capacity	Up to **1,673 kVA** (≈ **1,506 kW**) at 690V / **1,386 kVA** (≈ **1,247 kW**) at 400V
Voltage Levels	**400V / 440V / 690V**
Frequency Support	**50Hz and 60Hz**
Shore Connections	Two dedicated connection points, each located at FF Skagen, Scandic Pelagic
Connector Type	**Cavotec/Proconnect-type 350A connectors**, IEC/IEEE 80005-3 compliant
Compliance	Fulfills IEC/IEEE 80005-3 and Danish electrical safety standards

Environmental Range	Operational from **-15°C to +40°C**



The image shows the web-based control panel used by the Port of Skagen and vessel crew to operate the OPS system. This interface is provided by PowerCon and forms part of the fixed OPS unit installed at the port.

- The system allows the vessel's technical staff to select voltage (e.g., 440V) and frequency (e.g., 60Hz), and to activate one or more power outlets (up to four simultaneously).
- Each outlet is monitored in real time, showing voltage (V), current (A), frequency (Hz), and power output (kW). In this example, outlets 1, 3, and 4 are active, supplying a total of 609 kW, while outlet 2 is inactive.
- The panel also includes synchronization settings, ground supervision options, and manual adjustments such as voltage offset.
- The interface supports automatic energy logging and billing, with real-time kWh metering and integration into the port's invoicing system.

This setup ensures safe and flexible OPS use, empowering vessel crews to manage their connection efficiently while maintaining full control over power parameters.

Cable Management System (CMS)

A key innovation in the Skagen OPS setup is the Cable Management System (CMS), which allows for safe, flexible connection to vessels of varying sizes and quay-side positions. The CMS is a semi-automated unit equipped with 45 meters of heavy-duty cable, ensuring reach to the vessel's OPS inlet, even when vessel positions shift and length of the vessels vary.

The CMS connects directly to the outlet panel at each landing point and can be operated by trained port staff or vessel crew. It includes:

- Hydraulic or electric assist (semi-automated) for cable deployment and retraction
- Integrated locking and safety interlocks
- Weather-protected housing and controls

Control, Monitoring, and Safety

The OPS system is integrated with the port's existing control infrastructure and includes:

- Remote access and monitoring via a web-based interface
- Real-time energy metering and CO_2 reduction data logging
- Integration with billing system for consumption-based invoicing
- Safety features such as:
    - **Overload protection**
    - **Ground fault detection**
    - **Emergency stop buttons** at multiple points
    - Auto shutoff during disconnection or abnormal load variation

Selection Criteria and Standards Compliance

The technical configuration was selected based on:

- **Vessel demand**: Large pelagic trawlers typically use high volumes of electricity (for pumping, refrigeration, hydraulics) during unloading. The 1,673 kVA capacity meets this peak demand.

- **Compatibility**: Voltage/frequency flexibility and standardized connectors ensure integration with retrofitted vessels.

- **Location-specific needs**: Two main processors (FF Skagen and Scandic Pelagic) require direct shore connection at separate quays, necessitating fixed outlets.

- **Standards**: Full compliance with IEC/IEEE 80005-3 enables safe, internationally accepted operation.

7. OPS operational model in Port of Skagen

The business model for the OPS system at the Port of Skagen is based on transparent, fixed pricing and a commitment to delivering certified green electricity to vessel operators.

The OPS is targeted at large pelagic vessels landing at FF Skagen and Scandic Pelagic, where energy demand during unloading (10–30 hours) is high and continuous.

OPS usage is billed per kilowatt-hour (kWh) with a two-part rate:

- **Electricity**: DKK 1.60 per kWh
- **Cable and CMS charge**: DKK 0.13 per kWh
  → Total: DKK 1.73 per kWh

The Port of Skagen has secured a fixed electricity price, ensuring that rates will not fluctuate regardless of market conditions. Although OPS remains slightly more expensive than diesel today, the predictable pricing offers budgeting certainty and long-term benefits.

The electricity supplied via OPS is certified CO_2-free, backed by guarantees of origin from renewable sources. This enables vessel operators to reduce their environmental footprint and comply with ESG and climate reporting standards.

Roles and Responsibilities

Actor	Role
Port of Skagen	Operator of the OPS system; coordinates use; manages billing and CMS
Nord Energi Net	Grid operator; supplies power to the OPS system
Energy Supplier	Energi Danmark – supplies electricity to the port
Vessel Operators	OPS users; responsible for compatible equipment and coordination
Fish Processors	Indirect stakeholders; benefit from greener logistics

The Port of Skagen acts as the retail distributor of electricity to vessels but is not itself the energy producer. Electricity is sourced via the public grid, and the port handles internal billing and documentation based on measured consumption.

Calculation Summary – Port of Skagen Perspective

The transition to Onshore Power Supply (OPS) for pelagic vessels in Skagen Port has been assessed to understand both the environmental and economic implications for port operations. From the port's perspective, these calculations help illustrate the potential benefits and strategic considerations of OPS deployment.

Key results for the two pilot vessels (HG 265 *Asbjørn* and HM 379 *Lingbank*):

Indicator	Asbjørn	Lingbank	Total
Annual energy demand at quay (kWh)	443,520	192,000	635,520
CO_2 emissions – diesel generators (tons/year)	312.8	135.4	448.2
CO_2 emissions – OPS (tons/year)	42.6	18.4	61.0
Annual CO_2 reduction (tons)	**270.2**	**117.0**	**387.2**
Annual bunker fuel saved (litres)	88,704	38,400	127,104

For the port, these results show that even a limited number of vessels using OPS can deliver substantial emission reductions at berth. The shift also strengthens Skagen's position as a sustainable and regulatory-compliant port, increasing attractiveness to vessel operators and seafood industry partners.

Long-term expansion potential: Scaling OPS usage to 10 similar pelagic vessels could yield approximately 1,848 tons of CO_2 reduction and 840,000 litres of bunker fuel saved annually, assuming comparable operational patterns.

Economic perspective:

- Current OPS price structure: 1.60 DKK/kWh for electricity + 0.13 DKK/kWh for cable/equipment rental.
- At current diesel prices (5 DKK/litre), OPS is more expensive per kWh than onboard generation.
- Future increases in diesel prices, CO_2 taxation, and potential regulatory requirements are likely to improve OPS's economic competitiveness over time.

These calculations are preliminary and will be further developed and standardised during the ongoing EHFAF project.

8. Lessons learned from Port of Skagen and recommendations for future initiatives on OPS solutions

The implementation of OPS in the Port of Skagen has provided several key insights and lessons that can serve as valuable guidance for other ports considering similar investments. As OPS in the setup that is implemented at the Port of Skagen is a relatively new area, the project has highlighted both opportunities and challenges that may shape future deployments.

Understand the purpose – plan accordingly

One of the most important lessons is the need for careful upfront analysis of how the OPS will be used. Dimensioning and system setup must align with actual energy needs—such as whether the OPS is meant only for hotel load or also for energy-intensive operations like pumping and cooling during landings. Inadequate scoping may lead to systems that are either underpowered or unnecessarily expensive.

Accept the learning curve

OPS investments require entering new territory, especially for small- and medium-sized ports. This involves learning about regulatory standards, technical compatibility, grid integration, and stakeholder coordination. Ports should be prepared for extensive feasibility studies, technical clarifications, and procurement challenges.

Be strategic: Infrastructure first, then demand

A key decision at the Port of Skagen was to invest in the infrastructure before all vessels were OPS-ready. This helped break the chicken-and-egg dilemma and showed leadership. As a result, retrofitting among vessels is coming. Ports should consider leading by example to stimulate uptake rather than waiting passively for demand.

Standardization where possible

While full standardization is difficult due to vessel diversity, variations in demand and purpose, certain elements can be further standardized to simplify design, reduce costs, and support transferability. The IEC/IEEE 80005-3 standard proved valuable, and new vessels will likely be built to comply, making future OPS rollouts easier.

Allow for technical flexibility

Systems must be designed with flexible voltage and frequency support (e.g. 400V–690V, 50/60Hz) and the ability to scale. In Skagen, the integration of a semi-automated cable management system (CMS) provided adaptability for various vessel sizes and mooring positions. This kind of flexibility is critical for real-world operations.

Predictable pricing matters

The Port of Skagen opted for a fixed electricity price, giving users long-term predictability. Although current OPS use may be slightly more expensive than diesel, the CO_2-free certified electricity helps users meet ESG and regulatory goals, which adds value beyond fuel cost.

Collaboration is key

Successful implementation requires close collaboration across shipowners, processors, port staff and grid operators. The OPS project in Skagen succeeded due to early workshops, iterative design feedback, and joint problem-solving. Engaging users from the start ensures that the system fits actual workflows.

Plan for future proofing

Investments should be made with future retrofits and scaling in mind. Although only one or two vessels are OPS-ready, the infrastructure supports broader adoption. Similarly, the physical system is designed for weather resistance, remote monitoring, and integration into future billing and reporting systems.

9. Road Map - Implementation Manual for OPS in a Fishing Port

This roadmap details the experience from the Port of Skagen into a practical sequence of actions that other ports can adapt when planning OPS for fishing vessels, each step links to descriptions in this report.

Step 1 – Decision-Making and Strategic Alignment *(see Section 3.2)*

- Identify KPIs: CO_2 reduction targets, operational uptime, cost targets.
- Define needs: vessel types, unloading power demand, voltage/frequency range.
- Engage stakeholders early: vessel operators, processors, grid operator.
- Assess funding options.

Step 2 – Pre-Feasibility and Technical Design *(see Sections 3.2 & 5)*

- Measure/estimate energy demand during unloading.
- Determine OPS capacity (kW, voltage/frequency flexibility, cables).
- Check compliance with IEC/IEEE 80005-3.
- Assess grid connection and transformer needs.

Step 3 – Procurement and Tendering *(see Section 4)*

- Prepare tender documents with technical specs, delivery schedule, warranty/service terms.
- Evaluate bids on compliance and life-cycle cost.
- Include performance guarantees.

Step 4 – Installation and Integration ***(see Sections 5 & Visual Documentation)***

- Install OPS equipment and connect to port grid.
- Lay cabling to quay connection points.
- Integrate remote monitoring and billing.
- Ensure safety compliance.

Step 5 – Vessel Adaptation

- Retrofit vessels with OPS inlets and compatible switchboards.
- Align modifications with port readiness.

Step 6 – Testing and Commissioning ***(see Section 3.3)***

- Conduct no-load and full-load tests.
- Simulate operational use during unloading.
- Adjust for stability, safety, and compatibility.

Step 7 – Operation and Maintenance ***(see Section 6)***

- Implement pricing model (e.g., fixed kWh + cable/CMS fee).
- Monitor performance and carry out preventive maintenance.
- Train staff and vessel crew.

Step 8 – User Experience and Lessons ***(linked to Section 7)***

- **Status in Skagen:**
  OPS commissioned May 2025; tested with *HM379 Lingbank*. Crew feedback: connection process straightforward after short introduction; CMS offers flexibility; no technical faults during first use.

- **Guidance for other ports:**
  Plan early to collect both qualitative and quantitative feedback within 3-6 months of operation.

Step 9 – Transferability and Scaling

- Document specs, installation steps, and lessons learned.
- Identify which elements are adaptable to other ports.
- Share through workshops/networks.

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