Green Cranes

Green Technologies and Eco-Efficient Alternatives for Cranes and Operations at Port Container Terminals

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EXECUTIVE SUMMARY

GREENCRANES (Project code: 2011-EU-92151-S):
a EU co-funded action coordinated by: Fundación Valenciaport

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INTRODUCTION

One of the main strategic guidelines established by the European Commission on energy efficiency focuses is on ensuring an effective transition towards the use of energy sources which have a lower environmental impact in terms of greenhouse gas (GHG) emissions. This evolution should be sustainable in the mid-long term from different points of view, including economic, financial, environmental, and social perspectives. In the last few years, the introduction of renewable energies and alternative fuels by the industry and the transport sector has been greatly encouraged. However, despite important efforts, the total share of these greener alternatives remains modest in terms of the production and consumption energy mix on a European scale.

In January 2013, the European Commission launched the **"Clean Power for Transport: a European Alternative Fuels Strategy"** communication, which reflects the European transport sector's high dependency on oil and its sub-products. High economic costs as well as its environmental impact are seen as significant barriers to compliance with the 20/20/20 objectives established by the Commission.

Maritime transport and port and logistic sectors are obviously affected by this situation, given their strategic importance as key drivers of international trade and transporters of goods. Yet until recently, energy efficiency had not been considered as an important field for improvement in this sector. Fortunately, this situation has begun to change thanks to the keen awareness of industry and the different innovations developed by research teams as well as by port machinery manufacturers.

Within this context, the project **"Green Technologies and Eco-Efficient Alternatives for Cranes and Operations at Port Container Terminals – GREENCRANES" aims to be an innovative initiative which contributes to enhanced energy efficiency in port container terminals (PCTs).** GREENCRANES was awarded European funding through the Trans-European Transport Network (TEN-T). The project has been carried out from August 2012 until May 2014.

The main mission of the project is to provide tools for port container terminal decision-makers to make equipment and machinery more energy efficient. GREENCRANES aims to carry out different actions:

- To characterize the **energy profiles** of port container terminals, thus quantifying the amount of energy consumed and where.
- To analyze the **feasibility of eco-efficient alternatives** to significantly reduce the environmental impact of these facilities without affecting productivity.
- To carry out pilot tests for the alternatives with the **highest implementation potential and the greatest reduction of GHG emissions.**
- To provide **recommendations and guidelines for the port industry,** port container operators, public authorities, etc. based on the results obtained in the project.

1 MAPPING OF PORT CONTAINER TERMINALS' ENERGY PROFILES

The concept of **"Energy Consumption Profile"** has been introduced in GREENCRANES with the objective of answering two questions which are often unclear within the context of port container terminals. These are: how much energy is consumed at port container terminals and where.

Reality shows that there are important constraints which create difficulties in the knowledge and management of energy variables involved in PCT operational models. Traditionally, energy efficiency has not been a critical factor in the port industry due to the relatively low importance of energy costs as a percentage of the total expenditure of these facilities. However, in recent years, this perception has begun to change for different reasons, such as increases in energy prices, the adoption of strict environmental regulations that limit GHG emission levels, and civilian awareness of sustainability and the environmental impact of industrial activities. At the same time, technology is more than capable of making the transition from a carbon-based economy model (based mainly on fossil fuels) to a low-carbon production model based on renewable energy sources, and cleaner fuels, such as LNG, bio-fuels, and hydrogen.

In order to facilitate this transition in the port industry, several actions are currently under discussion, such as the adoption of LNG to power vessels and port machinery, electrification of traditional fuel-based activities, and on-site energy generation using renewable energies (wind, solar, etc.). GREENCRANES aims to foster this progressive evolution by demonstrating that the implementation of eco-efficient alternatives based on low-carbon emissions is possible from a technical, financial, and environmental point of view.

Aiming to obtain comparable and harmonized results, the study carried out in GREENCRANES took place in the three terminals participating in the project over the same time period, i.e. 2011 and 2012. The analysis focused on the main energy sources used at port container terminals, that is, electricity and fuel involved in container handling operations and services. The scope of the study was defined according to the key activities of port container terminals and their operational model.

This study concluded that **80% of electricity was used by reefer containers connected at the yard (43%) and ship-to-shore cranes (37%)** in charge of loading and unloading containers to and from vessels. **In terms of fuel consumption, the study found that 90% of total fuel was used by Rubber-Tyred Gantry (RTG) cranes (58%) and terminal tractors in charge of horizontal transport (32%).** In absolute figures, in 2012, **the three container terminals under study consumed more than 30 GWh of electricity,** which equals the average annual consumption of 3,000 Spanish homes. Similarly, **the amount of fuel consumed was almost 7 million litres. The associated carbon footprint generated was calculated as 11.7 Kg CO_{2eq} / TEU.**

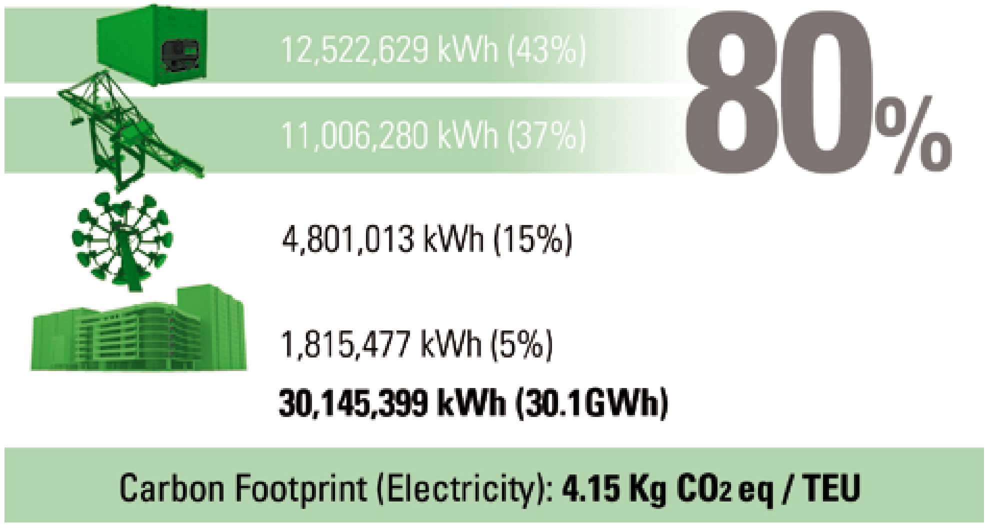


Figure 1. Distribution of Electricity Consumption
Aggregated Figures for Valencia NCTV, Livorno TDT and Koper Container Terminal (2012)

Source: Fundación Valenciaport, 2014

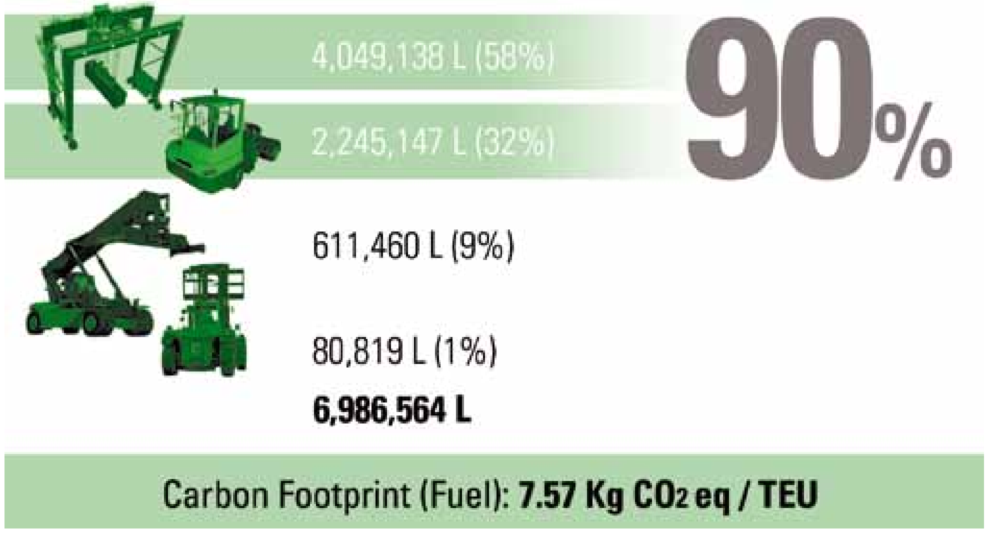


Figure 2. Distribution of Fuel Consumption
Aggregated Figures for Valencia NCTV, Livorno TDT and Koper Container Terminal (2012)

Source: Fundación Valenciaport, 2014

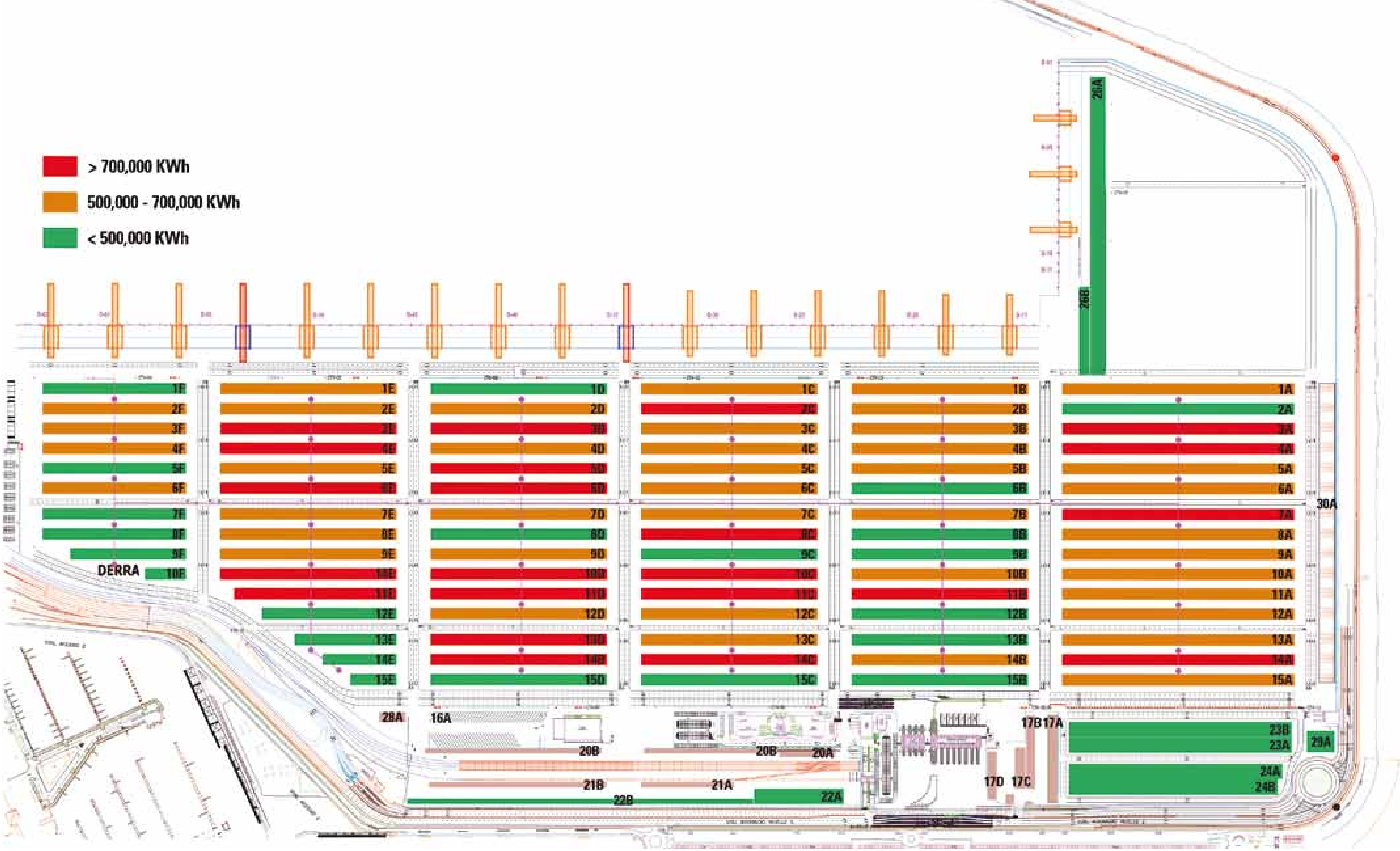


Figure 3. Energy Consumption Map for RTG Movements at Valencia NCTV (2012)

Source: Fundación Valenciaport, 2014

2 EVALUATION OF ECO-EFFICIENT ALTERNATIVES IN GREENCRANES

2.1 Investment Feasibility Methodology

GREENCRANES has designed a methodology to evaluate and select eco-efficient alternatives for PCTs based on technical, financial, and environmental criteria. Although the three aforementioned requirements had to be complied with in order to make a particular alternative viable in terms of implementation, the critical criterion was cost-benefit in terms of the investment required.

The environmental impact of the analyzed alternatives was always positive as all the studied solutions significantly decreased in GHG emissions, although this varied according to the different alternatives used. Environmental feasibility was based on the results obtained from the studies presented in Milestone 2 of the GREENCRANES "Report on PCT Energy Profiles" in which a detailed assessment of current GHG emission levels was provided for each PCT participating in GREENCRANES.

On the other hand, the technical viability reduced the number of alternatives as some of the cases studied were not suitable for different reasons such as a lack of technological maturity for quick deployment at PCTs, the unavailability of certified equipment in Europe (for instance, specific gas engines) and constraints that appeared via the new solutions which made them unfeasible from the point of view of port operations.

Taking into account the critical criterion of financial feasibility, GREENCRANES developed an approach based on the modelling and simulation of eco-efficient alternatives which were feasible from technical and environmental perspectives. The methodology for this evaluation was based on the concept of differential investment modelling. Differential investment considers the current situation (a process, a technology or a combination of both) as a base-line scenario on which a new solution is tested. This method develops differential investment evaluations in which costs, income, and investments are defined as the difference (positive or negative) with respect to the base-line scenario. The differential investment model calculates the cash-flow (positive or negative) generated by the new alternative and provides three investment variables as outputs: Net Present Value (NPV), Internal Rate of Return (IRR) and Investment Payback (IP).

In GREENCRANES, two differential investment models were developed. The first one was designed to evaluate the replacement (total or partial) of the vehicle fleets, and was a single variable model (the investment takes place exclusively in a machine/vehicle). The model was designed from an energy consumption point of view as it considered the substitution of traditional fuel-powered vehicles with new units powered by alternative fuels (LNG, bio-fuels, etc.). The model simulated the operational behaviour of vehicle fleets at port container terminals, taking the annual working hours of each vehicle and the work load of each machine as a reference.

The second model was designed to evaluate eco-efficient alternatives which required investments in a machine/crane/vehicle and also in a particular area of the facility. Thus, this model analyzed two investment variables at the same time. An example of this two-variable model is RTG yard electrification where investments are needed in RTG cranes and in the container yard.

Both types of models (single-variable and two-variable) analyzed a combination of scenarios and generated different solutions as outputs. In the case of the single-variable model, linear distribution was obtained for the reference output variables (NPV, IRR and IP). In the case of the two-variable model, the distribution was made up of an area, which was a combination of the different scenarios for the two investment variables analyzed. In both cases, the optimum point was reached via a combination of solutions which maximized NPV or IRR.

The GREENCRANES eco-efficient alternatives evaluated via this methodology are listed below:

- **Replacement of diesel-powered terminal tractors (TTs) with LNG-powered vehicles.** This eco-efficient alternative was evaluated for the real case of the terminal tractor fleet operating at the Noatum Container Terminal Valencia. With a fleet of 66 terminal tractors and 23 yard trucks, the evaluation studied the progressive replacement of the diesel-powered terminal tractor fleet with new machines powered by Liquefied Natural Gas (LNG).
- **RTG electrification.** Electrification of existing RTGs provided the greatest reduction in local GHG emissions but cost-benefit analyses have to be carried out to identify the optimum combination which maximizes two-variable investments (RTG and container stack).
- **Retrofitting of existing RTG cranes to run on LNG or dual-fuel technology.** This alternative was also considered for the specific case of NCTV where different families of RTGs operate. There were significant differences in energy consumption across these families, ranging from 13 l/h to 28 l/h. The objective was to evaluate whether it was better to replace high-consuming RTGs with a full LNG solution or with dual-fuel technology in order to reduce diesel consumption and also GHG emissions.
- **Retrofitting of existing RTG cranes with smaller gen-set equipment to save diesel fuel.** Another alternative to decrease GHG emissions and fuel consumption was to reduce the size of the gen-set which produced electricity for the RTG operating devices (spreader, trolley and hoist).
- **Retrofitting of existing reach stackers to run on hydrogen cells, compressed natural gas (CNG), LNG, or dual-fuel technologies.** Reach stackers are similar to RTGs in that they can be retrofitted to run on alternative fuels (in this case, natural gas). The evaluation of these alternatives was carried out for the specific case of Livorno Darsena Toscana Container Terminal.
- **Implementation of energy storage systems in RTGs (Flywheel technology).** Flywheel technology stores the excess of energy generated during an RTG cycle and supplies it during subsequent operations using batteries and super-capacitors. The analysis was carried out on the RTG fleet at the Port of Koper's container terminal.

For each of the abovementioned eco-efficient alternatives, a cost-benefit analysis was carried out. The key outputs were the following financial indicators: net present value (NPV), internal rate of return (IRR) and payback.

An on-line tool was developed in order to present the methodology to port operators interested in evaluating a particular business case. The tool can be tailored to the specific conditions of any container terminal.

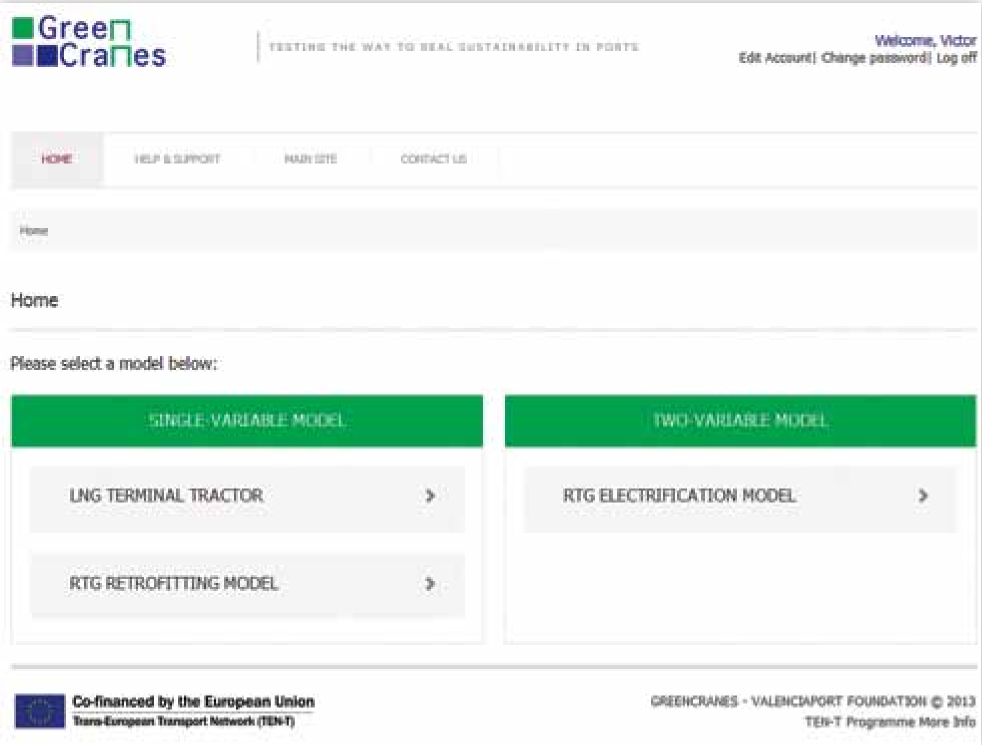


Figure 4. GREENCRANES On-Line Modelling Tool

Source: www.greencranes.eu

2.2 Adapting Terminal Tractor Fleets to LNG Fuel

2.2.1 Technical Aspects of LNG as a Fuel

Liquefied Natural Gas (LNG) used as fuel in vehicles is a feasible alternative which has already provided successful experiences in the road transport sector and offers interesting possibilities for its implementation at ports. Previous studies have concluded that terminal tractors powered with compressed natural gas (CNG) are not convenient due to several limitations:

- High fuel volume needed due to the nature of CNG (gas state).
- Problems with engine starts and stops.
- Reduction of engine power which introduced operational limitations when transporting heavy containers.

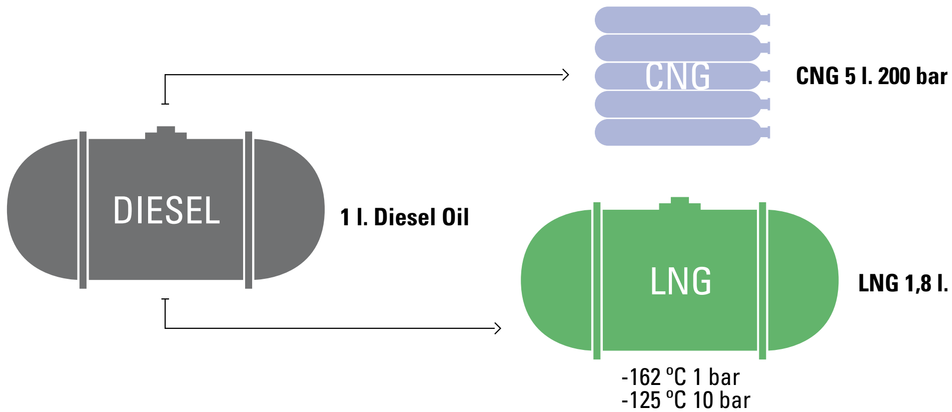


Figure 5. Volume Equivalence between Diesel Oil, CNG, and LNG

Source: Own source, based on Natural Bio-Gas Vehicle Association NGVA's information

From a technological point of view, the only alternative solution which can substitute diesel engines is LNG-based technology, as it guarantees the current degree of operational requirements with cleaner combustion and therefore reduces greenhouse gas (GHG) emissions. The retrofitting of existing terminal tractors to run on LNG was studied at an initial stage, but was disregarded due to technical constraints. The main reason for not considering this option was the lack of physical space in the existing vehicles to position the LNG tank, as this is double the size of a current diesel tank. This constraint applied to both full LNG power and dual-fuel technology alternatives. Thus, the other solution considered for the current study was replacing diesel TTs with new LNG-powered units, specifically designed for the GREENCRANES project. The evaluated solution implied the installation of a fuel station to supply LNG from a cryogenic tank to the LNG vehicles in the terminal. This cryogenic tank was regularly filled by LNG tankers.

The high investment involved in full deployment of this solution within the port terminal (estimated at €600,000) and a fleet of 20 LNG yard trucks to assure acceptable payback meant implementing the aforementioned pilot scheme by supplying LNG using a cryogenic LNG tanker (under renting conditions). Thus, supplies to the PCT equipment could be carried out to test whether the energy consumption savings derived from the use of LNG would yield acceptable payback of the full LNG installation.

The proposed installation, which already exists in other industrial sectors, would be an innovation within the port and logistics sector and would mean a step forward in the current state-of-the-art of fuel supply at European port container terminals. Cost estimates show major advantages of using LNG compared to standard fuels.

Table 1 shows the variables and values introduced in the single-variable model designed to evaluate the feasibility of substituting existing terminal tractors with new LNG-powered units.

PROCESS VARIABLES	
Total Working Hours (h)	8,395
Terminal Tractor (TT) Lifespan (h)	45,000
Availability Corrector Factor (%)	35
Shift Effective Duration (h)	5.7
Number of Shifts per Year (shift)	1,460
ENERGY CONSUMPTION VARIABLES	
Vehicle Diesel Consumption (l/h)	7.7
Diesel TT Energy Consumption (kWh/h)	82.7
LNG/Diesel Performance Losses (%)	10
LNG TT Energy Consumption (kWh/h)	91.9
ENERGY COSTS	
Diesel Price (€/l)	0.7440
Diesel Cost per Hour (€/h)	5.7
Diesel Energy Cost (€/ kWh)	0.0693
LNG Energy Cost without BoilOff (€/kWh)	0.0315
BoilOff Losses (%)	3
LNG Energy Cost with BoilOff (€/kWh)	0.0325
LNG Cost (€/h)	2.9
Energy Rate LNG/Diesel (%)	47
Savings (€/h)	2.75 €
FLEET MAINTENANCE	
δ TT Maintenance (€/h)	-0.60 €
INVESTMENT	
δ TT Investment (€/unit)	20,000
δ TT Investment (€/h)	0.4
LNG Station (€)	300,000
Cryogenic Tank (€)	300,000

Table 1. Input Variables Applied to Evaluate LNG Terminal Tractor Replacement

Source: Noatum, 2014

2.2.2 Environmental Aspects

According to the results obtained from the study carried out in Activity 1 of the project, NCTV presented the following CO_{2eq}[1] emissions from all the facility's energy centres. Terminal tractors were responsible for 23% of the total CO_{2eq} tonnes generated in 2011 (5,148 CO_2 tonnes) and in 2012 (5,203 CO_2 tonnes).

Figure 6. NCTV Carbon Footprint in 2012

Source: Noatum and Fundación Valenciaport, 2014

Two factors have to be considered when evaluating CO_2 reductions as a result of LNG conversion. On one hand, natural gas combustion reduces the amount of CO_2 by 25%. On the other, LNG engines lose thermal performance in comparison with diesel engines (estimated at 10%), resulting in higher fuel consumption. Thus, the net CO_2 reduction is estimated at 16% (moreover, NO_X and particulate matter are almost zero).

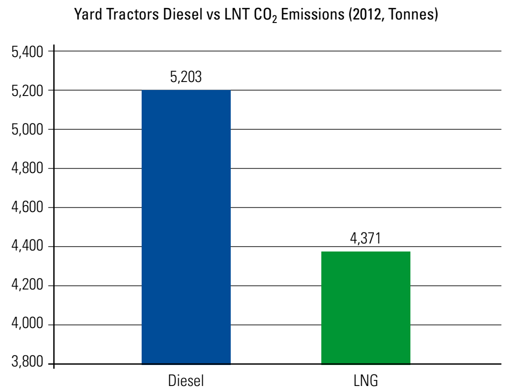


Figure 7. TT Replacement of Terminal Tractor Fleet at NCTV. Reduction of CO2 Emissions

Source: Noatum and Fundación Valenciaport, 2014

[1] CO_{2eq} tonnes include the contribution of CH4 and N2O emissions.

2.2.3 Financial Feasibility Analysis

The most sensitive parameter when evaluating a technological change in energy is the differential cost between the existing solution ("as-is") and the new alternative ("to-be"). In the case of replacing diesel terminal tractors with LNG power, the price evolution of the different fuels involved is a key variable to consider in the process decision. The following figure shows the price evolution of diesel A (GoA), industrial diesel (GoB), LNG, and electricity from 2005 to 2014.

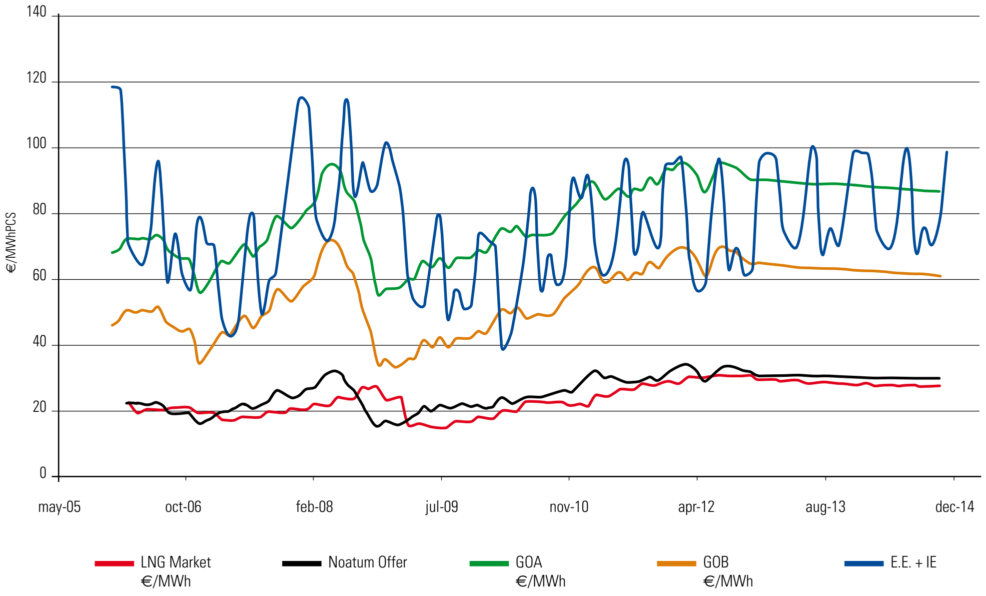


Figure 8. Spain Fuel and Electricity Price Evolution and Forecast 2005-2014

Source: Biomap Consulting

Figure 8 shows the unit cost of energy (€/MWh) from May 2005 to December 2014 (forecast). The electricity price includes current Spanish taxes on this energy, whereas for LNG, the graph shows the market price.

In general, there is a strong correlation between the price of diesel and the barrel of Brent. As LNG prices are usually correlated to diesel prices, it has been assumed that LNG costs approximately 43% of GoB costs. An important point to note is that the differential between LNG and GoB consists of an increase in the price gap when prices go up and a decrease in this gap when prices go down. In the case of Spain, energy costs are relatively low compared to the rest of Europe where the current crisis situation introduces the risk of tax increases on alternative fuels like LNG.

The most likely behaviour of energy costs in the short-middle term is for them to remain stable or for energy prices to decrease slightly. The financial feasibility study followed a methodology based on the concept of "differential investment". Thus, the differential cash-flow produced by the evaluated alternative was considered and all the common parameters and variables affecting both the "as-is" alternative and the "to-be" alternative were excluded, thus simplifying the approach to the problem without losing accuracy. In the the financial feasibility study study, the following assumptions and hypotheses were considered:

- The calculated variables (outputs of the study) were: Net Present Value (NPV), Internal Rate of Return (IRR) and Investment Payback.
- WACC: Weighted Average Cost of Capital. The WACC is the minimum return that a company must earn on an existing asset base to satisfy its creditors, owners, and other providers of capital, or they will invest elsewhere. In the case of Noatum, WACC is set at 10%.
- Current Current financial analyses assess the technical profitability of the investment, that is, shareholder profitability is not considered at this stage as this will be developed with the selected eco-efficient alternative (shareholder profitability includes financial costs, leveraging, the economic situation of the organization, etc.).

The proposed feasibility model provides the differential cash-flow of the investment evaluated for the replacement of diesel terminal tractors with LNG-powered machines. The input data are the variables shown in Table 1 as well as the demand distribution of the terminal. The model is flexible and allows different configurations. To evaluate the terminal tractor fleet, it was adjusted to an investment horizon of 17 years, which represents the concession time remaining for NCTV at the Port of Valencia. The following table shows the scenario distribution where the profitability of the investment becomes positive for certain machines.

New TT	δ INVESTMENT (€)	NPV (€)	IRR (%)	Payback (years)
	600,000.00 €	-600,000.00 €	-100%	41
2	640,000.00 €	-530,124.29 €	-100%	41
4	680,000.00 €	-464,101.81 €	-7.5%	41
5	700,000.00 €	-432,450.25 €	-5%	41
6	720,000.00 €	-397,668.17 €	-2.6%	41
7	740,000.00 €	-363,611.23 €	-0.6%	41
8	760,000.00 €	-330,162.94 €	0.9%	41
9	780,000.00 €	-297,349.83 €	2.3%	41
10	800,000.00 €	-263,240.77 €	3.6%	41
11	820,000.00 €	-229,841.13 €	4.6%	41
12	840,000.00 €	-197,020.84 €	5.6%	41
13	860,000.00 €	-164,878.62 €	6.5%	41
14	880,000.00 €	-131,666.34 €	7.3%	11
15	900,000.00 €	-99,077.54 €	8%	10
17	940,000.00 €	-33,930.04 €	9.3%	10
19	980,000.00 €	34,339.83 €	10.6%	9
21	1,020,000.00 €	102,791.86 €	11.7%	9
23	1,060,000.00 €	168,322.81 €	12.6%	9
25	1,100,000.00 €	231,108.79 €	13.5%	9
27	1,140,000.00 €	292,623.60 €	14.2%	8
29	1,180,000.00 €	352,717.65 €	14.9%	8
31	1,220,000.00 €	411,009.32 €	15.5%	8
33	1,260,000.00 €	467,456.93 €	16.0%	8
35	1,300,000.00 €	520,189.50 €	16.5%	8
45	1,500,000.00 €	778,635.62 €	18.4%	8
55	1,700,000.00 €	1,005,305.54 €	19.5%	8
65	1,900,000.00 €	1,173,437.85 €	20.1%	8
75	2,100,000.00 €	1,279,079.06 €	20.3%	8

Table 2. Single-Variable Model Outputs. TT LNG Replacement

Source: Noatum and Fundación Valenciaport, 2014

According to the results presented in Table 2, investment became feasible when **19 terminal** tractors were replaced. This scenario shows the threshold at which investment was advised, with NPV at €34,339.83, IRR at 10.60% and payback at 9 years. Figure 9 shows the evolution of NPV when replacing terminal tractors as they get older with LNG-powered units.

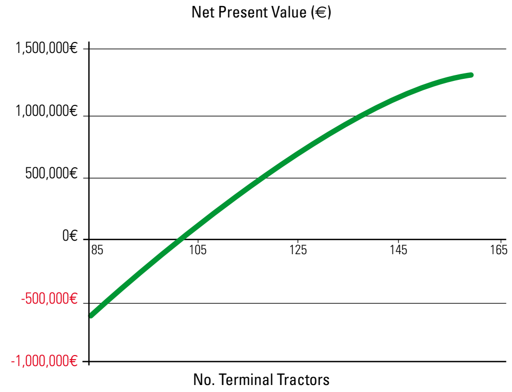


Figure 9. Net Present Value Evolution, TT LNG Replacement

Source: Noatum / Fundación Valenciaport, 2014

Figure 10 shows the evolution of IRR and the investment payback which are stable at 20% and 9 years respectively when 19 yard tractors are replaced.

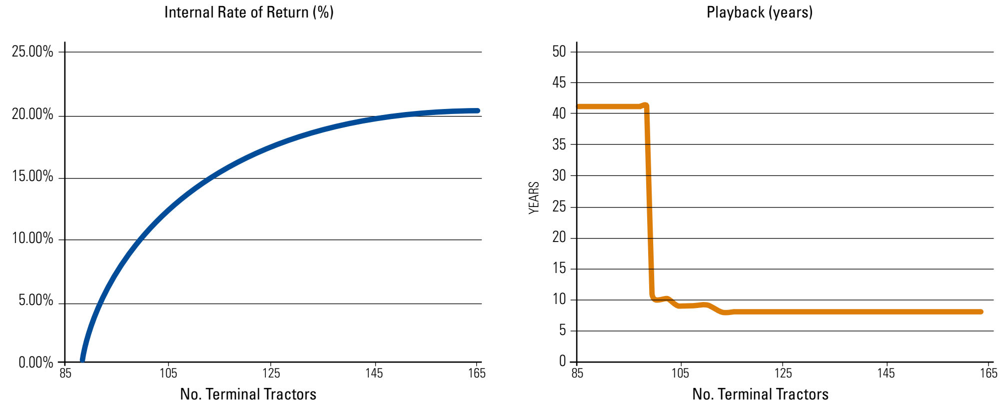


Figure 10. Internal Rate of Return and Payback Evolution, TT LNG Replacement

Source: Noatum and Fundación Valenciaport, 2014

The main findings of this analysis are:

*** The concept of fleet management is not often applied in port container terminals, thus affecting port operational performance and profitability.**

*** A equipment renewal plan can be a relevant instrument to maximise profitability in port container terminals.**

*** Depending on fuel prices in each country, the optimum number of terminal tractors to be replaced will vary.**

2.3 Electrification of Rubber-Tyred Gantry Cranes

2.3.1 Technical Aspects of RTG Electrification

Rubber-tyred Gantry cranes (RTGs) are yard machines which run on electricity provided by an on-board diesel generator. From an energy-efficiency point of view, the main problem of RTGs is their low-energy performance rate, as **this type of machine almost never works at its optimum running point (around 95% of the time) whilst more than half of its running time is in idle mode, waiting for work orders, or due to bottlenecks at terminals.** Moreover, some old-generation RTG families are equipped with oversized generators which provide more power than that which is strictly required in ordinary yard operations, thus increasing fuel consumption.

There are two alternatives available to effectively reduce energy consumption in this situation: either the whole machine can be electrified or the existing generator can be replaced by one which is suited to the real energy demands of yard operations.

An electrification project can be divided into three phases: distribution network, installation of cable reel or conductor bar, and machine retrofitting. A distribution network is usually installed by an electrical company. The implementation of cable reels or conductor bars is carried out by a company specialized in this type of equipment (Vahle, Conductix and Cavotec are reference companies in this type of projects). Finally, machines can be adapted by a port machinery manufacturer (Konecranes, Fantuzzi, Paceco, Cargotec, etc.). Important issues to take into consideration in this project are guarantee specifications and CE marking.

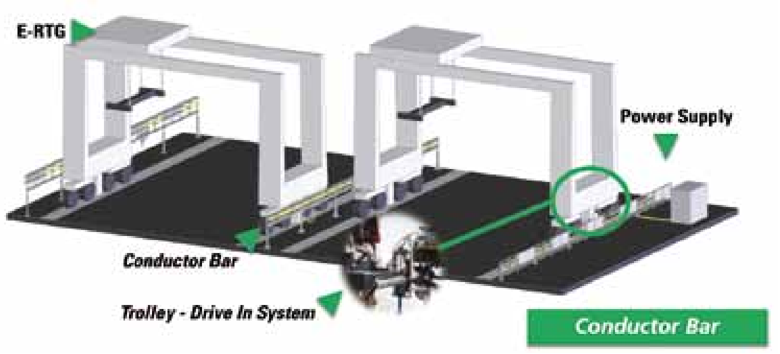


Figure 11. Conductor Bar RTG Electrification

Source: Fundación Valenciaport, 2014

Conductor bar electrification, also known as a conduct bar, bus bar or conduct rail (depending on the manufacturer) consists of supplying electricity to RTGs through conductive line rails housed in a steel structure positioned at least two metres high over the container stacks. The RTGs are equipped with a pantograph, which is connected (plugged in) to the conduct bar that provides electrical power (Figure 11). When the RTGs move to another container stack they are powered by the auxiliary diesel engine.

Electrification via a cable reel consists of a cable wound onto a motorized reel that unfolds and folds, depending on when the machine moves closer or further away from the starting point, on rails in the yard that can be installed without having to modify the paving in the yard. The rails prevent the cable from being crushed as a result of the movement of heavy machinery over it.

This solution electrifies the equipment in a similar way to the power system of ship-to-shore cranes. The main advantages that this system offers versus other electrical alternatives is that it is easy and quick to install and requires no changes in infrastructure, thus saving time and costs at the terminal.

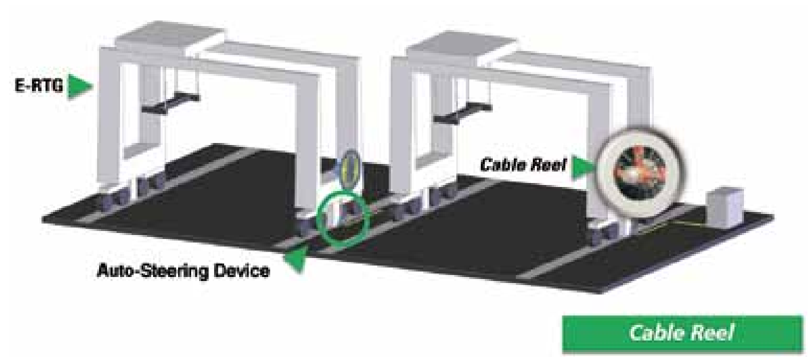


Figure 12. Cable Reel RTG Electrification

Source: Fundación Valenciaport, 2014

The study carried out in Greencranes on determining the energy consumption profile of the facilities showed that the RTG fleet had a broad fuel consumption range. Table 3 shows detailed fuel consumption (l) disaggregated by RTG type. It can be seen that the highest fuel consumption corresponds to the RTG B type, with both sub-families RTG B.1 and RTG B.2.

The RTG A family is used in very specific cases as they cannot operate in some areas of the terminal because of technical limitations. Thus, electrification of these cranes was not considered, since a key factor for guaranteeing investment feasibility was the intensive use of these machines throughout the year.

On the other hand, The RTG C family are intensively used at the terminal, which means that this fleet could be considered for electrification. Nevertheless, the RTG C fleet is highly optimized in terms of fuel consumption as they are latest-generation cranes which already feature advanced systems to reduce energy consumption.

Therefore, it would seem that the electrification of the RTG B fleet is the best option to maximize energy savings and reduce GHG emissions.

	CONSUMPTION (l)		MOVEMENTS (mov)		l / mov	
RTG FAMILIES	2011	2012*	2011	2012*	2011	2012*
RTG A.1	64,837	84,364	18,405	28,583	3.5	2.9
RTG A.2	78,710	91,152	30,078	37,929	2.6	2.4
RTG B.1	1,113,110	1,107,421	372,979	374,103	2.9	2.9
RTG B.2	1,537,785	1,519,685	603,799	584,945	2.5	2.6
RTG C.1	178,613	178,512	120,053	118,685	1.4	1.5
RTG C.2	884,924	834,520	755,538	707,171	1.1	1.1
TOTAL	**3,857,979**	**3,815,654**	**1,900,852**	**1,851,416**	**2.3**	**2.2**

Table 3. NCTV Fuel Consumption by RTG Manufacturer

Source: Noatum, 2014

* Data from January - October 2012

Figure 13 shows the importance of measuring energy variables at port container terminals. In this sense, the RTG B.2 performed fewer movements (603,799) than the RTGC.2 cranes (755,538). However, the RTG B.2 cranes used 685,000 litres more than the RTG C.2 cranes. In terms of energy costs, it can be said that movements performed by RTG B.2 machines cost almost twice as much as movements performed by the RTG C.2 group. This information is useful for port operators to decide which type of machine is best for certain operations in order to reduce the terminal's total energy costs.

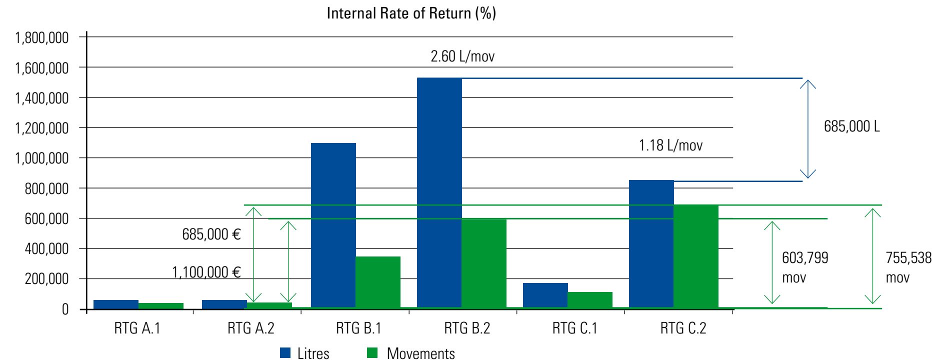


Figure 13. Comparison among RTG Groups at NCTV. Energy Consumption (l) and Movements (2012)

Source: Noatum and Fundación Valenciaport, 2014

2.3.2 Environmental Aspects

According to the results obtained from the study carried out in Activity 1 of the project, NCTV presented the following CO_{2eq} emissions in the facility's energy centres. RTGs were responsible for 45% of the total CO_{2eq} tonnes generated in 2011 (10,104 CO_{2eq} tonnes) and in 2012 (9,994 CO_{2eq} tonnes), taking into account that the last available data for this year came from October 2012. A breakdown of the total amount of CO_2 emissions produced by the RTG fleet showed that RTG B cranes were responsible for 71%, RTG C produced 28% of CO_2, and RTG A the remaining 2%. Thus, it would seem clear that efforts to reduce the CO_2 emissions from RTGs should be focused on the RTG B fleet, as shown in Table 4.

	CONSUMPTION (l)		CO_2 Diesel (Tonnes)	
RTG FAMILIES	2011	2012*	2011	2012*
RTG B.1	1,113,110	1,107,421	2,884	2,869
RTG B.2	1,537,785	1,519,685	3,984	3,938
SUB- TOTAL	2,650,895	2,627,106	6,869	6,807
RTG C.1	178,613	178,512	463	463
RTG C.2	884,924	834,520	2,293	2,162
SUB- TOTAL	1,063,537	1,013,032	2,756	2,625
RTG A.1	64,837	84,364	168	219
RTG A.2	78,710	91,152	204	236
SUB- TOTAL	143,547	175,516	372	455
TOTAL	**3,857,979**	**3,815,654**	**9,996**	**9,886**

Table 4. NCTV CO_2 Emissions Generated by RTG Type 2011-2012

Source: Noatum, 2014

Figure 14 shows the potential reduction of CO_2 emissions from the electrification of RTG cranes based on an estimated 90% reduction in local emissions. This estimate is based on the hypothesis that electrified RTGs would implement conductor bar technology and would only consume diesel fuel in container stack changes and other minor displacements.

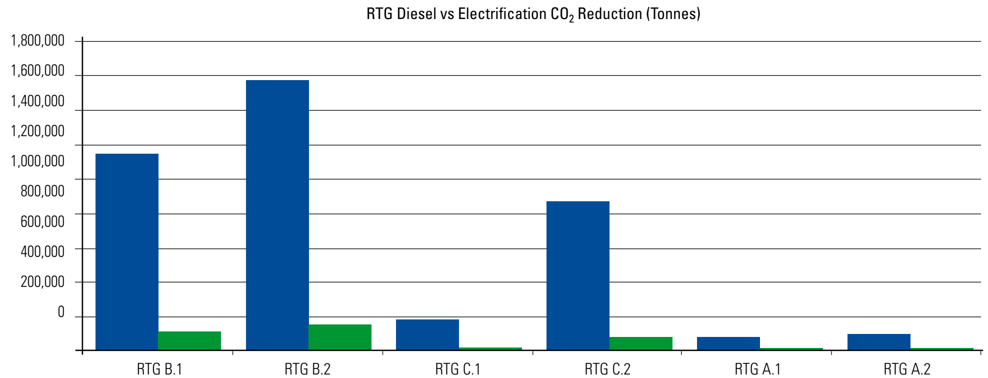


Figure 14. NCTV Comparison of Diesel and Electrified RTG CO_2 Emissions

Source: Noatum, 2014

2.3.3 Financial Feasibility Analysis

The electrification study evaluated different combinations of yard electrification considering the two technological solutions provided by the market, i.e. cable reel and conductor bar electrification. In this case, the two-variable model was applied to determine the optimum combination of number of cranes and electrified container stacks.

The main criterion adopted in the evaluation was that in both cases (cable reel or conductor bar electrification) **the first cranes to be electrified would be those with the highest fuel consumption.** In the case of NCTV, these machines were the RTG B family. Tables 5 and 6 show the model variables and the values used to carry out the financial feasibility analysis.

PROCESS VARIABLES		NUMBER OF MACHINES	
Total Working Hours (h)	7,986	RTG C	21
Shift Effective Duration (h)	5.5	RTG B.2	12
Number of Shifts per Year (shift)	1,460	RTG B.1	12
Number of RTG Families	4	RTG A	15
MAXIMUM CAPACITY (h / year)		**CAPACITY (mov / year)**	
RTG C	6,500	RTG C	71,240
RTG B.2	6,300	RTG B.2	66,528
RTG B.1	5,500	RTG B.1	46,750
RTG A	3,000	RTG A	21,000
TEMPORARY AVAILABILITY (%)		**AVERAGE WORKING HOURS BETWEEN STOPS (h)**	
RTG C	81	RTG C	250
RTG B.2	79	RTG B.2	200
RTG B.1	69	RTG B.1	200
RTG A	38	RTG A	100
ENERGY CONSUMPTION VARIABLES			
RTG C FAMILY		**RTG B.2 FAMILY**	
Diesel Fuel Consumption (l/h)	14.3	Diesel Fuel Consumption (l/h)	27.5
Energy Consumption (kWh / h)	153.6	Energy Consumption (kWh / h)	295.4
Diesel / Electrical Rate (%)	22	Diesel / Electrical Rate (%)	11
Net Electrical Consumption (kWh /h)	34	Net Electrical Consumption (kWh /h)	32.7
RTG Performance (mov / h)	10.9	RTG Performance (mov / h)	10.5
Diesel Consumption (kWh / mov)	14	Diesel Consumption (kWh / mov)	28
Electrical Consumption (kWh /mov)	3.1	Electrical Consumption (kWh /mov)	3.1
RTG B.1 FAMILY		**RTG A FAMILY**	
Diesel Fuel Consumption (l/h)	26.9	Diesel Fuel Consumption (l/h)	16.8
Energy Consumption (kWh / h)	288.9	Energy Consumption (kWh / h)	180.4
Diesel / Electrical Rate (%)	11	Diesel / Electrical Rate (%)	14
Net Electrical Consumption (kWh /h)	30.6	Net Electrical Consumption (kWh /h)	25.2
RTG Performance (mov / h)	8.5	RTG Performance (mov / h)	7
Diesel Consumption (kWh / mov)	34	Diesel Consumption (kWh / mov)	25.8
Electrical Consumption (kWh /mov)	3.6	Electrical Consumption (kWh /mov)	3.6

Table 5. Input Variables Applied to Evaluate RTG Electrification (I)

Source: Noatum and Fundación Valenciaport, 2014

ENERGY COSTS			
DIESEL		**ELECTRICITY**	
Price (€ / l)	0.7	Electricity Price (kWh)	0.1
Diesel Cost RTG C (€ / mov)	0.9	Electricity Cost RTG C (€ / mov)	0.4
Diesel Cost RTG B.2 (€ / mov)	1.9	Electricity Cost RTG B.2 (€ / mov)	0.4
Diesel Cost RTG B.1 (€ / mov)	2.3	Electricity Cost RTG B.1 (€ / mov)	0.4
Diesel Cost RTG A (€ / mov)	1.7	Electricity Cost RTG A (€ / mov)	0.4
ENERGY SAVINGS			
Savings RTG C (€ / mov)	0.5	Savings RTG C (€ / h)	6.2
Savings RTG B.2 (€ / mov)	1.5	Savings RTG B.2 (€ / h)	16.2
Savings RTG B.1 (€ / mov)	1.8	Savings RTG B.1 (€ / h)	16.0
Savings RTG A (€ / mov)	1.3	Savings RTG A (€ / h)	9.2
MAINTENANCE COSTS			
δ Maintenance RTG C (€ / mov)	0.0	δ Maintenance RTG C (€ / h)	1.0
δ Maintenance RTG B.2 (€ / mov)	0.2	δ Maintenance RTG B.2 (€ / h)	2.5
δ Maintenance RTG B.1 (€ / mov)	1.3	δ Maintenance RTG B.1 (€ / h)	4.0
δ Maintenance RTG A (€ / mov)	0.2	δ Maintenance RTG A (€ / h)	0.9
INVESTMENTS			
Conductor Bar RTG C (€ / unit)	100,000	Cable Reel RTG C (€ / unit)	260,000
Conductor Bar RTG B.2 (€ / unit)	130,000	Cable Reel RTG B.2 (€ / unit)	290,000
Conductor Bar RTG B.1 (€ / unit)	130,000	Cable Reel RTG B.1 (€ / unit)	290,000
Conductor Bar RTG A (€ / unit)	100,000	Cable Reel RTG A (€ / unit)	300,000
Conductor Bar Investment (€ / m)	425	Distribution Network Phase 1 (€)	3,500,000
Cable Reel Investment (€ / m)	60.5	Distribution Network Phase 2 (€)	2,500,000
Electrical Substation 132 kV (€)	3,000,000	Distribution Network Phase 3 (€)	2,500,000

Table 6. Input Variables Applied to Evaluate RTG Electrification (II)

Source: Noatum and Fundación Valenciaport, 2014

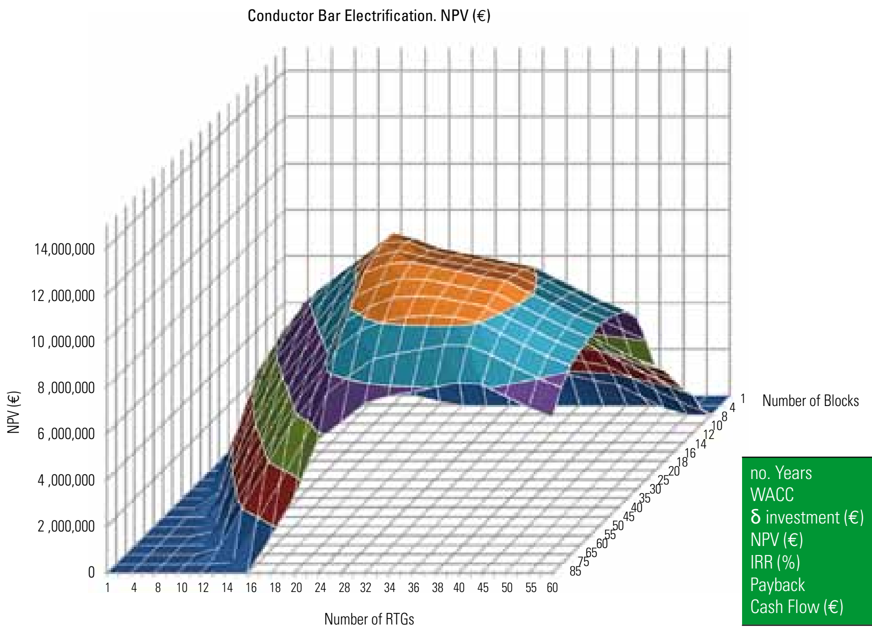
The two-variable model used a wide variety of variables to correctly simulate a complete electrification project investment in a PCT.

The first variable inputs corresponded to parameters which characterized the operational management of the RTG fleet at NCTV (total working hours per year, number of shifts, effective shift duration). Each RTG family presented a set of attributes which determined their performance in the general operational framework of the terminal (maximum capacity, availability percentage, average working hours between stops, etc.).

Energy consumption variables were key inputs for the model as they were needed to calculate the savings expressed in €/mov. and €/h derived from the electrification conversion. Thus, diesel and electricity prices were reference variables introduced in the model. Maintenance costs also affected investment profitability and so they were introduced in the model in the form of differential maintenance compared to the current situation in which RTGs are diesel-powered.

Finally, investments needed to be considered in the project evaluation as they were critical when evaluating its feasibility and profitability. Investments for conductor bar and cable reel implementation were considered as well infrastructure investments needed to ensure a suitable electricity supply (electricity sub-station and distribution network).

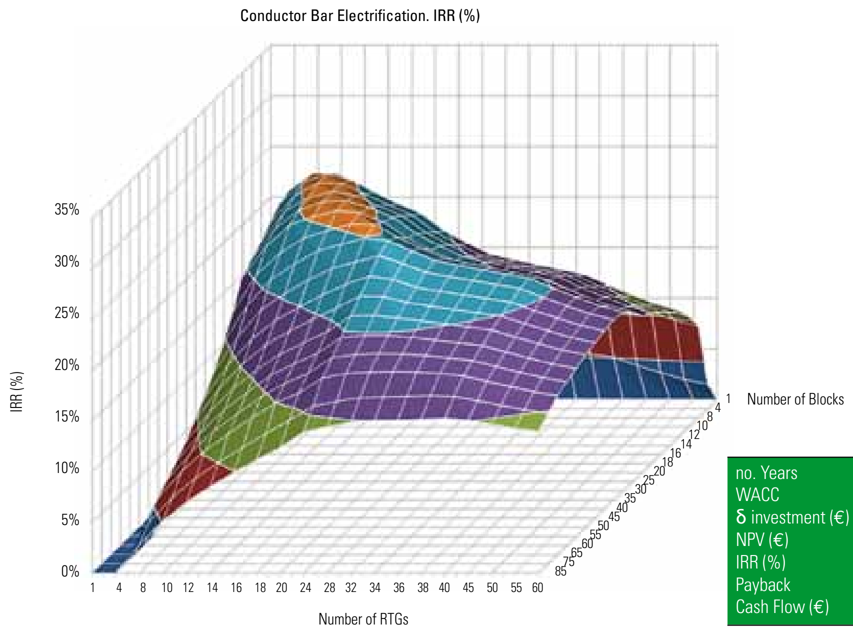
Figures 15 and 16 show the NPV and IRR from conductor bar electrification. The results provided by



no. Years	17
WACC	10%
δ investment (€)	6,437,939.57
NPV (€)	7,084,439.85
IRR (%)	25.64
Payback	6
Cash Flow (€)	2,177,771

Figure 15. NPV. RTG Electrification Using Conductor Bars

Source: Noatum and Fundación Valenciaport, 2014

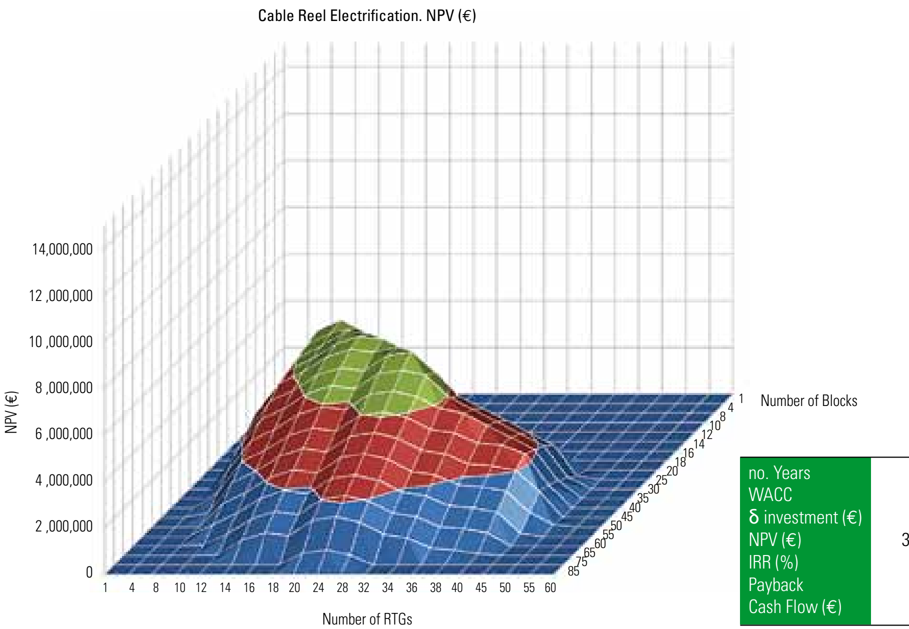


no. Years	17
WACC	10%
δ investment (€)	6,437,939.57
NPV (€)	7,084,439.85
IRR (%)	25.64
Payback	6
Cash Flow (€)	2,177,771

Figure 16. IRR. RTG Electrification Using Conductor Bars

Source: Noatum and Fundación Valenciaport, 2014

the model estimated that the maximum IRR ranged from 14 electrified RTGs and 18 container stacks through to 24 electrified RTGs and 35 container stacks.

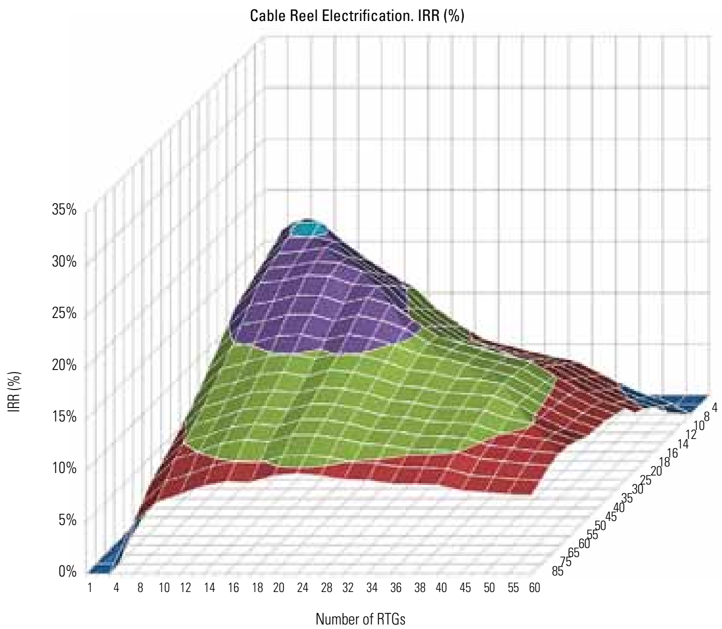


no. Years	17
WACC	10%
δ investment (€)	5,490,827
NPV (€)	3,750,859.4
IRR (%)	20.04
Payback	9
Cash Flow (€)	1,822,582

Figure 17. NPV. RTG Electrification Using Cable Reels

Source: Noatum and Fundación Valenciaport, 2014

Figures 17 and 18 show the NPV and IRR from cable reel electrification. The results provided by the model estimated that the maximum IRR ranged from 10 electrified RTGs and 12 container stacks through to 16 electrified RTGs and 18 container stacks.



no. Years	17
WACC	10%
δ investment (€)	5,490,827
NPV (€)	3,750,859.4
IRR (%)	20.04
Payback	9
Cash Flow (€)	1,822,582

Figure 18. IRR. RTG Electrification Using Cable Reels

Source: Noatum and Fundación Valenciaport, 2014

The main results of this part of the study are:

*** There is a lack of reliable information of RTGs fuel consumption in real life operations. Manufacturers should carry out consumption measures in real life operations and publish this type of information.**

*** RTG cranes are usually idle over 50% of time. Therefore, measures aiming to reduce consumption at idle times are highly recommended.**

*** Electrification of RTGs is the most convenient solution for greenfield terminals but retrofitting may be a much more profitable solution for existing terminals.**

2.4 ADAPTING RTGS TO RUN ON LIQUEFIED NATURAL GAS (LNG) OR DUAL-FUEL TECHNOLOGY

2.4.1 Technical Aspects of Adapting RTGs to Run on LNG

The study of adapting RTGs to run on liquefied natural gas (LNG) showed that significant technical and economic constraints still limit the application of this eco-efficient alternative. Assuming that electrification is the optimal solution for a "Greenfield" container terminal and for an existing facility in the long term, the conversion of diesel RTGs to LNG fuel was considered as an interesting short-term alternative, although previous experience in the port sector, and by extension, detailed information, were not available at the beginning of the project. The study was based on the following technical requirements:

- RTGs had to be re-filled at the yard during stacking operations as the cranes cannot be moved to a specific area to be re-filled. This was done through tankers which supply LNG on-site (Figure 19).

Figure 19. Mobile LNG Supply Fuel Station (Tanker)

Source: HAM, 2014

- The autonomy of the RTG had to be 48 hours. This was done by using a 2,000 litre diesel tank, which implied 4,000 l of LNG (in volume, 1 l gasoil is equivalent to 1.9 l of LNG). It is important to point out that LNG tanks cannot be filled to 100% as they must allow for boil-off.
- LNG boil-off had to be properly managed as the pressure of LNG tanks increases by 0.2 bar per day. LNG boil-off should not be a problem as RTGs work long enough on a continuous basis to consume the total volume of LNG before boil-off generates pressure problems.
- One of the important technical restrictions was the tank size and how and where it was located on the RTG, as they had to be placed horizontally on the crane structure. LNG tanks were standard size, so several units had to be placed on the RTG structure without compromising RTG stability.
- Safety conditions had to be studied in detail as the position of LNG tanks can cause accidents or gas escapes if there are collisions between the container and the crane structure or between cranes operating in the same lane or stacking area.

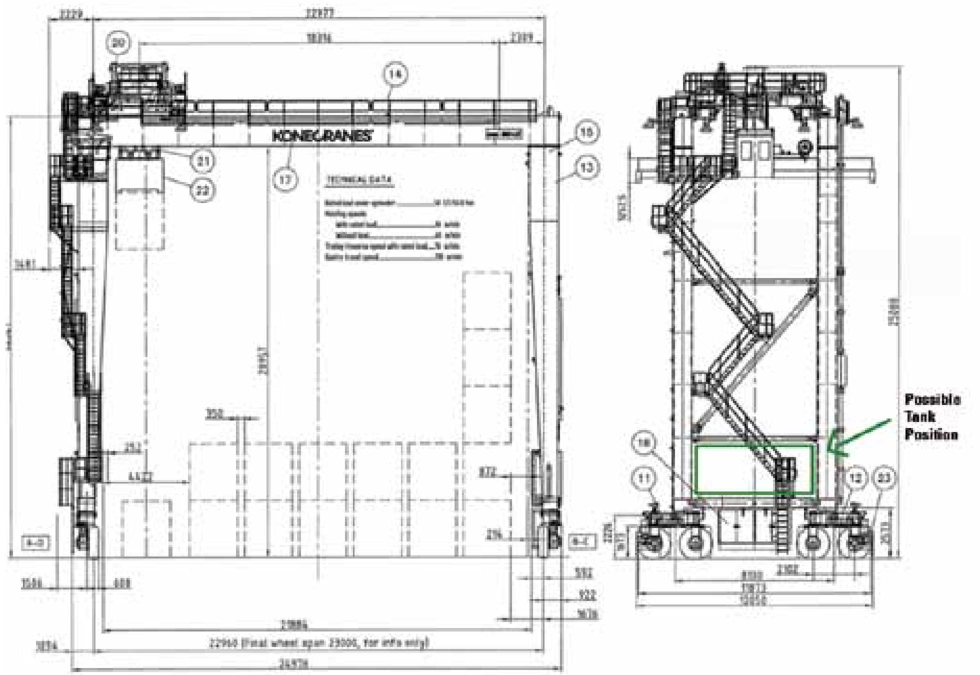


Figure 20. RTG Structure and Potential Positioning of LNG Tanks

Source: Konecranes and Fundación Valenciaport, 2014

The main technical constraint when replacing diesel-powered RTGs with LNG fuel is the implementation of a compatible gas generator to replace the current diesel gen-set. When the study was carried out, **no gas generators which were 100% compatible with RTG crane specifications (size, power, and rpm) were available and certified for the European market.** This constraint negatively conditioned potential pilot tests of an LNG-powered RTG in 2013 within the framework of GREENCRANES.

A second alternative involving LNG in RTGs centred on implementing dual-fuel generators in the RTG and dual-fuel kits for existing diesel generators. A dual-fuel engine is based on a traditional diesel engine with the addition of dual-fuel specific hardware. When the engine is operating in dual-fuel mode, natural gas is introduced into the intake system. The air-to-natural gas mixture from the intake is drawn into the cylinder, just as it would be in a spark-ignited engine, but with a leaner air-to-fuel ratio.

Once again, limitations for dual-fuel gas generators became apparent as no dual-fuel generators certified for the European market were available. The engine manufacturers Cummins and Volvo are currently working on RTG-compatible dual-fuel gas generators for the American market which will probably be available at the beginning of 2014. **The main conclusion from a technical point view was that the feasibility of LNG solutions to power RTGs is seriously affected by the lack of availability of appropriate generators in Europe, safety conditions, and the absence of adapted LNG tanks.**

2.4.2 Environmental Aspects

Following the same approach as in the case of RTG electrification, converting diesel-powered RTGs to run on LNG would significantly reduce CO_2, NO_X and particulate matter emissions. Table 7 shows the potential reduction of CO_2 emissions when replacing the RTG fleet at NCTV with full-LNG generators (first alternative) or dual-fuel technology (second alternative).

	CONSUMPTION (l)		CO_2 Diesel (Tn)		CO_2 LNG (Tn)		CO_2 Dual Fuel (Tn)	
RTG FAMILIES	2011	2012*	2011	2012*	2011	2012*	2011	2012*
RTG B.1	1,113,110	1,107,421	2,884	2,869	2,163	2,152	2,524	2,511
RTG B.2	1,537,785	1,519,685	3,984	3,938	2,988	2,953	3,486	3,445
SUB- TOTAL	**2,650,895**	**2,627,106**	**6,869**	**6,807**	**5,151**	**5,105**	**6,010**	**5,956**
RTG C.1	178,613	178,512	463	463	347	347	405	405
RTG C.2	884,924	834,520	2,293	2,162	1,720	1,622	2,006	1,892
SUB- TOTAL	**1,063,537**	**1,013,032**	**2,756**	**2,625**	**2,067**	**1,969**	**2,411**	**2,297**
RTG A.1	64,837	84,364	168	219	126	164	147	191
RTG A.2	78,710	91,152	204	236	153	177	178	207
SUB- TOTAL	**143,547**	**175,516**	**372**	**455**	**279**	**341**	**325**	**398**
TOTAL	**3,857,979**	**3,815,654**	**9,996**	**9,886**	**7,497**	**7,415**	**8,747**	**8,651**

Table 7. NCTV CO_2 Emissions by type of RTG Manufacturer. Diesel, LNG and Dual-Fuel Comparison

Source: Noatum and Fundación Valenciaport, 2014

* Data from January - October 2012

Figure 21 shows the potential reduction of CO_2 emissions when replacing the the diesel RTG A, B and C families with 100% LNG fuel and with dual-fuel technologies. In the first case, the total amount of CO_2 emissions would drop by 34% as a result of LNG's cleaner combustion and power adjustments. In the case of dual-fuel technology, a mix of 50% diesel and 50% LNG in a dual-fuel generator was used for this study. In this scenario, diesel emissions would only be reduced by 50%. Similarly, NO_X compounds and particles would be reduced by 90% in the case of full-powered LNG cranes and by 45% in the case of dual-fuel technology.

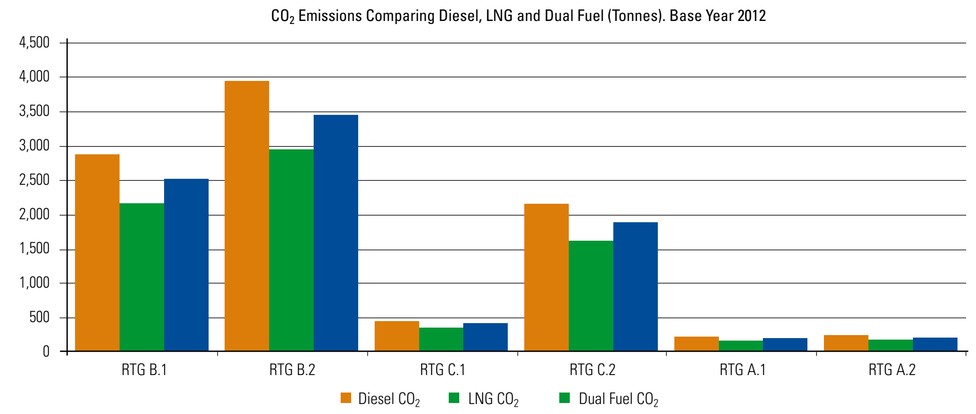


Figure 21. Diesel, LNG and Dual-Fuel Alternatives. CO_2 Emissions by RTG Manufacturer

Source: Noatum and Fundación Valenciaport, 2014

2.4.3 Financial Feasibility Analysis

This section details the financial feasibility analysis of the LNG RTG alternative. The first option assessed was LNG retrofitting with a small-sized (nominal power lower than 450 kW) gas gen-set to provide a fuel consumption saving of 14 l/h compared to the current diesel generator. The cost of this unit was estimated at €240,000 plus the cost of the LNG tanker. The annual saving per unit was estimated at €50,000. Figure 22 shows the investment profitability outputs obtained from the single-variable model application.

RTG B LNG RETROFITTING: SMALL GAS ENGINE	
Number of Machines	24
Investment per Unit	240,000 € + 300,000 € Tanker
Saving	14 l/h + 58% Fuel Cost
Annual Saving / Unit	50,000 €
Loss of Performance	Lifting speed is affected
Other Aspects	LNG tanker is needed

no. Years	10
WACC	10%
δ investment (€)	7,020,000
NPV (€)	2,594,794.75
IRR (%)	18.7
Payback	5
Cash Flow (€)	1,669,518

Figure 22. LNG RTG Retrofitting with Small Gas Engine Alternative

Source: Noatum and Fundación Valenciaport, 2014

The second alternative involved replacing current diesel generators with a medium-sized gas engine (nominal power over 450 kW) to provide a fuel consumption saving of 10 l/h. The cost of this unit was estimated at €170,000 plus the cost of the LNG tanker. The annual saving per unit was estimated at €35,000. Figure 23 shows the investment profitability outputs obtained from the single-variable model application.

RTG B LNG RETROFITTING: MEDIUM GAS ENGINE	
Number of Machines	24
Investment per Unit	170,000 € + 300,000 € Tanker
Saving	10 l/h + 58% Fuel Cost
Annual Saving / Unit	35,000 €
Loss of Performance	Lifting speed is not affected
Other Aspects	LNG tanker is needed

no. Years	10
WACC	10%
δ investment (€)	6,060,000
NPV (€)	2,394,220.06
IRR (%)	19.2
Payback	5
Cash Flow (€)	1,467,518

Figure 23. LNG RTG Retrofitting with Medium Gas Engine Alternative

Source: Noatum and Fundación Valenciaport, 2014

One of the main findings of this study is that at present no gas generator 100% compatible with RTG cranes is available and certified for the European market.

Taking into account the potential future role of ports as suppliers of LNG as fuel, there is a niche market for LNG compatible gas generators for port machinery.

2.5 ECO-RTG Retrofitting

2.5.1 Technical Aspects

Replacing existing RTG gen-sets with lower power units may be a suitable alternative as this solution is relatively low-cost, and is easy and quick to implement. This alternative could provide significant energy savings and reduce GHG emissions when applied to cranes which use large amounts of energy.

In Activity 1 of the project, a real meter analysis was carried out on a group of RTGs in order to determine the critical factor which increased the fuel consumption of RTG B family in comparison with RTG C. The analysis was carried out on the following RTG models:

- RTG B.1
- RTG B.2
- RTG C.1

A set of standard movements of empty and loaded containers were performed using the selected RTGs as shown in Figure 24.

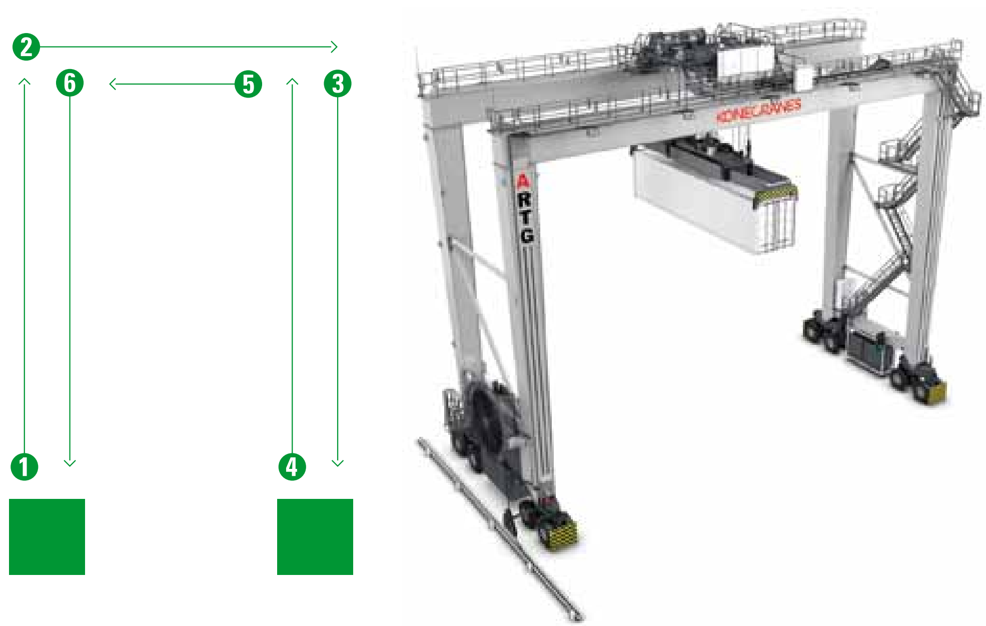


Figure 24. Standard RTG-Cycle Tested to Determine Energy Performance

Source: ABB and Konecranes, 2014

The analysis included testing under empty and loaded conditions. The loaded test involved a maximum load container (39 tonnes).

- Movement 1: Empty and loaded, combined with movement 2.
- Movement 2: Empty and loaded, combined with movement 1.
- Movement 3: Empty and loaded.
- Movement 4: Empty and loaded, combined with movement 5.
- Movement 5: Empty and loaded, combined with movement 4.
- Movement 6: Empty and loaded.

Movement 1 was also tested in the following conditions:

- Empty and loaded at maximum speed.
- Empty and loaded at average speed.

The main conclusions obtained from the analysis of RTG cycles can be summarized as follows:

- The gen-sets installed in the RTG Bs gave a nominal engine power of 900 HP (671 kW), whereas the RTG C units had 700 HP engines (522 kW).
- All the RTGs tested had implemented the ECO system which reduces the speed generator to 700 rpm after three minutes of crane inactivity.
- Power consumption during the test stood at around 330 kW when lifting containers, and 370 kW when lifting and moving them horizontally at the same time (hoist and trolley).
- The use of active rectifier sources made the power factor almost 1, which generated equal apparent and active power. Thus, the power gen-set could be reduced without losing performance.
- During the lift-down cycle in the RTG C unit, a negative current of 50A was registered, which implied power recovery of 25-30 kVA.
- Since RTGs mainly idle (without trolley and hoist movements), a large part of the RTG Bs units' energy inefficiency is due to the over-sized generators installed on the cranes, which directly pushes up energy consumption.

Two possible alternatives were considered to replace generators:

- Installation of a smaller gen-set (450-500 kW of nominal power), with lower consumption (16-18 l/h) than the existing equipment (28-30 l/h), yet maintaining operational performances (elevation speed, maximum load weight, etc.).
- Installation of a smaller gen-set with nominal power below 450 kW (375-400 kW) and lower consumption (13-14 l/h) requiring adjustment on operational performance and slightly increasing the time cycle (around 2%).

Figure 25. Example of Gen-Set Room and Electrical Control System

Source: Noatum, 2014

2.5.2 Environmental Aspects

The two selected alternatives would have a significant impact on reducing the amount of CO_2 emissions generated. Compared to the base scenario, in which the RTG B fleet consumes around 28 l/h in its operations, there are two possible alternatives, as described in the previous section.

On the one hand, replacing current 900 HP of nominal power (670 kW) diesel generators with smaller 450 kW generators that use 16 litres of fuel per hour would reduce the amount of CO_2 emissions by 43%. This reduction would be reached by replacing the generators in the entire RTG B fleet. In the case of the RTG B.2 group, the replacement would only affect the gen-set equipment, but in the case of the RTG B.1 units, the electrical control room would also have to be replaced as the drives and electronic systems are obsolete.

On the other hand, replacing the current RTG B generators with smaller generators whose nominal power is under 450 kW and which use 13 litres of fuel per hour would produce a reduction of 53% in CO_2 emissions. This second option would require adjustments to be made to operational performances (hoist and trolley speeds) and would increase the RTG cycle time by around 5%, although this percentage is small and is compatible with container operations. Additionally, studies would need to be carried out as to whether a nominal power lower than 450 kW is enough to ensure safety conditions in maximum load container operations.

Figure 26 compares the base scenario and the two possible generator replacement alternatives.

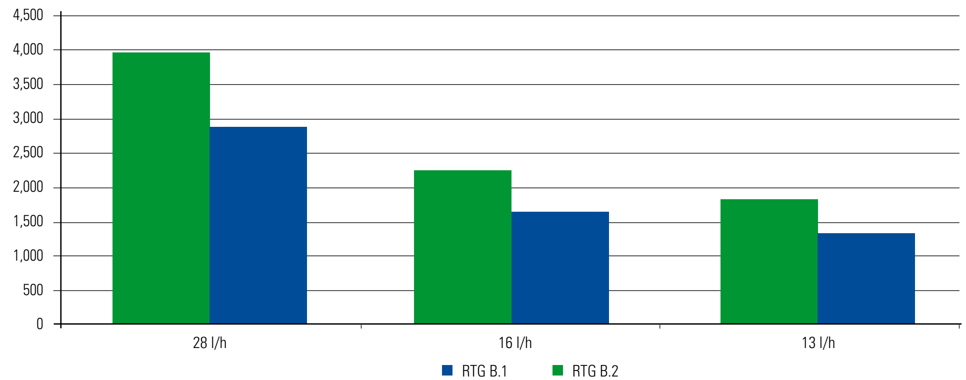


Figure 26. CO_2 Emission Reduction Comparing Different RTG Gen-Sets

Source: Noatum and Fundación Valenciaport, 2014

2.5.3 Financial Feasibility Analysis

This section details the financial feasibility analysis of the RTG motorization retrofitting alternative. The first option assessed was LNG retrofitting with a small-sized (nominal power 375-400 kW) gas gen-set to provide a fuel consumption saving of 14 l/h compared to the current diesel generator. The cost of this unit was estimated at €90,000. The annual saving per unit was estimated at €41,000. Figure 27 shows the investment profitability outputs obtained from the single-variable model application.

RTG B LNG RETROFITTING 13 LITRE GEN-SET	
Number of Machines	24
Investment per Unit	90,000 €
Saving	14 l/h
Annual Saving / Unit	41,000 € / unit
Loss of Performance	-15% Maximum lifting speed

no. Years	10
WACC	10%
δ investment (€)	2,160,000
NPV (€)	3,598,655.24
IRR (%)	44.6
Payback	4
Cash Flow (€)	999,936

Figure 27. Diesel RTG Retrofitting with Small Gas Engine Alternative

Source: Noatum and Fundación Valenciaport, 2014

The second alternative centred on replacing the current diesel generators with a medium-sized gas engine (450 kW of nominal power) to provide a fuel consumption saving of 10 l/h. The cost of this unit was estimated at €50,000. The annual saving per unit was estimated at €30,000. Figure 28 shows the investment profitability outputs obtained from the single-variable model application.

RTG B LNG RETROFITTING 16 LITRE GEN-SET	
Number of Machines	24
Investment per Unit	50,000 €
Saving	10 l/h
Annual Saving / Unit	30,000 € / unit
Loss of Performance	Lifting speed is not affected

no. Years	10
WACC	10%
δ investment (€)	1,200,000
NPV (€)	2,913,325.17
IRR (%)	58.5
Payback	3
Cash Flow (€)	714,240

Figure 28. Diesel RTG Retrofitting with Medium Gas Engine Alternative

Source: Noatum and Fundación Valenciaport, 2014

Thus, it can be concluded that re-motorization of oversized gen-sets is an interesting alternative and feasible from a technical point of view as well as from a financial perspective. Moreover, there would also be a major reduction of GHG emissions as a result of the significant decrease in fuel consumption (up to 50%).

2.6 ADAPTING REACH STACKERS TO RUN ON LNG DUAL-FUEL TECHNOLOGY

2.6.1 Technical Aspects

Dual-fuel technology consists of installing an air and gas mixer in the engine inlet air flow before the turbochargers. The gas flow is electronically controlled by a throttling valve, which operates according to the required engine output and speed. In order to avoid engine knocking a knocking detector/controller is installed, thus enabling the engine to operate at the most efficient gas/diesel ratio.

For diesel engine reach stackers to run on dual-fuel technology, they need to be adapted as follows:

- They require the installation of an additional LNG tank.
- Additional LNG injectors must be added to the existing diesel engine.
- The control and power conditioning electronics have to be integrated and tested.

With a dual-fuel solution, the diesel engine does not need any invasive structural changes and leaves the main components unchanged. The gas is introduced into the system by an additional fuel injector that can be added to diesel engines with minimal modifications to the cylinder head. No special pistons or cylinder are needed. The injected gas comes from a special tank, which is sized according to the required endurance. The following figures illustrate the operation of the dual-fuel system.

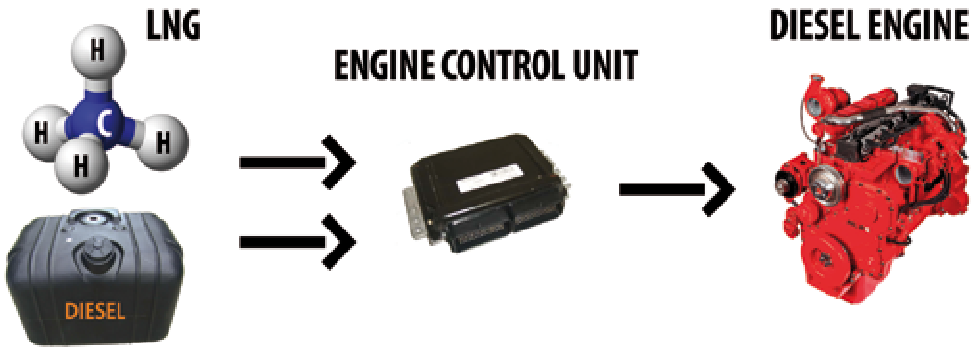


Figure 29. Dual-Fuel System Scheme

Source: Eco-Motive Solutions (Holdim Group), 2014

The dual-fuel system feeds the diesel engine with a mixture of LNG and diesel fuel. A measured quantity of natural gas is mixed with the air just before it enters the cylinder where it is compressed at the same pressure as when a diesel engine is fed with diesel fuel. The natural gas and air mixture does not ignite spontaneously under compression, so in the dual-fuel system the injection of diesel fuel acts like a spark-plug, igniting the main gas and air mixture. The ratio between the gas and air mixture and the diesel fuel is calculated by an electronic system that interacts with the original engine management system.

The dual-fuel system can be fitted to a standard diesel engine, which continues to operate normally. The most relevant difference is that the majority of power is generated by the combustion of natural gas which generates fewer polluting substances and GHG than diesel fuel.

The energy density of LNG fuel is 20%/30% less than diesel fuel and the typical diesel/gas ratio is 40%/50%. Thus, to obtain the same autonomy as unconverted reach stackers, the LNG tank must have a capacity of 288-390 litres (for a reach stacker which has a 600-litre diesel tank).

There are two alternative solutions for these volumes of LNG: a tank of about 420 litres (for example, the 410 l model HNLG-119 made by Chart) or two tanks of about 210 litres (for example model HNLG - 72 made by Chart that contains 245 litres).

However, there are other types of different-sized tanks on the market so designers can choose how to make the most appropriate use of the available space without impeding visibility and safety. Dual-fuel technology is the solution that creates the least impact in fuel-tank displacement in comparison with CNG, H_2, and LNG.

In addition to the Chart models, an LNG tank can be tailor-made to specific design requirements (diameter and length). Global Service has already enlisted the cooperation of HVM s.r.l., a leading company in the production and maintenance of cryogenic tanks.

A dual-fuel solution does not have the limitations of the previous solutions, in fact:

- **It requires a smaller volume LNG tank which can be positioned outside the vehicle.**
- **It avoids the problem of stopping vehicles out of operational periods as a result of a lack of LNG fuel (the dual-fuel engine can work with 100% diesel fuel).**

On the other hand, a dual-fuel solution has fewer benefits for the environment compared to the others. However, after weighing up all of these factors, the final decision foresees adapting reach stackers to run on LNG/diesel dual-fuel technology. Following this decision, a technical feasibility study was conducted by the Global Service team on four reach stackers made by the following three different brands equipped with three different types of engines:

- Kalmar Mod. DRF 450/65S5 - Engine on board: Volvo TAD 1250 VE; diesel fuel tank capacity: 550 litres; hydraulic oil tank capacity: 600 litres.
- Kalmar Mod. DRF 450/65S5 - Engine on board: Cummins QSM11.
- Konecranes Mod. SMV TB5 - Engine on board Volvo TAD 1250 VE; diesel fuel tank capacity: 650 litres; hydraulic oil tank capacity: 600 litres.
- CVS Mod. F478 - Engine on board Scania DC 1258; diesel fuel tank capacity: 530 litres; hydraulic oil tank capacity: 600 litres.

Kalmar and Konecranes models both have:

- The diesel tank on the left side of the cockpit and the hydraulic oil tank on the right.
- A ladder to climb on board on the left side of the cockpit.
- The same model of Volvo engine.

The Kalmar model also uses the Cummins engine. The Global Service team has verified that:

- The layout of these two models leaves enough room to place the additional LNG tank on the right side of the cockpit.

Picture of the left side of the Kalmar reach stacker cockpit, showing limitd space for LNG tank positioning

Picture of the right side of the Kalmar reach stacker cockpit, ideal for LNG tank positioning

Figure 30. Reach Stacker Possible Positioning for LNG Tank (I)

Source: Global Service, 2014

Slurce: Chart Inc. US

Slurce: Global Service

Figure 31. LNG Cryogenic Tank

Source: Global Service, 2014

2.6.2 Environmental Aspects

Dual-fuel engines significantly decrease pollution: CO, HC, NO_X and particulate matter (PM). Furthermore, they reduce CO_2 emissions into the atmosphere thanks to the high percentage of gas in the combined mixture.

2.6.3 Financial Feasibility Analysis

The dual-fuel alternative financial feasibility analysis used the same inputs as in the previous case (full LNG-powered reach stackers), except for the following:

- Diesel consumption per machine: 6.99 l/h (consumption 50% LNG and 50% diesel).
- Differential cost per machine: €30,000 (retrofitting investment per unit, dual-fuel kit).
- Cost of the LNG fuel station: €400,000 (reduction of €50,000 in the cost of the LNG fuel station since the LNG tank would be smaller than in the case of 100% LNG reach stackers).

New RS	δ INVESTMENT (€)	NPV (€)	IRR (%)	Payback
-	430,000 €	-316,614 €	-14.25%	41
1	460,000 €	-239,790 €	-5.12%	41
2	490,000 €	-172,042 €	0.52%	15
3	520,000 €	-115,814 €	4.26%	12
4	550,000 €	-68,975 €	6.87%	11
5	580,000 €	-29,222 €	8.77%	9
6	610,000 €	5,032 €	10.20%	9
7	640,000 €	34,142 €	11.26%	8
8	670,000 €	52,012 €	11.81%	8
9	700,000 €	57,145 €	11.89%	7
10	730,000 €	48,749 €	11.54%	7
11	760,000 €	29,799 €	10.91%	7
12	790,000 €	4,352 €	10.13%	7
13	820,000 €	-24,200 €	9.31%	7
14	820,000 €	-24,200 €	9.31%	7
15	820,000 €	-24,200 €	9.31%	7
16	820,000 €	-24,200 €	9.31%	7
17	820,000 €	-24,200 €	9.31%	7
18	820,000 €	-24,200 €	9.31%	7
19	820,000 €	-24,200 €	9.31%	7
20	820,000 €	-24,200 €	9.31%	7
21	820,000 €	-24,200 €	9.31%	7
22	820,000 €	-24,200 €	9.31%	7
23	820,000 €	-24,200 €	9.31%	7
24	820,000 €	-24,200 €	9.31%	7
25	820,000 €	-24,200 €	9.31%	7
26	820,000 €	-24,200 €	9.31%	7
27	820,000 €	-24,200 €	9.31%	7

Table 8. Single Variable Model Outputs. Dual-Fuel Reach Stacker

Source: Noatum, Global Service, TDT and Fundación Valenciaport, 2014

no. Years	10
WACC	10%
δ investment (€)	700,000.00
NPV (€)	57,145.02
IRR (%)	11.89
Payback	7

Table 9. Profitability Investment Summary Dual-Fuel Reach Stacker

Source: Noatum and Fundación Valenciaport, 2014

The previous table shows that the maximum profitability of the investment was reached when 10 reach stackers were retrofitted. A ten-year investment horizon would require a total investment of €700,000, payback would be achieved in 7 years and IRR would be 11.89%.

Figure 32 shows the evolution of NPV and IRR based on dual-fuel retrofitting of reach stackers.

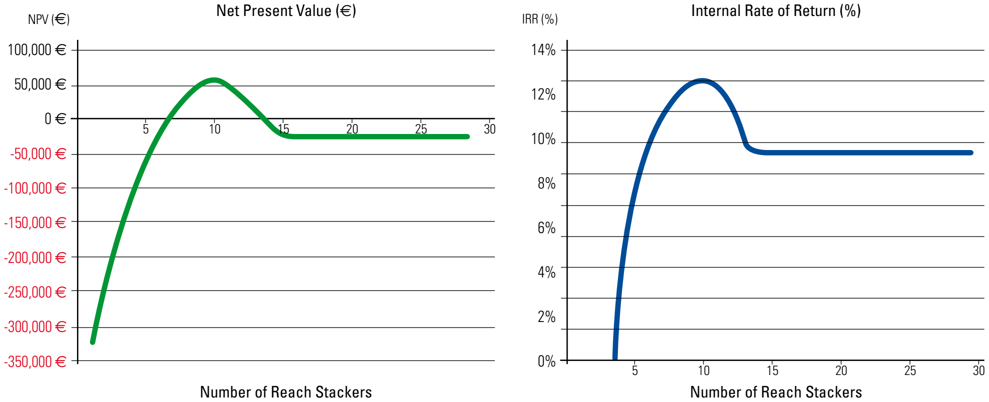


Figure 32. Net Present Value and IRR. Dual-Fuel Reach Stacker

Source: Global Service, Noatum and Fundación Valenciaport, 2014

The second option was sharply affected by the size of the fleet (there were not enough number of units working) and by the demand curve (there were too many shifts in which only 0, 1, or 2 machines were required). The following table shows results based on another demand curve, where the reach stackers work more intensively. The number of shifts in which few machines were required was reduced and increased by the same number in the shifts where more machines worked.

2012 Demand Curve

No. Reach Stackers	No. Shifts
0	283
1	113
2	158
3	157
4	84
5	82
6	68
7	177
8	120
9	120
10	77
11	39
12	15
13	4

Hipothetical Demand curve

No. Reach Stackers	No. Shifts
0	83
1	13
2	183
3	182
4	109
5	107
6	93
7	169
8	145
9	145
10	102
11	64
12	40
13	29

Table 10. Example of Hypothetical Shift Assignment

Source: Noatum, Global Service, TDT and Fundación Valenciaport, 2014

200 shifts from the first row (number of shifts with zero machines assigned) and 100 shifts from the second row (number of shifts with 1 machine assigned) were redistributed along the rest of rows (25 shifts per row) in order to smooth out the demand curve. The following graph shows the results of this simulation.

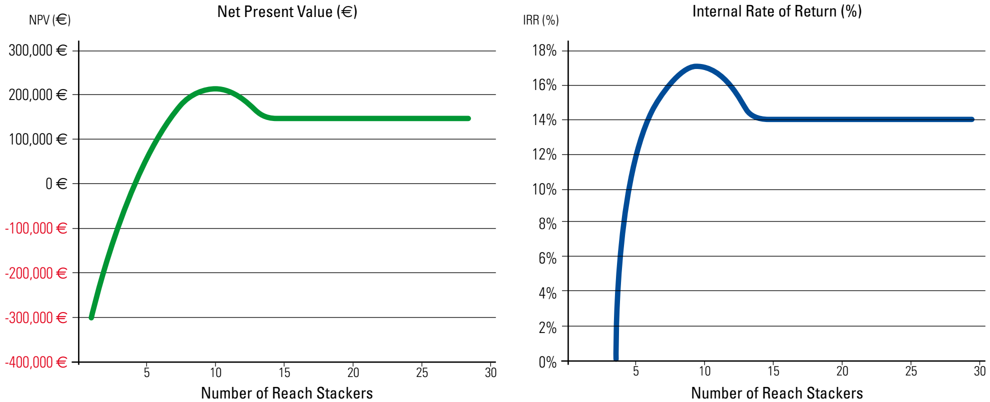


Figure 33. Net Present Value and IRR. Dual-Fuel Reach Stacker (Hypothetical Demand)

Source: Global Service, Noatum and Fundación Valenciaport, 2014

The main findings of this part of the study are:

*** Dual fuel technology may be the most appropriate solution for some port container terminals as it does not have the limitations of pure LNG solutions.**

*** A dual fuel solution requires a smaller volume of LNG tank which can be positioned outside the port vehicle.**

*** It also resolves the problem of having to stop vehicles as a result of a lack of LNG fuel.**

2.7 IMPLEMENTATION OF ENERGY MANAGEMENT SYSTEMS

An Energy Management System (EMS) helps organizations to integrate energy management into their business structures, thus saving energy and costs and also improving their energy, environmental, and business performance. Standards or documents that define energy management systems constitute the basic framework for organizations to establish good practices that improve energy efficiency. Conversely, misunderstanding the basic guidelines on energy management systems, or failing to comply with them, will move them away from energy efficiency improvements.

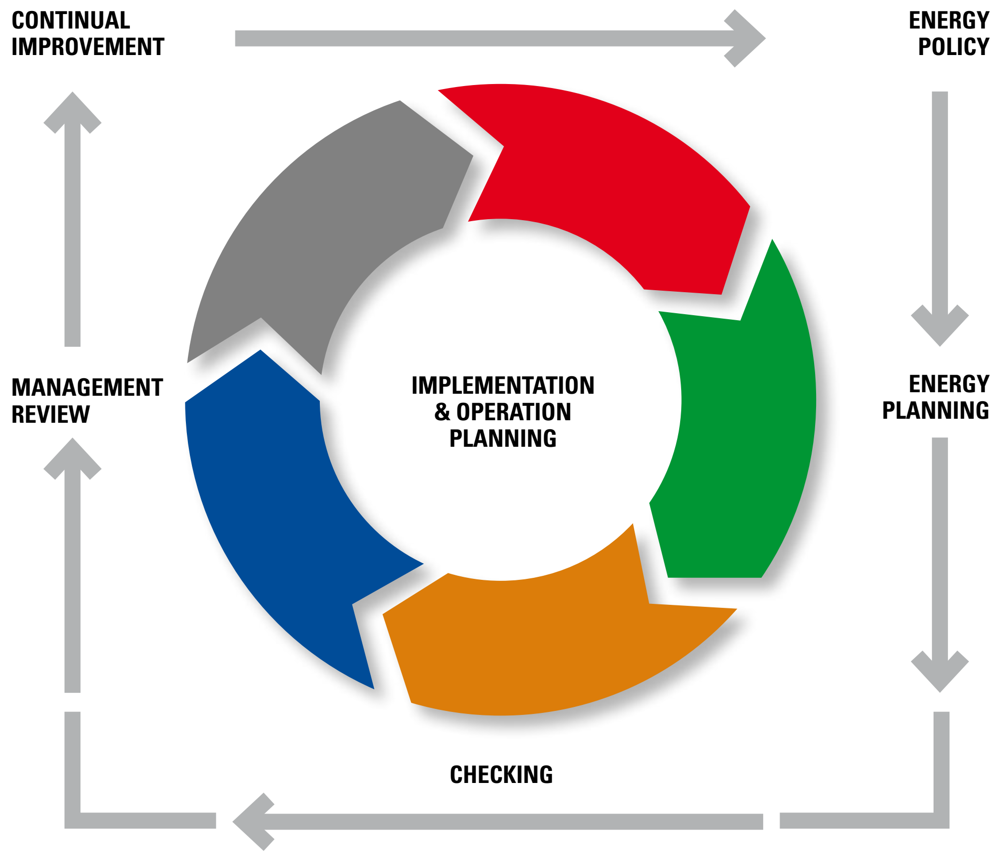
Ireland's Energy Management Standard IS 393 (2005) was the basis for the European EN 16001 standard that was adopted in July 2009. In June 2011, international standard ISO 50001 was adopted and represented an upgrade in terms of European standards. In December 2011, the Slovenian Institute for Standardization implemented its SIST EN ISO 50001 energy management standard in its national standardization scheme. In addition to standards, another important document that sets out the scope of energy management systems is the reference document in the IPPC "Energy Efficiency" Directive, which was released in February 2009. The "Energy Efficiency" reference document provides the best available techniques on energy efficiency, which larger organizations must meet to obtain an environmental permit.

An energy management system implemented according to the EN ISO 50001 standard is structurally similar to a quality management system (ISO 9001) or an environmental management system (ISO 14001). Standards in the field of management systems are a set of available best practices, which means that their implementation on the largest possible scale should be encouraged. One of the biggest obstacles in energy management system implementation, according to the EN ISO 50001 standard, is partial understanding of the provisions of the standard which can greatly limit effective implementation.

If an organization implements and maintains an energy management system based on a best available technique approach, it will continuously improve its energy performance year on year. Long-term cost savings of over 20% are regularly achieved.

Luka Koper has already established its quality management system according to EN ISO 9001, and its environmental management system, according to EN ISO 14001. Beside these two standards, Luka Koper has also implemented the ISO 22001 Food Safety Management System standard (2005) and the OHSAS 18001 Occupational Health and Safety Standard (2007).

ISO 50001 ENERGY MANAGEMENT SYSTEM



3 PILOT TESTS AND DEMONSTRATIONS

3.1 Pilot Test 1: LNG-Fuelled Terminal Tractor

The LNG-fuelled pilot test consisted of the design, manufacturing, and deployment of the first European LNG-powered yard tractor prototype in a port container terminal. The prototype was tested against a diesel-powered terminal tractor equipped with the latest emission control standards Stage IIIB. Both machines performed the same types of operations (horizontal transport, maritime and land operations, etc.) in order to obtain comparable data (fuel consumption, GHG emissions, cycle timing, etc.) and demonstrate the feasibility of adopting LNG as a suitable fuel at European port container terminals. The pilot test consisted of two different, parallel phases:

1. Development and testing of the LNG terminal tractor prototype.
2. Definition of a legal framework for LNG supply to ensure supply availability at NCTV.

1. Development and testing of the LNG terminal tractor prototype

Figure 34. LNG-Powered Terminal Tractor Prototype

Source: TERBERG and ALFALAND, 2014

This phase of the project represented a major challenge since there were no similar machines or prototypes on the market at the time. Thus, the LNG terminal tractor designed in the framework of GREENCRANES was the first machine to run on LNG at European port container terminals. The LNG yard tractor was developed by the companies Terberg, Alfaland, and Cummins Westport. These companies were chosen by Noatum under a competitive public tender to develop the LNG prototype which was put out in February 2013.

The prototype design respected the original functional structure of the standard machine, although some changes were introduced to ensure the operational compatibility of the new units in the real container terminal scenario. Thus, the new engine structure shared the same diesel technology such as the engine block, crankshaft, main bearing, piston rods, and exhaust gas recirculation.

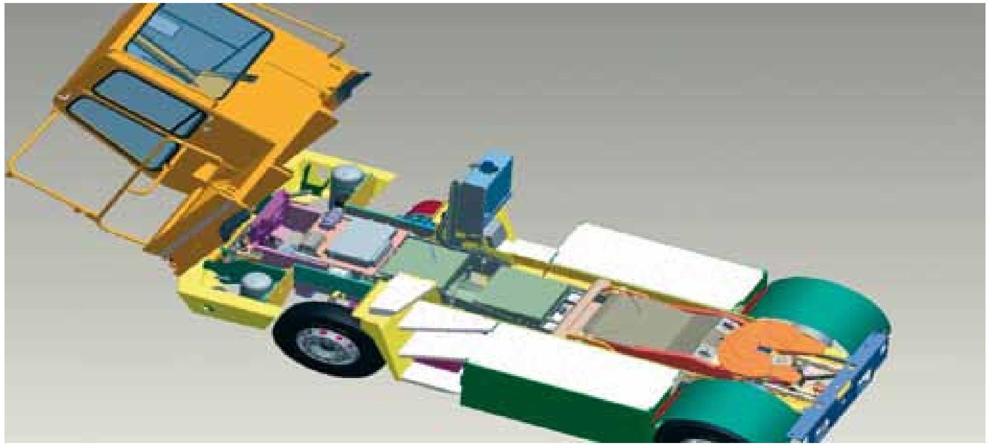


Figure 35. Simulation Design of the LNG Terminal Tractor

Source: TERBERG and ALFALAND, 2014

The most significant changes compared to the existing diesel units involved the positioning and size of the LNG tank, which was placed on the left side of the vehicle, and the distance between wheel shafts. In addition, the hydraulic tank, battery, and air compressor were all placed together on the right side of the machine.

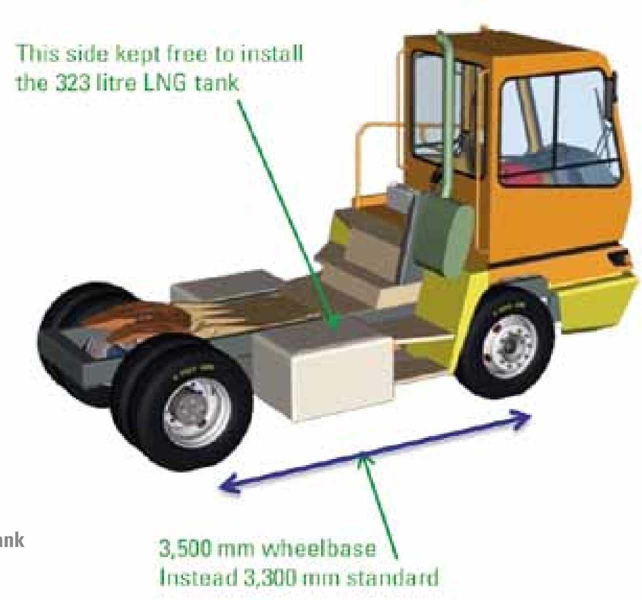


Figure 36. Location and Volume of the LNG Tank

Source: TERBERG and ALFALAND, 2014

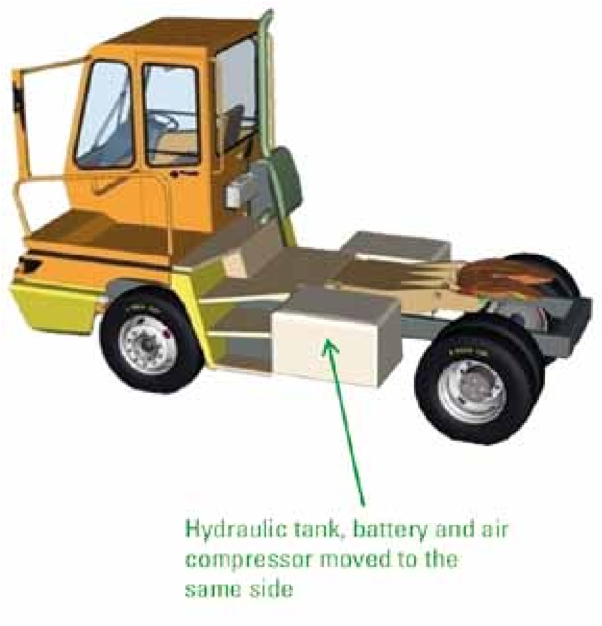


Figure 37. Location of Hydraulic Tank, Battery and Air Compressor

Source: TERBERG and ALFALAND, 2014

2. Definition of a legal framework for LNG supply to ensure supply availability at NCTV

The second phase of the pilot project (which ran in parallel to the design and manufacture of the LNG terminal tractor) centred on defining the legal framework (authorizations, permits, etc.) to ensure LNG supply availability at port container terminals. **Supplying LNG as a fuel is a new activity at ports and authorization protocols are in most cases undefined or have important gaps which must be addressed. This pilot project constituted a great opportunity to tackle uncertainties as all the affected stakeholders - port authorities, energy and technology providers as well as private operators - were involved in the scheme.** Alongside the development of the LNG terminal tractor prototype, Noatum launched a competitive public tender in May 2013 to choose an LNG provider.

The Spanish company, Gas Natural Servicios, was the provider selected, together with the technological partner, Ham Criogénica S.L. The selected solution for the supply of LNG during the pilot project was based on the provision of a mobile LNG fuel station which supplied LNG to the terminal tractor prototype during the pilot project (between one and three months). In order to allow LNG supply and refuelling operations at NCTV, a set of authorizations and permits had to be provided by the Port Authority of Valencia, as well as by other authorities such as the Spanish Ministry of Industry, and the Regional Ministry of Infrastructure and Transport.

The pilot project defined a roadmap for the necessary authorizations and permits. This roadmap will be useful for different stakeholders who may wish to introduce LNG as a fuel in other Spanish and European ports.

During the pilot project, LNG was supplied by a mobile LNG fuel station. This fuel station was refilled with tankers from the nearby LNG plant located at the Port of Sagunto, 30 km north of the Port of Valencia. Under this system, a flexible LNG supply was provided to the LNG terminal tractor during the testing period between October and December 2013.

Figure 38. Mobile LNG Supply Fuel Station

Source: HAM, 2014

This prototype was tested against the latest-generation diesel terminal tractor which complied with the Stage IIIB standard, and provided excellent results in terms of performance, energy consumption, and reducing pollutant emissions (elimination of particulate matter and reduction of 90% in nitrogen compounds as well as the reduction of CO_2 emissions). The LNG terminal tractor prototype was the first experience at European level in using LNG as a fuel in the port industry, and provided very promising perspectives for the short-term market of LNG vehicle fleets at European ports.

The LNG terminal prototype was the first experience in developing a regulatory framework for the safe and efficient supply of LNG at port terminals. Successful cooperation between the Port Authority of Valencia (government), Noatum (port operator), and Gas Natural Fenosa – HAM (energy provider and technological supplier) produced a roadmap which defined the steps needed to effectively deploy an LNG supply infrastructure for these facilities.

Figure 39. LNG Terminal Tractor Prototype at Noatum Container Terminal Valencia

Source: Noatum, 2014

The pilot test was conducted at Noatum Container Terminal Valencia where both vehicles (LNG and diesel units) worked during nearly 1,000 hours. During this period of time, both machines were monitored to obtain as much information as possible from both tractors. The purpose of the pilot project was to determine which technology (LNG or diesel) gave the best performance for different criteria: fuel consumption, autonomy, reducing emissions, etc.

The following figures show the main results of the test on different vehicles at the terminal (4th G and Gas 2nd correspond to the latest-generation diesel terminal tractor and the LNG prototype respectively).

The first figure shows fuel consumption rates, energy consumption and vehicle autonomy. In the case of the LNG terminal tractor, **the gas engine cylinder capacity was higher than that of the diesel engine as there were no suitable gas engines on the market for the required power application: 8,900 cm³ for LNG against 6,700 cm³ for diesel.** As a result of this, recommendations for gas engine manufacturers were defined as they would need to provide suitable gas engines for port terminal tractor fleets if this type of LNG terminal tractor is to be successful on the market.

		Fuel l/h; kg/h	Energy (kwh/h)	Autonomy (hours)
1st G	VOLVO 720 TAD	8.2	88	18-20
2nd G	VOLVO 750 TAD (Stage IIIA)	7.5	81	20-22
3rd G	CUMMINS QSB 6.7 (Stage IIIA)	6.3	68	+24
4th G	CUMMINS ISB6.7E5-225 (Stage IIIB)	5.7	61	+24
Gas 2nd	CUMMINS ISL9 G 250 (Stage IV)	6.9	101	17-18

Figure 40. Energy Performance and Fuel Consumption Results in GREENCRANES

Source: Noatum, 2014

The following table shows reductions in particulate matter and NO_X for the same vehicles. It should be noted that the LNG prototype was competing against an optimised and commercially developed diesel terminal tractor vehicle. However, the results were very good for the LNG prototype. The potential of this prototype in a commercial and optimised version would be very promising taking into account the results obtained.

		PM (g/h)	Nox (g/h)
1st G	VOLVO 720 TAD	9.6	481
2nd G	VOLVO 750 TAD (Stage IIIA)	8.8	292
3rd G	CUMMINS QSB 6.7 (Stage IIIA)	11.6	229
4th G	CUMMINS ISB6.7E5-225 (Stage IIIB)	1.0	33
Gas 2nd	CUMMINS ISL9 G 250 (Stage IV)	0.0	39

Figure 41. Particulate Matter and NOX Emission Results in GREENCRANES

Source: Noatum, 2014

3.2 Pilot Test 2: ECO-RTG Retrofitting

The second pilot project carried out at Noatum Container Terminal Valencia (NCTV) focused on rubber-tyred gantry (RTG) crane retrofitting to significantly reduce fuel consumption and GHG emissions. The selected solutions were adopted after a thorough analysis of different alternatives. Electrification and LNG retrofitting were studied but were not finally considered for pilot development for financial reasons in the case of electrification, and technical and safety reasons in the case of LNG retrofitting.

The RTG retrofitting pilot test was based on the conclusions drawn from Activities 1 and 2 of the project in terms of the oversized gen-sets installed in a large number of cranes. The analysis carried out included tests in empty and loaded conditions. The loaded test was carried out with a maximum load container (39 tonnes).

Re-motorization of RTG gen-sets is an interesting alternative, and is feasible from a technical point of view as well as from a financial perspective. Moreover, there would also be a major reduction of GHG emissions as a result of the significant decrease in fuel consumption (up to 50%).

Two possible alternatives were considered to replace the generators:

- Installation of a smaller gen-set of over 450 kW (500 kW, 15 litre displacement) of nominal power, with lower consumption (estimated at 16-18 l/h) than the existing equipment (28-30 l/h) yet maintaining the same operational performances (elevation speed, maximum load weight, etc.).
- Installation of a smaller gen-set with nominal power below 450 kW (375-400 kW and 13L displacement) and lower consumption (13-14 l/h) requiring adjustments on operational performance and slightly increasing the time cycle (estimated at around 2%).

The different tests took place in May-June 2013 and are shown in the following figures.

Figure 42. RTG Operating with 15L Displacement Gen-Set
Source: Noatum, 2014

The initial results of the tests performed showed that fuel consumption was still higher than expected, at around 20 l/h. Thus, more adjustments and improvements were carried out over the following months to achieve the fuel consumption objective of 16 l/h. These adjustments centred on optimizing the power management of the electronic systems which controlled the conversion of thermal energy in the engine to electrical energy.

Figure 43. Tests of the 15L Gen-Set on RTG at NCTV
Source: Noatum and Fundación Valenciaport, 2014

Implementation of the second alternative was more complex as it required reprogramming the crane's electronic system to adjust and properly distribute the power provided by the new gen-set (375-400 kW and 13 litre displacement) to the different elements and devices in the RTG (trolley, hoist, services, etc.). This reprogramming was needed to ensure that the machine could work with less power. This implied some loss of performance which was measured during the test. First estimates showed that the expected loss of performance was acceptable as it would only involve a one or two-minute delay per working hour. Taking into account the fact that RTGs usually have idle times of over ten minutes per working hour, the expected loss of performance would not affect the container terminal's operational model. The activities carried out in the second RTG retrofitting were:

- Dismantling the old gen-set.
- Installing the new gen-set (Volvo model TAD1355GE).

- Reprogramming "idle time" protocols.
- Reprogramming electronic system (Siemens).
- Testing and meters (fuel consumption, cycle timing, etc.).
- Certification of modifications.

In terms of emissions reduction, the two alternatives selected would have a significant impact on the amount of CO_2 generated. Compared to the base scenario, in which the RTG B fleet consumes around 28 l/h in its operations, there are two possible alternatives, as described in the previous section.

On one hand, replacing current 900 HP nominal power (670 kW) diesel generators with smaller 550 kW generators that use 16 litres of fuel per hour would reduce the amount of CO_2 emissions by 43%. This reduction would be reached by replacing the generators in the RTG B.1 fleet. In the case of the RTG B.1 group, the replacement would only affect the gen-set equipment.

On the other hand, replacing the current RTG B.1 generators with smaller engines whose nominal power is under 450 kW and which use 13 litres of fuel per hour would reduce CO_2 emissions by 53%. This second option would require adjustments to be made to operational performances (hoist and trolley speeds) and would increase the RTG cycle time by around 5%. However, this is a low percentage and is compatible with container operations. Additionally, studies would need to be carried out as to whether nominal power below 450 kW is enough to ensure safety conditions in maximum load container operations.

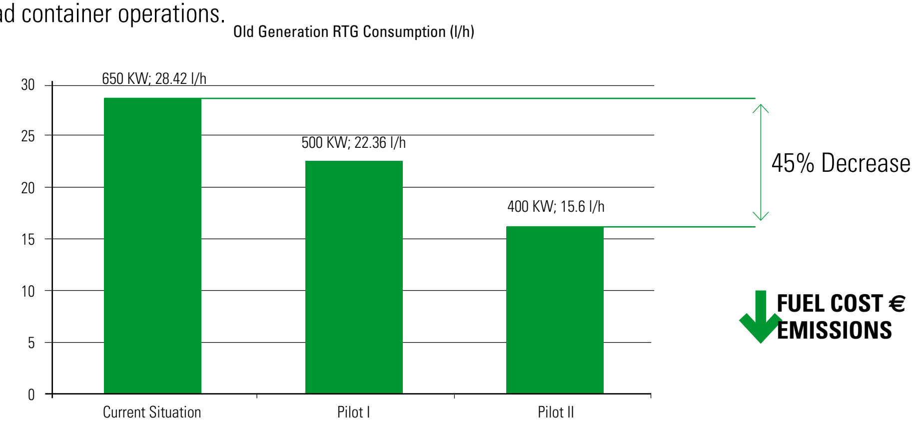


Figure 44. Pilots Results of Fuel Consumption Decrease

Source: Noatum and Fundación Valenciaport, 2014

3.3 Pilot Test 3: LNG Dual-Fuel Reach Stacker

Pilot test 3 included the design, implementation, and testing of a dual-fuel (diesel-LNG) powered reach stacker prototype in a port container terminal. It was a challenging project as the prototype was the first one to be powered with dual-fuel at a European port container terminal. The pilot test identified general requirements and also took into account the constraints and risks which could influence its outcomes. The pilot test was carried out in three main phases:

1. Design and adaptation of the selected solution based on the feasibility studies carried out in Activity 2, where different eco-efficient alternatives were studied from technical, environmental, and financial perspectives.
2. Bench-testing of the engine prototype to verify its technical operation and to identify the corrective measures and improvements to be implemented.
3. Testing of the reach stacker prototype at the Interporto Amerigo Vespucci and at the Darsena Toscana container terminal at the Port of Livorno to obtain comparable data (fuel consumption, GHG emissions, power, timing, etc.) to evaluate and demonstrate improvements in terms of reducing its carbon footprint and the energy the prototype would use.

Following the decision to choose dual-fuel technology (LNG-diesel), a technical feasibility study was conducted by the Global Service team on four reach stackers made by the following three brands (the most widely used brands at Italian terminals) equipped with three different types of engines:

- Kalmar Mod. DRF 450/65S5 - Engine on board Volvo TAD 1250 VE.
- Kalmar Mod. DRF 450/65S5 - Engine on board Cummins QSM11.
- Konecranes Mod. SMV TB5 - Engine on board Volvo TAD 1250 VE.
- CVS Mod. F478 - Engine on board Scania DC 1258.

Kalmar and Konecranes models both have:

- The diesel tank on the left side of the cockpit and the hydraulic oil tank on the right.
- A ladder to climb on board on the left side of the cockpit.

The Global Service team verified that:

- **The layout of the Kalmar and Konecranes models leaves enough room to place the additional LNG tank on the right side of the cockpit.**
- **The Kalmar model offers more options than the Konecranes model in placing the additional tank outside the vehicle.** In fact, the LNG tank can be placed under the chassis in front of the rear wheels or vertically near the right side of the cockpit. Thus, designers can choose

the best location for the tanks whilst ensuring that the systems that connect the cryogenic tank to the engine remain within the specified technical limits.

- **The Cummins engine enables the whole conversion process to take place in Italy without limiting the choice of the most suitable conversion kit.**
- **The CVS model offers fewer options for LNG tank placement than the Kalmar and Konecranes models and would require the installation of a smaller diameter LNG tank on the left side of the cockpit.**

1. Designing and adapting the chosen solution

Based on the above, the most suitable reach stacker for the pilot project was the Kalmar DRF 450-65S5 model, equipped with a Cummins QSM11 engine. This choice was also reinforced by the fact that:

- Kalmar had shown the greatest interest in taking part in the implementation of pilot test 3 and in analyzing future options for industry.
- Global Service has extensive experience in the use and maintenance of Kalmar reach stackers.

The following options for locating the tank were designed and tested:

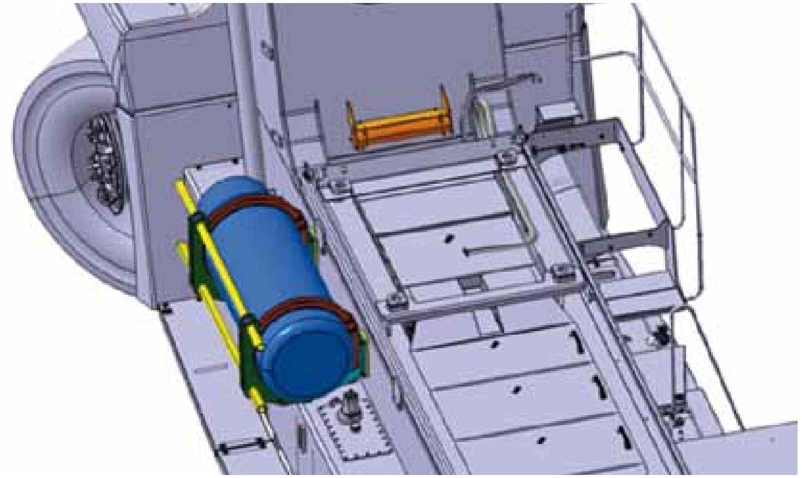


Figure 45. Horizontal Alternative Location on the Right Side of the Cockpit

Source: Global Service, 2014

This solution means easy tank installation, removal, and filling, but could prove more sensitive to possible side bumps and collisions.

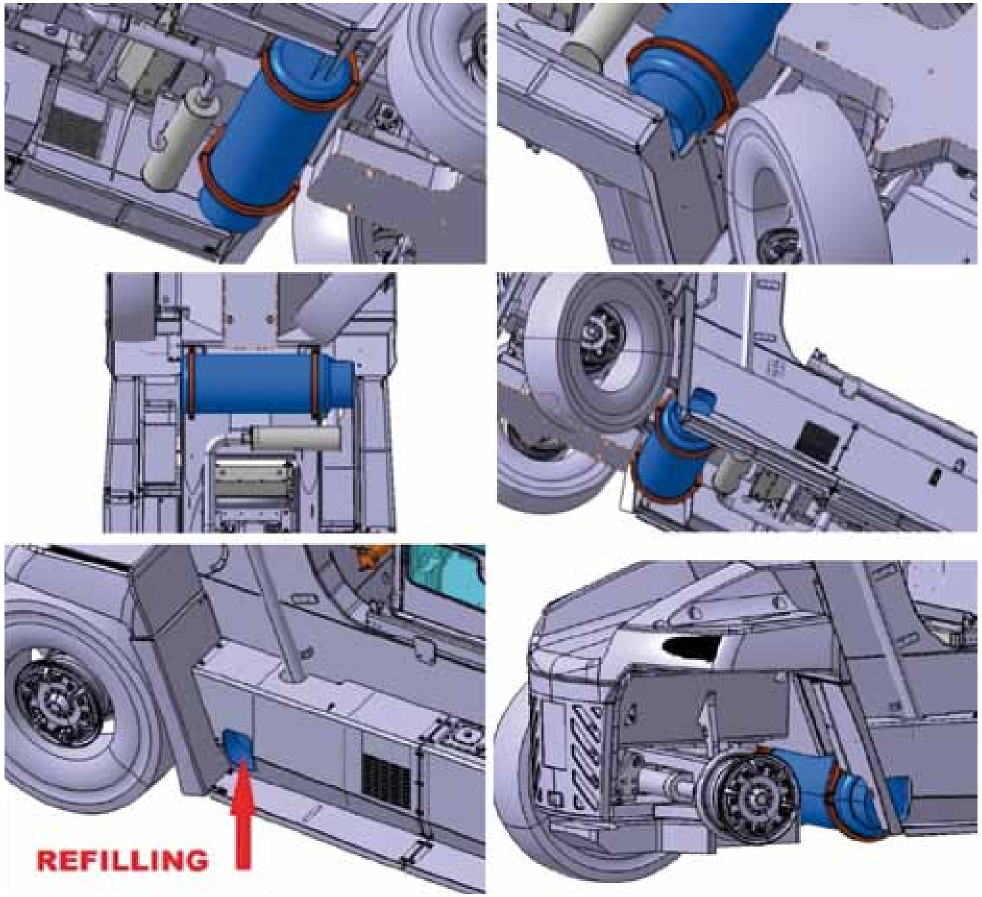


Figure 46. Alternative Location under the Chassis in front of the Rear Wheels

Source: Global Service, 2014

This solution offers excellent protection against bumps and collisions but involves modifying the bodywork to enable refuelling.

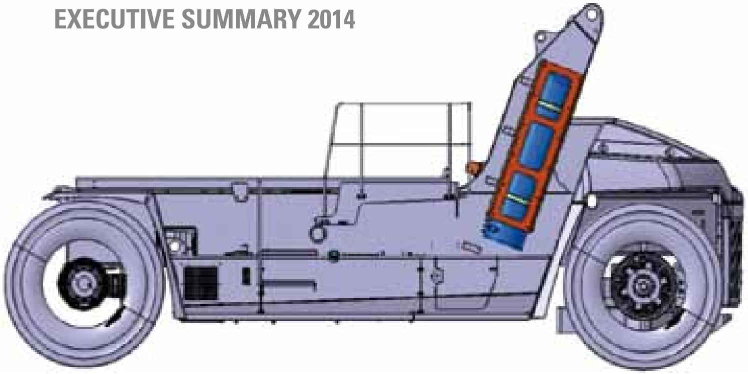


Figure 47. Alternative Location Vertical on the Right Side of the Cockpit

Source: Global Service, 2014

This solution offers more protection against bumps and collisions than the horizontal one, but still involves some refuelling difficulties.

After testing the three options and comparing the pros and cons of each solution, the horizontal position was chosen as being the most suitable. The designer then proceeded to define the size and optimal capacity of the tank by balancing the needs for autonomy with the available space in the reach stacker.

2. The reach stacker engine retrofitting process, from diesel to diesel-LNG

The preliminary steps of the process included dismantling the original Cummins engine from the Kalmar reach stacker; designing and building logistics for the transport and the test-bench; transferring it with the LNG tank to the company Ecomotive Solutions to retrofit the engine and carry out tests on an engine dynamometer.

Figure 48. Engine Retrofitting Activities

Source: Global Service, 2014

3. Tests at the Darsena Toscana container terminal and at the Amerigo Vespucci Interporto

Tests covering the entire operating cycle were carried out at the Amerigo Vespucci Interporto and at the Darsena Toscana container terminal. They aimed to validate the results of the bench tests in the field.

Figure 49. LNG Reach Stacker Prototype Working at Amerigo Vespucci Interporto and Livorno Darsena Toscana

Source: Global Service, 2014

The results of the field tests covering the entire operating cycle of the dual-fuel retrofitted Kalmar DRF 450-65S5 reach stacker with a Cummins QSM 11 engine fully confirmed the results obtained in the bench tests, when compared to the results of the original diesel model.

The power did not decrease and there were no major differences in the oil temperature, exhaust temperature, or intake manifold pressure between the dual-fuel retrofitted reach stacker and the diesel one. Moreover, the running time of the entire operating cycle remained the same.

In terms of fuel consumption, the registered average results were:

- Average fuel consumption of the diesel reach stacker: 16 l/h
- Average fuel consumption of the dual-fuel powered reach stacker:
  - Diesel 8 l/h;
  - LNG 7 kg/h (equal to 17 l/h) with an average replacement rate of 50%.

Given that diesel costs in Italy were €1.2 per litre and LNG costs were €0.8 per litre:

- **The hourly cost of the diesel-powered reach stacker was €19.20**
- **The hourly cost of the dual-fuel powered reach stacker was €15.20 (€9.60 cost of diesel + €5.60 cost of LNG)**

This meant an average cost saving of €4 per working hour (around 25%) with the dual-fuel powered engine compared to the diesel one. Given that a reach stacker averages a total of 4,000-5,000 working hours in a year, retrofitting it to dual-fuel technology would produce average cost savings of €16,000 to €20,000 per year.

3.4 Pilot Test 4: Real-Time Energy Consumption Monitoring System

The aim of the project was to set up a pilot energy monitoring and measurement system for the Port of Koper's container terminal that was based on detailed knowledge of energy consumption by measuring energy use and energy factors, but also enabled the creation of an accountability system for the energy efficiency indicators. The pilot project provided us with experience to extend the implementation of an energy management system that could be applied to the introduction of energy management systems in container terminals at other ports.

Luka Koper carried out the pilot test based on the ISO 50001 standard, which, in practice, generated savings by upgrading the energy management system and lowering greenhouse gas emissions, mainly based on the establishment of an energy efficiency indicator system (energy performance indicators EnPI) and integrating the energy management system into the company's management system.

In order to implement an energy management system, a pilot data capture system of energy consumption and energy factors was established within the project, and energy efficiency factors based on information integration were also created and tested. The established pilot energy consumption and energy factor system of the container terminal that was created within the project was integrated into the existing energy information system (energy efficiency BI), which is established at corporate level.

Since this was a pilot project, the data capture was mainly carried out in areas of significant energy consumption. The results of the successfully implemented pilot project provided the guidelines for further work. The project consisted of four parts:

1. **Pilot implementation of a detailed electrical energy consumption monitoring system at the container terminal (17 measuring points).**
2. **Pilot implementation of a transport machinery monitoring system (4 terminal forklifts, 2 reach stackers, 2 empty container forklifts, 2 RTGs) that also included implementation of wireless communication.**
3. **Pilot implementation of a transport machinery monitoring system that included a pilot upgrade of the information system and pilot implementation of a data monitoring system (fuel consumption monitoring, electrical energy and energy factors) of 7 RTGs made by KONECRANES.**
4. **Information system integration to support the energy monitoring system.**

Detailed information about these four parts is presented below.

1. Pilot implementation of a detailed electrical energy consumption monitoring system at the container terminal (17 measuring points)

A detailed electrical energy consumption monitoring system was implemented by installing additional metering and communications equipment in transformer stations at the Port of Koper's container terminal.

To integrate information, older existing measuring points were included in the monitoring structure along with 17 new measuring points, which meant that 23 measuring points were monitored each minute by the energy efficiency BI – the so called CSRE system.

The implemented pilot system enables an overview of minute-by-minute data and summaries of electrical energy consumption from all measuring points. Data on electrical energy consumption is stored on measuring points and is periodically gathered in the SEP2W system and copied to the CSRE database.

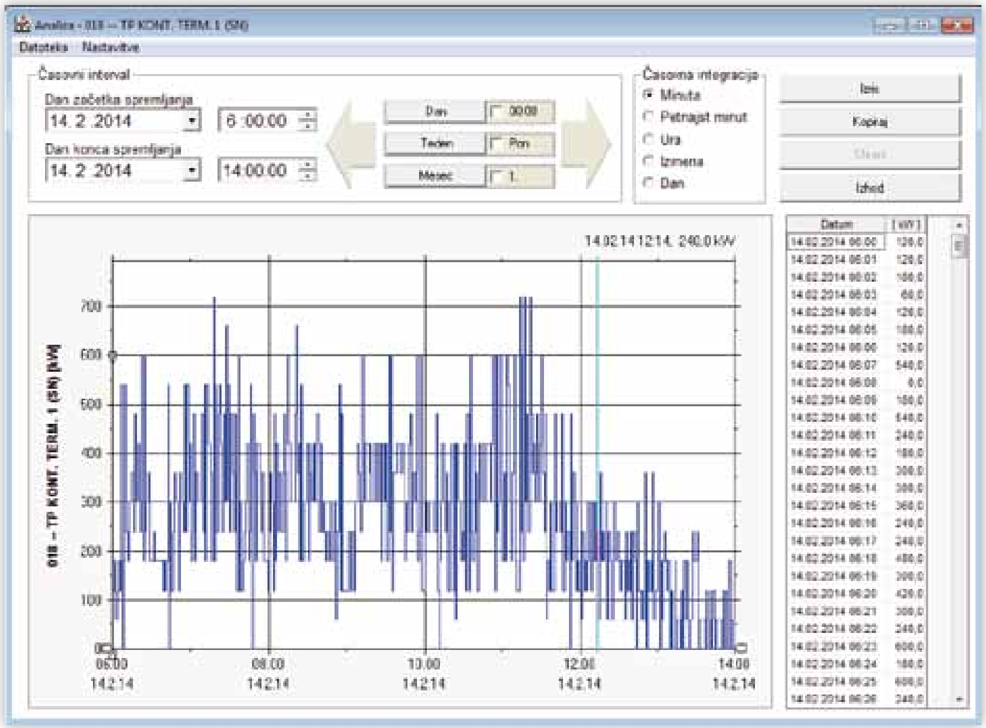


Figure 50. Example of Electrical Consumption Meters at the Koper Container Terminal

Source: Port of Koper, 2014

2. Pilot implementation of a transport machinery monitoring system (4 terminal forklifts, 2 reach stackers, 2 empty container forklifts, 2 RTGs) that also included implementation of wireless communication

The pilot implementation of a transport machinery monitoring system included 4 terminal forklifts, 2 reach stackers, 2 empty container forklifts, and 2 RTGs.

A meter that transmitted current pulses to a communication device was used to monitor fuel consumption. The communication device, in addition to collecting data, also monitors speed, and operating hours, and records vehicle positions. Every minute, the communication device sends data, which is recorded at 10 second intervals, to a server through a wireless connection. The server and the data, in the form of an xml file, can be remotely accessed through a "web" service.

Eight communication devices with software were supplied for the project. The service included five-month access to the server and data.

Conversely, data transfer from the monitoring equipment on two RTGs was implemented through the Konecranes monitoring system.

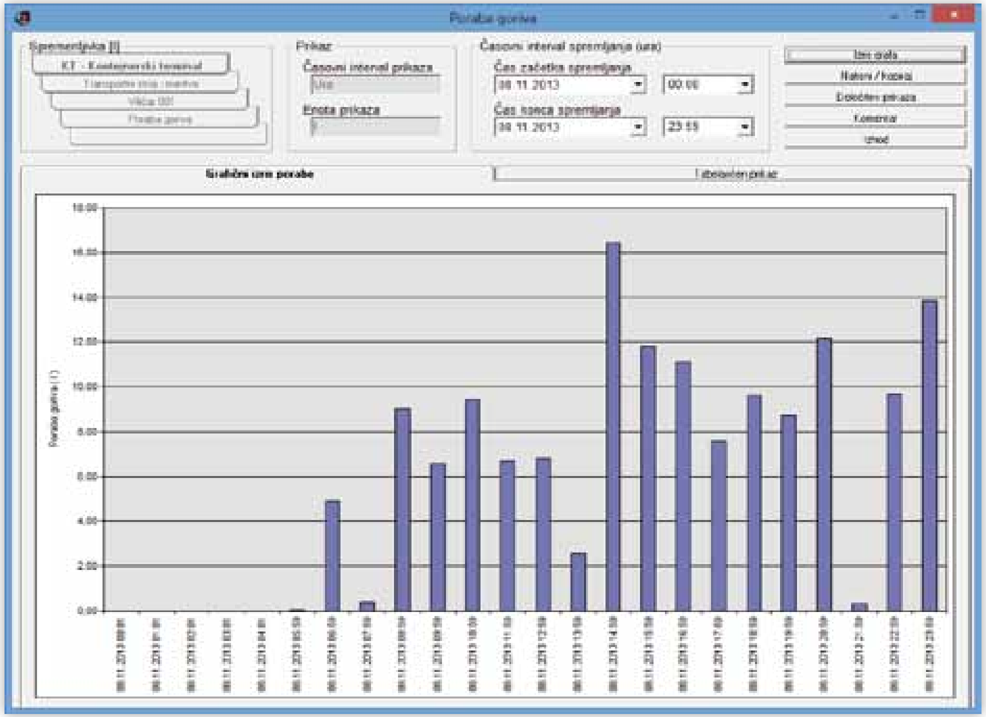


Figure 51. Energy Monitoring System Screenshot

Source: Port of Koper, 2014

3. Pilot implementation of a transport machinery monitoring system that included a pilot upgrade of the information system and pilot implementation of a data monitoring system (fuel consumption monitoring, electrical energy and energy factors) of 7 RTGs made by KONECRANES

The project included a pilot upgrade of the information system and pilot implementation of a data monitoring system (fuel consumption measurements (value from the engine manufacturer, electrical energy and energy factors) of 7 transport machines – RTGs made by the manufacturer KONECRANES. Additionally, fuel consumption monitors were attached to two RTGs, and the monitoring system was also upgraded to include data capture from monitors on all the RTGs in the project.

The integration of information from the production information system enabled a number of new functions that can also evaluate technological processes. For example, the ratio of total moves compared to useful moves has a major impact on energy consumption.

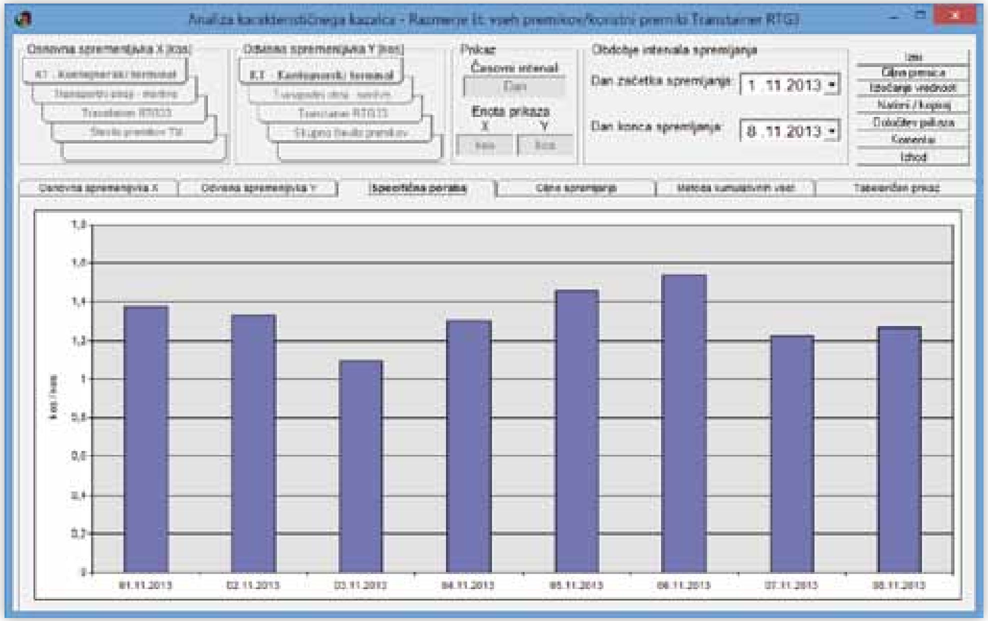


Figure 52. Ratio of All Moves versus Useful Moves

Source: Port of Koper, 2014

The summary analyses (manager button) give an important overview of process efficiency. Given the complexity of the process, it is important to establish a system of summary analyses that explain variations in energy consumption.

4. Information system integration to support the energy monitoring system

The information was integrated into the CSRE energy efficiency system from all the monitoring systems included in the project. Basic energy efficiency factors were defined in the system in accordance with the project assignment.

Besides monitoring energy use in one place, information integration enables the creation of performance indicators and as a result, an upgrade of the accountability systems and implementation of energy optimization and technological processes, as well as targeted action management.

Figure 53. Login Screen of the Energy Monitoring and Information System

Source: Port of Koper, 2014

Based on the implemented pilot project for energy use monitoring, numerous indicators can be established to enable more detailed insight into operational energy efficiency of monitored devices. For example, monitoring the operating hours of transport machines enables the automation of the operation monitoring process, whilst additional fuel use monitoring enables the evaluation of productivity for transport machinery use, not forgetting the technological process and the method of work.

The greatest advantage of automatic data capture is that it enables a detailed analysis of energy use in each monitored machine, and the evaluation of processes that have a direct or daily impact on energy use.

Statistical methods can be used to reveal the consequences of changes in technological and energy processes, but professionally qualified and responsible people are essential to achieve a decrease in energy consumption. It is also fundamental to establish a system of performance indicators, based on formally defined target values at corporate level or at a container terminal.

4 CONCLUSIONS

The GREENCRANES project, co-funded by the Trans-European Transport Network (TEN-T), has taken a step forward in innovation within the port industry, a sector which has considerable room for improvement in terms of energy efficiency and reducing greenhouse gas (GHG) emissions. **GREENCRANES, as a market-oriented innovation initiative focused on port container terminals, has achieved remarkable results which demonstrate that the evolution of European ports towards a low-carbon emissions model is feasible from a financial, technical, and environmental perspective, as well as providing benefits for the industry, businesses and society as a whole.**

The project has been developed under a collaborative framework involving port operators, manufacturers, and technological providers, as well as public authorities whose participation would not have been possible without the support of the European Commission. This collaborative framework is essential to overcome the existing innovation and technology gap in the port industry, a strategic sector of major importance in the European economy and society in general.

GREENCRANES has contributed to describing competitiveness and performance in the port industry in terms of operational costs, energy costs, and the impact of GHG emissions. This approach constitutes a significant and innovative step forward in the way that these strategic facilities incorporate energy efficiency concepts into their business strategy. The project has directly contributed to removing existing common barriers for European port container terminals, increasing know-how and the capabilities of stakeholders to effectively implement eco-efficient alternatives based on alternative fuels and smart energy management.

The project has facilitated real life pilot tests in three container terminals at the ports of Valencia (Spain), Livorno (Italy), and Koper (Slovenia), which represented a remarkable opportunity for port container operators to test the real feasibility of innovative technologies never before deployed in ports. One of the reasons why existing port container terminals are not currently investing in these technologies is precisely the lack of real life experiments and results from real trials and implementations. GREENCRANES has confirmed that this is due to cost restrictions, lack of communication between stakeholders, and a strong corporate culture based on operational efficacy (instead of efficiency) among others.

GREENCRANES has demonstrated that alternative fuels like liquefied natural gas (LNG) can effectively be adopted by ports for heavy-duty vehicles such as yard terminal tractors and reach stackers. Current technological advances, as well as the existing price gap between diesel fuel and LNG, provide an attractive scenario for the development of this new market. The current limitations on LNG supply as a fuel should progressively be solved in order to encourage European ports to adopt LNG as a major fuel in port operations.

GREENCRANES has also demonstrated that existing "old-generation" RTG cranes can be transformed into highly energy efficient cranes solely by retrofitting them with low-power generators, thus achieving energy savings of around 40%, and significantly reducing GHG emissions, without losing operational performance.

Finally, **the project has introduced smart energy management based on the integration of energy efficiency in all the business and operational areas of a port container terminal by means of energy-oriented key performance indicators (KPIs).**

GREENCRANES, as a pioneering initiative, has contributed to the definition of a new market perspective, increasing the level of dialogue between the agents involved in the port sector, both for commercial purposes and collaborative and win-win strategies. This new approach can accelerate the on-going transition of European ports towards more efficient operations using energy and cost efficiency as strategic enablers.

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