

# **EVALUATION OF ENVIRONMENTAL BENEFITS OF CHE EMERGING TECHNOLOGIES BY USING LCA**

**Nenad Zrnić**

**University of Belgrade, Faculty of Mechanical Engineering**

**Andrija Vujičić**

**University of Belgrade, Faculty of Mechanical Engineering**

## **Abstract**

In the era of climate change combat transport industry is recognized as a sector with one of the largest environmental footprints. A part of transport industry is container shipping and handling division, which is currently growing with the fastest rate. This massive growth of container sector is due to containers pouring from Asia, mainly from China.

Thus, container port operations are also experiencing significant increase in port emissions. This fact puts port authorities in position to find a way to reduce environmental impact of port operations and at the same time withhold increase in number containers being handled.

In response to the demanding task of reducing emissions and increasing TEU numbers Cargo Handling Equipment (CHE) industry offers variety of solutions. In this paper, state-of-the-art technology for Rubber Tired Gantry (RTG) cranes is being analyzed in order to find out the most eco-efficient solution. A conventional RTG crane is compared to hybrid Eco-RTG with super-cap energy storage system and electrified E-RTG crane. The last two solutions represent the latest trend in CHE industry.

The methodology used to carry out RTG cranes environmental impact comparison is Life Cycle Assessment (LCA) outlined in ISO 14040, as a tool which offers possibility to address entire product's life cycle in a consistent way. The obtained results of RTG cranes LCA are presented in accordance to ISO 14040 principles with the highlight on CML and TRACI impact assessment methods.

Based on the obtained results, the recommendations on reducing environmental footprint of ports are done by necessary improvements on RTG cranes. Since, the objective of this paper is twofold, use of LCA methodology as a tool in the early stage of design is promoted due to its possibility to offer preliminary information and details of processes and materials.

## **1 Introduction**

The issue of emissions in the changing global climate and recent economic uncertainties is pushing policy makers and industries to promote strategies and technologies for reduction of emissions and fuel consumption. In addition to this, the public is placing demands for more environmental operations of industries, but without jeopardizing current comfort and consumers' habits.

The climate change combat placed one industry more than any other under complete scrutiny – the transport industry. Transport systems have significant impacts on climate change, accounting for between 20 and 25 percent of world energy consumption and CO<sub>2</sub> emissions [1]. Greenhouse gas emissions from transport are increasing at a faster rate than any other energy using sector [2].

The container sector is currently the fastest growing industry. Container shipment and handling division is experiencing explosive growth due to containers pouring from Asia, mainly from China [3]. In the U.S. only, container shipments more than quintupled in from 1980 to 2006 [4]. Shipment to and from U.S. ports rose from roughly 8.4 million Twenty Foot Equivalents (TEUs) to 44.4 million TEUs in this period. Over the last decade alone, container shipments rose 80.8 percent.

This massive growth will account for a significant increase of emissions by container port operations. Container port operations can be divided into three sectors. The first is offshore and involves the passage of transoceanic ships to their berths, the second involves activities within the port boundaries such as unloading of containers from the ships and their transfer by cargo handling equipment (CHE) and the third includes the trucks and trains that originate within or near the port, but which leave the ports on highways and rail lines to serve distant markets.

Each sector is significant source of air pollution, but CHE is probably the major part of port emissions contributing to regional and community environmental degradation, since their emissions occurs near residential areas bordering the ports [5]. Thus environmental efficiency of port operations is equally important as key performance figures such as number of TEU operations and overall capacity of terminals [6]. This fact challenges port authorities and industries behind port operations to increase number of container handlings and at the same time to reduce overall emissions and environmental impact.

## **2 Features and environmental impact of Rubber Tired Gantry cranes**

Deeper look into the impact of CHE emissions reveals that Rubber Tired Gantry (RTG) cranes (Figure 1) which are used to move intermodal containers from truck to stack and back again, have share of more than 40 percent [6]. In response to this, CHE industry developed a variety of technologies and systems, to reduce fuel consumption and emissions and improve overall RTG efficiency. This includes emerging technologies such as, variable speed generators (VSGs), hybrid RTGs with regenerative breaking and

super caps technology (Eco-RTGs) and electrified zero emission models (E-RTGs). All of these solutions show significant improvements over conventional cranes, reducing CO<sub>2</sub>, NO<sub>x</sub> and SO<sub>2</sub> emissions and cutting operation costs up to 90 percent [7]. Beside emerging technologies listed above, industry is experimenting with alternative fuels for CHE and RTG such as LPG, CNG and biofuels.



Figure 1: RTG crane

RTG cranes are powered with an onboard diesel generator set which provides movement autonomy, but alongside with a huge weight of crane (often over 100 tonnes) it is responsible for significant level of fuel burning and emissions. The operating power spectrum and diesel generator working principle are the main reasons for inefficiency of conventional RTG. The most of time diesel engines works at a high engine speeds when the fuel consumption and smoke emissions are at the highest level despite a maximum power outputs are required only in 4 percent of the operating time (Figure 2).

The average fuel consumption of a RTG crane with 40 tonnes lifting capacity ranges between 20 and 30 liters of diesel per operating hour, while at the peak power fuel consumption exceeds 100 liters per hour. Since, the quantity of diesel burned directly determines the emissions it is easy to provide a picture and scale of CO<sub>2</sub> emissions for RTG cranes. The annual emission of conventional RTG crane operating in ports terminals easily exceeds 350 tonnes of CO<sub>2</sub> (based on the usually used diesel calorific value with a density of 830-850 kg per cubic meter at 15 °C) [8].

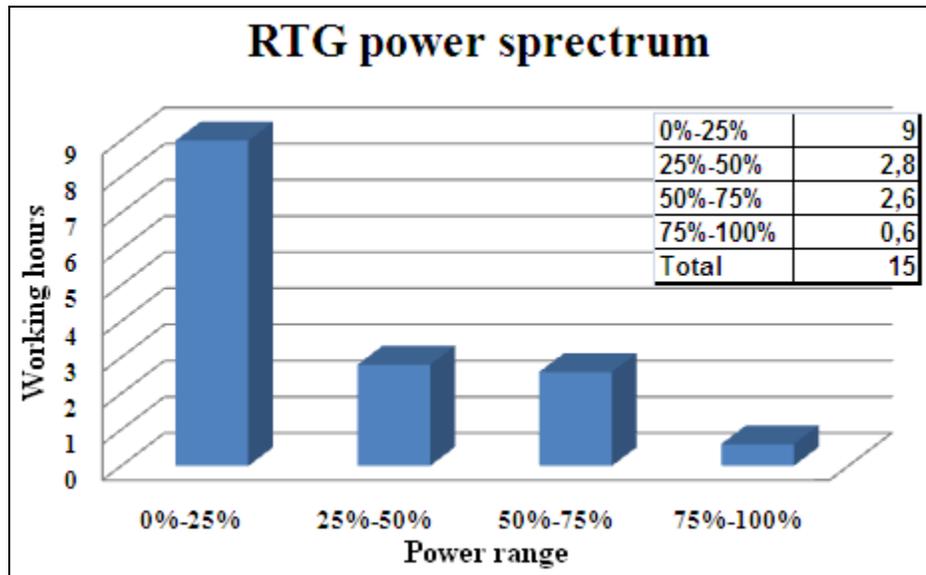


Figure 2: RTG power spectrum

The power and requirements of RTG cranes used for unloading shipping containers are highly suitable for a hybrid application, because frequent lifts require short bursts of power and most of the energy is regenerated when the container is hoisted down. The hybrid RTG crane super-caps provide the complementary power that adds up to the generator set power needed to achieve peak power (capacity to level the power provided by the prime power source to the average demand). This is also a reservoir that recuperates the energy regenerated (an average of 70% of the energy when hoisting containers down) by the hoist drive when the load is hauled down [9]. Finally, the recycled energy enables the reduction of fuel consumption. With this option it is possible to use concept of “downsizing” and install smaller more fuel efficient diesel engine.

On the other side, E-RTG uses diesel engine only during maintenance operations and block changes and 80 percent to 95 percent of time runs on electricity. In this way problem of idling and RTG power spectrum is overcome. An electric E-RTG which was at first offered with motorized cable reel solutions is often avoided due to its narrowed movability and limited flexibility, accompanied with manual block changes. Latest models of E-RTGs overcome this disadvantage with the drive-in conductor bar solution with collector trolley that automatically engages and disengages. This feature puts electric E-RTGs in prime again. Advertised by manufacturers (Wampfler, Cavotec, and Vahle) E-RTG promises over 75 percent CO<sub>2</sub> reduction compared to conventional cranes. It is important to emphasize that this result can vary depending on power grid mix emission of CO<sub>2</sub> per kWh. In case where the power supply comes from plant burning brown coal results worsens but still to level of 60% of CO<sub>2</sub> reduction over conventional RTG. If the better example is considered, where carbon neutral port operations are goal,

such as installment of electricity-generating wind turbines as in port of Rotterdam [10], reduction of CO<sub>2</sub> for E-RTG over conventional RTG can be as much as 10 times.

### **3 Objective**

Certain solutions for RTG cranes have advantages over others and certain terminal configurations and port authorities favor some of them, but from environmental point of view it is important to find out which solution is more eco friendly. Again, certain methodologies for assessment of environmental impact of products have advantages over others, but according to the authors' opinion the most appropriate way is to carry out Life Cycle Assessment (LCA) of three most widespread implemented technologies of nowadays RTG cranes which include conventional solution and two emerging technologies (hybrid and electrified zero emission RTGs).

Thus, the objective of this paper is twofold. The first objective is to evaluate environmental benefits of emerging technologies for RTG cranes over conventional and the second is to promote the use of (LCA) methodology for this purpose. In this way, comparison of RTG cranes will offer results which could be used in further research of CHE emerging technologies.

Once the environmental impact of manufacturing stage of a conventional type of RTG is obtained, these results could be used for evaluation of environmental performances of future CHE technologies. Essentially, RTG support structure and its corresponding manufacture process are basically unchanged since these machines have been introduced in operation. Majority novel solutions offered for brand new cranes are also available as upgrades for older models.

### **4 Methodology**

LCA methodology outlined in ISO 14040 (2006) was used in order to quantify and compare the potential environmental impacts of different Rubber Tired Gantry cranes since it offers possibility to address entire product's life cycle in a consistent way [11].

#### **4.1 About LCA**

As a core of Life Cycle Design (LCD), LCA is a quantitative tool for assessment of environmental impacts of products and services such as global warming, ozone depletion, (smog) creation, eutrophication, acidification, toxicological impact on humans and ecosystems, the depletion of resources and others. It is a systematic approach for analyzing the entire life cycle stages of products from material extraction through manufacturing, distribution, use and end-of-life. Therefore, it is often called a "cradle-to-grave" analysis.

The pioneer works regarding LCA appeared in 1970 in US as a method for evaluation of resource and energy use. This methodology was developed to scope resource and energy consumption with air and land emissions through life cycle of product and packages. After publishing the principles of the LCA by ISO (1997), the wider acceptance of this methodology took place.

The LCA study is defined with framework which is divided into four phases according to ISO14040-43:

1. Goal and scope definition
2. Life Cycle Inventory
3. Life Cycle Impact assessment
4. Interpretation

When performing an LCA, one should first define the application, purpose and intended audience. Also, as the part of goal and the scope of the study the geographical and temporal limitations are defined. After completing this step, all inputs (materials and energy) and outputs (emissions) involved in the studied product system are computed with respect to the Functional Unit (FU). FU is a quantified reference performance of the product/service and is encompassed by system boundaries (Figure 3). “Cut-off” criteria can be added later to system boundaries.

The input and output data are then collected through iterative process with data classification and calculation for a given product system or process in order to make Life Cycle Inventory (LCI). This is the most complex process of LCA and is usually offered by software solutions for some modest budget studies.

Finally, the Life Cycle Impact Assessment (LCIA) is carried out when evaluation of a product life cycle is required. This is done based on a functional unit, in terms of recognized environmental impact categories, such as global warming, acidification, ozone depletion, etc. The emissions are converted to impacts potential, through processes of classification and characterization. In order to conduct LCIA different methods can be used, from problem-oriented to the damage-oriented approach. Most common LCIA methods are TRACI and CML. The TRACI method is developed by US EPA while CML is invented by the University of Leiden, Netherlands. More details on the development of mentioned methods can be found in the review paper [12].

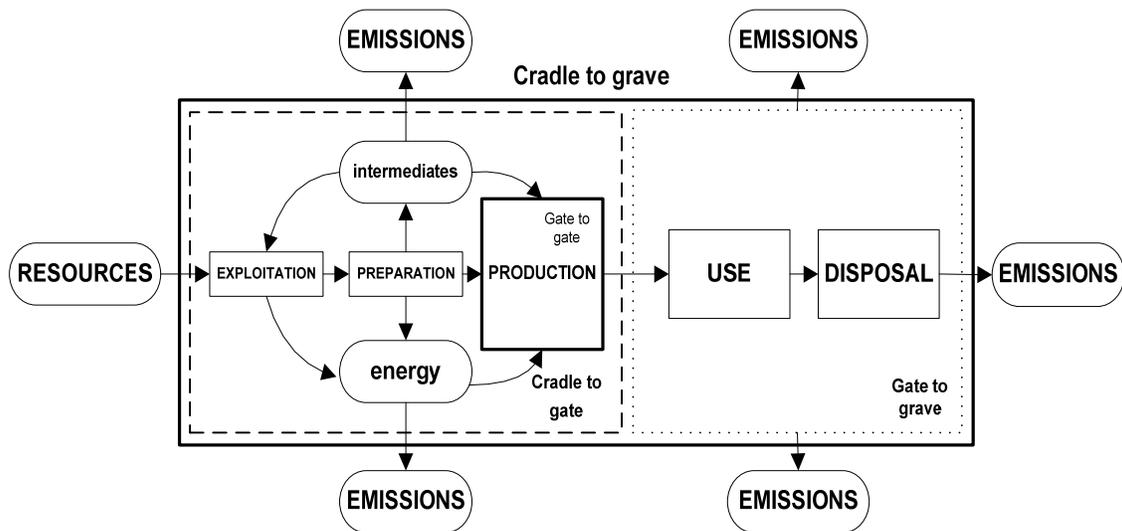


Figure 3: System boundaries [12]

## 4.1 LCA of Cargo Handling Equipment

The application of LCA studies in the field of material handling has obtained attention in the recent engineering researchers, but unfortunately little literature on the subject is available [13, 14, 15, 16]. However, future research regarding LCA of CHE can become an interesting tool due to several facts. Firstly, it offers consistent comparison of both production phase of machine, propulsion system and even alternative fuel solution. LCA can address assessment of environmental burden of fossil fuel extraction, production, distillation and distribution and electricity production as well. Secondly, it offers evaluation based on inventory data without need for on site measurements.

## 4.2 Assumptions for LCA of RTG cranes

Since conventional model of RTG crane is set as basic model, other two models: the hybrid RTG and electrified E-RTG are essentially upgraded versions of the basic model which use same gantry structure. The difference between basic (conventional) model over hybrid and E-RTG is in add-ons over standard diesel generator set. This principle of modeling allows the authors to use the most of inventory base of the first RTG crane which is in accordance with real life, dockside experience where conventional cranes already in use are modernized by new state-of-the-art add-on features.

The system boundaries are defined according to ISO 14000 recommendations and responding to work principle of used LCA software. The assessment is divided in two parts. First is “cradle to gate”, sometimes noted as “upstream”, where iron ore extraction and depletion and materials processing is addressed, then parts production and gantry

assembly and finally distribution is evaluated. The second stage of this assessment “gate to grave” basically consist of “use” and “downstream” phase in one. It refers to operational life of crane at port and scrapping and disposal/recycling.

The manufacturing step has been modeled as common parameter for all the three RTG cranes and is chosen to be the same. This includes the raw materials, the manufacturing processes, the energy consumption and the transport by rail and truck of the manufactured car to the end-user determent only for conventional RTG. The components which are specific to the Hybrid and E-RTG technology are modeled separately and added over results of conventional crane. For example carbon super-caps energy storage for Hybrid crane and collector trolley for E-RTG.

The “cut-off” criteria in manufacturing phase is applied, leaving out components with weight of less than 5 percent of the total mass of crane, thus excluding parts which contribution to overall results of this phase is insignificant.

The Functional Unit (FU) defined in this assessment, although simplified, corresponds to the use of a RTG cranes in port operations during average 5000 working hours per annum and 15 years of lifetime. The FU is 1 working hour of container manipulation which consists of 32 percent of hoisting operations, 16 percent of spreader movement and 52 percent of crane movement across the port yard.

The work environment of RTG cranes is in accordance with GaBi software inventory base. The power grid mix is chosen to be current EU-25 (ports at EU seas). Fuel used for diesel generator set is off-road petroleum diesel with high sulphur content.

The end-of-life has been modeled with respect to the state-of-the art in EU recycling plants and according to GaBi software available data. The recycling process of large steel sheet gantry construction and consumption of resources during the recycling process have been included having in consideration the dominance of steel material over others.

### **4.3 LCA of RTG cranes**

The LCA of three RTG cranes is carried out using state-of-the-art software GaBi developed by PE International as the most represented LCA tool on the market [12]. A full LCA was conducted, and the necessary input/output data were determent using immense GaBi data base. Since modeling the life cycle of such a complex machine as RTG crane, certain assumptions (see subsection 4.2) are adopted to simplify the assessment. These approaches are common in order to lower the costs of LCA and eliminate data uncertainties [13], especially due to fact that study is entirely independent. The goal of study is intended solely for scientific research and therefore critical review is not necessary.

The adopted conventional structure of RTG crane with lifting capacity of 40 tonnes is shown in Figure 4. Its self weight is ca. 115 tonnes, which consist of 80 tonnes steel box gantry structure, spreader and trolley with total weight of 25 tonnes and remain weight of diesel generator set, cables and other features. This support structure is adopted for evaluation of all three analyzed solutions of RTG cranes. Adopted drive system is on

board diesel generator set. It has got 600 kVa AC/DC generator with 6 cylinders, 12 liter (732 cubic inches) diesel engine with power of over 300 kW.

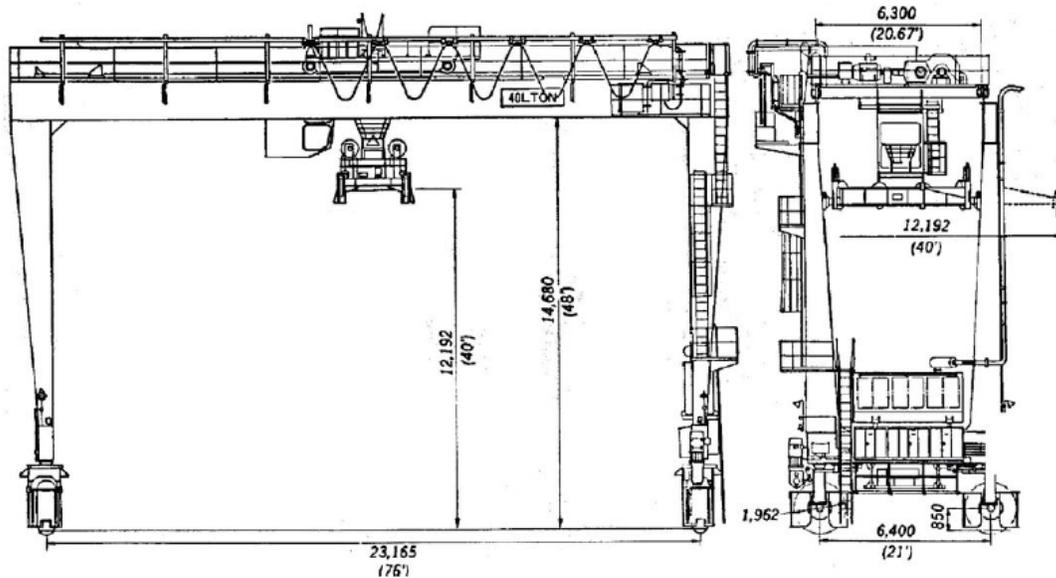


Figure 4: 40 tonne RTG crane

## 5 Results

The obtained results of the LCA of RTG cranes are presented in accordance to ISO 14040 principles with the highlight on two most representative impact assessment methods Dutch CML and US TRACI. The results are also divided according to the system boundaries: “Cradle-to-gate”, “Gate-to-grave” and finally as entire life-cycle-impact-assessment “Cradle-to-grave”. In this way, overview of footprints of “upstream” and “off-road” or operational part of life are clearly divided.

As for the most vehicles and long-life machineries (life cycle over 5 years) the use phase tends to be the most dominant one part of entire life cycle. The same applies to RTG cranes. The operational life of RTG cranes spans from 15 to 30 years with engine overhauling which puts the use phase in focus since it contributes to overall results in great proportion. Environmental profile of RTG crane is given in Figure 5. Nevertheless it is important to conduct entire LCA in order to rule out significant issues that could appear in the production phase.

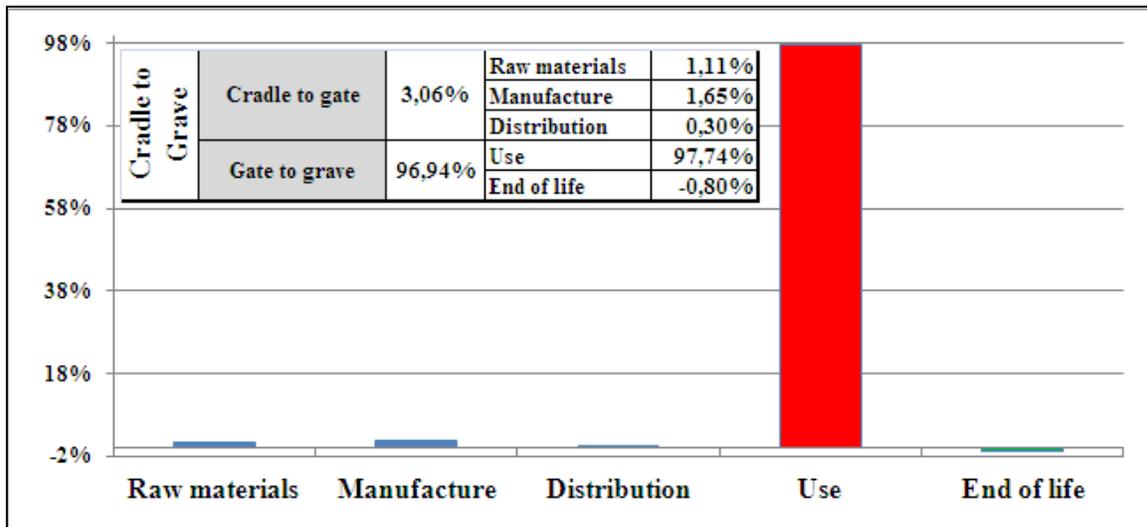


Figure 5: Environmental profile of RTG crane

## 5.1 Results of Cradle-to-gate assessment

In the “cradle-to-gate” assessment which consists of raw material, manufacturing, and distribution phase, overall impact is 3.06 percent of entire life cycle impact. The most dominant phases of “cradle-to-gate” are raw material and manufacturing. The impact of raw material depletion of iron ore is due to large mass of gantry ~ 80 tonnes and trolley with spreader ~ 25 tonnes.

Manufacturing process has most significant impact of upstream phase, which comes from massive electric energy use ~ 500,000 kWh. Carbon emission from electric energy production (EU-25) is identified as “significant issue” of manufacturing process. The add-ons for conventional crane which convert it to hybrid or electrified show symbolic contribution, but it was important to identify these impacts in order to make distinction between three crane models. Also, adaptation of port terminals, with installments of conductor bars (there are also cable reel solutions) necessary to provide electricity from grid for E-RTG, showed environmental impact much smaller than 5 percent of production phase of crane. The results of “cradle-to-gate” assessment by CML and TRACI interpretation are given in Tables 1 and 2 respectively.

Table 1: Cradle to Gate results CML method

<b>CRADLE TO GATE (raw materials, production, distribution)</b>			
<i>Method: CML 2001 dec.2007</i>	<b>Conventional</b>	<b>Hybrid</b>	<b>E-RTG</b>
GWP (CO2e) [kg CO2-Eq.]	<b>335.830,77</b>	<b>350.533,44</b>	<b>344.437,66</b>
AP [kg SO2-Eq.]	<b>1.766,85</b>	<b>2.317,85</b>	<b>1.812,51</b>
EP [kg Phosphate-Eq.]	<b>96,93</b>	<b>139,93</b>	<b>98,99</b>
ODP [kg R11-Eq.]	<b>0,06</b>	<b>0,06</b>	<b>0,06</b>
POCP [kg Ethene-Eq.]	<b>100,11</b>	<b>102,91</b>	<b>102,78</b>
Radioactive waste (kg)	<b>745,19</b>	<b>771,27</b>	<b>773,13</b>

Table 2: Cradle to Gate results TRACI method

<b>CRADLE TO GATE (raw materials, production, distribution)</b>			
<i>Method: TRACI</i>	<b>Conventional</b>	<b>Hybrid</b>	<b>E-RTG</b>
Acidification Air [mol H+Eq.]	<b>933,58</b>	<b>937,59</b>	<b>934,65</b>
Eutrophication Water [kg N-Eq.]	<b>24,00</b>	<b>24,00</b>	<b>24,00</b>
Global Warming Air [kg CO2-Eq.]	<b>335.818,04</b>	<b>355.967,12</b>	<b>343.206,03</b>
Human Health Criteria [kg PM2,5-Eq.]	<b>199,23</b>	<b>199,23</b>	<b>199,23</b>

## 5.2 Results of Gate-to-grave assessment

RTG cranes are one of largest machines on the tires in the world with significant environmental impact which could be compared with 100 passenger mid-size cars with average annual mileage. This fact along with long life cycle of crane shaped results of “gate-to-grave” assessment. With almost 97 percent of entire life cycle, “use phase” is most important environmental issue of RTG cranes. The results of “gate-to-grave” assessment by CML and TRACI interpretation are given in Tables 3 and 4 respectively.

Table 3: Gate to Grave results CML method

<b>GATE TO GRAVE (Use phase + End of life)</b>			
<i>Method: CML 2001 dec.2007</i>	<b>Conventional</b>	<b>Hybrid</b>	<b>E-RTG</b>
GWP (CO2e) [kg CO2-Eq.]	<b>6.001.753,30</b>	<b>3.589.048,47</b>	<b>1.449.100,33</b>
AP [kg SO2-Eq.]	<b>78.435,43</b>	<b>46.904,38</b>	<b>12.348,04</b>
EP [kg Phosphate-Eq.]	<b>13.513,51</b>	<b>8.081,08</b>	<b>1.554,53</b>
ODP [kg R11-Eq.]	<b>0,00</b>	<b>0,00</b>	<b>0,21</b>
POCP [kg Ethene-Eq.]	<b>8.361,44</b>	<b>5.000,14</b>	<b>1.099,17</b>
Radioactive waste (kg)	<b>0,00</b>	<b>0,00</b>	<b>2.756,25</b>

Table 4: Gate to Grave results TRACI method

<b>GATE TO GRAVE (Use phase + End of life)</b>			
<i>Method: TRACI</i>	<b>Conventional</b>	<b>Hybrid</b>	<b>E-RTG</b>
Acidification Air [mol H+Eq.]	<b>4.450.249,43</b>	<b>2.661.251,13</b>	<b>698.156,07</b>
Eutrophication Water [kg N-Eq.]	<b>4.616,07</b>	<b>2.765,23</b>	<b>530,17</b>
Global Warming Air [kg CO2-Eq.]	<b>6.169.662,32</b>	<b>3.767.032,03</b>	<b>1.449.098,83</b>
Human Health Criteria [kg PM2,5-Eq.]	<b>40.011,83</b>	<b>23.967,12</b>	<b>21.003,59</b>

### 5.3 Results: Cradle-to-Grave assessment

The LCA carried out in this research shows a significant reduction of Global Warming Potential (GWP), Acidification Potential (AP) and Eutrophication Potential (EP) for hybrid RTG and E-RTG crane models over conventional. Positive outcome is due to significant reduction of consumption of diesel fuel in “use phase” which finally reduces emissions of CO<sub>2</sub>, and NO<sub>x</sub> and SO<sub>2</sub> especially in case of E-RTG crane. Relatively higher level of environmental impact of Hybrid and E-RTG cranes in production phase is of little significance to overall results since this stage has small share in entire 15 years long life cycle.

The results show that the GWP is generally in correspondence to FU and expected CO<sub>2</sub> emissions. The AP and EP results are at such a high level due to NO<sub>x</sub> and SO<sub>2</sub> emissions which are directly related to sulphur content of diesel fuel used by RTG cranes. The Photochemical Ozone Creation Potential (POCP) also known as summer smog creation potential is also detected due to CO emissions and incomplete combustions which often occur at higher loads and revolutions of diesel engine. The results of entire life cycle of crane are given in Tables 5 and 6 and Figures 6, 7, 8 and 9.

Table 5: Cradle to Grave results CML method

<b>CRADLE TO GRAVE</b>			
<i>Method: CML 2001 dec.2007</i>	<b>Conventional</b>	<b>Hybrid</b>	<b>E-RTG</b>
GWP (CO2e) [kg CO2-Eq.]	<b>6.337.584,07</b>	<b>3.939.581,91</b>	<b>1.793.537,99</b>
AP [kg SO2-Eq.]	<b>80.202,27</b>	<b>49.222,23</b>	<b>14.160,56</b>
EP [kg Phosphate-Eq.]	<b>13.610,44</b>	<b>8.221,01</b>	<b>1.653,52</b>
ODP [kg R11-Eq.]	<b>0,06</b>	<b>0,06</b>	<b>0,26</b>
POCP [kg Ethene-Eq.]	<b>8.461,55</b>	<b>5.103,05</b>	<b>1.201,95</b>
Radioactive waste (kg)	<b>745,19</b>	<b>771,27</b>	<b>3.529,38</b>

Table 6: Cradle to Grave results TRACI method

CRADLE TO GRAVE			
Method: TRACI	Conventional	Hybrid	E-RTG
Acidification Air [mol H+Eq.]	4.451.183,01	2.662.188,72	699.090,72
Eutrophication Water [kg N-Eq.]	4.640,07	2.789,23	554,17
Global Warming Air [kg CO2-Eq.]	6.505.480,36	4.122.999,15	1.792.304,87
Human Health Criteria [kg PM2,5-Eq.]	40.011,83	23.967,12	21.003,59

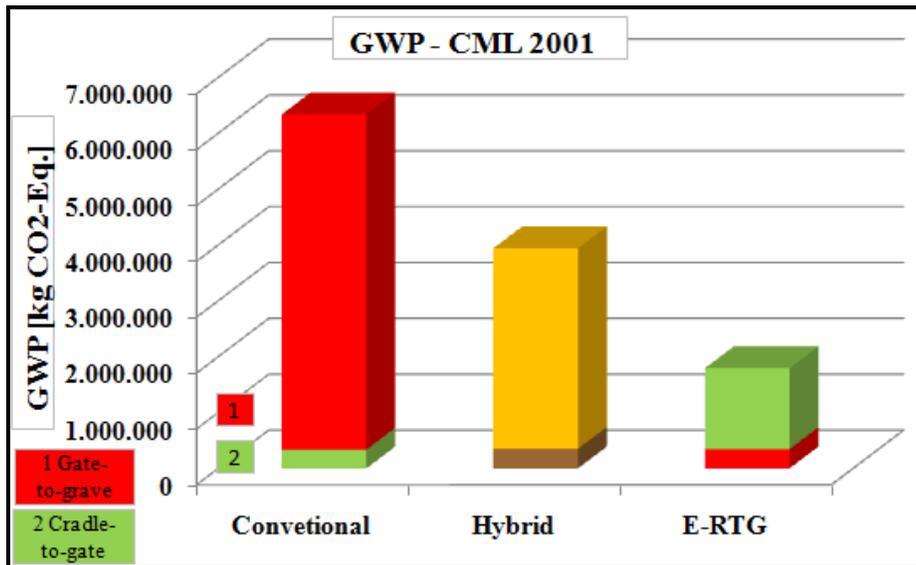


Figure 6: Global-warming-potential of RTG cranes

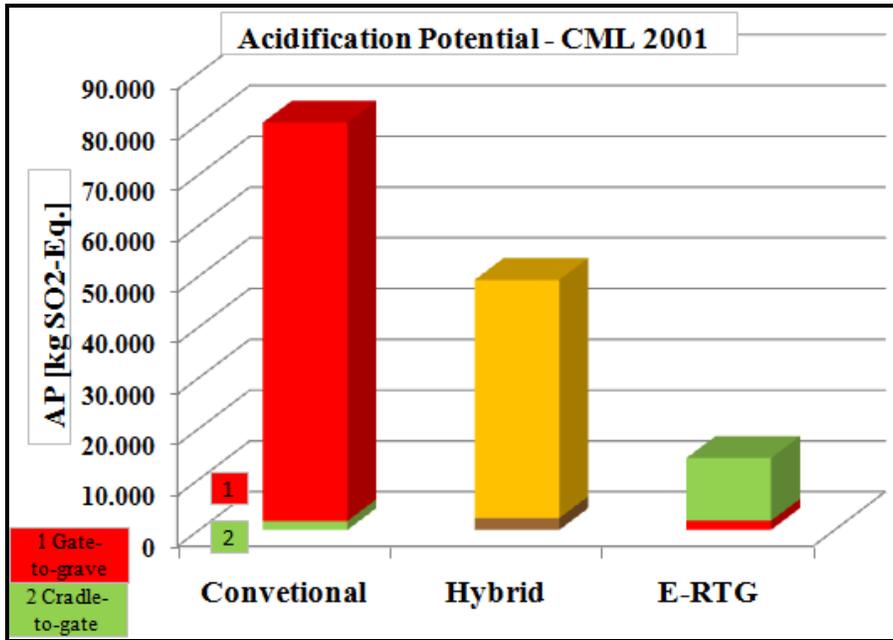


Figure 7: Acidification-potential of RTG cranes

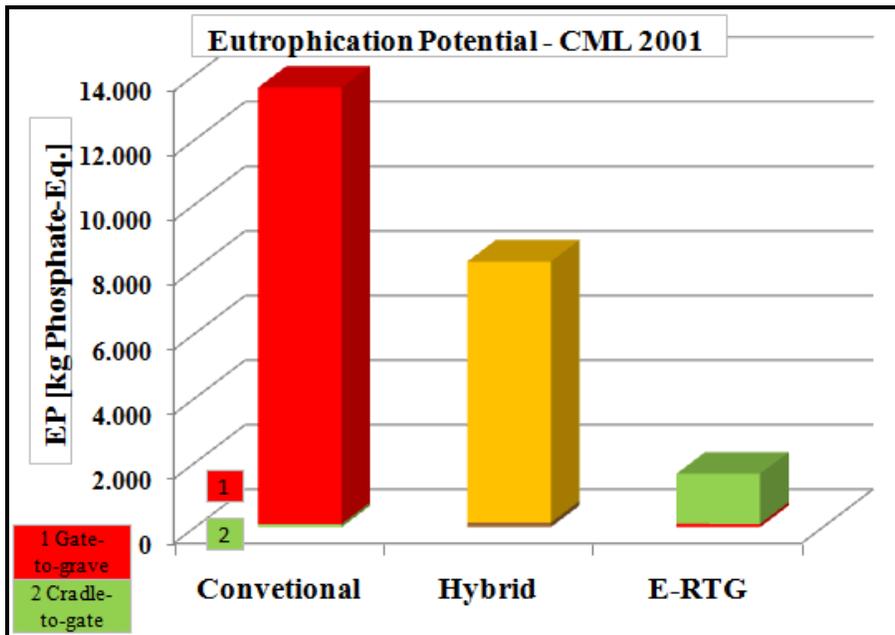


Figure 8: Eutrophication-potential of RTG cranes

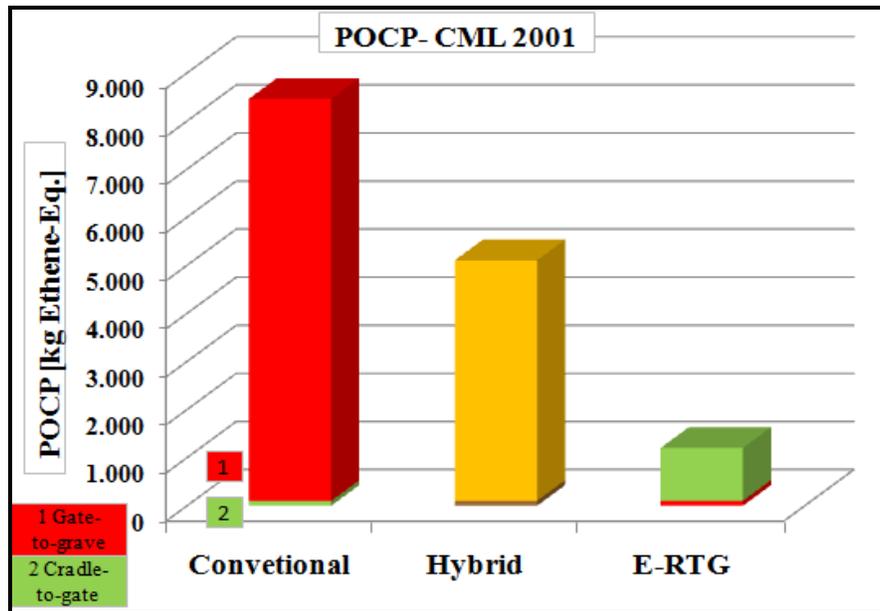


Figure 9: Photochemical-ozone-creation-potential of RTG cranes

## 6 Conclusion

After analyzing the results and comparison between conventional RTG and Hybrid and E-RTG a clear conclusion can be made. Today, when environmental concerns are part of almost everyday discourse conventional RTG cranes are obsolete. The hybrid super-cap systems and electrified solutions offered by CHE industry are desirable from both environmental and entrepreneurs perspective. The Hybrid and E-RTG have significant emission reduction and fuel saving potentials and their introduction in to the port operations has almost no environmental downside. In this way emerging CHE technology for RTG cranes could settle environmental concerns of port authorities without jeopardizing everyday container handlings and at the same time lower operational and maintenance costs in long term.

On the other side, as second objective of this paper the assessment of environmental benefits of emerging technologies could serve as appropriate example of linkage between researchers of LCA methodology and engineers and designers of CHE industry. One of the greatest potentials of the LCA as designer tool is its possibility to offer preliminary information and details of processes and materials necessary in early development stages of port machinery. Some efforts have already been carried out in this direction, although much more information needs to be publically available as to environmental impacts and life cycles of conventional products [17].

In order to further promote the LCA as CHE designer support tool, the interaction between industry and LCA researchers is vital. With information provided by industry

and dockside operators, environmental impact assessments are prone to more than just statistical estimations. In the mean time the pioneer work with LCA as tool for comparison of emerging CHE technology feeds designer with parameters to make decisions regarding environmental efficiency of products and overall sustainability of industry operations.

## Acknowledgements

A part of this research is the contribution to the Ministry of Education and Science of the Republic of Serbia funded project TR 35006.

## References

- [1] Moriarty, P. and Honnery D., “The prospects for global green car mobility,” *Journal of Cleaner Production*, 16, 1717-1726 (2010).
- [2] Geerlings, H. and van Duin, R., “A new method for assessing CO<sub>2</sub>-emissions from container terminals: a promising approach applied in Rotterdam,” *Journal of Cleaner Production*, 19, 6–7, 657–666 (2011).
- [3] Inoue, S., “Climate initiative of the World’s ports”, *Climate Action*, 45-47 (2008)
- [4] Cannon, J. S., *U.S. Container Ports and Air Pollution: A Perfect Storm*, An Energy Future, Inc. Study, (2008).
- [5] Cannon, J. S., *Container Ports and Air Pollution*, An Energy Future, Inc. Study, (2009).
- [6] Jurong port, “Jurong port, Singapore”, - *JP Carbon footprint report*, (2010).
- [7] Obata, K., Sakamoto, T., Yoshioka, N., Fujisawa, N., Yoshikawa, H., Monzen, T., “Grid-Powered Electric Transfer Crane,” *Mitsubishi Heavy Industries Technical Review*, 47, 2, (2010).
- [8] Radovanovic, M., *Fuels (in Serbian)*, University of Belgrade, Faculty of Mechanical Engineering, Belgrade (1994).
- [9] Zrnić, N., Bošnjak, S., Đorđević, M., “Design for modernization – A way for implementation of eco improvements of port’s cranes”, *Machine Design*, Faculty of technical sciences, Novi Sad, 07-13 (2010).
- [10] Green port, “APM Terminals and Eco-efficiency philosophy,” *Green port journal*, pg. 44-47 (November 2009).
- [11] Uherek, E., Halenka, T., Borken-Kleefeld, J., Balkanski, Y., Berntsen, T., Borrego, C., Gauss, M., Hoor, P., Juda-Rezler, K., Lelieveld, J., Melas, D., Rypdal, K., Schmid, S., “Transport impacts on atmosphere and climate: Land transport,” *Atmospheric Environment*, 44, 4772-4816 (2010).
- [12] Vujičić, A. and Zrnić, N., “State-of-the-art in life cycle assessment as a core of life cycle design,” *Proceedings of the 10th International Conference on Accomplishments in Electrical, Mechanical and Informational Engineering DEMI 2011*, University of Banja Luka, Bosnia and Herzegovina, 203-208 (2011).

- [13] Ostad-Ahmad-Ghorabi H. and Collado-Ruiz D., "Tool for the environmental assessment of cranes based on parameterization", *Int J Life Cycle Assess*, 16, 392–400 (2011).
- [14] Buño, J. L.A. and Gutierrez, B. C., *Life Cycle Assessment of Two Parts of a Crane - Supporting member, crane member*, MSc. Thesis, Department of Applied Physics and Mechanical Engineering, Division of Manufacturing Systems Engineering, Luleå University of Technology, Sweden (2010).
- [15] Zrnić, N. and Vujičić, A., "Reduction of RTG cranes emission by using hybrid technology, Proceedings of the conference," *Proceedings of the International Conference REACT, Shaping Climate Friendly Transport in Europe: Key findings & Future Directions*, University of Belgrade, Faculty of Transport and Traffic Engineering, Belgrade, Serbia, 180-187 (2011).
- [16] Awuah, O. K., Checkel, D., Askari, N., "Evaluation of belt conveyor and truck haulage systems in an open pit mine using life cycle assessment," *Environment CCIM Bulletin*, 102, 1116, 1-6 (2009).
- [17] Collado-Ruiz, D. and Ostad-Ahmad-Ghorabi H., "Influence of environmental information on creativity," *Design Studies*, 35, 479-498 (2010).