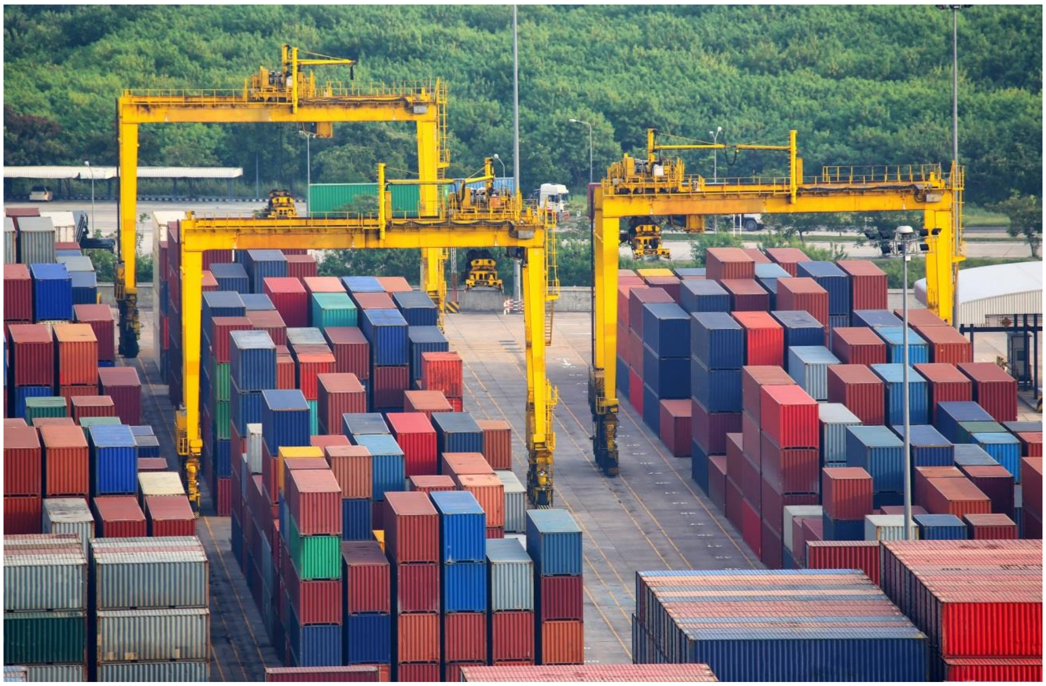
Environmental Defense Fund (EDF) Logistics Project: The Greening of Rubber-Tired Gantry Cranes in Ports

In partnership with the Port of Oakland



15.915 Laboratory for Sustainable Business

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Problem Statement and Overview

Rubber Tire Gantry (RTG) cranes are a major contributor to maritime port emissions, adding to port-area air quality issues and global greenhouse gas emissions. In the United States, nearly all RTG cranes are powered by large displacement diesel generators. Diesel generators allow RTGs the flexibility they need to move between lanes, and the power they need to quickly move containers. However, the diesel generators used in today's RTGs have significant drawbacks. First, diesel fuel prices have been and are expected to trend higher, resulting in increased fuel costs for ports. Second, the average diesel generator used in today's RTGs emit significant amounts of pollutants that contribute to health concerns of local communities as well as larger-scale global concerns of climate change.

Sponsored by the Environmental Defense Fund (EDF), this project involved analysis of options for greening of Rubber Tired Gantry (RTG) cranes in maritime ports in terms of energy and emissions reduction. The investigation was conducted by students in the MIT Laboratory for Sustainable Business class with Professor John Sterman serving as faculty mentor. For the provision of technical and operational information, the Port of Oakland functioned as a port partner. As a result of the investigation, solutions were provided in terms of energy storage, a reduction in idle time, powertrain improvements, the use of alternative fuels, and electrification. Decision criteria were used to provide business case justifications for these solutions, which included capital requirements and operating cost savings as applicable. Finally, information was provided on the local and global emissions impact, potential challenges for implementation of the solutions, and avenues for possible further study.

Objectives

Armed with the information provided in this report, EDF can help promote awareness and provide guidance to US ports to assess their options and choose solutions to reduce the emissions impact and energy usage of RTG cranes. To produce the content of this report, we have:

i. Surveyed the current landscape of technology that may reduce RTG crane energy usage and emissions output.
ii. Identified existing technologies in the commercial market.
iii. Quantified the financial performance and emissions impact of implementing each option.

iv. Surveyed the operational feasibility of implementing technology.
v. Identified and evaluated the necessary parameters for commercial viability and scaling.

Summary of Recommendations and Conclusions

Based on our findings, we recommend the following:

i. From a financial considerations perspective, net present value (NPV) positive technological options with likely payback period of under 10 years include a diesel-electric hybrid solution with energy storage using ultracapacitors, an engine start-stop system to reduce idle time, and the adoption of CNG as an alternative fuel.
ii. From an environmental considerations perspective, we analyzed the different retrofit options from the perspective of global carbon dioxide (CO_2) emissions as well as local tailpipe emissions of nitrous oxide (NOx), sulfur oxide (SOx), carbon monoxide (CO), hydrocarbon (HC), and particulate matter (PM). The options have varying levels of impact on these different types of emissions, and each port would need to assess which combination is best suited to meet their objectives.

We understand that the decision to implement a given technology will be based on both financial and environmental considerations, among other concerns specific to particular ports. This analysis is meant as a tool to facilitate such decision-making; it is not evaluative in terms of recommending a 'best' solution.

Background

The Environmental Defense Fund

Founded in 1967 by scientists who worked on banning the pesticide DDT, the Environmental Defense Fund (EDF) is a non-profit organization that seeks enduring solutions to safeguard natural systems.

EDF plays a unique role as an environmental agency in that it actively seeks to work across disciplines and with diverse groups of people. The agency partners with scientists to gain rigorous, fact-based data, communities to understand local interests and needs, economists and businesses to align environmental goals with market forces, and policy-makers to implement change. EDF seeks to be trusted as a non-partisan force for environmental progress. Over 90% of EDF's 2013 expenditure of $121 million was funded by donations and grants; the organization does not accept money from corporate partners.

EDF seeks to solve the most critical environmental problems facing the planet. It has been drawn to its current focus areas of climate, oceans, ecosystems, and health. The aim of the MIT-EDF Ports and Logistics project is to further work in the area of climate, by reducing port-related carbon emissions. [1]

Port of Oakland

The Port of Oakland was established in 1927 and is a private-public partnership with the City of Oakland, operating as an independent department of the city. The port is self-funded, receiving no tax dollars, and is required by the City Charter to deposit revenues into the City Treasury. The port physically occupies 19 miles of linear shoreline[2] on the eastern shore of San Francisco Bay, dedicating 665 acres to maritime activities. It encompasses a container port, an airport, and retail and commercial buildings. The port directly and indirectly supports over 73,000 jobs in the Northern California region, of which over 37,000 are direct jobs[3].

The Port of Oakland serves as the principal ocean gateway for international containerized cargo shipments in Northern California. It is the 5th busiest cargo container port in the United States and the 3rd busiest on the United States West Coast, based on twenty-foot equivalent units (TEUs) handled annually; in 2013, over 2.3 million TEUs passed through the port. In 2013 the port's operating revenues were $316 million, of which $152 million was attributable to maritime operations. Operating income was $66 million. The port projects flat to modest growth (1%-2% per year) through 2016, while facing the challenge of rising operating costs.

Sustainability features in the Port's vision and mission statement. According to the Port's strategic plan for 2011-2015, the port's vision is to be an "**innovative** and **sustainable** Port through an aggressive focus on business and optimal performance." In line with its stated vision and mission, the Port of Oakland is constructing infrastructure for shore power in almost all its berths, with at least 3 berths completed as of the end of 2013; shore power is intended to reduce emissions of air pollutants from docked vessels. The port has also implemented regenerative braking in its ship-to-shore cranes. Other sustainability initiatives are underway in the airport and in the other non-maritime operations.[4]

By virtue of its location in the state of California, the Port of Oakland is further incentivized to reduce its emissions output. Under Assembly Bill 32 (AB-32) – the Global Warming Solutions Act

[1] http://www.edf.org
[2] http://www.portofoakland.com/pdf/environment/publicAccess.pdf
[3] http://portofoakland.com/pdf/about/JobsBrochure.pdf
[4] http://www.portofoakland.com

of 2006, the cost of emissions in California is certain to increase over the next six years. The California Air Resources Board (ARB) must commence with developing actions to reduce greenhouse gases and to create a scoping plan to meet the mandates of the law, which are stipulated as follows: the state of California is required under the law to return to 1990 levels of greenhouse gas emissions by 2020. A cap and trade program is a key element to AB-32, and is designed to be effective in 2015 for distributors of transportation. Under this regulation, the price of carbon emissions is expected to increase over the next few years, with the extent of the increase determined by market forces on carbon allowances and offsets.[5]

Industry Background

In the United States, the top water ports by total tonnage (inclusive of bulk cargo, in addition to containerized cargo) include the ports of South Louisiana, Houston TX, New York / New Jersey, Long Beach CA, and New Orleans LA. The Port of Oakland was ranked 35th in terms of total tonnage in 2011, according to the U.S. Department of Transportation. In terms of container shipping, Los Angeles is the biggest American port (8.1 million TEUs[6] handled annually), followed by Long Beach (6.1 million TEUs) and NY / NJ (5.5 million TEUs); the port of Oakland ranked 5th in container volume domestically.[7]

Internationally, the world's top container ports include many Asian ports: in China, Shanghai (32.5 million TEUs / annum), Hong Kong (23.1 million TEUs), Shenzhen (22.9 million TEUs), Ningbo (16.8 million TEUs); Singapore (31.7 million TEUs); and the port of Busan in South Korea (17.0 million TEUs). Dubai, UAE and Rotterdam, Netherlands are also high-volume ports, each shipping over 11 million TEUs per year.[8]

Sustainability Challenges

The growth of international trade and global economic interdependency in the past century has necessitated an exponential rise in international shipping and logistics. According to the UNCTAD[9], total cargo (including oil and bulk cargo) measured in millions of tons loaded increased from 2,566 million in 1970 to 8,408 million in 2010. This increase represents a compounded annual growth rate (CAGR) of over 3% and reflects a tripling of shipping volume

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[5] http://www.arb.ca.gov/cc/ab32/ab32.htm

[6] TEU – Twenty Foot Equivalent Unit: a standardized shipping container 20ft long, 8ft wide, 8ft 6in high. Another popular container size 40ft long is called a Forty Foot Equivalent Unit (FEU). 45ft, 48ft and 53ft long containers are less commonly used.

[7] http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_01_57.html

[8] http://www.worldshipping.org/about-the-industry/global-trade/top-50-world-container-ports

[9] United Nations Conference on Trade and Development

over less than four decades. Dr. Martin Stopford of Clarkson Research Services estimates that if global trade trends of the past century continue, the 8 billion tons of cargo shipped in 2010 will roughly triple to 23 billion tons by 2060, tripling the carbon footprint of shipping if measures to reduce carbon emissions are not implemented.[10]

The capacity of ports will need to expand proportionate to the increase in global trade and shipping. The technology utilized in ports in handling these trade items will be a contributing component to the carbon emissions impacting our climate, and therefore merits a thorough optimization analysis.

Cranes form a major portion of cargo handling equipment at any container port. Many of these cranes employ heavy-duty diesel engines, and emissions from these engines have a very direct effect on air quality in and around the port. In the US, emissions standards for non-road diesel engines were phased in over the late 1990s, and Tier 1 standards for emissions control came into effect in 2000. These standards have become progressively more stringent and by 2015, compliance with Tier 4 Final standards will become compulsory for all new diesel engines.[11] Tier 4 Final standards translate to nitrous oxide (NOx) and particulate matter (PM) emissions that are 90% lower as compared to Tier 1 standards, as shown in Figure 1. To this day, old cranes that do not conform to the latest emissions standards are being utilized at several ports in the US and around the world.

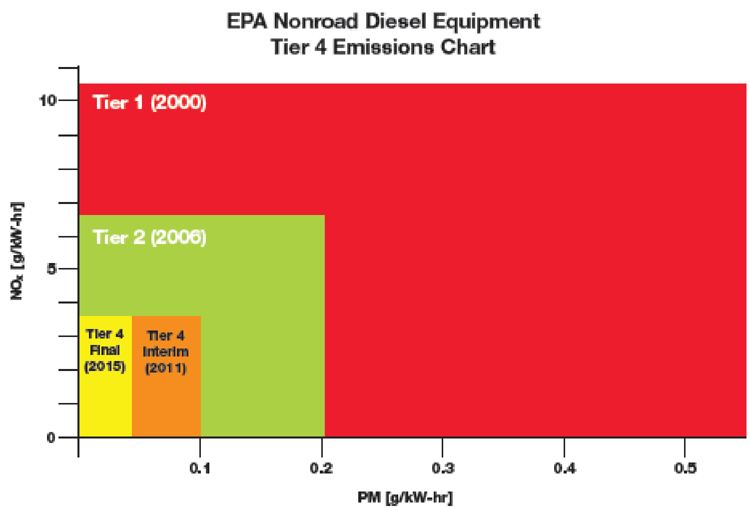


Figure 1: EPA Non-road Diesel Equipment Emissions Chart[12]

[10] Stopford, Martin. "How shipping has changed the world & the social impact of shipping." Global Maritime Environmental Congress. 7 Sept. 2010.
[11] http://www.dieselnet.com/standards/us/nonroad.php
[12] http://cumminsengines.com/brochure-download.aspx?brochureid=310

Operation of Rubber-tired Gantry (RTG) Cranes

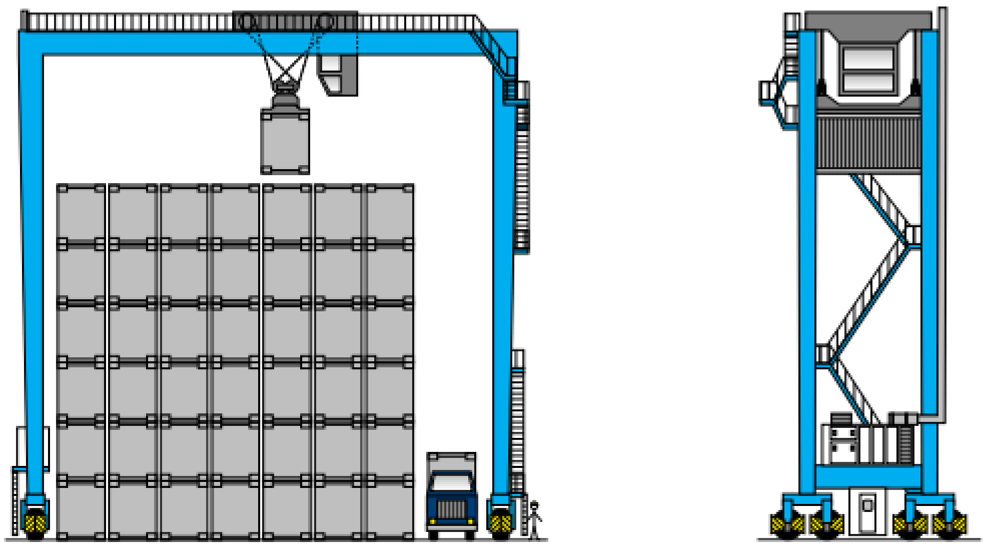


Figure 2: Front & Side View of RTG Crane[13]

RTG cranes straddle multiple lanes of stacked containers (see Figure 2), and can move 20 or 40 foot long containers weighing up to 65 tons. As the name suggests, rubber-tired gantry cranes run on rubber tires that enable them to move from one line of stacked containers to another. The capacity of an RTG is defined by the maximum height and width of the stack, the maximum weight of the container that can be lifted, and the power of the onboard diesel engine if applicable. As an example, the RTG shown in Figure 2 has a maximum lifting height of '1 over 6' and a maximum span of '7 + 1 truck lane'. The suspended portion of the crane, which receives the container, is called the "spreader". The main purpose of an RTG is to load and unload containers from trucks, and for the on-shore movement of containers.

The majority of RTGs in use today are powered by large diesel engines. The engine runs a generator to produce electricity. All cranes drives are powered by electric motors using the electricity generated onboard. RTGs function by making 3 basic movements:

1) Hoisting (and lowering) – to raise (or lower) the spreader
2) Trolley movement – to move the spreader transversely across the stack
3) Gantry movement – to move the entire crane along the length of the stack

[13] Mulder, Steven. "Energy Management Strategy for a Hybrid Container Crane" < http://repository.tudelft.nl/assets/uuid:8e3d73b0-b495-410c-9e7e-e5d23efaa2bc/Mulder_S..pdf>

The maximum potential for regenerating power on an RTG crane is while lowering a container; energy can be captured from the movement of the crane which occurs by virtue of the container's own weight.

Analysis and Results

To evaluate the potential ways for ports to reduce the environmental impact of RTG cranes, our team took a three-step approach. First we identified broad categories and sub-categories of potential actions that may reduce the environmental impact of the cranes, as shown in Figure 3. Specific action categories include energy storage, the reduction of idle time, power train improvements, electrification, and the adoption of alternative fuels. Second we identified the necessary financial and environmental data necessary for the comparison of options against each other. Finally, we conducted primary and secondary research with governmental agencies, ports, and equipment vendors to quantify the environmental impacts and financial returns associated with each option. In the following sections we review each option we considered and discuss the benefits and potential hurdles associated with implementing each option.

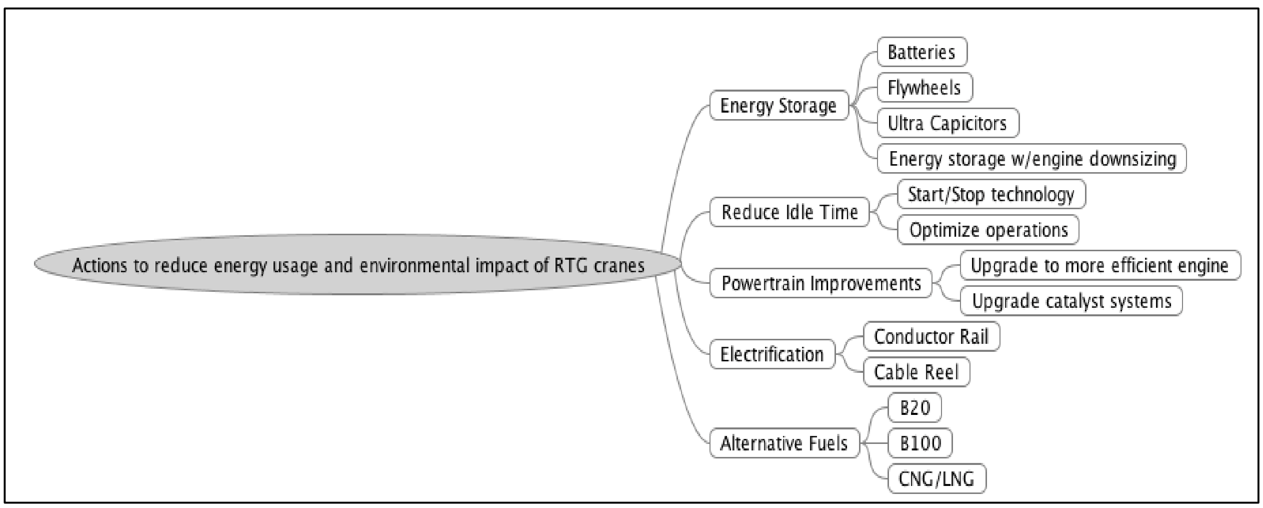
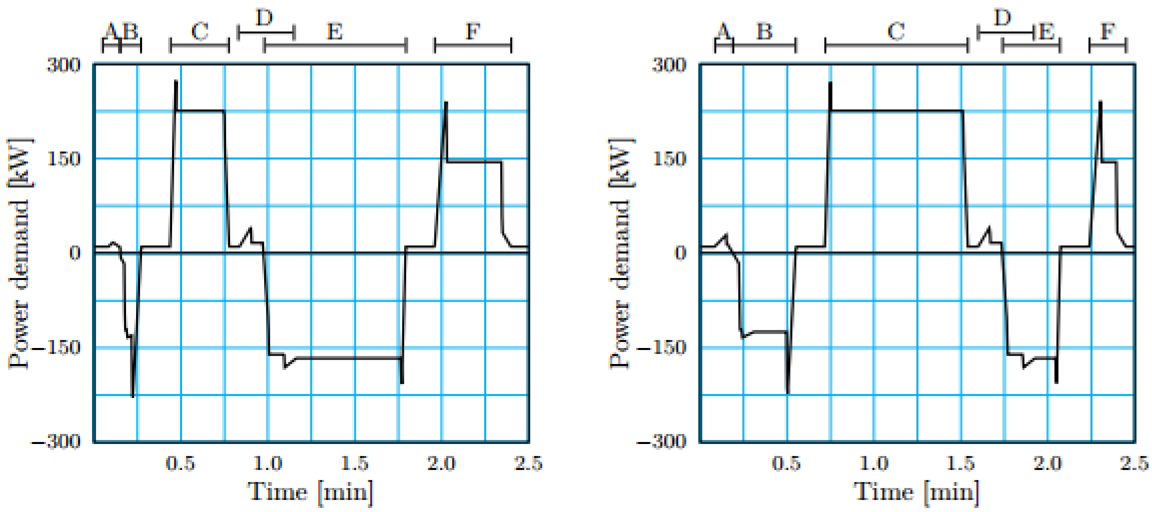


Figure 3: Potential actions considered to mitigate environmental impact of RTG cranes.

Energy Storage

When a container is lowered, the hoisting motor is not performing any work. In fact, the lowering motion is being driven by the weight of the container; therefore the movement has the potential to produce electricity (analogous to a generator). In a conventional RTG, no way exists to gainfully use this generated electricity. Therefore, the electricity is fed to large resistor banks, converted to heat, and eventually dissipated via direct contact with air.



(a) Loading a container down to a truck **(b)** Unloading a container up from a truck

Figure 4: Typical power demand during loading and unloading of a 40t container from a truck onto the stack (row 6, height 5)[14] A-F indicate movements: A. move the trolley over the pick-up point (either above the stack or a truck); B. lower the empty spreader onto the container; C. hoist the container up to clear the top of the stack; D. move the container over the release point; E. lower the container to the release point; F. lift the empty spreader from the container.

Figure 4 gives a visual representation of the power generated when lowering a container. It also clearly shows the momentary peak in power demand just as the hoisting motion commences.

Studies performed by the Georgia Port Authority on their ship-to-shore (STS) cranes showed that on average, the cranes generate electricity for 18 minutes during every hour of operation.[15] The potential for regeneration is expected to be similar for RTG cranes. Additionally, the need for maximum power on an RTG's diesel engine exists for only 4% of operating time[16], which implies that if the peak power demand can be reduced, the diesel engine can be downsized.

[14] Mulder, Steven. "Energy Management Strategy for a Hybrid Container Crane" <http://repository.tudelft.nl/assets/uuid:8e3d73b0-b495-410c-9e7e-e5d23efaa2bc/Mulder_S..pdf>
[15] http://eslpwr.com/PDF/WCN-considerations-of-electrified-RTGs-0213.pdf
[16] http://www.react-transport.eu/index.php/knowlage-base/Belgrade%20Conference%20Presentations%20-%20Material/Session%2001/S1_1_Reduction%20of%20RTG%20cranes%20CO2%20emission%20by%20using%20hybrid%20technology%20.pdf/download

Batteries

One way to capture the energy generated in an RTG crane's lowering motion is by storing the energy in onboard battery banks (as is the case in hybrid cars). This stored power can then be used to:

1) Reduce the peak load demand on the engine during the next hoisting operation
2) Supplement the electric power supplied by the diesel generator
3) Run auxiliaries like computers, lights and air conditioning, allowing the engine to be shut down during idle periods

While RTG manufacturers have invested heavily in R&D for such hybrid systems, they believe that the very high upfront and maintenance costs make them unpopular under current market conditions.

Ultracapacitors

Ultracapacitors serve a similar purpose as batteries. The advantage of using ultracapacitors is that they are highly efficient and have higher power density as compared to batteries.

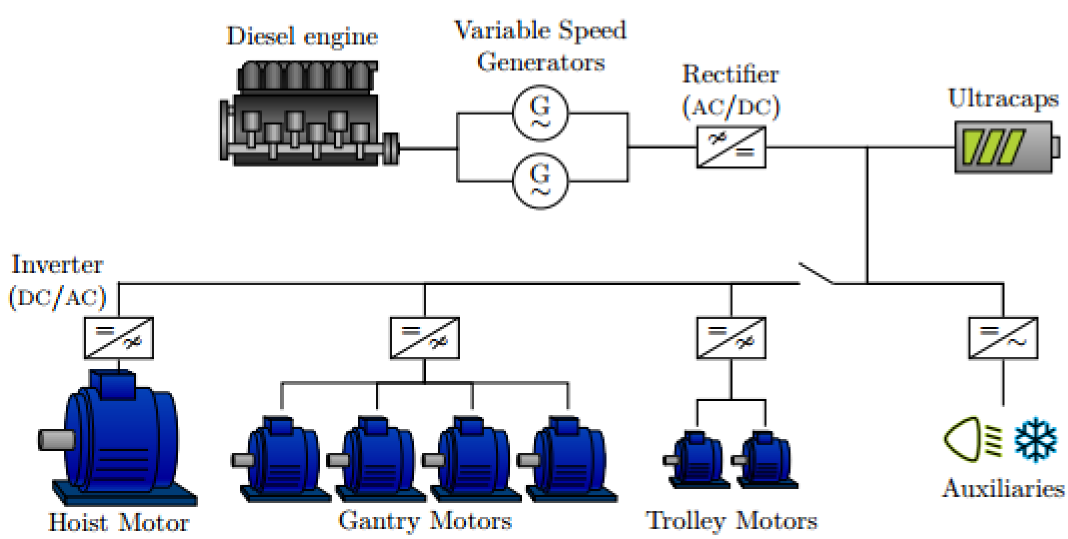


Figure 5: Power architecture of RTG using ultracapacitors with variable speed generators[17]

Figure 5 shows a schematic layout of an RTG that combines the benefits of a variable speed generator with ultracapacitors to recover and store energy. With this system, the diesel engine would need to run at high speed only when there is high power demand (mostly during

[17] Mulder, Steven. "Energy Management Strategy for a Hybrid Container Crane" < http://repository.tudelft.nl/assets/uuid:8e3d73b0-b495-410c-9e7e-e5d23efaa2bc/Mulder_S..pdf>

hoisting). At other times, smaller power demands can be supplied either by the engine running at a low speed, or by the ultracapacitors.

Flywheels

A third way to store the energy generated during the descent of a container is with a flywheel. The use of flywheels to store energy predates chemical batteries and capacitors by centuries, and modern advances have made the flywheel an economic, efficient, safe, and low-maintenance alternative to electrical storage options. A modern commercial high-speed flywheel is depicted in Figure 6.

Figure 6: Commercial high-speed flywheels spin at 36,000rpm and can store more energy than required to lift a fully loaded container. [11]

Flywheel retrofit systems are a proven technology in RTG applications and can be installed in less than one day. Flywheels with a 2.1MJ capacity have shown fuel reductions between 15% and 37%. Greater fuel economy savings are achievable by replacing the original engine with a downsized engine. By installing a flywheel system (or any other energy storage system), the original engine is no longer required to produce the same peak power, and so can be replaced with a smaller, more fuel efficient engine. Compared with batteries and ultracapacitors, flywheels require a smaller upfront investment to realize similar fuel saving benefits.

Reduce Idle Time

Start/Stop Technology

Engine start/stop technology is becoming increasingly popular for passenger cars. The technology is relatively easy to implement, so the engine itself doesn't need to be modified; rather, the installation of a more powerful starter motor is sufficient.

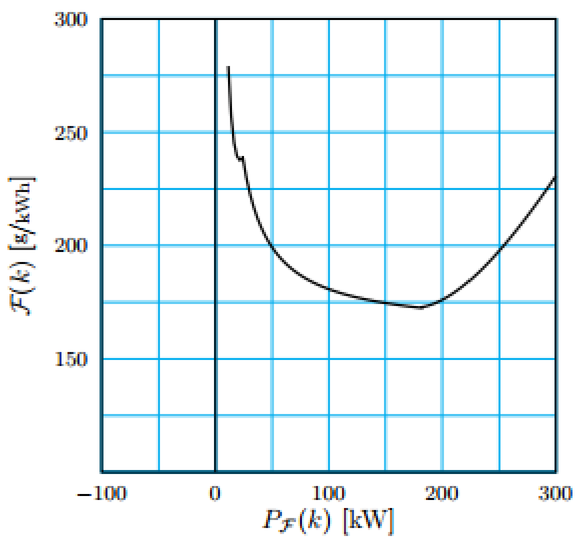


Figure 7: Specific fuel consumption for a 300kW diesel generator[18]

Figure 7 shows that at very low loads (i.e. idling conditions), fuel consumption per kWh of power generated becomes much higher. By stopping the engine instead of keeping it idling, there would be a significant reduction in fuel consumption and therefore emissions.

However, challenges exist in the frequent stop/starting of large engines, such as the potential for an increase in engine wear due to poor lubrication conditions during starting.

Many RTGs in operation today have two diesel engines: a large engine for container handling, and a small 'pony' engine to only supply auxiliaries, allowing the large engine to be shut down during idle periods. However, a practical challenge on some cranes with this setup is that the changeover between generators causes a momentary interruption of power, and therefore a reboot of the crane's computer control systems. As a result, this fuel saving feature is often disabled. Battery backup for computers, in the form on an uninterrupted power supply unit, would help to solve this problem.

[18] Mulder, Steven. "Energy Management Strategy for a Hybrid Container Crane" <
http://repository.tudelft.nl/assets/uuid:8e3d73b0-b495-410c-9e7e-e5d23efaa2bc/Mulder_S..pdf>

Optimize Operations

Cost and emissions savings can be realized by operating RTGs more efficiently. Often, such optimization measures require minimal capital investment. However, personnel would need to be re-trained and motivated to adopt new operating procedures.

Some examples are:

1) In most ports, agreements with labor unions require a minimum number of RTGs to be in operation every day. As a result, on days when activity is below normal levels, more cranes than required are put into service and they spend a large portion of the day idling. Renegotiating union contracts to only run the optimal number of cranes would help improve efficiencies in such a scenario.
2) In some ports, the starting up and shutting down of RTGs is done only by qualified mechanics, not by the crane operators. As a result, even if the operator knows that he/she will be idle for an extended period, he/she may need to keep his/her crane's engine running until a mechanic is available to turn off the machine.

While these operational solutions require zero technological changes in ports, it is important to understand that they involve high levels of organizational and political complexity. A re-negotiation of contracts with union labor would entail an understanding of the interests and needs of the port workers – job security, economic benefits, and feeling engaged and valued on the job – as well as the economic perspective of the bottom line. For example, it is politically complex to suggest a solution like paying workers not to work in order to reduce emissions, because in such a scenario workers feel, and managers perceive, the workers' level of dispensability.

To manage the high levels of organizational complexity that an operations optimization exercise would entail, we suggest instituting a process of continuing improvement that involves joint fact-finding by all workers around questions of sustainability, efficiency, and personal contributions to the organization. We expect that such an exploratory process involving both management and labor will increase engagement at all levels of the organization, and will generate credibility and buy-in for proposed solutions. Since this process has the potential to be high-conflict between the different parties involved, management may want to consider hiring of a professional facilitator who can both mediate any conflicts that erupt and also train employees to improve the communicative environment within the organization.

Powertrain Improvements

Improve Engine Efficiency

Figure 7 above shows that the specific fuel consumption for any engine is the lowest when it is running in a certain optimal load range. The engine manufacturer will determine this range through extensive bench testing of the engine. One way to improve the efficiency of existing engines would be to modify their operations to run as close as possible to the optimal load range. Some ways to achieve this optimization are:

1) Retrofits to shave off peak load demand (batteries, ultracapacitors, flywheels etc.)
2) Reduced idling time by shutting down the engine when not required
3) Optimizing utilization of RTGs through better scheduling and planning

A more effective, but highly capital intensive way to improve efficiency would be to replace the entire engine with one that meets the latest efficiency and emissions standards stipulated by Tier 4 Final. If engine replacement is combined with the installation of power regeneration technology, it would be possible to downsize the engine and enjoy additional efficiency and emissions benefits, though the life-cycle analysis impacts of retiring machines before the end of their useful lives should be considered. Partial funding from the EPA may be available for such upgrades through the National Clean Diesel Campaign's Diesel Emissions Reduction Act (DERA) grants. Since 2008, nearly 60,000 pieces of clean diesel technology have been funded by DERA grants, a number of which involve upgrading engines from a lower to a higher tier[19].

Upgrade catalytic systems

Large diesel engines can be retrofitted with exhaust treatment systems to reduce PM and NOx emissions.[20] Retrofit methods to achieve this reduction include exhaust gas regeneration (EGR), diesel particulate filters (DPF), diesel oxidation catalysts (DOC) and selective catalytic reduction (SCR). DPFs & DOCs can reduce PM, HC and CO emissions. EGR and SCR help to reduce NOx emissions.[21] In order to achieve optimal results, it may be necessary to use 2 or more of these methods in conjunction; however, these upgrades do not reduce CO_2 emissions.

It is important to note that while catalytic systems will drastically reduce harmful exhaust emissions, there will be no improvement in fuel economy and in fact, there may be a small negative impact on fuel efficiency which implies increased operating expense. It may be

[19] http://www.epa.gov/cleandiesel/projects/
[20] http://www.deere.com/en_US/docs/pdfs/emissions/large_engine_technology_final.pdf
[21] http://www.epa.gov/cleandiesel/technologies/retrofits.htm

possible to get EPA grants through the National Clean Diesel Campaign for installing these emissions reduction upgrades. Verified diesel emission control strategies (VDECS) from several providers are commercially available.[22]

Alternative Fuels

B20 & B100 Biodiesel

Another way for ports to reduce their environmental impact is to change the types of fuels they use in RTGs. Switching from regular diesel to biodiesel is a low/no investment cost option to reduce air pollutants and greenhouse gases. Biodiesel is typically sold in two varieties, B20 (20% biodiesel / 80% regular diesel) and B100 (100% biodiesel). The emissions benefits vary almost linearly with the percentage of biodiesel in the fuel mixture. For example, B100 contains virtually no sulfur so that SO_x emissions are reduced 100% compared to regular diesel fuel, while B20 SO_x emissions are reduced by 20% compared to regular diesel fuel. Figure 8 shows how B100 and B20 compare for other important pollutants.

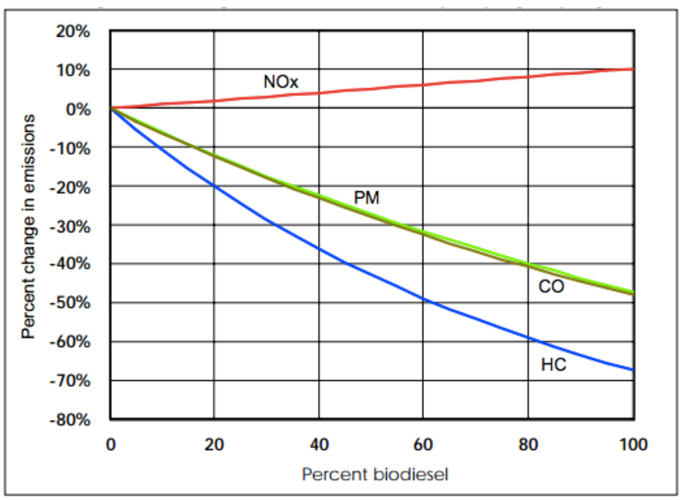


Figure 8: Significant hydrocarbon, carbon monoxide, and particulate matter reductions are realized with biodiesel, while NO_x emissions are moderately degraded.[23]

In addition to the significant reduction to the pollutants shown in Figure 8, switching to biodiesel fuels can provide great reduction in greenhouse gas production. Engines burning biodiesel and conventional diesel emit similar levels of CO_2 from the tailpipe. However burning

[22] http://www.arb.ca.gov/diesel/verdev/vt/cvt.htm
[23] http://epa.gov/otaq/models/analysis/biodsl/p02001.pdf

B100 biodiesel reduces the global CO_2 impact by 78%, since the feedstocks used to produce biodiesel absorb a portion of the CO_2 emitted from the engine.[24]

While switching to biodiesel fuels offers many advantages, there are several disadvantages as well. First, biodiesel is more expensive than regular diesel. We find that B20 costs roughly 2% more than conventional diesel, while B100 costs about 10% more in the current market. Additionally, market prices of biodiesel are volatile and sensitive to regulations and policies around renewable energy. A second challenge is that biodiesel contains less energy per gallon compared to conventional diesel: 8% less for B100 and 1.6% less for B20. Thus ports should expect fuel costs to increase 19% if switching to B100, and 4% if switching to B20. A third challenge is that biodiesel has greater sensitivity to cold temperatures, with high-level biodiesel blends gelling as temperatures approach 0^oC. Finally, a switch to biodiesel raises questions related to the stability of the biodiesel supply chain, combined with the uncertainty of long-term contract rates inherent in an emerging commodity product. A supply chain risk mitigation avenue to be explored is the possibility of partnering with businesses in the local region that convert waste to B100.

Natural Gas

A second alternative fuel to consider is CNG (compressed natural gas). Natural gas offers many benefits over diesel both in terms of cost and in terms of emissions. Given today's average diesel and CNG prices, CNG would allow ports to decrease fuel costs by 38% while performing the same amount of work. [25] In addition to this absolute cost benefit, switching to CNG and diversifying the portfolio of fuels used would decrease exposure to changes in diesel fuel prices.

CNG also offers reduced tailpipe pollutants and greenhouse gas emissions. CO2 generation is reduced by 27% compared to diesel. Other tailpipe pollutants that impact air quality in the port vicinity are also significantly reduced as shown in Figure 9.

[24] http://www.nrel.gov/docs/legosti/fy98/24772.pdf

[25] http://www.cngnow.com/average-cng-prices/pages/default.aspx

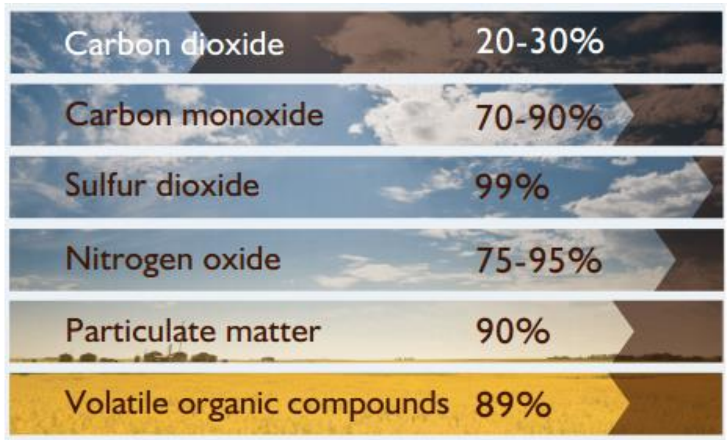


Figure 9: Expected pollutant reduction when switching from diesel to CNG[26]

Some challenges must be overcome to make the switch from diesel to CNG, however. First, ports must either replace the diesel generator on RTG cranes with a new CNG engine, or retrofit existing engines to run on CNG. In addition to the engine change itself, ports need to ensure an adequate supply of natural gas to the site and install fueling filling infrastructure, if the infrastructure is not already present.

Electrification

Conductor Rail

So far we have explored ways to reduce the fuel consumption of the diesel generators that power RTG cranes, ways to capture and reuse the energy currently unharnessed when lowering containers, and ways to reduce the emissions impact of RTG engines through the adoption of alternative fuels. We now examine the implications of powering RTGs directly with grid electricity and abandoning the diesel generators used to hoist containers. There are two ways to accomplish this conversion: (i) via "conductor rail" also known as "busbar" power, or (ii) via "cable reel" power.

When converting an RTG crane from diesel to electric via the conductor rail method, several advantages are realized. First, the cranes need only use diesel power to move between container lanes while disconnected from the electrified rail. This results in a 95% reduction in diesel fuel usage, and a corresponding 95% reduction in RTG air pollutants in and around the port. Second, the energy generated as containers descend need not be wasted, but is instead fed back into the grid for other cranes to use. Third, moving away from diesel engines and toward electrification decreases overall maintenance costs and increases crane uptime.

[26] http://www.encana.com/pdf/natural-gas/transportation/heavy-alternative-brochure.pdf

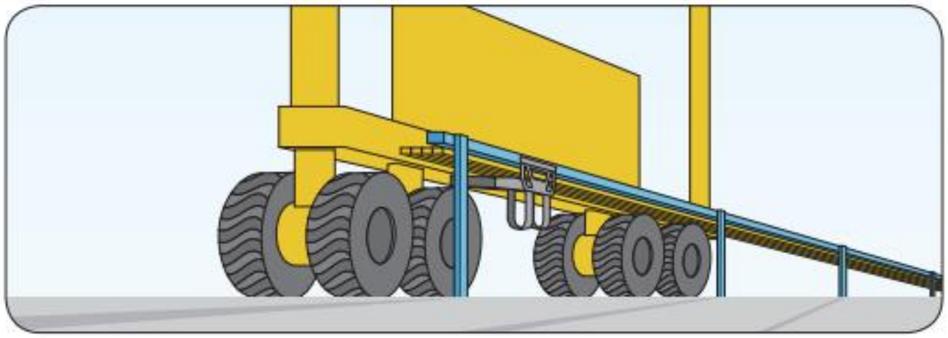


Figure 10: Conductor rail systems do not require the RTG crane to plug or unplug when moving between container lanes.[17]

Cable Reel

The second way to convert RTG cranes to electric is via cable reel installation. This method also results in a 95% reduction in port area RTG emissions since the diesel generators are only used to move the RTG between container lanes or to maintenance facilities[27]. Cable reel systems have been broadly adopted in ship-to-shore and rail-mounted-gantry crane applications. Applying this technology to RTG cranes requires the installation of the reels and cable, as well as channels along the yard that the cable rests in while the crane moves.

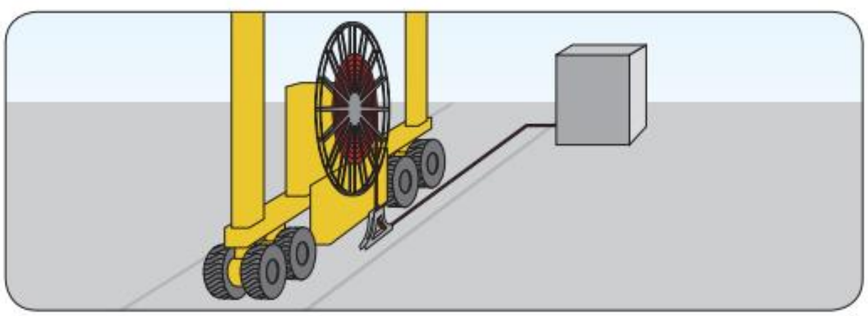


Figure 11: Cable reel systems require that the crane be unplugged to move between container lanes.[18]

There are two concerns with cable reel systems compared to conductor rail systems. First, it is possible that debris could build up in the cable channels if the channel crosses trucking intersections in the yard. Second, some time is lost whenever an RTG needs to be unpluged from the grid, moved to another lane, and then plugged back in. With drive-in conductor rail systems, an RTG can simply drive away from the rail whenever it needs to without unplugging and replugging.

[27] http://www.conductix.us/sites/default/files/downloads/Brochure_-_E-RTG_Electrification.pdf

Recommendations

In assessing the benefits, drawbacks, and hurdles associated with each RTG technology option, it is important to keep in mind that there is no one-size-fits-all solution. There are significant benefits and tradeoffs associated with each option. Ports need to weigh the factors that are important to their particular contexts and assess which investments best fit each case. However, two important angles from which to assess the various options available are the financial angle and the environmental, emissions angle.

In the analysis we conducted (as shown on the accompanying Analysis Matrix spreadsheet, Exhibit 1 & 2), we quantify both the financial and the environmental implications of the various options considered: energy storage, idle time reduction, powertrain improvements, electrification, and alternative fuels. It is assumed that the total useful life of an RTG is 30 years, with major retrofits in consideration when the crane is on average halfway through its useful life; therefore we assume the cranes on average have another 15 years of useful life.

Our analysis is referenced against an RTG with a 1,000 horsepower (hp) diesel engine conforming to Tier 1 emissions standards, and with no means to regenerate power when lowering a container. We assume that the RTG runs for on average 3,000 hours per year, consuming 10,000 gallons of ultra-low sulfur diesel fuel. Some of the emissions and cost increases/savings are given as a percentage change as compared to this reference base. It is possible in the spreadsheet to factor in the impacts of grants, tax credits, salvage value, carbon tax and an escalation in the cost of diesel fuel; the following summary of our recommendations does not consider these factors. For further accuracy in results, inputs such as initial investment, discount rate, and salvage value should be amended to reflect values applicable to each specific port under analysis.

Financial considerations

Options for more sustainable RTG technology vary widely in required upfront investment, operational savings, and overall expected net present value (NPV). In the following calculations, we determine NPV, assuming fifteen years of remaining useful life, and a cost of capital of 2%, based on long-term bonds that the Port of Oakland has issued.[28] We assume also that a gallon of diesel costs $3.89, the current average in the USA. The financial tradeoff is roughly between the initial capital outlay versus fuel costs recouped over the period of the retrofit's useful life.

[28] http://www.portofoakland.com/pdf/about/2014_pbs_06.pdf

Energy Storage

Switch to a diesel-electric hybrid with a downsized Tier 4 engine

Amongst energy storage options, switching to a diesel-electric hybrid powertrain with a downsized Tier 4 engine requires the highest upfront capital outlay, an estimated $500,000 per crane. We factor in an additional annual maintenance cost of $10,000 (for battery replacement) and a 60% reduction in fuel costs. We derive a negative NPV of ($326,000) and an overall required payback period of 38 years.

Hybrid retrofit with existing diesel engine

The capital outlay of this option is expected to be $350,000. We factor in an incremental additional maintenance cost of $10,000 (for battery replacement) and a 40% reduction in fuel costs. NPV is expected to be negative ($273,000), with an overall payback period of 63 years.

Flywheels

The capital outlay of flywheels is expected to be $120,000. We expect minimal additional maintenance costs associated with flywheels, and a fuel cost reduction of 25%. Expected NPV is a positive $5,000 with a payback period of 12 years.

Ultracapacitors

Ultracapacitors require the least capital outlay of the energy storage options, at $80,000 per crane. Because ultracapacitors have a useful life of roughly 6 years, we factor in maintenance costs of roughly $7,000 per year. We expect a fuel cost reduction of 40% and derive a positive NPV of $34,000 with a payback period of 9 years. It is important to note that initial investment may be higher if major modifications to the crane's electrical systems are required.

Idle Time Reduction

Engine Start-stop

We estimate an upfront capital outlay of $35,000 for the cost of installing instrumentation and an auxiliary power unit, as well as the cost of upgrading the starter motor. We assume minimal additional maintenance costs and a fuel savings per year of 20%. This option yields a positive NPV of 64,000 with a payback period of under 5 years.

Operations optimization

Operations optimization is contingent on labor regulations, the port's relationship with labor unions, and the appetite for change. These factors are not readily quantifiable without a much more precise understanding of the port in question and should be analyzed on a case-by-case basis.

Powertrain Improvements

Upgrade to a more efficient engine

This option is highly capital intensive at an estimated $300,000 initial cost. We expected a fuel cost savings of 5% per year and an additional yearly cost for Diesel Emissions Fluid (DEF), yielding a negative NPV of ($278,000) and an unrealistic payback horizon.

Retrofit exhaust after-treatment systems

This option requires initial capital outlay of $115,000 and annual additional DEF costs. There are zero fuel cost savings. Therefore, NPV is negative ($121,000).

Electrification

Conductor Rail

This option requires capital outlay of $470,000. This initial investment includes a $1 million infrastructure investment, spread over 4 cranes, to install permanent conductor rails to serve 2 adjacent container stacks. In our current case, with an expected annual diesel fuel cost reduction of 95%, we yield a negative NPV of ($116,000) and an overall payback period of 17 years. It is important to note, however, that we have not factored maintenance costs into our NPV calculation; maintenance costs are expected to be 58% lower than an equivalent diesel RTG, which would significantly increase the expected NPV.

Cable Reel

This option requires capital outlay of $333,000, yielding fuel cost reduction of 95%. We calculate a positive NPV of $18,000 and a payback period of 12 years. We have not factored maintenance costs into this NPV calculation; maintenance costs are expected to be 58% lower than an equivalent diesel RTG, which would significantly increase our expected NPV.

Alternative Fuels

Biodiesel B20

Switching fuels to biodiesel requires no initial investment outlay. We expect a 4% increase in fuel costs per year, yielding a negative NPV calculation of ($20,000) per crane.

Biodiesel B100

Switching to biodiesel B100 requires no initial investment outlay. We expect a 19% increase in fuel costs per year, yielding a negative NPV calculation of ($93,000) per crane.

CNG with new engine

This option requires an initial upfront cost of $225,000. We expect a fuel cost savings of 38% per year, yielding a negative NPV of ($34,000) and a payback period of just over 15 years.

CNG with retrofit on existing engine

This option requires an initial upfront cost of $50,000. We expect fuel cost savings of 38%, yielding a positive NPV of $137,000 and a payback period of 3 years.

Summary

Among the various options explored, the options of CNG retrofit, engine start/stop, and retrofitting ultracapacitors yield a positive NPV and a reasonable payback period of under 10 years. The CNG retrofit engine yields the highest NPV and the shortest payback period of the options we have considered. The engine start-stop option for the reduction of idling time also has an attractively positive NPV and a low payback period; this option has the additional benefit of a low initial capital outlay. Amongst energy storage options, retrofitting ultracapacitors appears the least capital intensive and shows a positive NPV.

Environmental considerations

Besides cost considerations, ports must consider how air quality, both locally around the port and globally, is impacted by their operations. Locally, the communities near ports are often sensitive neighbors with whom the ports hope to maintain healthy relations. Besides local emissions, however, the global overall impact of emissions also matters. As long as electricity is generated by fossil fuels, electrification reduces and displaces CO_2 and other emissions, but does not eliminate them. The following sections summarize the relative impact of the various retrofit options in the context of global CO_2 emissions, as well as local tailpipe emissions of NOx, SOx, CO, HC, and PM10 (particulate matter less than 10 micrometers in diameter). Percentage reductions of the various emissions are benchmarked from the standard of an engine meeting Tier 1 emissions standards. Overall, the decision of which type of emissions is of the highest priority in terms of air quality improvement is a consideration for individual ports to keep in mind, in a balance of regulatory and community needs with more global concerns.

CO2 Emissions (Lifecycle)

In terms of CO2 emissions, the greatest reductions occur with a shift in fuel usage to biodiesel B100 (-78%), the installation of a hybrid diesel-electric system with batteries (-60%), and electrification either by busbar or cable reel (-53%). On the other hand, powertrain improvements of upgrading to a more efficient Tier 4 engine or retrofitting exhaust after-treatment systems results in negligible or no reduction in CO2.

NOx Emissions (Tailpipe)

NOx emissions see the greatest reduction with electrification (-95%), installation of a hybrid diesel-electric system with batteries (-90%), and using CNG as an alternative fuel (-85%). On the other hand, NOx emissions increase slightly if biodiesel B20 is used (2%), or if biodiesel B100 is used (10%).

SOx Emissions (Tailpipe)

SOx emissions are a function of sulfur content in the fuel used and quantity of fuel consumed. The greatest reduction is realized with the adoption of the alternative fuel types B100 (-100%) or CNG (-100%), and with electrification (-95%). On the other hand, powertrain improvements impact SOx emissions negligibly, if at all.

CO Emissions (Tailpipe)

CO emissions see the greatest reduction with electrification (-95%), or with the adoption of CNG as the alternative fuel (-80%). Powertrain improvement options impact CO emissions negligibly, if at all.

HC Emissions (Tailpipe)

HC emissions see the greatest reduction with electrification (-95%). Switching to alternatives fuels B100 and CNG has a significant impact (-60% to -65%), as does powertrain improvements (-60%) and the installation of a diesel-electric hybrid system (-60%). The usage of flywheels with existing engine, the engine start-stop method of reducing idling time, and the usage of biodiesel B20, yield less significant HC emissions reductions (around a 20% decline).

PM10 Emissions (Tailpipe)

PM10 emissions see the greatest reduction with electrification (-95%), the installation of a hybrid diesel-electric system with batteries and a downsized engine (-90%), powertrain improvements (-90%), and the adoption of CNG fuels (-90%). PM10 emissions are not impacted much by switching to B20 biodiesel (-10%).

Summary

Among the various options explored, the installation of a hybrid diesel-electric system with batteries and a downsized engine results in significant reductions in both global CO_2 emissions and local tailpipe emissions. Electrification and CNG alternative fuel options also dramatically reduce both local and global emissions. The use of biodiesels such as B20 and B100 reduces most categories of emissions, but slightly increases the emission of NOx locally.

Application

This report explored options for RTG crane technology that can be useful for emissions reduction, while also highlighting operational and financial benefits where applicable. While this exploration was conducted for the Environmental Defense Fund in the context of the Port of Oakland, we believe that the broad survey nature of the various technologies available for RTG cranes can be of informational value to other ports considering further sustainability measures. RTG cranes in particular are a type of machinery that have not been heavily targeted for green technology efforts – while they are not the largest contributors to emissions in ports, they represent a non-trivial proportion. We believe that greener technologies on RTG cranes represent an open frontier in the quest to reduce emissions and stabilize climate change.

Exhibit 1: Snapshot of Analysis Matrix

MIT Sustainability Lab - EDF Logistics Project - Greening of RTGs
May 15, 2014

		Economics									Environmental						Vendors	References
	Type of Solution	Investment ($)	EPA Grants, Subsidies, Tax Credits ($)	Salvage value of used equipment ($)	Incremental Maintainence Cost ($/yr/crane)	Fuel Cost ($/yr/crane)	Other Costs ($/yr/crane)	NPV ($)	Annual ROI %	Payback Period (yrs)	CO2 (lifecycle)	NOx (Tailpipe)	SOx (Tailpipe)	CO (Tailpipe)	HC (Tailpipe)	PM10 (Tailpipe)		
Energy Storage	Battery (Diesel-electric hybrid with downsized T4F er	500,000	0	0	10,000	-60%	270.30	(325,553)	3%	38.3	-60%	-90%	-60%	-60%	-60%	-90%	ABB, Mi-Jack	21,23,24
	Battery (Hybrid retrofit without downsized engine)	350,000	0	0	10,000	-40%	0	(273,096)	2%	62.9	-40%	-40%	-40%	-40%	-40%	-58%		19,22
	Flywheels	120,000	0	0	0	-25%	0	4,862	8%	12.3	-25%	-30%	-25%	-25%	-25%	-66%	Vycon	14,15,16
	Ultracapicitor (retrofit, without downsizing engine)	80,000	0	0	6,667	-40%	0	33,601	11%	9.0	-40%	-40%	-40%	-40%	-40%	-58%	Siemens, ABB	19,20
Reduce idle time	Engine Start/Stop	35,000	0	0	0	-20%	0	63,693	22%	4.5	-20%	-20%	-20%	-20%	-20%	-20%	EcoTrans	27
	Optimize operations	Refer to written report																
Powertrain Improvements	Upgade to more efficient engine (Tier 4 Final)	300,000	0	0	0	-5%	641.97	(277,703)	0%	230.2	-5%	-60%	-5%	-5%	-60%	-90%	Cummins, CAT, Vol	22,23,24,26
	Retrofit exhaust after-treatment systems (SCR+DPF)	115,000	0	0	0	0	675.76	(121,258)	-1%	-	0%	-60%	0%	0%	-60%	-90%	Johnson Matthey	22,23,24
Electification	Conductor Rail "Busbar"	470,000	0	0	-58%	-95%	0	(116,035)	6%	17.2	-53%	-95%	-95%	-95%	-95%	-95%	Conductix, Kalmar	3,4,5
	Cable Reel	333,000	0	0	-58%	-95%	0	18,279	8%	12.2	-53%	-95%	-95%	-95%	-95%	-95%	Conductix (Omaha	3,4
Alternative fuels	Biodiesel B20	0	0	0	0	4%	0	(19,601)	-	-	-15%	2%	-20%	-11%	-21%	-10%		1,2,7,8
	Biodiesel B100	0	0	0	0	19%	0	(93,107)	-	-	-78%	10%	-100%	-45%	-65%	-45%		1,2,7,8
	CNG (new engine)	225,000	0	0	0	-38%	0	(34,375)	7%	15.2	-27%	-85%	-100%	-80%	-60%	-90%	Catepillar	
	CNG (retrofit engine)	50,000	0	0	0	-38%	0	137,194	30%	3.4	-27%	-85%	-100%	-80%	-60%	-90%	OmniTek, Californi	6,9, 10, 11, 12

Notes

1) Standard RTG for this analysis has the following specs:
- Boxes high: 1 over 6
- Boxes across: 6 + truck lane
- Max load: 50 tons
- Fuel: Ultra Low Sulfur Diesel (ULSD) [Sulfur < 15ppm]
- Engine power: 1000 hp (750 kW)
- Average annual running time: 3000 hrs

2) All values are in comparison to a 1000 hp diesel engine complying with Tier 1 emission standards for non-road use

3) Typical emissions (in Metric tons/year) from this RTG over 1 year with ULSD consumption of 10,000 gallons

CO2	101.80
NOx	1.16
HC	0.16
CO	1.44
PM	0.07

Exhibit 2: Benefits & Hurdles for RTG Greening Options

Catagories	Options	Benefits	Hurdles
Energy Storage	Battery	Modular diesel-electric hybrid retrofit solutions available from established RTG manufacturers	Life of batteries is approx 5 year, after which they need to be replaced High capex to replace engine for max savings/emission reduction
	Flywheels	15-35% fuel consumption reduction Small footprint Low maintainence Quick installation time	Investment cost
	Ultracapicitor	Higher energy storage density as compared to batteries Can be integrated with variable speed diesel engine Additional savings possible by fine-tune energy mngt system	Life of ultracapacitors is 5-6 years, after which capacitor banks need to be replaced High capex to replace engine for max savings/emission reduction
Reduce idle time	Engine Start/Stop	Relatively low capital investment for retrofit Huge savings in diesel consumption when low number of moves per hour (longer idling time between moves)	Increased engine wear due to frequent start/stop Modification to engine starting mechanism may be necessary
	Optimize operations	Large savings can be realized with very low upfront investment Does not require any retrofits or purchase of new assets Can empower employees to strive for continuous improvement	Possible challenges from workers' labor unions Need to combat inertia to change in large organization
Powertrain Improvements	Increase Engine Efficiency	Large reduction in emissions, especially NOx an PM Compliance with latest EPA standards for off-highway diesel engines	Operating and maintenace expenses increase as compared to conventional engine Tier 4 Final technology is relatively new and engine costs are high
	Upgrade catalytic systems	Large reduction in emissions, especially NOx an PM Catalytic systems can be fitted onto existing engine	Operating and maintenace expenses increase as compared to conventional engine No reduction in fuel consumption after retrofit
Electification	Conductor Rail "Busbar"	95% reduction in fuel consumption 95% emissions reduction Reduced maintenance and downtime Maintain flexibility of cranes	Investment cost Infrastructure installation Crane operator training
	Cable Reel	95% reduction in fuel consumption 95% emissions reduction Reduced maintenance and downtime	Investment cost Infrastructure installation Crane operator training Must unplug and replug cable when moving between lanes
Alternative fuels	B20	Decreased tailpipe and greenhouse gas emissions Compatible with existing engines No upfront investment needed	4% increased fuel costs Availability
	B100	Large decrease in tailpipe and greenhouse gas emissions	19% increased fuel costs Availability Temperature limitations
	CNG	Decreased tailpipe and greenhouse gas emissions 38% fuel cost reduction	Investment cost Ensure adequet infrastructure for increased load Increased filling time