

This article was downloaded by: [University of Michigan]

On: 18 October 2012, At: 12:54

Publisher: Taylor & Francis

Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



## International Journal of Sustainable Transportation

Publication details, including instructions for authors and subscription information:

<http://www.tandfonline.com/loi/ujst20>

### Life-Cycle Emissions from Port Electrification: A Case Study of Cargo Handling Tractors at the Port of Los Angeles

Jae Kim <sup>a</sup>, Mansour Rahimi <sup>a</sup> & Josh Newell <sup>b</sup>

<sup>a</sup> Epstein Department of Industrial and Systems Engineering, University of Southern California, Los Angeles, California

<sup>b</sup> School of Natural Resources and Environment, University of Michigan, Ann Arbor, Michigan

Accepted author version posted online: 20 Sep 2011. Version of record first published: 22 Dec 2011.

To cite this article: Jae Kim, Mansour Rahimi & Josh Newell (2012): Life-Cycle Emissions from Port Electrification: A Case Study of Cargo Handling Tractors at the Port of Los Angeles, International Journal of Sustainable Transportation, 6:6, 321-337

To link to this article: <http://dx.doi.org/10.1080/15568318.2011.606353>

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: <http://www.tandfonline.com/page/terms-and-conditions>

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae, and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand, or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

## Life-Cycle Emissions from Port Electrification: A Case Study of Cargo Handling Tractors at the Port of Los Angeles

Jae Kim,<sup>1</sup> Mansour Rahimi,<sup>1</sup> and Josh Newell<sup>2</sup>

<sup>1</sup>Epstein Department of Industrial and Systems Engineering,  
University of Southern California, Los Angeles, California

<sup>2</sup>School of Natural Resources and Environment, University of Michigan,  
Ann Arbor, Michigan

### ABSTRACT

To reduce greenhouse gas emissions, ports around the world are considering using electric cargo handling equipment. To assess the benefits of the strategy, this study provides a comparative life-cycle assessment between diesel and electric yard tractors in a case study of the Port of Los Angeles. Results indicate a significant reduction in life-cycle emissions as the port shifts to electric vehicles and as the port's electricity supplier increases its use of renewable energy sources (e.g., wind and solar). The results also demonstrate that even with aggressive electrification strategies, the port's legislated reduction targets are not achievable by the year 2030.

**Key Words:** greenhouse gas emissions, life-cycle assessment, Port electrification, Port of Los Angeles, renewable energy

### 1. INTRODUCTION

With the passing of the landmark AB32 (Global Warming Solutions Act) in 2006, California has initiated an ambitious plan to cut its greenhouse gas (GHG) emissions to pre-1990 levels by 2020 and 80% below pre-1990 levels by the year 2050 (California Energy Commission 2007). The City of Los Angeles took a step further by adopting the *Green LA* plan, which calls for reducing GHG emissions 35% below 1990 levels by 2030 (City of Los Angeles 2007). Key regulations such as these at the

---

Received 21 December 2010; revised 12 July 2011; accepted 14 July 2011.

Address correspondence to Mansour Rahimi, University of Southern California, Epstein Department of Industrial and Systems Engineering, 3715 McClintock Ave. 206B, Los Angeles, CA 90089. E-mail: mrahimi@usc.edu

state and local government levels aimed at reducing GHG emissions are prompting public utilities, businesses, and other entities in Los Angeles to plan, assess, and implement new strategies to reduce their carbon footprints, while remaining economically competitive.

One important entity is the Port of Los Angeles (POLA), which is directly responsible for approximately 919,000 jobs and \$39 billion in annual wages and tax revenues in the Los Angeles basin (Vera 2008). As a major center of economic activity, the port is also a focus of attention due to its environmental impacts and is constantly searching for new strategies to reduce its impact locally and regionally. One such strategy is called *port electrification*: the process of transforming the port's power sources from internal combustion to electricity. Among all the operations conducted within the port's boundary, working with cargo handling equipment (CHE) (e.g., yard tractors) is the most important one directly under the control of port management. Electrification is an attractive alternative for CHEs since they are powered by diesel fuel and their emissions are concentrated locally. The Port of Houston, for example, has begun construction of the Bayport Container and Cruise Terminal, a \$1.4 billion project that incorporates 21 electric ship-to-shore cranes and will provide infrastructure to support shore power (Electric Power Research Institute 2008). Furthermore, another study by the Electric Power Research Institute (EPRI) outlines opportunities for electrification and assesses the viability of using currently available technologies such as electric forklifts and yard tractors (Electric Power Research Institute 2006).

Port electrification is viewed by some as the ultimate strategy to reduce emissions within the boundary of the port (Green LA 2007). In this strategy, direct emissions are viewed as tailpipe emissions—zero for electric vehicles. However, looking at this strategy from a broader spatial-temporal (i.e., “systems”) view of emissions production, one needs to consider both *direct* and *indirect* emissions. It is this systems perspective that is the impetus for this study. In the context of this study, indirect emissions are the emissions produced during all key phases of the electricity generation cycle, which have not been considered by most studies, such as the EPRI ones mentioned above. To examine the effects of including indirect (in addition to direct) emissions, the first objective of this study is to provide life-cycle emissions accounting between diesel and electric yard tractors. After this comparison, the study model takes into account future transition to less carbon intensive renewable energy sources for electricity generation as well as projected increases in yard tractor use for the years 2020 and 2030.

We begin by examining emissions from the electricity generation process. POLA buys all of its electricity from the Los Angeles Department of Water and Power (LADWP), with carbon-intensive generating sources. It is also interesting to note that LADWP treats electricity derived from solar, hydro, and nuclear as zero emissions (LADWP 2009<sup>1</sup>). This treatment is both problematic due to incomplete accounting of indirect emissions. To remedy this incomplete accounting and high uncertainty in emissions-factor calculations, we estimate the indirect emissions based on a literature review of previous reputable life-cycle studies. To model increases in yard tractor use in our future estimates, we use the number of containers moving

<sup>1</sup>LADWP, e-mail message to author on March 23, 2009, regarding Green Port Electricity.

through the port (known as “container throughput”). Our hypothesis is that rapid increase in container throughput is the dominant driver of the overall emissions. Therefore, electrification of CHEs may not allow the port to achieve its emission targets, even with an increased LADWP renewable portfolio.

## 2. BACKGROUND

As one of the region’s economic drivers, POLA is a critical part of the continuing growth and vitality of the Southern California region. More than 7.8 million TEU (twenty-foot equivalent unit) containers moved through the port alone in 2008 alone, generating over \$240 billion in economic activity in the United States (Port of Los Angeles 2010). In addition, it is associated with more than 3.3 million jobs (direct and indirect) across the U.S. (Port of Los Angeles 2010). Furthermore, it is the gateway for international commerce—responsible for providing entry to more than 43% of the volume of goods imported to the United States (Salin 2010). However, despite the port’s significant contribution to the regional economy, it is also a source of local and regional air pollution. For example, the emission of sulfur dioxide, nitrous oxide, and particulate matter (PM) from the exhaust pipes of diesel trucks serving the port poses severe health hazards to the local population (Kim, Teffer, and Zeldin 2000). In Los Angeles, deaths caused by ischemic heart disease are linked to the effects of PM<sub>2.5</sub> (Jerrett et al. 2005). Aside from these criteria air pollutants, the port is also responsible annually for over one million metric tons of CO<sub>2</sub> and other GHG emissions and its yard tractors alone contribute to about 94,000 metric tons of CO<sub>2</sub>-equivalent emissions per year (Starcrest 2009).

To reduce the effects of GHGs, POLA has outlined plans under the regional Climate Action Plan (CAP). Although the final draft of CAP has not been officially released, preliminary drafts indicated programs for green power, alternative fuel vehicles, green buildings, and tree planting. Essentially, CAP is an attempt to emulate the success of an earlier Clean Air Action Plan (CAAP). Under CAAP, POLA, working jointly with the Port of Long Beach aims to reduce PM pollution from port-related activities by at least 47% within five years and NO<sub>x</sub> and SO<sub>x</sub> by 45% and 52%, respectively (Port of Los Angeles and Port of Long Beach 2006). Despite the success of CAAP, achieving similar success for GHG reductions is highly uncertain, when we consider the key difference in the nature of these pollutants. Carbon dioxide and other GHGs are *global* pollutants whereas PM, NO<sub>x</sub>, and SO<sub>x</sub> are *local* pollutants. This key difference makes measuring and reducing GHGs a less geospatially-bounded task. Thus, there is a need to measure both direct and indirect emissions from fuel and energy sources upstream, in addition to the emissions from the point of use.

### 2.1. LADWP’s Energy Portfolio

Table 1 summarizes LADWP’s proportion of the energy sources for the production of power (LADWP 2008).

Relative to the rest of the state generators (e.g., Pacific Gas and Electric, Southern California Edison), LADWP has significantly higher proportions of coal and natural gas, generating a CO<sub>2e</sub> emissions factor of approximately 561 g/kWh.<sup>1</sup>

**Table 1.** Percentage of LADWP power mix for 2007.

Energy source	(%)
Non-renewable	
Coal	42
Natural Gas	34
Sub-total	76
Renewable	
Biomass & Waste	1
Geothermal	0
Small hydroelectric	5
Large hydroelectric	6
Solar	0
Wind	2
Nuclear	10
Sub-total	24
Total	100

LADWP expects the carbon intensity of its electricity to decrease to 343 g/kWh by the year 2020.<sup>2</sup> However, as stated previously, these projections suffer from incomplete accounting because they do not treat the emissions from all energy sources on a life-cycle basis.

## 2.2. Emission Factor for Electricity

On a very small scale, the port has been testing the feasibility of replacing a diesel yard tractor with an electric one (Port of Los Angeles 2009). For the electric truck emission calculations, electricity is treated as a homogeneous commodity regardless of the source and time of generation (Balqon 2009). The actual emissions, however, differ for each source and type of electricity generation process. For this reason, it is common in emissions inventory reports to utilize average emissions factors. These factors represent an aggregate estimate of emissions from a broad set of electricity generation processes. Unfortunately, there is no standard protocol for accounting and calculating these emissions factors resulting in various methodologies and ranges of values. For example, the United Nations has established its own framework to calculate emission factors from grid electricity and has created the Emissions Factor Database (EFD) as a library of emission factors (UNFCCC 2009). Several other studies have attempted to offer different protocols (see British Standards Institute 2008; Marnay et al. 2002), but high degrees of uncertainty exist on the proper geospatial and temporal scales in calculating these emission factors. From a life-cycle assessment (LCA) perspective, we also see differing emission factors from power generation processes (Hondo 2005; Pacca and Horvath 2002; Kintner-Meyer Schneider, and Pratt 2007).

<sup>2</sup>LADWP, e-mail interview response to author on March 17, 2010, on carbon intensity factors.

### 2.3. Comparative Life-Cycle Assessment (LCA) and Indirect Emissions

Life-cycle assessment (LCA) seeks to track environmental impacts throughout the life-cycle, including raw material extraction, production, processing or manufacturing, transportation, distribution, storage, use, and disposal (i.e., life-cycle phases). The standard LCA method consists of sequential steps: definition of goal and functional unit, delimitation of scope or system boundary, life-cycle inventory (LCI), and life-cycle impact assessment (see Keoleian and Spitzley 2006; Jimenez-Gonzalez 2000; Curran 1996). LCA is particularly useful to accurately compare the respective impacts of products and processes in each life-cycle phase. A comparative LCA is performed when one wishes to compare two products or production systems that have similarities in their life-cycle stages (e.g., see Boureima et al. 2009, for a comparison of hybrid, electric, LNG and gasoline vehicles). In this study, we employ a consequential LCA because we model the expected effects on emissions based on a technology change from diesel to electric yard tractors. This is an effective methodology to assess and analyze the net impacts of one technology replacing another identical one in function (e.g., see UK Environmental Agency 2005; Subic et al. 2010; Guinee et al. 2001). In this approach, only significant differences are explored and accounted such as those in the fuel cycle and engine production. Other elements of the LCA are the same for both vehicles (e.g., chassis, truck body, capacity). This allows us to reduce data uncertainty and complexity by comparing only those elements that are influenced by different technologies.

### 2.4. Port's Yard Tractor Fleet

Yard tractors are directly under the control of the port's management decision hierarchy. Therefore, data on emissions, usage, and future adoption rates are easier to obtain and more accessible/verifiable. Yard tractors are vehicles that haul containers within a port's boundaries. Because they do not carry containers long distances or to final destinations, the port categorizes these trucks as "cargo handling equipment" (CHE), which encompasses other equipment such as forklifts, sweeper trucks, and cranes. Currently, about 95% of the port's CHEs are diesel-powered (1,059 out of 1,114), with the rest propane-powered (Starcrest 2009). Within the CHE category, the yard tractors are the largest emitters of GHGs with an annual emission of about 94,000 CO<sub>2e</sub> metric tons (Starcrest 2009). It is also the case that modernizing the Port's heavy-duty trucks from older diesel-powered trucks (Clean Truck Program) has been effective in reducing toxic pollutant emissions (NO<sub>x</sub>, SO<sub>x</sub>, and PM; Starcrest 2009). The port's electric demonstration project (using Nautilus E30 trucks) is expected to take this a step further, eliminating all exhaust emissions in this category.

## 3. ANALYSIS AND RESULTS

To achieve the objective of modeling and assessing the overall impacts of electrification on GHG, we perform a comparative LCA study. We then proceed with a modeling of the total emissions from yard tractors. Since the number of tractors in service varies with changing operational demands, we model the number of tractors based on the growth projections of container throughput. Another driving

factor that determines total emissions is the changes in the energy portfolio of LADWP. Therefore, we also model the changes in the carbon intensity of LADWP's energy portfolio given current projections on renewable adoptions. Using these two projections, we simulate multiple scenarios for the total emissions.

### 3.1. Energy Source Emission Factors Based on LCA

The first task is to calculate LADWP energy portfolio's weighted average emissions factor on a per-kilowatt-hour basis. To compute a single weighted emission factor for electricity provided by LADWP, we review various published LCA studies for each energy source. It is important to note that because LCA studies by nature are confined by the scopes, system boundaries, and assumptions set forth in each study, one must be carefully in study selection. Therefore, we choose studies that have comparable attributes to those of LADWP's generation portfolio. For example, for wind energy, we compare the output capacity and whether the plant is on-shore or off-shore. Our computation assumes that each kilowatt of electricity supplied by LADWP is uniform in composition. That is, each kilowatt is composed of 42% coal, 34% natural gas, and 10% nuclear, and so on. For coal, we estimate an emission factor of 1,000 grams CO<sub>2e</sub>/kWh based on a study that estimated the U.S. average for emissions from coal power (NAP, 2010). The emission factors for SO<sub>x</sub>, NO<sub>x</sub>, and PM are considered as 7.0, 3.4, 9.8 g/kWh, respectively (Spath, Mann, and Kerr 1999). We reiterate that our values indicated here account for not only the direct emissions but also indirect emissions from production, transportation, and waste disposal. Natural gas is the second-highest energy source for LADWP. Its emission rate is lower than that of coal at 490 g CO<sub>2e</sub>/kWh (National Academies Press 2010). The emissions factors for SO<sub>x</sub>, NO<sub>x</sub>, and PM are 0.32 g/kWh, 0.57 g/kWh, and 0.13 g/kWh, much lower than those from coal (Spath et al. 1999).

It is well-known that LADWP plans to expand its share of renewable sources. Its growth strategy hinges primarily on the expansion of wind energy, which is projected to make up 75% of the entire power mix in the distant future (LADWP 2008). Although the production of electricity from wind turbines generates no direct emissions, it generates indirect emissions from the production, assembly, maintenance, and disposal of the wind power plants (or "wind farms"). Based on our review of wind LCA, we conclude that the emission factor for electricity generation from wind turbines for LADWP is approximately 14 grams of CO<sub>2e</sub>/kWh (see Dones, Heck, and Hirschberg 2003). Wind energy generation emission factors for SO<sub>x</sub>, NO<sub>x</sub>, and PM are 0.032, 0.048, and 0.0035 g/kWh, respectively (World Energy Council 2004).

The emission factor for small hydroelectric (less than 30 MW) was obtained using an LCA study with the latest technology in construction and maintenance of the power plant (Bergerson and Lave 2002). This study estimates the emission factor at 11 g CO<sub>2e</sub>/kWh. Large hydroelectric have higher emissions because they require dam structures that lead to severe environmental damages in all life-cycle phases. Sediment deposits accumulate behind a dam and release methane upon the decommissioning of the dam. Damming also causes massive flooding of biomass that releases methane. We use the emission factor of 240 grams of CO<sub>2e</sub>/kWh from a complete LCA of the Hoover dam accounting for the methane release from sediment deposits and biomass flooding (Pacca 2007).

## Life-Cycle Emissions from Port Electrification

Recent data from LCA studies for biomass, solar, nuclear, and geothermal are considered for their emissions factors. The factors for biomass are from a study by the University of Michigan (Spitzley and Keoleian 2004). Although they currently make up less than 1% of LADWP's energy portfolio, solar and geothermal projects are expected to add significant capacity in the near future. The emissions factors for solar (photovoltaic and thermal) are from a comprehensive life-cycle study by Fthenakis, Kim, and Alsema (2008), for geothermal we used a study by Energy Center of Wisconsin (2009) and for nuclear we used a study by IER (1997). These values are listed in Table 2.

Based on these values, LADWP's overall weighted average emission factor for the generation of electricity is approximately 600 grams of CO<sub>2e</sub>/kWh. Note that by incorporating the life-cycle emissions, the weighted emission factor is significantly higher than LADWP's current estimate of 560 g CO<sub>2e</sub>/kWh.<sup>1</sup> We note that even with such an increase, the Port achieves a sizable shift in the spatial characterization of its pollutants and their toxic effects. Since electric tractors do not produce tailpipe emissions, the emissions of toxic pollutants are essentially "shifted" away from the ports, thus away from a densely populated urban area (i.e., Los Angeles County) to the electricity generation sites that tend to be in sparsely populated areas. Therefore, the impacts to human health from toxic pollutants generated by CHESs are somewhat alleviated.

### 3.2. Comparative LCA of Yard Tractors

Our comparative LCA considers three phases in its vehicle life-cycle: production, use, and disposal. In the use phase, we define the functional unit as the amount of emissions per operating hour. The conventional measure of emissions per mile is not appropriate since the majority of a yard tractor's daily activity is in a state of waiting or idling. We convert this measure into emissions per vehicle, using the average number of operating hour per vehicle. We begin by examining the emission estimates of the diesel and electric yard tractors in the use phase of the life-cycle.

#### 3.2.1. Diesel Yard Tractor Emissions Estimates

We rely on the Port's extensive emissions inventory data and equipment emission factors (Starcrest 2009). This document gives the aggregate emissions generated by

**Table 2.** Life-cycle emission factors for different energy sources (g/kWh).

Energy source	CO <sub>2e</sub>	SO <sub>x</sub>	NO <sub>x</sub>	PM
Non-renewable				
Coal	1,000	7.000	3.400	9.800
Natural gas	490	0.320	0.570	0.130
Renewable				
Biomass and waste	31	0.370	0.650	0.030
Geothermal	120	0.000	0.000	0.000
Large hydroelectric	240	0.370	0.650	0.030
Small hydroelectric	11	0.027	0.074	0.005
Solar	50	0.370	0.180	0.000
Wind	14	0.032	0.048	0.004
Nuclear	20	0.032	0.070	0.007



the diesel yard tractors, accounting for engine type, power, utilization, and so on. POLA diesel-powered yard tractors operate at full capacity for approximately six hours per day, 300 days per year (Starcrest 2009). The average emissions of CO<sub>2e</sub>, SOx, NOx, and PM were calculated with the following two assumptions: (a) the fleet of diesel yard tractors currently in operation is identical in engine-type, age, and performance, and (b) each diesel yard tractor operates an average of 1,769 hours annually (Starcrest 2009). Given these assumptions, the amount of emissions attributed to each operating hour of a typical diesel-powered yard tractor is shown in Table 3.

As expected, CO<sub>2</sub> is the dominant GHG emission and NOx is the dominant pollutant emission during operation. Normalized over an operation year, each diesel tractor is responsible for approximately 86 metric tons of CO<sub>2e</sub> and 560 kg of NOx.

**3.2.2. Electric Yard Tractor Emissions Estimates**

We make the following assumptions to convert the electric tractor emissions factors into the functional unit of kg per operating hour:

- Each tractor requires 3.5 hours of charging at 40kW to operate at full capacity (Port of Los Angeles 2009).
- E30 electric tractor operates at the equivalent capacity to that of the diesel tractor (i.e., approximately six hours per day, 300 days per year).
- Hourly rate of electricity consumption (amount of power required for an hour of operation) is approximately 140 kWh/6 hours (Port of Los Angeles 2009).

Given these assumptions, the emission factor for the operation of the E30 electric tractors is approximately 14 kg CO<sub>2e</sub> per operating hour. The emissions factors for PM, NOx, and SOx are 99, 39, and 73 grams per operating hour, respectively.

**3.2.3. Production and Disposal Phases**

From an LCA perspective, diesel and electric yard tractors vary significantly in terms of their engine production processes. The main difference resides in the

**Table 3.** Emissions for diesel tractor per operating hour.

	Kg
<b>Greenhouse gases</b>	
CO <sub>2</sub>	44.00000
N <sub>2</sub> O	0.00087
CH <sub>4</sub>	0.00087
Sub-total (in CO <sub>2e</sub> )	44.00174
<b>Particulates</b>	
PM10	0.0082
PM2.5	0.0076
DPM	0.0082
Sub-total	0.02400
NOx	0.29000
Sox	0.0005

### Life-Cycle Emissions from Port Electrification

production and disposal of a high-capacity battery for electric tractors. For this study, we assume that all electric trucks utilize lithium-ion phosphate batteries due to their high safety standards, low production costs, and lack of toxic heavy metals and corrosive acids and alkalis (present in other battery technologies such as lead-acid or lithium-manganese). The emissions associated with the production phase are estimated using two studies that compare the emissions from advanced vehicle batteries (Majeau-Bettez, Hawkins, and Stromman 2011; Notter et al. 2010). The CO<sub>2e</sub> emission of lithium-ion battery production is approximately 250 g/Wh. The batteries used in the electric yard tractors considered in this analysis are rated at 250 kWh (Balqon 2009). This results in a total emission of 62,500 kg CO<sub>2e</sub>. The emissions of SO<sub>x</sub>, NO<sub>x</sub>, and PM are 300, 39, and 98 kg, respectively. Emissions associated with the production of a diesel engine are estimated based on a lifecycle inventory study on diesel car production (Schweimer and Levin 2006). We calculate the proportion of impacts caused strictly by the engine parts based on the approximate weight contribution (i.e., 311 of 1164 lbs of total vehicle curb weight attributed to the engine parts). We then scale the impacts to a heavy-duty diesel engine based on the engine displacement, proportional to an engine's power output. We assume a 12.1 L diesel engine for the diesel yard tractor. The resulting emissions are 3,500 kg CO<sub>2e</sub>, 64 kg SO<sub>x</sub>, 32 kg NO<sub>x</sub>, and 12 kg PM.

For the disposal phase, we again assume that the difference between the diesel and electric yard tractors stems from electric tractor's lithium-ion battery and the diesel tractor's engine. We estimate the lithium-ion battery's impacts from disposal based on the results obtained from Notter et al. (2010). By scaling the results in Notter's study (34.2 kWh vehicle battery with respect to the battery's power output and mass), the estimated emissions for the E30 electric yard tractor is 8,340 kg CO<sub>2e</sub>, 18 kg SO<sub>x</sub>, 12 kg NO<sub>x</sub>, and 18 kg PM. For the diesel engine, we again use the results from Schweimer and Levine (2006) to scale the disposal impacts based on engine displacement. The calculated emissions are 370 kg CO<sub>2e</sub>, 0.89 kg SO<sub>x</sub>, 1.1 kg NO<sub>x</sub>, and 0.2 kg PM.

We sum the emissions from all three phases to present a complete life-cycle picture for yard tractor emissions. A summary of all three phases of the comparative LCA is shown in Table. The E30 electric tractor generates approximately 40% of the CO<sub>2e</sub> emissions of that of a diesel tractor over the lifetime. Although the

**Table 4.** Comparative LCA emissions for electric versus diesel tractors (kg/10 year lifetime).

Vehicle type		Production	Use	Disposal	Total
Electric	CO <sub>2e</sub>	62,500	256,000	8,340.00	327,000
	SO <sub>x</sub>	300	1,270	18.00	1,590
	NO <sub>x</sub>	39	647	12.00	700
	PM	98	1,640	18.00	1,760
Diesel	CO <sub>2e</sub>	3,500	777,000	370.00	781,000
	SO <sub>x</sub>	64	9	0.89	74
	NO <sub>x</sub>	32	5,100	1.10	5,130
	PM	12	425	0.20	440

“zero-emissions” claim made by electric vehicle proponents is incorrect on a life-cycle basis, the use of electric tractors in this case does yield a large reduction in CO<sub>2e</sub> emission. The tradeoff, however, is an increase in SO<sub>x</sub> and PM emissions. Again, this increase is less concerning since the emission occurs at the power generation plants, often located in less densely populated regions.

As indicated in this table, the use phase dominates the GHG emissions. Therefore, net effect of electrification hinges heavily on the number of yard tractors and the length of time they are in use. E30’s manufacturer, Balqon, guarantees a cycle life of 2000 battery charges before being degraded to 80 percent of original capacity at full charge (Balqon 2009). This is equivalent to approximately 6 to 7 years assuming 300 days of operation annually. The E30 would still be functional but at a lower power output in subsequent years. In this study, we assume an operation lifespan of 10 years to make direct comparisons to the diesel tractor because recent trends in battery technology indicate a longer lifespan in the near future. Development of electric vehicle technology has been accelerating with anticipation for significant increases in battery specific energy and power, resulting in a longer lifespan before year 2020 (Boston Consulting Group 2010). With an assumption of an average of 10-year lifespan, the CO<sub>2e</sub> savings from the use of E30 tractor accumulates to about 450 metric tons. The use of the E30 tractor also yields a reduction in the emissions of NO<sub>x</sub>. The emission of SO<sub>x</sub> and PM, however, are significantly higher which can be attributed to the high proportion of coal in the production of LADWP’s electricity.

### 3.3. Yard Tractor Growth Projections

We model the changes in the number of yard tractors in operation by using container throughput projections. The container throughput is expected to grow by 40% and 120% for years 2020 and 2030, respectively, from the baseline year 2006 (IHS Global Insight 2009). According to the port’s forecast, the number of yard tractors to serve this throughput is expected to increase to 1,588 and 2,395 vehicles for the years 2014 and 2023 (Starcrest 2008). Fitting the forecasted number with historical data, the expected number of yard tractor turns out to be a second-order polynomial function, from 1,259 vehicles in 2010 to 3,112 vehicles in 2030.

Despite the electric yard tractor’s emissions advantages, maintaining a high adoption rate is difficult because of the high initial investments. Currently, the price of the E30 tractor is approximately \$190,000 and the charger price is about \$75,000 (Port of Los Angeles 2009). Unless the price of electric tractors becomes more competitive to that of a conventional diesel tractor, high adoption will remain elusive. Studies estimate that electric vehicles would become cost competitive when the price of high capacity batteries fall to approximately \$250 per kWh or \$62,500 for the E30 battery (Boston Consulting Group 2010). However, the U.S. Advanced Battery Consortium projects a gradual decline from the current cost of \$1,000 to \$1,200 per kWh by year 2020 (Boston Consulting Group 2010). Therefore, rather than assuming a completely electric fleet, we examine three different adoption rates for the electric yard tractors: 20, 35 and 50%. The adoption rate reflects the percentage of electric yard tractor out of the total fleet at any given year. That is, any new addition or replacement of an existing yard tractor would be carried out to keep the percentage of electric yard tractors versus the overall fleet constant. The resulting numbers of electric yard tractors are shown in Table 5.

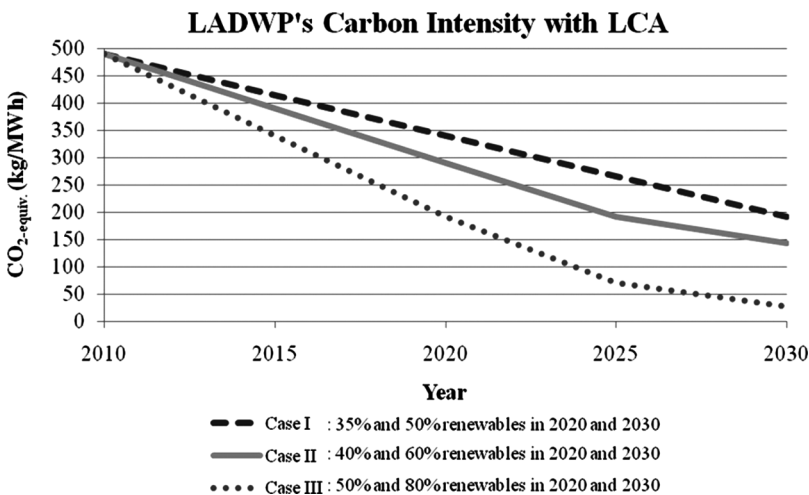
**Table 5.** Projected number of electric yard tractors at POLA.

Adoption rate	2010	2015	2020	2025	2030
20%	315	417	528	648	778
35%	441	584	739	908	1,089
50%	630	834	1,056	1,297	1,556

**3.4. LADWP’s Renewable Portfolio Projections**

LADWP excludes nuclear and large hydro as renewable energy in its portfolio. Under this assumption, LADWP expects to exceed 20% renewable in its energy portfolio by the end of 2010 and achieve 40% renewable by 2020 (Hodel 2010). We present three adoption scenarios where LADWP reaches a renewable portfolio of 50%, 60%, and 80% at the end of year 2030. Based on these projections, we model the emissions on a per-kWh basis. We use the emission factors for different energy sources using the data from the LCA studies selected previously. To create a more realistic set of projection scenarios, we first reduce coal and substitute with wind. Then as the coal proportion reaches zero, we begin reducing natural gas from the portfolio and replacing wind and small hydro. Since the carbon intensities of wind and small hydro energy are much lower than those of coal and natural gas, LADWP’s overall emissions decrease with higher rates.

We began with an estimated 20% renewable sources for all cases in year 2010. The resulting carbon intensity projections for three different scenarios are shown in Figure 1 Case I assumes that LADWP achieves 35% and 50% renewable sources in its portfolio by 2020 and 2030, respectively. In Case II, LADWP achieves a more aggressive 40% and 60% renewable by 2020 and 2030. In Case III, these two numbers go up to 50% for 2020 and 80% for 2030.



**Figure 1.** Projected carbon intensity of LADWP energy portfolio.

Downloaded by [University of Michigan] at 12:54 18 October 2012

The actual projections by LADWP show that nonrenewable sources (i.e., coal and natural gas) will remain significant in the energy portfolio, with only 35% renewable sources by 2020 (Glauz, 2007). Therefore, the results from the three cases explored here offer a range for the actual emissions from POLA’s yard tractors if LADWP successfully reaches 80% renewables by 2030.

**3.5. Overall Emissions Estimates and Target Reductions**

We are now ready to model the total emissions from yard tractors and compare against the target reductions. We calculate the emissions based on the projected number of electric and diesel yard tractors shown in Table 5. The emissions for a diesel tractor remain unchanged in subsequent years but the emissions for an electric tractor decrease because the carbon intensity of LADWP’s energy portfolio decreases in all scenarios. We recalculate using the projections to compute the total emissions for the target years of 2020 and 2030. We condense the results into two “snapshots” reflecting these projections. Again, we consider the same three cases mentioned above for the rate at which the LADWP renewable portfolio increases. Each case assumes a starting point of 20% renewable portfolio by the end of 2010. The results are shown in Tables 6 and 7.

We now use these estimates to compare against targets set forth by AB32 and Green LA mandates. Assuming that POLA is required to cut emissions to pre-1990 levels in all categories, the emissions associated with the yard tractors must also be cut proportionally. The estimates for pre-1990 emissions level, however, are still unpublished, as POLA has yet to release them officially under its Climate Action Plan. Therefore, we instead compare our projection results with the lowest emissions data currently available. The lowest reported emissions data for yard tractors are for the year 2009, when they contributed 80,252 metric tons of CO<sub>2e</sub> emissions (Starcrest, 2010). We set our reduction target for year 2020 at this level and 35% below for year 2030. Note that the emission levels in 1990 are most likely much lower than those of 2009, considering the tripling of container throughput, from 2.1 million TEUs to 6.7 million TEUs (Port of Los Angeles 2010). Therefore, the 80,252 metric tons of CO<sub>2e</sub> target for year 2020 and the 52,171 metric tons CO<sub>2e</sub> (35% reduction) for year 2030 are both underestimates for the actual emissions targets. For the 2020 target, even in the best-case scenario, the emissions will exceed the target by nearly 10,000 metric tons. In 2030, the situation will be worse; the emissions will exceed the target by over 50,000 metric tons. The results of our analysis show that at any given set of LADWP renewable portfolio and POLA’s electric adoption rate, these targets are unreachable.

**Table 6.** Estimated CO<sub>2e</sub> emissions from yard tractors at POLA in 2020 (metric tons).

		Projected LADWP renewable portfolio (2020)		
		Case I (35%)	Case II (40%)	Case III (50%)
Electric yard tractor adoption rate	20%	130,657	129,555	127,352
	35%	117,262	115,720	112,634
	50%	97,170	94,966	90,559

## Life-Cycle Emissions from Port Electrification

**Table 7.** Estimated CO<sub>2e</sub> emissions from yard tractors at POLA in 2030 (metric tons).

		Projected LADWP renewable portfolio (2030)		
		Case I (50%)	Case II (60%)	Case III (80%)
Electric yard tractor	20%	187,594	186,027	182,247
adoption rate	35%	165,915	163,721	158,429
	50%	133,396	130,263	122,703

### 3.6. Emissions Mitigation Potential

Although the results indicate that the emissions reduction targets set by AB32 and Green LA are unreachable with POLA's aggressive adoption of electric yard tractors and LADWP's adoption of renewable energy sources, the emissions mitigation potential is significant (see Table 8 Sfor all cases). In the baseline "business-as-usual" case where POLA continues its operations without any electric yard tractor adoption, the emission levels would exceed targets by 105% and 363% in years 2020 and 2030. In the best case scenario (Case III with 50% electric adoption), the emissions targets are exceeded by only 13% and 135% in years 2020 and 2030. This potential mitigation of emissions is not insignificant despite the violation of the emissions targets.

We also consider other steps POLA is taking to reach mandated emission cuts under the electrification strategy. Under the Technology Advancement Program (TAP), the Port (working jointly with the Port of Long Beach) is implementing pilot projects that are aimed at reducing emissions (San Pedro Ports, 2011). For yard

**Table 8.** Estimated CO<sub>2e</sub> emissions from yard tractors at POLA and percentages over the target.

% Electric	LADWP portfolio	2020		2030	
		CO <sub>2-equiv.</sub> (Metric tons)	Over target	CO <sub>2-equiv.</sub> (Metric tons)	Over target
0%	Baseline	164,145	+105%	241,791	+363%
20%	Case I	130,657	+63%	187,597	+260%
	Case II	129,555	+61%	186,027	+257%
	Case III	127,352	+59%	182,247	+249%
	Case I	117,262	+46%	165,915	+218%
35%	Case II	115,720	+44%	163,721	+214%
	Case III	112,634	+40%	158,429	+204%
	Case I	97,170	+21%	133,396	+156%
50%	Case II	94,966	+18%	130,263	+150%
	Case III	90,559	+13%	122,703	+135%

tractors, the use of hydrogen fuel-cell hybrid electric (FCHV) truck is being considered. This technology is also a “zero tailpipe emissions” vehicle but does have significant emissions from the hydrogen fuel-cycle. Issues ranging from high costs for infrastructure support, technical barriers, and safety are some of the major hurdles that raise uncertainty for successful adoption of this technology (Frenette and Forthoffer 2009). Nevertheless, the potential success of such a program along with the current lithium-ion battery tractors offers significant potential emission reductions. The use of biodiesel fuel is also being considered under TAP. Although some studies suggest that biodiesel’s emission rate of GHGs is less than half that of diesel, the actual impacts of its wide use are still highly debated (Institute of Transportation Studies, 2007). When accounting for land-use changes, some studies have shown that biodiesel’s actual emission savings versus conventional diesel is negligible or even negative (see Rustandi and Wu 2010; Institute of Transportation Studies, 2007). The combined adoption of electric, hydrogen, and biodiesel fuel vehicles into the yard tractor fleet has various implications on overall emissions based on underlying assumptions on adoption and each fuel’s carbon intensity. Further research is necessary to develop and analyze multiple feasible strategies based on these technologies. The cumulative effects may indeed further reduce overall GHG emissions. However, whether such reductions (or any combination of them) are sufficient to overcome the additional operational requirements caused by increasing container throughput should be the subject of future studies in this area.

#### 4. DISCUSSION

The results of this study reveal that the main driver of overall CHE emissions is POLA’s container throughput. In other words, no amount of emissions reductions on a per vehicle basis or the lowering of the carbon intensity of LADWP’s projected energy portfolio can overcome the increases in equipment use associated with increasing throughput. To reach emissions reductions to pre-1990 levels, the only option available seems to be a reduction in the port’s container throughput. This result seems to indicate the port’s limited control in meeting its targeted emissions. However, the port’s decision to electrify its yard tractor fleet will lower emissions on a per vehicle basis. Electrification does offer a significant reduction in the port’s GHG emissions as well. It also “shifts” toxic pollutants such as diesel particulate matter from the ports (i.e., densely populated urban areas) to energy generation sites that tend to be less populated, thus pose less hazards on human health. It is also evident that the magnitude of the port’s GHG reduction hinges on LADWP’s ability to increase its renewable portfolio and remove coal from its energy sources.

Finally, we are faced with a dilemma: to use cleaner engines, or to push the emissions upstream to the power generation sources elsewhere. And in either case, the aggressive targets of the current climate legislations seem unapproachable. One only hopes that there may be new engine technologies in the future that generate ultra low emission rates to make reaching pre-1990 levels more feasible. Another alternative would be for the power generation facilities to commit large investments in infrastructure and power distribution networks following aggressive policies on renewable energy sources, particularly wind and solar. We hope both could be done sooner rather than later.

### REFERENCES

- Balqon. 2009. Nautilus Zero Emission. Santa Ana, CA: Balqon Corporation.
- Bergerson J, Lave L. 2002. A Life-cycle Analysis of Electricity Generation Technologies: Health and Environmental Implications of Alternative Fuels and Technologies. Pittsburgh, PA: Carnegie Mellon Electricity Industry Center.
- Boureima FS, Messagie M, Matheys J, Wynen V, Sergeant J, Van Mierlo J, De Vos M, De Caevel M. 2009. Comparative LCA of electric, hybrid, LPG and gasoline cars in Belgian context. EVS24 International Battery, Hybrid, and Fuel Cell Electric Vehicle Symposium, Stavanger, Norway, May 13–16.
- BCG. 2010. Batteries for Electric Cars: Challenges, Opportunities, and the Outlook to 2020. Boston, MA: The Boston Consulting Group. Available: <http://www.bcg.com/documents/file36615.pdf> (accessed June 2011).
- BSI (British Standards Institute). 2008. PAS 2050: Specification for the Assessment of the Life-cycle Greenhouse Gas Emissions of Goods and Services. London, U.K.: British Standards Institute.
- California Energy Commission. 2007. 2007 Integrated Energy Policy Report. Sacramento, CA: California Energy Commission.
- City of Los Angeles. 2007. Climate Action Plan. Los Angeles, CA: City of Los Angeles Harbor Department Environmental Management Division.
- Curran MA. 1996. Environmental Life-Cycle Assessment. New York: McGraw Hill.
- Dones R, Heck T, Hirschberg S. 2003. Greenhouse Gas Emissions from Energy Systems: Comparison and Overview. PSI Annual Report 2004 Annex IV. Villigen, Switzerland: Paul Scherrer Institut.
- ECW (Energy Center of Wisconsin). 2009. Ten-year Update: Emissions and Economic Analysis of Geothermal Heat Pumps in Wisconsin: Update of Geothermal Analysis Prepared in 2000. Madison, WI: Energy Center of Wisconsin.
- EPRI (Electric Power Research Institute). 2006. Common Issues of Seaport Electrification. Palo Alto, CA: Electric Power Research Institute.
- EPRI (Electric Power Research Institute). 2008. Electrification at Ports: A Port of House, Texas Electrification Case Study and Options for Electric Cranes. Palo Alto, CA: Electric Power Research Institute.
- Frenette G, Forthoffer D. 2009. Economic & commercial viability of hydrogen fuel cell vehicles from an automotive manufacture perspective. *International Journal of Hydrogen Energy* 34:3578–3588.
- Fthenakis V, Kim H, Alsema E. 2008. Emissions from photovoltaic life-cycles. *Environmental Science and Technology* 42(6):2168–2174.
- Glauz W. 2007. Concentrating Solar Power for Los Angeles. Presentation at a meeting of the Los Angeles Department of Water and Power, Los Angeles, CA, September 24.
- Green LA. 2007. Climate Action Plan: Strategies for Municipally-Controlled Sources. Los Angeles, California: City of Los Angeles Harbor Department Environmental Management Division.
- Guinee JB, Huppes G, Heijungs R. 2001. Developing an LCA Guide for Decision Support. *Environmental Management and Health* 12(3):301–311.
- Hodel R. 2010. LADWP's Renewable Portfolio Standard: Challenges and Implementation. Presentation at a meeting of the Los Angeles Department of Water and Power, Los Angeles, CA, March 5.
- Hondo H. 2005. Life-cycle GHG emission analysis of power generation systems. *Energy* 30(11–12):2042–2056.
- IER. 1997. ExternE National Implementation Germany. (Contract: JOS3-CT95-0010, JOU2-CT-0264). Berlin, Germany: European Commission.



- IHS Global Insight. 2009. San Pedro Bay Container Forecast Update. Philadelphia: The Tioga Group.
- Institute of Transportation Studies. 2007. A Low-Carbon Fuel Standard for California: Part I – Technical Analysis. Davis, CA: Institute of Transportation Studies, University of California, Davis.
- Jerrett M, Burnett RT, Ma R, Pope A, Krewski D, Newbold KB, Thurston G, Shi Y, Finkelstein N, Calle EE, Thun M J. 2005. Spatial analysis of air pollution and mortality in Los Angeles. *Epidemiology* 16(6):727–736.
- Jimenez-Gonzales C, Kim S, Overcash M. 2000. Methodology for developing gate-to-gate life cycle inventory information. *International Journal of Life Cycle Assessment* 5(3):153–159.
- Keoleian G, Spitzley D. 2006. Life cycle based sustainability metrics. In: Abraham MA (ed.), *Sustainability Science and Engineering, Vol. 1: Defining Principles*, Amsterdam, The Netherlands: Elsevier, pp. 127–159.
- Kim B, Teffera S, Zeldin M. 2000. Characterization of PM<sub>2.5</sub> and PM<sub>10</sub> in the South Coast air basin of Southern California. Part 1: Spatial variations. *Journal of the Air and Waste Management Association* 50(12):2034–2044.
- Kintner-Meyer M, Schneider K, Pratt R. 2007. Impacts assessment of plug-in hybrid vehicles on electric utilities and regional U.S. power grids. Part 1: Technical Analysis. *Online Journal of EIEC* 1, paper #4.
- LADWP. 2008. Green Power Annual Report. Los Angeles, CA: Los Angeles Department of Water and Power.
- Majeau-Bettez G, Hawkins T, Stromman A. 2011. Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles. *Environmental Science and Technology* 45(10):4548–4554.
- Marnay C, Fisher S, Murtishaw S, Phadke A, Price L, Sathaye J. 2002. Estimating Carbon Dioxide Emissions Factors for the California Electric Power Sector. Berkeley, CA: Environmental Energy Technologies Division.
- National Academies Press. 2010. Electricity from Renewable Resources: Status, Prospects, and Impediments. [http://books.nap.edu/openbook.php?record\\_id=-12619&page=195#](http://books.nap.edu/openbook.php?record_id=-12619&page=195#) (accessed May 2010).
- Notter D, Gauch M, Widmer R, Wager P, Stamp A, Zah R, Althaus H. 2010. Contribution of li-ion batteries to the environmental impact of electric vehicles. *Environmental Science and Technology* 44(17):6650–6656.
- Pacca S. 2007. Impacts from decommissioning of hydroelectric dams: A life-cycle perspective. *Climate Change* 84:281–294.
- Pacca S, Horvath A. 2002. Greenhouse gas emissions from building and operating electric power plants. *Environmental Science and Technology* 36(14):3194–3200.
- Port of Los Angeles. 2009. Electric Truck Demonstration Project Fact Sheet. Los Angeles, CA: Port of Los Angeles. <http://www.portoflosangeles.org/environment/etruck.asp> (accessed November 2010).
- Port of Los Angeles. 2010. TEU Statistics. Los Angeles, CA: Port of Los Angeles. <http://www.portoflosangeles.org/maritime/stats.asp> (accessed May 2010).
- Port of Los Angeles. 2011. Alternative Maritime Power<sup>TM</sup>. Los Angeles, CA: Port of Los Angeles. [http://www.portoflosangeles.org/environment/alt\\_maritime\\_power.asp](http://www.portoflosangeles.org/environment/alt_maritime_power.asp) (accessed June 2011).
- Port of Los Angeles, Port of Long Beach. 2006. San Pedro Bay Ports Clean Air Action Plan (Technical Report). Los Angeles, CA: Port of Los Angeles and Port of Long Beach.
- Rustandi F, Wu H. 2010. Biodiesel production from canola in Western Australia: Energy and carbon footprints and land, water, and labour requirements. *Industrial and Engineering Chemistry Research* 49(22):11785–11796.

## Life-Cycle Emissions from Port Electrification

- Salin D. 2010. Impact of Panama Canal Expansion on the U.S. Intermodal System. Washington, DC: United States Department of Agriculture.
- San Pedro Ports. 2011. Clean Air Action Plan: Technology Advancement Program 2010 Annual Report. Los Angeles, CA: Port of Los Angeles and Long Beach. <http://www.cleanairactionplan.org/programs/tap/default.asp> (accessed June, 2011).
- Schweimer G, Levin M. 2006. Life Cycle Inventory for the Golf A4. Wolfsburg, Germany: Volkswagen Group. [http://www.volkswagenag.com/vwag/vwcorp/info\\_center/en/publications/2007/01/Golf\\_A4\\_Life\\_Cycle\\_Inventory.-bin.acq/qual-BinaryStorageItem.Single.File/golfa4\\_english.pdf](http://www.volkswagenag.com/vwag/vwcorp/info_center/en/publications/2007/01/Golf_A4_Life_Cycle_Inventory.-bin.acq/qual-BinaryStorageItem.Single.File/golfa4_english.pdf) (accessed June, 2011).
- Spath P, Mann M, Kerr D. 1999. Life-cycle Assessment of Coal-fired Power Production. Golden, CO: National Renewable Energy Laboratory, U.S. Department of Energy.
- Spitzley D, Keoleian G. 2004. Life-cycle Environmental and Economic Assessment of Willow Biomass Electricity: A Comparison with Other Renewable and Non-Renewable Sources (Report No. CSS04-05 R). Ann Arbor, MI: Center for Sustainable Systems.
- Subic A, Schiavone F, Leary M, Manning J. 2010. Comparative life cycle (LCA) of passenger seats and their impact on different vehicle models. *International Journal of Vehicle Design* 53(1/2):89–109.
- Starcrest. 2008. San Pedro Bay Ports Emissions Forecasting Methodology and Results. Poulsbo, WA: Starcrest Consulting Group.
- Starcrest. 2009. The Port of Los Angeles 2008 Inventory of Air Emissions. Poulsbo, WA: Starcrest Consulting Group.
- Starcrest. 2010. The Port of Los Angeles 2009 Inventory of Air Emissions. Poulsbo, WA: Starcrest Consulting Group.
- UK Environmental Agency. 2005. Life Cycle Assessment of Disposable and Reusable Nappies in the UK. Almonsbury, UK: United Kingdom Environmental Agency.
- United Nations Framework Convention on Climate Change. 2009. Methodological Tool: Tool to Calculate the Emission Factor for an Electricity System, Version 2. EB50 Report, Annex 14. United Nations.
- Vera R. 2008. The Port of Los Angeles Response to Sea Level Rise Induced by Climate Change. Pomona, California: California State University.
- World Energy Council. 2004. Comparison of Energy Systems Using Life-cycle Assessment. London: World Energy Council.