Environmental Implications of Construction Site Energy Use and Electricity Generation

Aurora L. Sharrard, S.M.ASCE; H. Scott Matthews, A.M.ASCE; and Michael Roth

Abstract: The construction industry is responsible for environmental impacts that include air emissions, waste generation, and the use of land, water, and energy. However, most prior construction research attention has focused on these impacts only for material selection and building operation. The focus here is the environmental and energy implications of the construction process, specifically on-site energy consumption. Existing estimates of energy use and environmental emissions for the industry are tied to large construction vehicles, but other equipment consumes energy in various forms. This research creates a broader boundary for considering the energy use and environmental impacts of engines and vehicles used for construction activities by estimating these effects and comparing them to other national-level impacts. Results indicate that fuel use estimates for construction equipment are almost double the levels suggested by government reports; accordingly, air emission impacts are 30% larger for particulate matter and almost double levels of oxides of nitrogen and volatile organic compounds. Quantitative and qualitative analysis regarding how U.S. diesel engine and fuel regulations could significantly reduce air emissions from construction sites is also provided. If fully implemented, these regulations could initiate the manufacture and use of portable generators that make on-site electricity generation comparable to the electricity grid in terms of air emissions.

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CE Database subject headings: Construction industry; Construction equipment; Construction sites; Energy consumption; Fuels; Environmental impacts; Emissions; Electric power demand; Engines.

Introduction

The construction industry creates a litany of environmental impacts, partly due to its large consumption of energy (Hendrickson and Horvath 2000). However the industry’s energy consumption is not well understood because of the decentralized nature of construction and subcontracting activities. Because the construction industry has been relatively unregulated in the past, it has great potential for change that could benefit the environment while not sacrificing productivity. Some of the major environmental impacts of the construction process have to do with stormwater management, demolition debris, and energy consumption; the focus of this paper is the latter. Energy on a construction site is usually provided by gasoline and diesel fuel, electricity, and natural gas. Of these four energy sources, diesel fuel and electricity are responsible for the greatest total air emissions. Because the environmental impacts of construction activities have never been adequately quantified, the assumption that the effects of construction are negligible in comparison with the other building phases is supposition. As the value of construction work completed in 2002 was 11% of the U.S. gross domestic product, even if the environmental impacts from construction are small compared to other building or infrastructure life cycle phases, these impacts may be large when looked at with various scopes or scales (DOC 2005a,b).

Aggregate data on energy and resource use in the construction sector are available from the 2002 Census report for the construction sector (DOC 2005a). For the economic census of construction, roughly one-fifth of known construction businesses were selected with fairly robust selection criteria. As with other Census studies, the survey results were used to statistically approximate average industry estimates. The report summarizes data for all construction expenditures in 2002, including energy costs. Expenditures are summarized for the entire industry and divided into three subcategories: construction of buildings, heavy and civil engineering construction; and special trade contractors. The Census data also contain information on construction industry expenditures categorized as follows: employment/labor, subcontracting, materials, and power/fuels. Out of $648 billion in total nonlabor expenses in 2002, the construction industry spent $15 billion on energy, of which $11 billion was spent on gasoline and diesel fuel, $1.1 billion on natural gas, and $2.6×10^9 on electricity (DOC 2005a). Compared to total construction industry expenditures, overall spending on power/fuels represents about 2.5% of given costs; specifically, power/fuel spending is approximately 4% of heavy construction, 3.7% of special trade contracting, and 1.2% of building construction costs.

Because no physical or thermal units were provided, average

1 Portions of an older version of this manuscript were presented at ASCE’s 2005 Construction Research Congress.
2 Research Manager, Green Building Alliance, 645 14th St., Pittsburgh, PA. E-mail: aurorassharrard@yahoo.com
3 Associate Professor, Dept. of Civil and Environmental Engineering and Dept. of Engineering and Public Policy, Carnegie Mellon Univ., 119 Porter Hall, Pittsburgh, PA 15213. E-mail: hsm@cmu.edu
4 321 Le Roi Rd., Pittsburgh, PA 15208. E-mail: mroth18@gmail.com

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2002 industrial energy costs were determined so that aggregate comparisons could be made. Although overall U.S. industrial spending on electricity in 2002 was $49 billion, the construction industry only spent a fraction of that $2.6 billion on electricity (EIA 2005a). Consequently, construction represents 1% of the overall electricity use in the United States and 5.3% of all industrial electricity purchases. Given a 2002 average industrial price of electricity of 4.91 cents/kWh, the construction industry bought 52 TW·h of electricity in 2002, which is 179 × 10^12 Btu (189,000 TJ), assuming an on-site consumption heat rate of 3.412 Btu/kWh (3.6 MJ/kWh) (EIA 2002, 2005a). Note that given the inefficiency in the electricity generation process, the amount of primary energy (coal, natural gas, etc.) needed to produce a kilowatt-hour of electricity is actually much higher—about 10,360 Btu/kWh (10.9 MJ/kWh) for fossil fuel-based power plants (EIA 2002). Consequently, the electricity purchased annually by the construction industry requires 5.43 × 10^12 Btu (573,000 TJ) of total energy.

Likewise, assuming the 2002 average industrial price of $4.02/1,000 ft^3 of natural gas ($142/1,000 m^3), the construction industry used 267 × 10^9 ft^3 (272 × 10^12 Btu at 1,020 Btu/cf) of natural gas, equivalent to 287,000 TJ (EIA 2002, 2005a). As total industrial use in 2002 was 7.5 × 10^12 ft^3 (8,100 TJ) and overall U.S. use was 23 × 10^12 ft^3 (24,800 TJ), the construction industry represented 3.6% of industrial purchases and 1.2% of total U.S. consumption (EIA 2001).

Finally, the $11 billion spent on gasoline and diesel fuel in 2002 at a retail cost of $1.03/gallon ($0.27/L) yields 10.6 × 10^9 gallons (1,500 TJ) of fuel used (EIA 2006). At an average heat rate of 132,000 Btu per gallon (37 MJ/L), this is 1.4 × 10^15 Btu (1.5 PJ) (Davis and Diegel 2005). It should be noted that the “retail cost” of gasoline and diesel fuel is a relative term, as some construction use of petroleum-based fuels is tax exempt; this estimate is shown here as an order of magnitude estimate is revisited later in the paper.

Thus, an initial estimate of the total energy used by the construction industry in 2002 is between 1.8 × 10^15 Btu (2,000 PJ) and 2.2 × 10^15 Btu (2,400 PJ)—assuming on-site consumption and primary electricity heat rates for fossil fuels). These estimates are 1.9% of total U.S. energy consumption estimates (EIA 2005a). Using the same method delineated earlier, Fig. 1 summarizes energy use for the overall construction industry and its subsectors. In all, it is clear that gasoline and diesel fuel represent the majority of energy consumption in the industry with 62–75% of all use.

The share of natural gas in construction is fairly constant at 10–13% of energy required, and electricity varies between 10 and 25% of total energy. These estimates are refined and discussed subsequently.

### Estimating Construction Energy Use by Category

While the energy consumption estimates for the construction industry do not represent a large share of overall U.S. energy consumption, the environmental impacts of the construction industry’s energy use relative to other sectors were also considered. Energy and fuel consumption by the construction industry is an interesting topic not only due to the large share of gasoline and diesel used by construction vehicles, but also because of the Environmental Protection Agency’s (EPA) 2004 Nonroad Diesel Rules affecting vehicles and fuels (EPA 2004a). Because the construction industry has not been subject to strict EPA regulations in the past (i.e., Tier 1–3 regulations) EPA’s nonroad rules may provide large potential to reduce the environmental impacts of construction.

To begin to make these comparisons, an estimate of the construction industry’s share of diesel and gasoline consumption is required. Of the $11 billion the construction industry spent on gasoline and diesel fuel in 2002, it is estimated that $8 billion was spent for on-highway vehicles and $2.9 billion was spent for off-highway gasoline and diesel fuel use (DOC 2005a). Unfortunately, these are the most specific estimates available.

Off-highway (on-site) diesel fuel is used to power bulldozers, excavators, cranes, generators, and other types of equipment. Generators are used to meet additional electricity demands for construction.
lighting, welding, and elevators, reaching areas of the site to which it is difficult to supply “grid electricity” and for which excess demand cannot be met by an electricity grid hookup. Sites demanding a significant amount of welding require this type of flexible electricity and thus often require on-site diesel generators.

An initial challenge in disaggregating the construction industry’s diesel and gasoline purchases is the distinction between on- and off-highway usage. Presumably, the Department of Commerce’s (DOC) “off-highway” category corresponds to EPA’s “nonroad engine and vehicles” category. However, the DOC gives no guidance regarding the breakdown of gasoline and diesel consumption for on- and off-highway purposes. For this approach, updates to the EPA National Air Quality and Emissions Trends Report were used to guide further disaggregation (EPA 2004c, 2005). For example, in the EPA’s “on-road” category, the largest share of particulate matter (PM) emissions comes from heavy-duty diesel vehicles, some of which are unquestionably construction vehicles; consequently, the contribution of the construction industry to on-road vehicle fuel consumption needs to be estimated.

The Energy Information Administration’s (EIA) Transportation Energy Data Book (an aggregate of a variety of sources) provides energy consumption estimates for various vehicle categories. Table 1 summarizes the construction-related off-highway categories for 1997 and 2002 (Davis and Diegel 2005). It should be noted that a 2004 Oak Ridge National Laboratory study revised all previous off-highway estimates using a combinations of EPA’s NONROAD 2002 and the 1997 Vehicle and Inventory Use Survey (VIUS) (Davis and Truett 2004).

Whereas more concrete estimates of off-highway construction fuel use are being developed, on-highway fuel use attributable to the construction industry has been largely overlooked. The national-level estimates compiled in Fig. 1 may or may not represent on-highway small-medium truck use, but the data based on the DOC’s vehicle inventory and use survey, and provided in Table 1, definitely does (Davis and Diegel 2005; DOC 2005a).

Using this perspective, the overall construction fuel use values shown in Table 1 are 54% higher than the data in Fig. 1. Consequently, the percentage of gasoline and diesel vehicles utilized for construction are obtainable for both 1997 and 2002. Due to the variance between these two numbers, an average of the 1997 and 2002 percentages were utilized. Meanwhile, gasoline consumption has dropped over this same time period.

For 1997, gasoline use was estimated at 289 million gallons, with 270 million gallons used in 2002 [1.1 and 1.0 × 10^6 L, respectively, Davis and Diegel (2005)]. Likewise, diesel use was estimated at 4.8 × 10^8 gallons in 1997 and 5.5 × 10^8 gallons in 2002 [18 and 21 × 10^6 L, respectively, Davis and Diegel (2005)]. Given these values, the implied average cost per gallon of gasoline and diesel used by the construction industry in off-highway situations in 2002 was $0.51 [or $0.13 L—calculated from $2.9 billion spent on off-highway fuel and the 5.8 × 10^8 gallons of off-highway fuel used, Davis and Diegel (2005), DOC (2005a)].

This estimate suggests that the overall construction industry consumption of gas and diesel in 2002 was 21.5 × 10^6 gallons (or 81 × 10^6 L—calculated from $11 billion of expenditures at $0.51/gallon). The $0.51/gallon average calculated here is well below the average 2002 retail price, but consistent assuming that a large amount of construction fuel purchases are tax exempt.

To help allocate the broad categories in Table 1, the Transportation Energy Data Book also summarizes DOC estimates for construction’s share of vehicle activity and fuel use for 2002 highway vehicle use (DOC 2004). Based on Department of Energy (DOE) survey results, the percentages of gasoline and diesel vehicles utilized for construction are obtainable for both 1997 and 2002. Due to the variance between these two numbers, an average of the 1997 and 2002 percentages were utilized. Consequently, the percentage of gasoline and diesel vehicles utilized for the construction analysis shown in Table 1 are as follows: 6% of light trucks [those less than 10,000 lb (4,536 kg)], 19% of medium trucks [10,000 to 26,000 lb (4,536 to 11,793 kg), and 17% of heavy trucks were used for construction in 2002 (Davis and Diegel 2003, 2005). However, the DOE provides detail in only two truck categories (light and medium/heavy), whereas information from other sources is in three divisions [light, medium, and heavy trucks, Davis and Diegel (2005)]. As a result, an average of the DOC’s 1997 and 2002 estimates are that 72% of overall truck fuel use comes from light trucks, 5% from medium trucks, and 22% from heavy trucks; these percentages were estimated based on gasoline fuel use tracked by the DOC survey and used to aggregate the medium and heavy truck categories into the medium/heavy truck category shown in Table 1. Based on these estimates, 20% of the medium/heavy truck energy shown in Table 1 is from medium trucks and 80% is from heavy trucks. Additionally, the aggregated medium/heavy truck category’s share of construction energy shown in Table 1 is 17%. As the total fuel usage in Btu was the only number available for 1997, the 1997

<table>
<thead>
<tr>
<th>Year</th>
<th>Gasoline</th>
<th>Diesel</th>
<th>Total</th>
<th>Construction industry share (%)</th>
<th>Construction industry total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light trucks (on-highway)</td>
<td>1997</td>
<td>6,260</td>
<td>250</td>
<td>6,510</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>6,940</td>
<td>270</td>
<td>7,210</td>
<td></td>
</tr>
<tr>
<td>Medium/heavy trucks (on-highway)</td>
<td>1997</td>
<td>490</td>
<td>3,820</td>
<td>4,310</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>600</td>
<td>4,690</td>
<td>5,290</td>
<td></td>
</tr>
<tr>
<td>Construction equipment (off-highway)</td>
<td>1997</td>
<td>38</td>
<td>700</td>
<td>740</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>36</td>
<td>800</td>
<td>840</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1997</td>
<td>6,790</td>
<td>4,770</td>
<td>11,550</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>7,570</td>
<td>5,760</td>
<td>13,330</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. 1997 and 2002 Estimates of Gasoline and Diesel Use for Construction in Petajoules (Davis and Diegel 2003, 2005; DOC 2005a)

Note: As previously mentioned, 2002 off-highway consumption values were estimated based on average annual growth rates between 1997 and 2001. Numbers may not sum due to rounding.
gasoline and diesel fuel usage estimates were backcalculated based on the 2002 ratio of gasoline and diesel usage to total fuel usage, respectively (Davis and Diegel 2003, 2005).

Thus, per Table 1, the estimate of construction energy used by both on- and off-road construction vehicles in the form of gasoline and diesel fuel was approximately $1.8 \times 10^{15}$ Btu in 1997 and $2.1 \times 10^{15}$ Btu in 2002 (1,900 and 2,200 PJ, respectively); these estimates are more than 50% larger than the original estimate provided in Fig. 1, which was $1.4 \times 10^{15}$ Btu (1.4 PJ). This discrepancy is most likely a result of the DOC’s statistical survey of construction companies, which is unable to see through the subcontracting levels to smaller companies (DOC 2005a). In many cases, this inability to adequately quantify subcontractor energy use with a survey could prove to be significant for site-related activities.

If the 2002 gas and diesel energy value estimates calculated for Table 1 (2,200 PJ) are used in place of the gas and diesel estimates in Fig. 1 (1,400 PJ), then the estimated total energy used in construction increases to 2,500–2,900 PJ (2.5–2.9 $\times 10^{15}$ Btu—for site and primary electricity use, respectively). These revised estimates are almost double the lower range of the earlier estimate of 1,300 PJ (1.2 $\times 10^{15}$ Btu). Given that the estimate of 1.8–2.2 $\times 10^{15}$ Btu (1,900–2,300 PJ) of construction energy used in 2002 provided in Fig. 1 is widely utilized, questions arise concerning the accuracy and use of data obtained from the construction industry.

Assuming the same average ratios of gasoline and diesel use to total fuel use for the entire construction industry, a backcalculation of these numbers yields estimates of 2002 construction industry energy use of about $1.1 \times 10^{15}$ Btu of gasoline and $8.3 \times 10^{15}$ Btu of diesel (1,160 and 880,000 TJ, respectively). Comparing these values to annual volumetric sales of gasoline and diesel in the United States, this approximation represents 3% of gasoline and 21% of overall U.S. diesel fuel use (EIA 2005a).

**Effects of EPA Nonroad Diesel Rules**

Construction industry energy and fuel consumption is an interesting topic not only due to the large share of gasoline and diesel vehicles used by the industry, but also because of the EPA’s 2004 Nonroad Diesel Rule affecting vehicles and fuels (EPA 2004b). The vast majority of conventional air emissions in the United States come from burning fossil fuels, which are the primary source for construction energy use. Because the construction industry has not been subject to strict EPA regulations in the past (i.e., Tier 1-3 regulations), EPA’s nonroad rules provide large potential to reduce construction’s environmental impacts.

EPA’s Nonroad Rule affects diesel fuel and diesel engines used in nonhighway situations. Much of EPA’s ongoing regulatory efforts have been for mobile sources, most predominantly for on-highway vehicles. As emission standards for these vehicles have been lowered over the last 20 years, there is relatively little room for improvement left and the current focus has switched to non-highway engines, which produced 60% more particulate matter emissions than highway-based engines in the year 2000 (EPA 2004b).

The construction industry is not the only industry being held to the EPA’s nonroad standards; many agricultural, material handling, industrial, and utility equipment industries are also affected. Regardless, the construction industry has been and will continue to be substantially affected by the new regulations. Whereas the subsequent focus of this paper is on-site portable generators, it should be noted that stationary generators (i.e., those used as emergency backup power sources for buildings) are excluded from the EPA’s regulations.

Most recent sulfur emission legislation has been focused on power plant emissions. However, the EPA’s new rules on diesel fuel will reduce the sulfur content in diesel fuel by 99% by 2010 (from 3,000 ppm down to 15 ppm) and decrease the limit at which off-highway diesel engines can emit NOx and PM10 by 90% by the year 2015 (EPA 2004b). The EPA regulates these emissions by setting limits on particular engine types (e.g., in g/hp h).

**Construction Nonroad Diesel Engine Emissions**

Emissions from nonroad engines, specifically diesels, are an emerging target of attention and regulation. Part of the reason for this increasing awareness is that the EPA documented more particulate matter emissions from nonroad sources than from highway sources for the first time ever in 1995. In the year 2002, the EPA estimated total transportation emissions of particulate matter less than 10 μm in diameter (PM10) from all sources was 515,000 short tons (467,000 t) (EPA 2005). Of this quantity, 60% were from nonroad engines and vehicles [311,000 short tons (282,000 t)]. Diesel equipment is 54% of this nonroad total (169,000 short tons; 153,000 t; or 33% of the U.S. transportation total) and construction vehicles represent 42% of the nonroad diesel equipment emissions (71,000 short tons; 64,000 t; or 14% of the U.S. transportation total).

It should be noted that nonroad construction gasoline engines emit only 2,000 short tons (or 2,000 t) of PM10 per year, a negligible amount when compared to the diesel PM10 emissions (EPA 2005). Thus, from a PM10 perspective, construction diesel use causes disproportionately high environmental impacts. Using a similar approach, it can be determined that off-highway diesel construction vehicles contribute 764,000 short tons of NOx emissions (693,000 t, or 7% of the U.S. total nonroad NOx emissions), which contribute to ozone and climate change problems (EPA 2005).

**Emissions from On-Road Gasoline and Diesel Generator Engines Used for Construction**

Using a method similar to that used earlier to allocate and estimate nonroad construction vehicle energy use, light, medium, and heavy-duty truck emissions from construction were also estimated. Table 2 combines EPA emission estimates of PM10, NOx, and volatile organic compounds (VOC) with the results from Table 1 to estimate air emissions from construction on- and off-road vehicles (EPA 2005). Note that we have only reallocated emissions in EPA’s inventory, not added emissions. As a result, these numbers may now be matched up with those presented previously in Table 1 so that air emissions are associated with fuel usage.

In Table 2, “on-highway” construction vehicles are added to the EPA’s current definition of “construction” (which only includes off-highway vehicles). Consequently, estimated 2002 vehicle emissions from construction increase by 32% for PM10, 96% for NOx, and 125% for VOCs. These improved estimates of energy use and environmental emissions for construction activities are much higher than existing EPA national-level data. However, the very data sources referenced in this analysis as underestimat-
ing construction energy use and emissions are the exact same sources heavily utilized by others to estimate the environmental impacts of the construction industry. As a result, past environmental assessments or life cycle analyses dependent on this type of underestimated national data, as well as other survey data from the construction industry, may be underreporting these effects (Gambatese and Rajendran 2005; Guggemos and Horvath 2005; Hendrickson and Horvath 2000; Ochoa et al. 2002; Ruether et al. 2004).

Effects for On-Site Generators

In the past, many EPA diesel emission regulations have only been applicable to on-highway engines and most sulfur emission legislation has been focused on power plant emissions, both basically ignoring emissions from off-road diesel vehicles. As mentioned previously, the EPA’s Nonroad Rule will reduce sulfur content in diesel, as well as diesel engine NO\textsubscript{x} and PM emissions. The EPA regulates these emissions by setting limits on particular engines (e.g., in g/hp h).

A case study was created to show the prospective effects of the new EPA Nonroad Rule. The two biggest on-site energy sources are diesel fuel and electricity, but on construction sites, diesel fuel is often used both to power heavy machinery and to produce extra on-site electricity via generators. Consequently, electric generators are a relevant choice for a case study, especially as there are other ways of generating power, most obviously the electricity grid.

On construction sites, electricity from the grid is used to power lights, elevators, and trailers, while generators provide power for more immediate electricity needs like welding and other hand tools. Because grid and generator electricity differ tremendously in magnitude, it is very likely that there is a difference in how much pollution grid and electricity generated on-site emit per kWh of electricity produced. If a large difference does exist, the potential to reduce emissions without sacrificing productivity exists through application of the EPA Nonroad Rule. Consequently, as the stringent EPA regulations are phased in for nonroad diesel generators and construction equipment over the next several years, it is possible that the form of “cleaner” electricity generation could shift between the electricity grid and on-site generators (in terms of air emissions).

An inventory of portable generators was not available for the United States, so a Canadian generator inventory was used as a proxy (Tushingham 2004). In Canada, there are over 620,000 portable generators that each average 134 h of operation per year; 92% of these generators are smaller than 19 kW (25 hp) in size. The Canadian data set does not specify what percentage of generators are used by any industry or user group, including construction. Despite the fact that there are obvious climate, recreational, and use differences between the United States and Canada that could lead to differences in generator use, the Canadian generator inventory is most likely strongly linked to U.S. ownership.

Interestingly, the Canadian inventory also notes that about 90% of fuel used in on-site generators is gasoline, whereas many U.S. generators run on diesel fuel (Tushingham 2004). The fact that many Canadian generators are run on gasoline instigates the idea that applying the EPA diesel rules to portable diesel generators in the U.S. could cause significant increases in diesel generator price, consequently causing a simple substitution of gasoline for diesel as a generator fuel. As a result, the market for low-power diesel generators could evaporate, taking with it any potential environmental improvements in the category of construction site electricity generation. As a preventative measure, perhaps portable gasoline generators should also be included in such nonroad regulations to eliminate a scenario perpetuated by the EPA’s fuel-based regulations.

Per the Canadian generator inventory, most construction diesel generators range from 1 to 300 hp (1 to 225 kW), with most falling between 3 and 25 hp (2 and 19 kW). However, the new EPA rule covers engines above 750 hp (560 kW), which also incorporates engines in large construction vehicles. Table 3 summarizes the history of EPA’s Tier 1-4 rules for nonroad diesel engines with capacities up to 75 hp (56 kW); the EPA reports these emission limitations in units of g/hp h (EPA 2004b). Although the EPA Nonroad Rule applies to engines up to about 1 MW, only the low end of the range is shown here because it is most relevant to on-site generators. In Table 3, nonmethane hydrocarbons (NMHC) are included in the NO\textsubscript{x} (+NMHC) column. Like NO\textsubscript{x}, NMHCs are significant precursors to ozone formation; due to this common path to ozone, EPA often regulates NMHC and NO\textsubscript{x} together.

To help place the EPA’s nonroad air emission regulations in context, Fig. 2 summarizes current emission factors from overall grid electricity generation sources, as well as current and future portable generators. Although sulfur dioxide emission values have not been previously discussed, they are assumed to be negligible for generators under the EPA’s Nonroad standards.

A comparison of the emission values in Fig. 2 illustrates that portable generators less than 19 kW (25 hp) are currently creating about an order of magnitude more PM\textsubscript{10} and NO\textsubscript{x} emissions than

### Table 2. 1997 and 2002 Emissions from Construction Engines in Thousand Metric Tons (Davis and Diegel 2005; EPA 2005)

<table>
<thead>
<tr>
<th>Year</th>
<th>All sources</th>
<th>Construction industry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PM\textsubscript{10}</td>
<td>NO\textsubscript{x}</td>
</tr>
<tr>
<td>Light trucks (on-highway)</td>
<td>1997</td>
<td>34</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>29</td>
</tr>
<tr>
<td>Medium/heavy trucks (on-highway)</td>
<td>1997</td>
<td>170</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>110</td>
</tr>
<tr>
<td>Construction equipment (off-highway)</td>
<td>1997</td>
<td>73</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>66</td>
</tr>
<tr>
<td>Total</td>
<td>1997</td>
<td>280</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>200</td>
</tr>
</tbody>
</table>

Notes: PM\textsubscript{10} = particulate matter less than 10 μm in diameter; NO\textsubscript{x} = nitrogen oxides; and VOC = volatile organic compounds. Numbers may not sum due to rounding.
grid electricity. However, by the implementation of Tier 4 requirements in 2008, these generators will be very close to grid PM$_{10}$ emissions for coal-fired electricity, though still larger than grid emissions for NO$_x$. As generators adhering to the EPA’s Nonroad Rule are gradually replaced, diesel generator emissions of SO$_2$ will remain much lower than those of the electricity grid, whereas CO emissions will remain much higher. Additionally, as shown in Fig. 2, PM$_{10}$ emissions from larger 25 to 75 hp generators will be 60% below the grid’s PM$_{10}$ emissions by 2013. Because PM$_{10}$ is so important in terms of air emissions from diesel engines and the EPA Nonroad Rule, this calculated reduction in PM emissions is significant. Although the next decade will likely see environmental improvements in grid electricity, large changes like the ones illustrated here are unlikely.

### “Hybrid” Engine Discussion

One aspect that has been purposely excluded from this analysis is the replacement cycle or time lag needed to achieve the above-calculated results. The EPA Nonroad Rule will phase in over the next 7 years, but will apply only to new equipment purchases. Because many of the engines and vehicles in the nonroad category have been, are, and could be forced into long lifetimes, it could take 20 years or more to achieve any substantial benefits from air emission reduction. However, the numbers still speak for themselves: when diesel engine conversion occurs as mandated by the EPA Nonroad Rule, adhering generators will be able to create power that is more comparable to the air emissions level of the U. S. electricity grid per kW h.

#### Table 3. 1999–2013 Emission Standards for Nonroad Diesel Engines up to 37 kW (50 hp) in Grams/Kilowatt Hour (Adapted from Matthews et al. 2005) (EPA 2002, 2004b)

<table>
<thead>
<tr>
<th>Engine rating</th>
<th>Horsepower</th>
<th>Tier Year</th>
<th>PM$_{10}$ NO$_x$ (NMHC) CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kilowatts</td>
<td>Horsepower</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;8</td>
<td>&lt;11</td>
<td>1 2000</td>
<td>1.0 10.5 8.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 2005</td>
<td>0.8 7.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 2008</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1 2000</td>
<td>0.8 9.5 6.6</td>
</tr>
<tr>
<td>8–19</td>
<td>11–25</td>
<td>2 2005</td>
<td>7.5</td>
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<td>19–37</td>
<td>25–50</td>
<td>1 1999</td>
<td>0.8 9.5 5.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 2004</td>
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Notes: PM$_{10}$=particulate matter less than 10 μm in diameter; NO$_x$=nitrogen oxides; NMHC=nonmethane hydrocarbons; and CO=carbon monoxide.

#### Fig. 2. 2002 electricity generation emission factors in grams/kilowatt hour (EIA 2005a; EPA 2005)
Construction sites use many generators that are less than 25 hp. As illustrated by Table 3, these small generator engines emit more NO\textsubscript{x} per kW or hp than other larger engines and the electricity grid. Thus, compared to other diesel engines on the construction site, small generators are heavy polluters, raising the question: "Is there a cleaner way to meet nongrid electricity demand on a construction site besides utilizing small (less than 25 hp) diesel generators?" Other than utilizing more electricity from the grid, which can be difficult and expensive depending on mobility and availability, one possible way to reduce the air emissions from smaller generator engines might be to combine them with other on-site equipment, thus creating a larger engine with more functions.

For example, a construction site might use two types of equipment: excavators and small diesel generators. Instead of having a large excavator engine (200 hp) and a small generator engine (1–11 hp), excavators could be manufactured with slightly larger engines that have the capacity to simultaneously lift a normal load and produce electricity to run small on-site equipment. The cost of adding additional horsepower to a 200 hp engine would most likely be less than the cost of buying an entirely separate small generator. One other possible way to combine generator-created power and daily construction activities might be to utilize technology similar to that used in hybrid passenger cars for regenerative braking (that recaptures a portion of the potential energy utilized by heavy machinery and the like that would otherwise be lost).

In a brief reality-based extension of this example, if a 10 kW (16 hp) generator costs $11,500; a larger model that produces 15 kW (20 hp) of electricity might cost $12,100. As a result, the upgrade cost for adding 5 kW (4 hp) would be $600, or $150/hp. Therefore, if an excavator with a 200 hp engine costs $100,000, an increase in engine size of 25 hp would perhaps add $3,750 to the price of the excavator. The 225 hp excavator would now cost 3.75% more than it did originally, but provide capacity for both normal excavator activities and energy generation. Additionally, the $3,750 cost of obtaining this extra horsepower and functionality is roughly 30% of the cost for a new 20 hp generator (which costs $12,100). Based on this simple example, as long as the cost to upgrade to a bigger engine remains less than $485/hp and generator prices do not decrease, this “add-on power” scenario could be a viable and price-effective alternative to stand-alone small generators. In addition to saving money, combining small generators with larger equipment could lead to efficiencies of scale and further reductions in air emissions under the EPA Nonroad Rule.

Per the EPA's Nonroad Rule, by 2014, any engine larger than 75 hp will release fewer NO\textsubscript{x} and PM emissions per kW h than the average U.S. electricity grid or smaller engines (EPA 2004b). As a result, as long as a construction site’s electricity-producing generator has an engine larger than 75 hp, on-site power generation will be cleaner than the electricity grid.

Due to the fact that excavators are fairly mobile, they may not be the best piece of equipment for large-scale implementation of "hybrid construction equipment." However, other heavy equipment might provide more realistic conversion of potential energy into electricity or battery storage for smaller on-site activities. Consequently, depending on how often large equipment is being utilized, this type of combination engine could lower the overall capital costs for construction companies while simultaneously reducing air emissions even further than the numbers provided in Table 3 (as emission levels for larger engines are even smaller per kW h) (EPA 2004b).

An existing market alternative for contractors desiring “cleaner” on-site electricity generation are microhybrid trucks like the Chevrolet Silverado/GMC Sierra and Dodge Ram, which can use the electric component of their motors to generate electricity on-site for as long as 32 h (Truett 2005). These vehicles are available only in small numbers, but their price is comparable to other Silverado models. Of the over 900,000 Silverados sold in 2005, only 2,000 were hybrids (Chevrolet: Silverado Is Vital 2006; Truett 2005). However, these hybrids are now in larger production; though numbers are not yet available for 2006, sales are presumably larger due to higher gas prices and larger availability, as 3,000 Silverado / Sierra hybrids were planned for 2006 (Truett 2005). Of the 38×10^6 pickup trucks registered in 2002, only 2.3×10^6 (6%) were utilized by the construction industry (DOC 2004). Assuming that an average construction industry pickup truck has a lifetime of 10 years, introduction of 3,000 Silverado/ Sierra hybrids per year only replaces 2% of the yearly replacement fleet of construction pickup trucks. Additionally, there is no guarantee that all of these vehicles are even used to generate electricity on construction sites. However, given larger future availability and a larger replacement rate of the existing U.S. construction fleet, there is great potential for these light-duty hybrid vehicles to reshape the on-site energy profile of construction sites (DOC 2004).

Although on-site electricity generation with existing goods like these microhybrid trucks is an interesting alternative to traditional diesel generators, the market penetration is poor (less than 1% of new Silverados in 2 years) and statistics on actual construction site use are nonexistent. However, per Table 3, electricity generated on-site by a Tier 2 diesel generator in 2006, a Tier 4 diesel generator in 2014, and a microhybrid truck in 2006, would produce 0.8, 0.4, and 0 g of PM\textsubscript{10} per kWh. NO\textsubscript{x} and carbon monoxide (CO) emissions can be similarly estimated with Table 3, though all emissions estimates ignore off-site and life cycle impacts. A full analysis of hybrid vehicles is beyond the scope of this paper, but provides potential for future work.

Though not explicitly addressed in this analysis, lead demand for microhybrid trucks is quadruple that of traditional trucks due to the requirement for three additional lead-acid batteries (Higgins et al. 2007). This increased lead demand is associated with lead emissions from the life cycle of mining and melting lead. If these larger lead emissions are directly associated with the on-site power generation capability these microhybrid trucks provide, then the “emission free” appeal of these vehicles is negated.

Conclusions

Historically, the construction industry has been a major source of pollution in the United States. This paper quantifies just how significant construction is in terms of energy usage, using 2.5–2.9 PJ of energy annually, accounting for 2.6–3% of the U.S.’s entire energy consumption (which includes passenger vehicles and shipping). This level of energy consumption roughly equates the construction industry’s annual energy consumption with that of all residential households in the Midwest United States (EIA 2005a).

Additionally, calculations using public governmental data and estimates indicate that current estimates of the construction industry’s energy usage and air emissions are at only half of what the construction industry actually uses. These prevalent underestimations initiate questions regarding the accuracy of current data regarding the construction industry that has been gathered by survey. It should also be emphasized that the very data sources ref-
enced in this analysis as underestimating construction energy use and emissions are the exact same sources heavily utilized by others to estimate the environmental impacts of the construction industry. Consequently, all current estimates of the construction industry’s environmental impacts are half of what they should be.

Due to the EPA’s Nonroad Rule, air emissions (especially particulate matter and oxides of nitrogen) will be significantly reduced. Though this legislation has great potential to reduce the construction industry’s environmental impacts (especially in terms of development and utilization of “clean as grid” electricity), there is still much room for improvement. Additionally, due to equipment lifetimes, environmental benefits will be smaller in the next few years than they will be in the long-run because replacement cycles for the entire U.S. generator “fleet” might take 10–20 years, if not longer. The construction industry and the environment can benefit from technological innovations such as multifunction equipment, hybrid equipment, and other design changes that can be both economically and environmentally friendly while not sacrificing productivity.

It should also be noted that the calculations performed for this analysis use average prices, which are in themselves probably underestimates of the construction industry’s energy use, as the average U.S. price of fuel is not the average construction industry price. Additionally, all air emission inventories are simply reallocated, not reestimated. Consequently, this investigation is only the first step in quantifying the environmental impacts of the construction industry. Further inventories need to be compiled and combined to create a complete picture of the construction industry’s environmental impacts. Future research should incorporate this and other inventories into a full life cycle assessment of on-site construction processes.

This analysis utilizes and revises existing inventories of construction energy use and emission production. However, data specifically associated with construction sectors are not as prevalent as they are for other industries. More inventories of the construction industry’s resource use and environmental impacts need to be created to further understand the economic and environmental impacts of construction processes.

Additionally, the DOC’s Vehicle Inventory and Use Survey (VIUS) was last completed in 2002 and has since been discontinued. This survey provided integral information to this analysis and to other analyses of the construction industry; with its termination, understanding of the construction industry’s environmental impacts took a step backwards. Due to the cessation of the VIUS, future comparisons between government-estimated and revised inventories of construction industry energy use will not be possible. Given that this analysis indicates that actual construction industry energy use is twice the amount commonly assumed by government sources, elimination of such an important data source is critical.

Consequently, along with reinstitution of VIUS, this analysis discovered that an inventory of U.S. generators used by construction and other industries is needed. Data tracking on-site energy use, generation, and demand is also difficult to obtain without approaching companies on a one-by-one basis. Acquisition and release of more specific inventories for the construction industry is required if the environmental impacts of the construction industry are ever to be understood as thoroughly as those of the manufacturing industries.

Future Research

The analysis detailed within is part of an effort to expand the body of knowledge regarding the primary and secondary energy and environmental impacts of the construction industry. The estimates provided in Table 1 and Table 2 will be utilized in the future to create an input-output-based hybrid life cycle assessment model for the construction industry. This tool will provide environmental impact estimations for construction projects on a sector-specific level. A complete analysis to determine the on-site and life cycle emissions of hybrid construction equipment and hybrid trucks equipped with generators would also help frame future discussions of how to make construction sites more sustainable.

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