M I N E T A   T R A N S P O R T A T I O N   I N S T I T U T E

Analyzing the Potential of Hybrid and Electric Off-Road Equipment in Reducing Carbon Emissions from Construction Industries

MTI Report 12-78

MINETA
TRANSPORTATION INSTITUTE
MTI

MINETA TRANSPORTATION INSTITUTE
LEAD UNIVERSITY OF MNTRC

The Mineta Transportation Institute (MTI) was established by Congress in 1991 as part of the Intermodal Surface Transportation Equity Act (ISTEA) and was reauthorized under the Transportation Equity Act for the 21st century (TEA-21). MTI then successfully competed to be named a Tier 1 Center in 2002 and 2006 in the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU). Most recently, MTI successfully competed in the Surface Transportation Extension Act of 2011 to be named a Tier 1 Transit-Focused University Transportation Center. The Institute is funded by Congress through the United States Department of Transportation's Office of the Assistant Secretary for Research and Technology (OST-R), University Transportation Centers Program, the California Department of Transportation (Caltrans), and by private grants and donations.

The Institute receives oversight from an internationally respected Board of Trustees whose members represent all major surface transportation modes. MTI's focus on policy and management resulted from a Board assessment of the industry's unmet needs and led directly to the choice of the San José State University College of Business as the Institute's home. The Board provides policy direction, assists with needs assessment, and connects the Institute and its programs with the international transportation community.

MTI's transportation policy work is centered on three primary responsibilities:

Research

MTI works to provide policy-oriented research for all levels of government and the private sector to foster the development of optimum surface transportation systems. Research areas include: transportation security; planning and policy development; interrelationships among transportation, land use, and the environment; transportation finance; and collaborative labor-management relations. Certified Research Associates conduct the research. Certification requires an advanced degree, generally a PhD, a record of academic publications, and professional references. Research projects culminate in a peer-reviewed publication, available both in hardcopy and on TransWeb, the MTI website (http://transweb.sjsu.edu).

Education

The educational goal of the Institute is to provide graduate-level education to students seeking a career in the development and operation of surface transportation programs. MTI, through San José State University, offers an AACSB-accredited Master of Science in Transportation Management and a graduate Certificate in Transportation Management that serve to prepare the nation's transportation managers for the 21st century. The master's degree is the highest conferred by the California State University system. With the active assistance of the California Department of Transportation, MTI delivers its classes over a state-of-the-art videoconference network throughout the state of California and via webcasting beyond, allowing working transportation professionals to pursue an advanced degree regardless of their location. To meet the needs of employers seeking a diverse workforce, MTI's education program promotes enrollment to under-represented groups.

Information and Technology Transfer

MTI promotes the availability of completed research to professional organizations and journals and works to integrate the research findings into the graduate education program. In addition to publishing the studies, the Institute also sponsors symposia to disseminate research results to transportation professionals and encourages Research Associates to present their findings at conferences. The World in Motion, MTI's quarterly newsletter, covers innovation in the Institute's research and education programs. MTI's extensive collection of transportation-related publications is integrated into San José State University's world-class Martin Luther King, Jr. Library.

REPORT 12-78

ANALYZING THE POTENTIAL OF HYBRID AND ELECTRIC OFF-ROAD EQUIPMENT IN REDUCING CARBON EMISSIONS FROM CONSTRUCTION INDUSTRIES

Matthew Holian, PhD
Jae-Ho Pyeon, PhD

September 2017

A publication of

Mineta Transportation Institute
Created by Congress in 1991

College of Business
San José State University
San José, CA 95192-0219

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. CA-MTI-17-1533	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Analyzing the Potential of Hybrid and Electric Off-Road Equipment in Reducing Carbon Emissions from Construction Industries		**5. Report Date** September 2017 **6. Performing Organization Code**
7. Authors Matthew Holian, PhD and Jae-Ho Pyeon, PhD		**8. Performing Organization Report** MTI Report 12-78
9. Performing Organization Name and Address Mineta Transportation Institute College of Business San José State University San José, CA 95192-0219		**10. Work Unit No.** **11. Contract or Grant No.** DTOS5915P00030
12. Sponsoring Agency Name and Address U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology University Transportation Centers Program 1200 New Jersey Avenue, SE Washington, DC 20590		**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code**
15. Supplemental Notes		

16. Abstract

This report quantifies the likely impact recent improvements in emissions technology in the heavy construction equipment fleet will have on national and state-level carbon emissions from construction industries. Specific technologies examined in this report include hybrid and electric-powered off-road equipment. Innovation in the equipment manufacturing industry, and adoption of innovative technology by construction firms, is driven by a wide range of factors, some of which can be influenced by public policy. Therefore, this paper describes policies available to public decision makers at the local, state and national levels that impact equipment use and development decisions, including those that encourage the use of green equipment in government procurement, local level job site emissions regulations, and state and nationally mandated emissions standards, fuel taxes, and direct research subsidies.

17. Key Words Construction; innovation; policy, legislation and regulation; environmental quality; impacts	**18. Distribution Statement** No restrictions. This document is available to the public through The National Technical Information Service, Springfield, VA 22161		
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 88	**22. Price** $15.00

Form DOT F 1700.7 (8-72)

Library of Congress Catalog Card Number:
2017953759

To order this publication, please contact:

Mineta Transportation Institute
College of Business
San José State University
San José, CA 95192-0219

Tel: (408) 924-7560
Fax: (408) 924-7565
Email: mineta-institute@sjsu.edu

transweb.sjsu.edu

091117

ACKNOWLEDGMENTS

We thank Jack Estill, Anthony Fournier, Phil Lewis, Perry Lindstrom, Lee Padgett, Cory Parmer, and Kelly Perl for useful discussion and help in obtaining information, Kevin Allen and Noe Vidales for excellent research assistance, and Stacey Cler for editorial assistance. All errors remain our own.

The authors thank MTI staff, including Executive Director Karen Philbrick, PhD; Publication Support Coordinator Joseph Mercado; and Executive Administrative Assistant Jill Carter.

TABLE OF CONTENTS

Executive Summary 1

- **I. Introduction** 3
- **II. The Construction and Equipment Manufacturing Industries** 7
- **III. Measuring GHG Emissions in the Construction Industry** 21
- **IV. Quantifying the Role of Green Equipment in Reducing GHG Emissions from Construction** 30
- **V. Conclusion: Encouraging Development and Adoption of Clean Tech in Construction** 47

Appendix 53

Acronyms and Abbreviations 70

Endnotes 72

Bibliography 82

About the Authors 87

Peer Review 88

LIST OF FIGURES

1. Examples of Hybrid and All-Electric Off-Road Construction Equipment 4

2. US Employment in Construction, 2006-2017 7

3. Fuel Use Factors for Comparable Caterpillar Models, 1990-2017 15

4. Age Distribution of Heavy Construction Equipment 32

5. Map of eGRID Subregions 53

LIST OF TABLES

1. Data for Construction Machinery Manufacturing Industry for 2012 9

2. Measures of Concentration for Machinery Manufacturing Industry and Select Subsectors 10

3. Global Construction Equipment Manufacturing Industry, 2015 11

4. Manufacturers by Hybrid Construction Equipment Type 13

5. Four Types of Heavy Construction Hybrid Technology 13

6. Hybrid Equipment Fuel Savings by Manufacturers 14

7. Comparing Fuel Usage and NO_x Emissions in the UC Riverside Experiment 16

8. CAT 336E H Hybrid Excavator Performance Criteria 18

9. Energy Consumption in Construction, Units are Trillion Btu 22

10. Inputs and Outputs of EPA Method 23

11. Highway, Street, and Bridge Construction: Emissions in lbs 28

12. Activity Estimates for Two Types of Construction Equipment, by Age 33

13. Diesel Excavators 34

14. Average Fuel Consumption by Equipment Type 35

15. Adoption and Fuel Use Assumptions for Excavator Analysis 36

16. Calculating Average Fuel Use in Medium and Large US Excavator Fleet in 2012 38

17. Diesel Crawler Tractor/Dozers Population 42

18. Hybrid Electric Experiment and Energy Consumption 45

19. Hybrid Electric Experiment and GHG Emissions Under Three Scenarios 45

20. NERC Subregions and Emissions Factors 54

21. Average Fuel Consumption for CAT Excavators, 1990-2017 55

22. Average Fuel Consumption for CAT D7 Dozers, 1990-2017 55

23. Average Fuel Consumption for CAT Wheel Loaders, 1990-2017 56

24. Econ Census Data for Construction Industry and its Subsectors 57

25. Econ Census Data for Construction Industry and Subsectors 59

26. Expenditures on Fuel, from 2012 Economic Census 62

27. Fuel Prices 63

28. Quantities 64

29. State-Specific Emissions Factors 66

30. GHG Emissions in lbs 68

EXECUTIVE SUMMARY

Over the last 25 years, technological innovation in the heavy construction equipment industry has led to dramatic reductions in criteria air pollutants such as particulate matter (PM). However much less is known about how advances in construction equipment technology have impacted Greenhouse Gas (GHG) emissions from the construction industry.

Study Methods

This report surveys the construction and equipment manufacturing industries, describes the latest and emerging technologies, and presents an updated GHG emissions inventory for the construction industry which for the first time presents emissions estimates at both the state and subsector level. It then utilizes a scale-composition-technique model, which accounts for the size of the equipment fleet, as well as the fuel economy and hours of operation of individual machines, to estimate the impact of the greening of the construction equipment fleet on GHG emissions.

Findings

With regard to hybrid equipment, this study documents improvements in fuel efficiency in several types of heavy construction equipment, including excavators, bull dozers and wheel loaders. Figure 3 in Chapter 2 reports fuel use factors, which along with activity load are the prime determinant of both fuel consumed and GHG emitted by construction equipment. The fuel use factors shown there for hybrid excavators, dozers and loaders are 27%, 20% and 12% lower than the contemporaneous conventional equipment. These figures are broadly in line with the findings from the study's review of twelve specific models, from ten different manufacturers, which revealed fuel use reductions of 10-45%, with an average of 28%, attributable to hybrid equipment.

In addition to hybrid heavy equipment, this report also examines the nascent battery-electric construction equipment industry. Although electric equipment has long been in use in, for example, certain mining applications, innovations in battery technology have only recently enabled the commercial availability of small to medium-sized battery excavators. The available evidence suggests that replacing diesel with electric equipment holds potential to reduce GHG emissions much more sharply than hybrid technologies, which themselves are associated with relatively modest—though non-trivial—reductions in GHG emissions. Using the energy consumption estimates from one experiment involving diesel and electric mini-excavators, this report documents that this technology could enable emissions to fall in each of the 50 states. When substituting battery electric for diesel excavators, GHG emissions from excavation are 59% lower on average, and this figure ranges from 79% in the state with the greenest electricity grid (New York) to a still-large 34% in Colorado, where more electricity is generated using high-emissions fuels like coal.

Among the results of the scale-composition-technique analysis, the study estimates that in a counterfactual world where excavator technology failed to advance since 2001, CO2 emissions would be 335 million pounds higher each year; this is comparable with two years of emissions that result from the entire construction sector in the District of Columbia, or with six months of emissions that result from the entire construction sector in Alaska.

Policy Implications

The large emissions reductions shown to result from improved technology speak for a policy focus on innovation. This report surveys the following policy options: green performance contracting for highway construction, regulating new engine technology, equipment use, and regional air quality; raising fuel taxes, and subsidizing the development and use of off-road clean tech.

I. INTRODUCTION

Greenhouse gas (GHG) emissions are on the rise. Global energy-related carbon dioxide (CO^2) emissions—the largest driver of climate change[1]—are projected to increase from 32.3 billion metric tons in 2012 to 43.2 billion metric tons annually in 2040, with most of the growth in emissions occurring in developing nations.[2] Half of all anthropogenic GHGs emitted between 1750 and 2011 have occurred in just the last 40 years.[3] According to the Intergovernmental Panel on Climate Change (IPCC), the 30-year period from 1983 to 2012 was likely the warmest of the last 1400 years in the Northern Hemisphere, and it is extremely likely that anthropogenic GHG emissions were the dominant cause of the observed warming since the mid-20th century. Surface temperature is projected to rise further over the 21st century, and it is, "…very likely that heat waves will occur more often and last longer, and that extreme precipitation events will become more intense and frequent in many regions. The ocean will continue to warm and acidify, and global mean sea level to rise."[4]

Faced with this likely future scenario, governments and citizens around the world have mobilized. The challenge of confronting climate change requires actions on many fronts. In the US, GHG emissions result primarily from electricity generation (30%), transportation (26%), industry (21%), commercial and residential (12%), and agriculture (9%).[5] Each of these areas presents unique challenges and opportunities for reducing emissions. The focus of this report is on industry and, in particular, on reducing GHG emissions in the construction sector and the role of "clean technology" construction equipment.

The construction sector is large (currently about 4.6% of total US employment)[6] and is interrelated with other large emitting sectors, such as the operation of commercial and residential buildings, and the use of highways and other transportation infrastructure. A 2008 US Environmental Protection Agency (EPA) study of industrial emissions found construction accounts for about 9% of all industrial emissions, which was 1.74% of total emissions.[7] Several subsequent studies have examined GHG emissions in the construction sector, which we review in this report. Our study builds on this literature by providing an updated and comprehensive assessment of all subsectors of construction.

We also utilize the construction subsector "highway, street and bridge construction" as a representative example of a construction subsector, and provide a more detailed characterization of it throughout the narrative portion of this report. We present data and calculations for each of the construction subsectors in an online Appendix.[8] We focus on the roadway construction subsector for a variety of reasons, and this guides our selection of the technologies on which we focus, as well as the policies we chose to feature in this report. We hope this allows our report to strike the right balance across as many potential uses of it as possible.[9]

One topic that has been neglected by previous research on GHG emissions from the construction industry is an intentional discussion of the role of *innovation,* specifically, innovation in construction equipment.[10] This industry—defined in the US by the Census Bureau according to the North American Industry Classification System (NAICS) code 333120 "Construction Machinery Manufacturing"—includes large multinational firms like

Caterpillar and Komatsu. Each of these firms has recently released hybrid electric-diesel equipment with GHG emissions that are lower than previous generations. Some firms also have developed all electric equipment. Examples of commercially available, green construction equipment are shown in Figure 1. Examples from the three largest equipment manufacturers are featured, but Figure 1 also includes a product from Takeuchi, a smaller manufacturer. The Yellow Table, an industry source described later in the report, ranked it the 37th largest equipment manufacturer, with revenues of $755 million. The fact that average revenue of the three largest firms is around $18 billion suggests that innovative green products can come from both small and large firms.

The Caterpillar D7E (dozer)

The Komatsu HB215LC-1 (excavator)

John Deere 664K (wheel loader)

Takeuchi e240 Battery Powered Excavator

Figure 1. Examples of Hybrid and All-Electric Off-Road Construction Equipment[11]

The purpose of this report is to examine the role of innovation in one industry, equipment manufacturing (NAICS code 333120), in reducing emissions in another, construction (NAICS code 230000).[12] We examine several methods of measuring emissions, and forecast the likely emissions reductions that will occur under several scenarios, including various new equipment adoption-rates by construction firms, and innovation-rates by equipment manufacturers. We also discuss public policies that affect equipment adoption decisions by construction firms, as well as policies that affect research and development (R&D) decisions by equipment manufacturers, and their possible impact on GHG emissions.

We emphasize that although our measurement of emissions is focused just on specific subsectors of the US construction industry, innovations in equipment manufacturing can have positive repercussions well beyond the US construction industry. As these innovations spread, GHG emissions in the rest of the world will fall as construction firms there adopt the cleaner equipment. Also, in industries like agriculture and mining, which use equipment with similar characteristics, innovations in construction equipment manufacturing could lead to emissions-reducing innovations there as well. Hoy et al. (2014) discuss advanced vehicle technology in the agricultural equipment industry, though they focused on alternative fuels and other innovations, not hybrid or electric equipment that is our focus.[13] Likewise, Hill et al. (2011) study the GHG reduction potential of a broad class of heavy-duty vehicles in the context of the European economy, but do not examine the off-road construction equipment that is our focus.[14] We do not attempt to quantify these cross-industry and international impacts, but simply note the public-good nature of new ideas is a major potential benefit of a policy focus on innovation.

The structure of this report is as follows. In the next chapter, we describe both the construction and equipment manufacturing industries, and then review hybrid and electric technologies in the construction equipment manufacturing industry. We turn in Chapter III to the issue of measuring GHG emissions in the construction industry. This chapter begins by reviewing methodologies for project-level and economy-wide inventories of GHG emissions from the construction sector. Building on previous approaches, we then present an improved methodology for economy-wide inventories that utilizes the most recent state-level energy consumption data, allowing us to document for the first time GHG emissions from construction both geographically (by state) and by industry (by construction subsectors). This modeling innovation proves to be useful in assessing electric equipment in particular, as emissions from electricity generation vary considerably across regions. Chapter IV combines the industry and technological facts from Chapter II, with the GHG emissions estimates from Chapter III, to present estimates of the emissions reductions likely to occur in construction from the adoption of clean technology and the resulting greening of the off-road equipment fleet. Though these estimates are subject to error both in the measurement of emissions and forecasts of future innovation and firm adoption, the goal is to provide best-guess estimates that are reasonable, and we conduct some sensitivity analysis as a way of quantifying the uncertainty surrounding these estimates. Innovation is by its nature impossible to predict, but projections based on history and an accurate picture of present conditions are indispensable. To provide some context for decision makers, we discuss in the conclusion (Chapter V) various policies that encourage greater use and faster development of electric and hybrid equipment, taking into account incentives facing both construction firms and equipment manufacturers. The policies we discuss include federal and state technology standards for off-road vehicles, fuel taxes, local and regional ordinances limiting emissions from construction sites, so-called “green procurement” practices, which reward the use of green equipment in government contracting, and directly subsidizing research and development of off-road clean technology.

Finally, as long-term trends point towards a greater focus on limiting GHG emissions around the world, it is critical that decision makers understand the full set of impacts that result from various policies, for climate change and GHG emissions, as well as for public health and other areas. For example, GHG emissions may indeed be lower in a certain type of hybrid equipment compared to new but traditional and older generation equipment, but certain criteria pollutants, such as nitrogen oxide and particulate matter, which have important consequences for public health, could actually be higher. We discuss a situation where this actually occurred later in the report.[15] Although there are nuances associated with this specific example, it highlights that while a single-minded focus on GHG reduction may make sense in terms of legislative compliance, ensuring that policies work for the well-being of society as a whole require a focus on social welfare broadly conceived. Although a comprehensive benefit-cost analysis is beyond the scope of this report, in the conclusion we offer some general thoughts on this important issue.

II. THE CONSTRUCTION AND EQUIPMENT MANUFACTURING INDUSTRIES

The purpose of this report is to examine the role of innovation in the equipment manufacturing industry (NAICS code 333120) in reducing emissions in the construction industry (NAICS code 23), and specifically for the subsector 237310 (highway, street, and bridge construction). We begin this chapter by providing descriptive background information from the Census Bureau based on standard definitions of these industries, after which we describe characteristics of modern clean technology construction equipment.

The Construction Sector

We begin with some definitions of the construction industry. NAICS defines the construction industry at three levels of aggregation. The most aggregate definition is the so-called "two-digit" designation of 23—construction. One level down, construction is broken into three "three-digit" subsectors: 236: Building; 237: Heavy and Civil Engineering Construction; and 238: Specialty and Trade Contractors. Finally, the Census defines 31 "six-digit" subsectors. Detailed statistics on the construction industry for 2012—the last year from which the detailed Census information is available—are found in the Appendix Tables A5 and A6. Table 24 presents data on number of firms, employment, and salary information for construction industries. Table 25 presents additional data for these industries, including relevant cost categories (such as materials, fuel and machinery), as well as the value of construction work, and variables indicating the importance of governmental versus private sector projects. Figure 2 below shows historical trends in employment in this industry from 2006-2017; as this figure makes apparent, the macroeconomic situation now in 2017 is better for construction than it was in 2012.

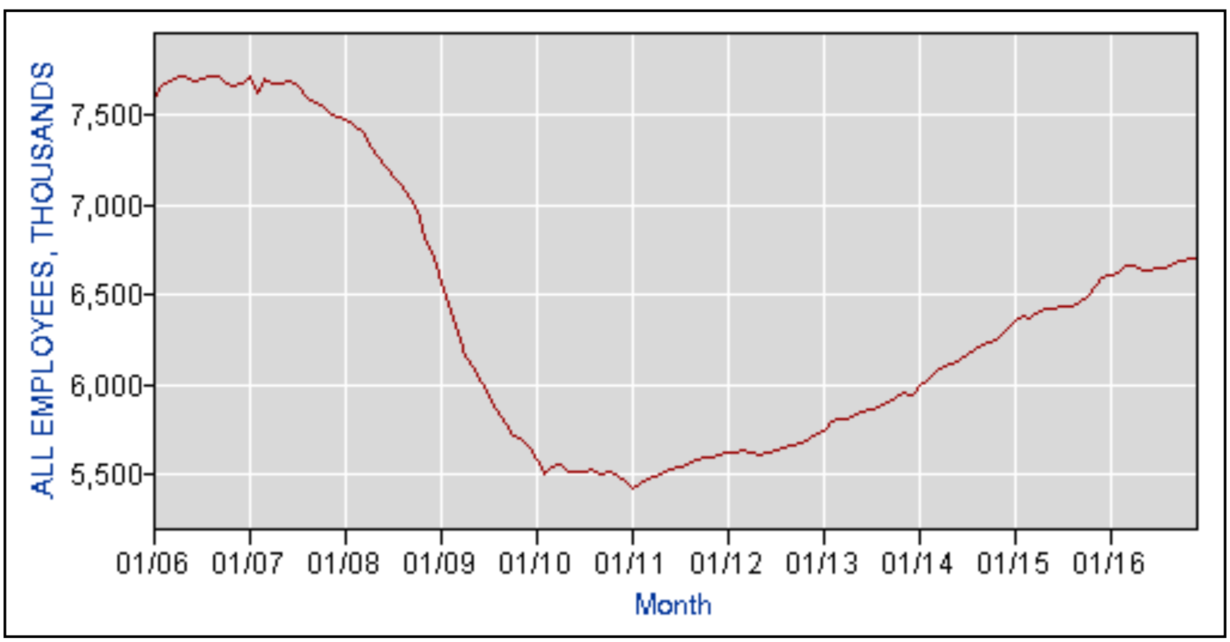

Figure 2. US Employment in Construction, 2006-2017

Source: Current Employment Statistics survey https://data.bls.gov/timeseries/CES2000000001?amp%253bdata_tool=XGtable&output_view=data&include_graphs=true

In 2012, nearly 600,000 construction firms employed 5.7 million workers. About 73% of these workers were construction laborers while other employees include managerial and administrative positions. These other positions, on average, pay $59,000 annually, versus $44,039 for laborers. The Economic Census provides a variable indicating the value of fringe benefits employees receive without differentiating between laborers and other employees; the average value of fringe benefits received by all workers and employees was $12,741 in 2012.

Looking across three-digit industries, both measured in terms of number of firms and employees, industry 238 (specialty trade contractors) is the largest of the three, followed by industry 236 (construction of buildings). Only about 17% of employees in construction jobs were in heavy and civil engineering (industry 237), though this industry pays both laborers and other employees better on average, whether measured by average wage or fringe benefits.

In terms of six-digit construction industries, Appendix Table 24 reveals large variation in employment in subsectors and, to a lesser extent, in compensation. Some of the highest employment is in specialty trade industries, including plumbing, heating and air-conditioning contractors (subsector 238220) and electrical contractors (subsector 238210). Among heavy and civil engineering subsectors, highway, street and bridge construction (industry 237310) is the largest employer, while among building construction subsectors, the largest employer is commercial and institutional building construction. Table 24 also reveals variation in compensation; other heavy and civil engineering construction workers were the highest paid, while framing and siding contractors the lowest.

Appendix Table 25 presents data on other relevant characteristics of these industries. The total value of construction work in the two-digit construction industry was $1.35 trillion in 2012. The majority of construction projects in 2012 were private sector projects, while 17.5% were state and local projects, and 4.6% federal. In terms of the three-digit industries, a large percentage of heavy and civil engineering projects were governmental; combined, federal, state and local governments accounted for 43.1% of projects in this industry, more than double the percentage of government projects in the other two three-digit industries. This is largely driven by the six-digit subsector “highway, street and bridge construction” where a full 71.9% were government projects. This important fact motivates our study in the conclusion of policies giving preferential treatment to construction firms using clean equipment.

It is also worth noting that the cost of materials and supplies was 16 times higher than the cost of power. Studying the role of green building materials is beyond the scope of this report, but this topic has received the attention of both the scholarly literature and government agencies.[16] Despite the potentially large emissions reductions possible through recycling building materials and other practices, our focus on off-road equipment is warranted by the fact that over $24 billion was spent in 2012 on power and fuels.[17] In the next chapter, we will use more detailed data on power and fuels, including breakdowns of fossil fuel and electricity consumption, as our primary source for estimating GHG emissions in these industries.

Table 25 also reveals some facts concerning the cost of equipment that is the focus of this report. Construction firms often lease heavy, off-road equipment like excavators and bulldozers. In 2012 across all subsectors, construction firms spent $13.668 billion on lease payments for equipment. Although the data does not break down construction firm spending on equipment specifically, it does indicate total capital expenditure (for many subsectors, it may be safe to assume that equipment compromises the largest share of capital expenditures) totaled $18.8 billion. Adding to this the cost of maintenance of $6.6 billion, the total amount spent on owning (buying and maintaining) equipment would appear to be no more than twice the amount spent on renting equipment (and given the maintenance expenditure is over both machinery and buildings, this figure would indeed appear to be an upper bound.) However, while the apparent preference for owning versus leasing equipment holds in most subsectors, this is not true in all; for example in industrial building construction (236210), equipment rental payments are more than the sum of capital expenditures and maintenance.

The Construction Equipment Manufacturing Sector

Turning now to a rather different industry, equipment manufacturing is represented by the three-digit NAICS code 333, "machinery manufacturing." It is further subdivided into 40 six-digit subsectors, including "farm machinery and equipment manufacturing" (333111), "construction machinery manufacturing" (333120) and "mining machinery and equipment" (333131). Although in terms of technology each of these subsectors share varying levels of similarities, we present data initially only from the 2012 Economic Census for Construction machinery manufacturing.

Table 1 reveals that the construction machinery manufacturing industry ships over $42 billion in products (and some services) annually. This compares with the approximately $18.8 billion in capital expenditures made by construction firms in 2012 (Appendix Table 25). These statistics may suggest that US construction firms purchase about half the output of US construction equipment manufacturing firms, but, of course, in reality construction firms are buying equipment from US and international equipment manufacturers, and US manufacturers are selling equipment around the world as well, so the statement doesn't hold true as a literal description of exchange between these two domestic industries.

Table 1. Data for Construction Machinery Manufacturing Industry for 2012 (NAICS code 333120)

Statistic	Value
Number of companies	696
Number of establishments	781
Establishments with 0 to 19 employees	410
Establishments with 20 to 99 employees	261
Establishments with 100 employees or more	110
Number of employees	62,302
Average annual salary	$54,504
Average value of fringe benefits	$19,289
Value of shipments and receipts (in thousands)	$42,193,450

Source: EC1231SG1 Manufacturing: Summary Series: General Summary: Detailed Statistics by Subsectors and Industries: 2012.

Overall employment in the US construction equipment manufacturing industry equals 62,302 full-time workers, roughly one-tenth the size of the construction industry, with an average salary of $54,504, which is comparable with wages in construction. There are over 100 establishments with over 100 employees, indicating on the face of it at least, a lightly concentrated industry in competitive terms.

Measurement of competition is most commonly in terms of concentration ratios (CRs). Concentration is the term used by industrial organization economists to describe the structure of an industry. On one level "structure" simply refers to the number of firms in an industry. The number of firms in an industry is also considered to be an important determinant of the level of competitiveness and also innovation, though theory and empirical findings so far do not point to any commonly agreed upon consistent relationships—both competitive and monopolized industries can exhibit innovation of varying types.

In Table 2 we show CRs for the subsectors of the four-digit sub-industry "Agriculture, construction, and mining machinery manufacturing" (3331). This subs-industry is itself divided into three, five-digit subsectors: "Agricultural implement manufacturing" (33311), "Construction machinery manufacturing" (33312), and "Mining and oil and gas field manufacturing" (33313). Although until now we have been referring to construction machinery manufacturing by its six-digit NAICS code 333120, in fact this sector is not divided any further than the five-digit level.[18] In other words, the subsector 333120 is identical to the subsector 33312, though the same is not true for 33311 and 33313.

In Table 2, we see that the three-digit machinery manufacturing industry (NAICS 333) is not very concentrated according to a four-firm concentration ratio of 15%. Table 2 also includes the concentration ratios of the top 8, 20, and 50 companies. A similar conclusion is reached when referencing the Herfindahl-Hirschman Index(HHI) with a measurement of 90.9.[19] Looking at subsectors, the agricultural and construction subsectors are similar in terms of the four firm concentration ratios and HHIs.

Table 2. Measures of Concentration for Machinery Manufacturing Industry and Select Subsectors

Manufacturing type:		Machinery	Agricultural implements	Construction machinery	Mining / oil / gas field
NAICS code		333	33311	33312	33313
Number of companies		*21,831*	*1,185*	*696*	*849*
Value of shipments ($1,000)		402,177,024	42,276,419	42,193,450	32,734,395
% share of value of shipments from X largest companies	4	15	55.6	58.6	31.1
	8	19.8	64.2	70.3	42.5
	20	28.8	74.3	81.7	59.8
	50	40.1	84	89.7	73.9
Herfindahl-Hirschman index (HHI)*		90.9	1,456.0	1,376.0	335.3

Source: Economic Census 2012, Manufacturing: Subject Series: Concentration Ratios: Share of Value of Shipments. (EC1231SR2)

* Among 50 largest companies; see footnote 19 for additional details.

Moving now from the domestic US market to the global market, the "Yellow Table" published annually in *International Construction* provides a valuable source of information on the global industry. It reports revenue figures for the largest 50 firms. Table 3 below reports select data on select variables from the Yellow Table[20] for the largest 20 global firms. Five US firms are included in this list, including the global sales leader Caterpillar, Terex, John Deere, Oshkosh Access Equipment, and Manitowoc Crane Group. In 2015 revenue for these 50 firms totaled $159 billion.

Although the Yellow Table only reports figures for the largest 50 companies, when compared to other measures of total revenue of construction equipment industry, the Yellow Table appears to capture the large majority of international sales. An article from Statista reported industry-wide revenues in 2015 of $171 billion.[21] The Yellow Table recorded $159 billion in total revenue for the top 50 companies, capturing 92% of the total revenue. However, Statista indicated this was up from the 2014 figure of $161 billion, while Yellow Table indicated revenue had fallen 2.6% from 2014 to 2015. Statista indicates market size continued to increase through 2016 and was projected to increase further in 2017, from $181 billion to $192 billion, respectively.

The Yellow Table also indicates which of the following products are produced by each firm: backhoe loaders, mini excavators, skid-steer loaders, powered access, telescopic handlers, cranes, concrete equipment, dozers/crawler loaders, compaction/road building, graders, excavators (13t+), wheeled loaders, articulated dump trucks (ADTs), rigid haulers, drilling/foundations, breakers and attachments, crushing and screening.

Table 3. Global Construction Equipment Manufacturing Industry, 2015

Rank	Company	Country	Revenue ($ million)
1	Caterpillar	US	28,283
2	Komatsu	Japan	16,877
3	Hitachi Construction Machinery	Japan	7,790
4	Volvo Construction Equipment	Sweden	7,785
5	Terex	US	7,309
6	Liebherr	Germany	7,129
7	John Deere	US	6,581
8	XCMG	China	6,151
9	Sany	China	5,424
10	Doosan Infracore	Korea	5,414
11	Zoomlion	China	4,376
12	JCB	UK	4,117
13	Kobelco Construction Machinery	Japan	3,689
14	Metso	Finland	3,550
15	Oshkosh Access Equipment (JLG)	US	3,507
16	CNH Industrial	Italy	3,346
17	Hyundai Heavy Industries	Korea	2,711
18	Wirtgen Group	Germany	2,666
19	Manitowoc Crane Group	US	2,305
20	Atlas Copco Construction Technique	Sweden	2,171

Source: Access International May-June 2013 p. 14.[22]

The Development and Use of Electric and Hybrid Off-Road Construction Equipment

Having presented basic background information on the relevant industries, we now turn our focus to the evolution of specific technologies in equipment manufacturing. This subsection describes the current state of technology in terms of functionality and especially fuel consumption, as fuel use is directly tied to carbon emissions, and to a lesser extent investment and maintenance costs, and impacts on local public health. Equipment manufacturers develop new products and technologies in response to numerous factors. In Chapter V, we discuss direct regulation of technology in terms of emissions standards for new equipment (which targets manufacturers) and other policies that provide incentives to manufacturers by targeting construction firms. Some types of regulation impact construction firm equipment fleet decisions, while other actions, such as government contracting practices, or other factors like fuel taxes, have a direct impact on construction firms, which in turn can indirectly impact equipment manufacturers' research and development decisions.

Whereas on-road regulations (for example concerning automobiles) have targeted both criteria pollutants and fuel consumption, non-road diesel regulations on both equipment manufacturers and construction firms have so far only targeted criteria pollutants. Emissions from non-road diesel equipment contain carbon monoxide (CO), nitrogen oxides (NO_x), non-methane hydrocarbons (NMHC) and particulate matter (PM). The U.S. Environmental Protection Agency (EPA) began to regulate diesel exhaust emissions from new non-road diesel engines in the mid-1990s.[23] Tier 1 standards were set in 1994. Subsequently, non-road diesel emissions have fallen dramatically—the Final Rule for Tier 4 standards, which were phased in over the 2008-2014 period, notes "We estimate particulate matter reductions of 95 percent, nitrogen oxides reductions of 90 percent, and the virtual elimination of sulfur oxides from non-road engines meeting the new standards."[24]

Below we present some estimates of the reduction in fuel consumption enabled by new technologies; these reductions are nowhere near the magnitude of the reductions in criteria pollutants, but the new hybrid technologies do enable fuel reductions on the order of 20-30% compared to conventional diesel equipment. It is important to note that conventional diesel equipment has, in some cases, also improved substantially in terms of fuel economy compared to pre-regulation model years. A growing demand for more cost effective construction equipment in the construction machinery market, along with growing regulatory pressure for reducing greenhouse gas and other emissions from government are two driving forces leading construction equipment manufacturers to develop electric and hybrid technologies.[25] This subsection first addresses hybrid technologies, which have been commercially available for several years already, followed by a description of electric equipment in general and battery-powered electric equipment in particular.

A summary of evolution of hybrid loaders and excavators is given in the article titled, "A comprehensive overview of hybrid construction machinery."[26] Komatsu initiated hybrid construction machinery research in 1997. Since then heavy hybrid construction equipment technologies have improved significantly. The first hybrid loader was developed by Hitachi in 2003 and Komatsu developed the first commercial hybrid excavator in 2008.[27] We also profile a hybrid dozer manufactured by Caterpillar, and a battery powered mini-excavator produced by Takeuchi.

Today, more than a dozen examples of hybrid construction equipment are commercially available; a 2015 report by JP Morgan describes the differences between the types of hybrid equipment currently available, and lists the eleven models reproduced in Table 4 below.

Table 4. Manufacturers by Hybrid Construction Equipment Type

Hybrid Equipment Type	Manufacturer and Equipment
Crawler Dozer	Caterpillar Model D7E
Electric-Heated Asphalt Screed	LeeBoy Model 9000 Caterpillar Model AS4252C
Excavator	Hitachi Model ZH210 Komatsu Model HB215LC-1 Caterpillar Model 336E H
Mini-Excavator	Terex Model TC16
Telescopic Material Handler	Merlo Model 40,7
Vibratory Roller	Bomag Model BW 174 AP AM
Wheel Loader	Volvo Model L220F John Deere Model 644K

Source: JPMorgan 2015.

In the construction industry, the term "hybrid" is defined as "any equipment type that has two power sources, or equipment that can collect, store and reuse energy. Hydraulic and electrical regenerative energy systems are used in hybrid construction equipment. These energy systems can be used separately or together to reduce the load on hydraulic pumps and to generate electricity to run pumps, motors and other electrical systems."[28] The article by JP Morgan describes the various types of hybrid technology, and we summarize this discussion in Table 5 below.

Table 5. Four Types of Heavy Construction Hybrid Technology

Category	Example	Description
Hydraulic Hybrids	Caterpillar 336E H Excavator	Use hydraulic regenerative braking converting kinetic energy into hydraulic energy and storing the pressure to be used during an energy-saving mode, which reduces energy and fuel costs.
Electric Hybrids	Komatsu HB215LC-1 Hybrid Excavator	Use an electric motor acting as a generator when the swing arm is slowed or stopped. During the braking process, the motor is reversed, which allows the motor to generate electricity. This electrical energy is then stored in a battery or capacitor and later released to help the swing arm's acceleration.
Diesel-Electric Hybrids	Caterpillar D7E Crawler Dozer	Convert mechanical energy into electrical energy eliminating the need for traditional torque converters, transmissions and drive trains for generators and drive motors. The diesel engine powers a generator, which in turn produces electrical energy to power the drive motors, hydraulic pumps and other electrical operating systems. Diesel-electric hybrid technology is being used in crawler dozers, wheel loaders and asphalt pavers.

Electric-Heated Screeds	LeeBoy Model 9000	Used with hot-mix asphalt to comply with the 2014 EPA regulations. Screeds are metal plates used to flatten and smooth recently laid asphalt mix. The paver's screed is heated in order to keep the hot-mix material pliable and deliver a better and smoother finish.

Source: JP Morgan 2015.

Construction machinery manufacturers have studied fuel consumption of hybrid equipment in comparison to similar conventional equipment. The majority of manufacturers reported fuel savings of 25% or more in comparison to similar conventional equipment.

Fuel savings of hybrid equipment for various manufacturers reported in research papers and a magazine article has been integrated into Table 6. Many of these estimates come from manufacturer's field tests. For example, in "Comparison of Fuel Consumption for Komatsu Hybrid Excavator," Inoue (2008) reports that the fuel use of a PC200-8 hybrid is 25% less than the non-hybrid model under average use, while case studies from three companies reveal reductions of 30, 31, and 41% respectively.

Table 6. Hybrid Equipment Fuel Savings by Manufacturers

Manufacturers & Equipment	Fuel Savings
Caterpillar 336E H Excavator	33%
Komatsu HB215LC-1 Excavator	40%
New Holland Excavator	40%
Hitachi Excavator	25%
Komatsu Excavator	25% - 41%
Doosan Excavator	8% - 24%
Hyundai Excavator	25%
Hitachi Loader	25% - 30%
John Deere 644K Loader	25%
Joy Global Loader	45%
Volvo Loader	10%
Caterpillar D7E Dozer	10% - 30%

Sources: [29,30,31]

Firms selling the equipment calculated the estimates reported in Table 6 above. A few studies by academic researchers have examined fuel consumption and emissions from traditional and hybrid technology. Regarding traditional technology, a recent article by Lewis and Rasdorf[32] presents average fuel use figures of 0.11 L/kWh for pre-regulation (Tier 0) equipment, falling to 0.09 and 0.08 L/kWh for equipment meeting Tier 1 and 2 emission standards, respectively. For Tier 3 and beyond, little academic research exists, though below we discuss recent research by UC Riverside that examined fuel use of hybrid and new conventional diesel equipment, and found results that are largely in line with the estimates in Table 6 above. For other fuel use rates, we directly consulted the industry technical specifications. For example, the Caterpillar Performance Handbooks list fuel factors for excavators, dozers, and loaders (see Figure 3 below). Tables 21-23 in the Appendix list these figures, which are an important input in the method developed in Chapter IV of this report.

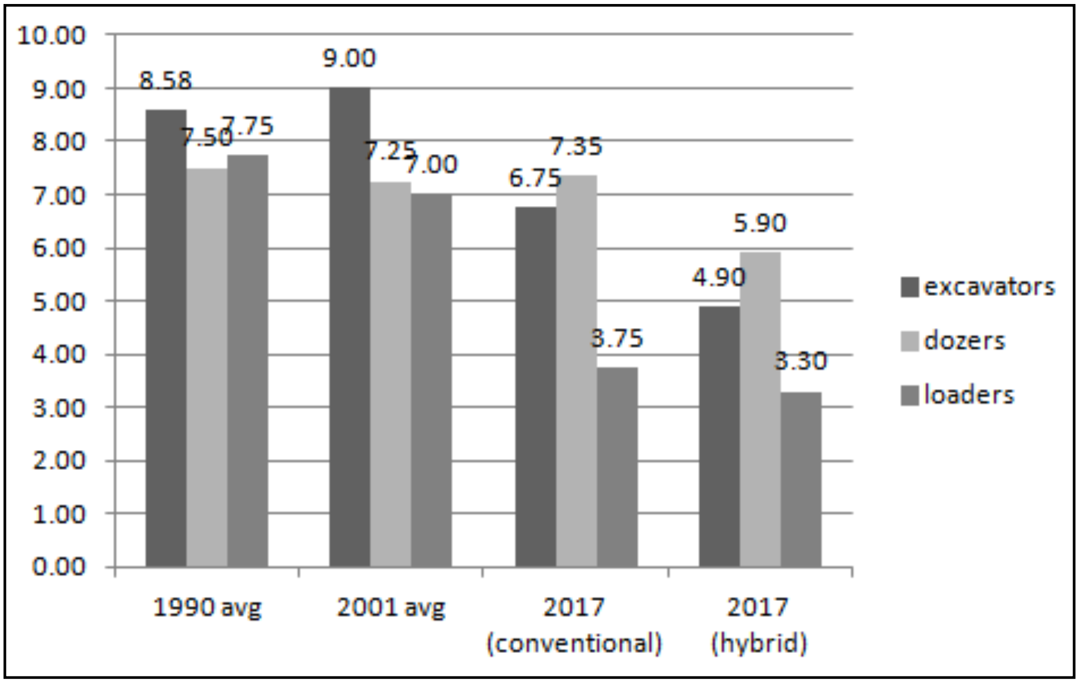

Figure 3. Fuel Use Factors for Comparable Caterpillar Models, 1990-2017 (Ave. Fuel Cons. (Gal/Hr))

Source: Caterpillar Performance Handbooks.

Recently, researchers at UC Riverside's Bourns College of Engineering Center for Environmental Research and Technology (CE-CERT) compared hybrid diesel construction equipment with newly improved conventional diesel equipment and compared emissions and fuel use under comparable tasks.[33] In this study, hybrid Caterpillar D7E bulldozers were tested and their field performance was compared with Caterpillar D6T dozers, the most similar non-hybrid dozers, in six sites in four California counties—Riverside, San Diego, Orange and Sacramento—under various distance and loading conditions. In the same way, hybrid Komatsu HB215LC-1 excavators were tested and compared with Komatsu PC200 excavators.

The researchers found that hybrid construction vehicles showed a significant reduction in fuel consumption and greenhouse gas emissions compared to the conventional diesel equipment that served as the control group. Fuel savings ranged from 7 to 28% for hybrid dozers and -1 to 28% for hybrid excavators. It is significant considering the fact that hybrid diesel construction equipment and new conventional diesel construction equipment are already much cleaner than old diesel equipment. The use-weighted average fuel savings is shown in Table 7.

Table 7. Comparing Fuel Usage and NO_x Emissions in the UC Riverside Experiment

Category	Equipment	Oxides of Nitrogen (NO_x)	Fuel Consumption
Dozer	New Conventional Caterpillar D6T	100%	100%
	Hybrid Caterpillar D7E	113%	86%
Excavator	New Conventional Komatsu PC200	100%	100%
	Hybrid Komatsu HB215LC-1	101%	84%

Source: UCR Today 2013.
Notes: Percentages for hybrid equipment are in reference to the emissions from the baseline conventional equipment, which is normalized to 100.

In addition to documenting fuel use reductions similar to industry claims, the researchers also found an increase of harmful emissions such as oxides of nitrogen (NO and NO_2) with an average of 13% for hybrid dozers and 1% for hybrid excavators compared to new conventional diesel machines as shown in Table 7. The actual ranges of oxides of nitrogen emissions (NO_x) were -2 to 21% for hybrid dozers and -18 to 11% for hybrid excavators.

However, it was also reported that these were different findings from those of the manufacturers. Nealon stated that manufacturers reported fuel consumption savings and greenhouse gas emission reduction by 20% for the hybrid dozers and excavators. The reason may be that in this study the researchers compared the hybrid dozers and excavators with newly improved conventional diesel machines emitting much less emissions than older diesel machines.

As Egelja insisted that hybrid excavators should be commercially viable and profitable for the customers, it is important for the manufacturers to focus on getting the best fuel economy for customers.[34] Based on an expert's interview, it is also reported that this might be the reason for increased NO_x using the first-generation hybrid technology. Although the increase of NO_x is a critical issue, researchers concluded that this issue can be resolved easily with minor modifications for the next generation hybrid equipment as follows:

- Caterpillar D7E hybrid bulldozer: "The hybrid bulldozer NO_x dis-benefit (compared to D6T bulldozer) appears to be real where a slight change in engine control module (ECM) calibration could eliminate this affect. Based on the power vs. engine speed analysis, it appears the engine is operating in an area of higher NO_x. If the engine manufacturer tuned the engine to lower NO_x in the rpm range where the engine tends to operate during in-use operation they might obtain a NO_x benefit instead of a dis-benefit."[35]

- Komatsu HB215LC-1 hybrid excavator: "Possible ECM timing improvements to reduce the hybrid excavator NO_x emissions to have a more consistent hybrid benefit for all modes. By changing the ECM fuel injection timing one can reduce NO_x emissions. This may be part of the reason for the slightly higher NO_x emissions due to the different operating location with-in the engine map. Slight ECM calibrations may be necessary to prevent a NO_x dis-benefit."

Nealon also concluded that the CE-CERT researchers expect, “as the technology continues to mature that emissions performance will improve, much as it has with hybrid cars and light trucks.”

The CE-CERT researchers emphasized the importance of “significant deployment of next generation hybrid and zero-emission technologies” because it is also necessary for California to meet the “health-based federal eight-hour ozone standard.” The researchers also recommended that hybrid technology in the construction machine industry should significantly be improved to make cleaner construction equipment.

Although there is significant fuel cost savings for hybrid equipment, several factors have limited the success of these products in the heavy construction equipment market. One of the major constraints is cost. Typically, the initial purchase price of hybrid excavators is approximately 20%–50% higher compared to conventional excavators. Compared with traditional construction machinery, hybrid equipment requires an additional energy storage device which requires extra storage space. So, the equipment is larger and takes up more room. The energy storage technology is still in the early stages of development.[36] Lin et al. (2010) also reported some operators experienced excess noise and vibration with hybrid systems.

The listed price of Caterpillar D7E, the world’s first hybrid dozer, was $600,000. This was about $100,000 (approximately 20%) more than an equivalent non-hybrid bulldozer, the conventional Caterpillar D7R. However, according to Caterpillar Inc. managers, it is reported that it will take about two and a half years before the fuel expenditure savings exceeds the purchase price premium.[37]

A case study about fuel savings for an Arkansas landfill was performed and a Caterpillar D7E was used primarily for spreading and compacting waste at the Northeast Arkansas Solid Waste District Landfill. According to the landfill operations manager, “the D7E consumes approximately 40 gallons of fuel per day less than the machine that it replaced. At $3.50 per gallon of diesel fuel, the Northeast Arkansas Solid Waste District landfill is saving $140 in fuel costs every day the D7E works. With a targeted service life of 20,000 hours, the D7E could reap more than $300,000 in fuel savings for the district.”[38]

Caterpillar’s first hybrid excavator, 336E H uses a new hydraulic hybrid technology reducing fuel consumption up to 33% compared with CAT 330/336D conventional excavators. In addition to fuel savings, customers are interested in their return on investment on hybrid equipment. Based on Caterpillar’s estimate, “customers can realistically expect to see a return on their investment for the hybrid excavator model in as little as one year.”[39] Although fuel prices have a direct impact on the customer’s return on investment period, this is critical information encouraging more customers to buy the hybrid excavators. There are more performance criteria such as durability, reliability, validation, and product support and the performance of CAT 336E H hybrid excavator was better than the conventional excavators as shown in Table 8.

Table 8. CAT 336E H Hybrid Excavator Performance Criteria

Performance Criteria	Performance/Support of CAT 336E H Excavator
Fuel Savings	The 336E H saves up to 25% fuel compared to a standard 336E, and up to 33% fuel than the 330/336D.
Return on Hybrid Investment	Assuming today's fuel prices and a high-production application for a 336E H, Caterpillar estimates customers can realistically expect to see a return on their investment for the hybrid excavator model in as little as one year.
Durablity and Reliability	Caterpillar designed the 336E H to deliver the same durability and reliability customers expect of all Cat machines, including large excavators like the standard 336E.
Validation	In a formal production study completed in August 2012, results were impressive, including greater fuel efficiency, and lower cab and spectator noise levels than the 336E and 336D.
Product Support and Dealer Readiness	Customer support for the 336E H is provided exclusively by the on-the-ground support of Caterpillar's worldwide dealer network. The 336E H can also be bundled with extended warranties and service contracts.

Source: Caterpillar 2012.

Turning now to electric equipment, we begin by describing this segment of the equipment market, which is presently very small but is projected, at least by some sources, to grow quickly. Electric equipment (and hybrid equipment too, for that matter) is not new and has in fact been around for decades, but the difficulty of powering this equipment with grid power using lines has meant the technology historically has only been used in select applications.

The recent development of battery power may mean that all-electric, battery-powered equipment will someday compete with today's diesel models. Innovation in the electric vehicle market is the topic of several recent IDTechEx reports. One titled "Industrial and Commercial Electric Vehicles on Land 2017-2027" revealed that "the industrial and commercial sector represents 60% of the value of the electric vehicle market as a whole, and this sector is set to grow 4.5 times in the next decade."[40] This report forecasts over $15 billion of hybrid and pure electric construction vehicles being sold in 2027, more than today's combined sales by number two and three in the conventional construction machine business today. Another report by the same organization titled "Electric vehicles in construction are the future" noted that although currently buses are the largest part of the electric vehicle value market (due in significant part to their popularity in China), electric vehicles in other industrial applications, sectors such as construction, mining and agriculture, are indeed gradually becoming large sectors.[41]

Construction contractors use electric construction equipment for various construction activities such as excavating, loading, hauling, and dumping. During this process, "…such machines are increasingly used in urban environments with associated legislative and market pressure for no carbon dioxide, acid gas or particulate emissions, better performance and near silent working including indoors. The machine typically made for outdoors is appearing with an indoor and night time option at the flick of a switch" (Harrop, 2016). Currently the mini excavator market is approximately $5 billion globally and the majority of compact construction vehicles may be EVs, hybrid or pure electric in 2025 based on the IDTechEx forecast.

In some areas, obtaining sufficient diesel fuel is impossible. Electrically driven heavy hydraulic excavators are ideal when cheap electricity is readily available but they require an electricity supply cable and cannot be used in locations where no power supply is available. Although there is the critical problem of power supply, large electrically driven hydraulic excavators are very attractive for mine excavation when the required electricity supply infrastructure is ready.[42] The electrically driven heavy hydraulic excavator has many advantages compared to the conventional diesel engine machines (Yamamoto et al. 2009):

- Fuel consumption is approximately one-fifth of diesel engine excavators
- Maintenance cost savings of 20 to 30%
- No exhaust emissions
- No leaks of fuel or engine oil
- Lower noise

Although electric and hybrid technologies are leading technologies to reduce GHG emissions and save fuel energy in the construction machinery industry, current electric vehicle technology has many limitations and needs to be improved significantly to be applied directly in heavy construction machinery.

Despite these limitations, we conclude this chapter with information on commercially available, battery-powered excavator and wheel loader. Although for hybrid equipment we found more than a dozen examples, we present only two case studies given the fact that this technology is still in its infancy. Harrop (2016) summarized the electric equipment market as follows, “For light duty there are small wheel loaders and even small excavators that are pure electric.”[43] We have found examples of both. Below we describe a Takeuchi excavator and a Wacker Neuson wheel loader.

Wacker Neuson focuses on building zero emission compact equipment known as its ‘E’ lineup producing electric rammers, dumpers, mini excavators, and wheel loaders.[44] Kramer 5055e is the largest battery-powered wheel loader most recently developed with two lead acid battery-driven electric motors. This machine can work up to five hours on a charge and is designed for various work such as urban areas or indoor construction sites requiring minimum emissions and noise. Wacker Neuson also produces the WL20e electric wheel loader similar to the Kramer 5055e. In addition, the battery powered DT10e damper and AS30e rammer are available. However, no sales figures and research data were available that would allow calculating a potential GHG emission reduction.

Takeuchi, which claims the title of introducing the world’s first fully electric hydraulic excavator, has several products that demonstrate the technological feasibility of using battery-powered equipment in construction projects. The company’s first battery excavator, the Takeuchi TB117 “utilizes a lithium-ion battery that when fully charged can power the machine for up to six hours of uninterrupted service, and performance that is on par with the current TB016 (13.8 hp)."[45] They also produce an electric model that uses grid power.[46] Comparing energy use in a similar diesel unit versus the Takeuchi e210 battery-powered excavator, the operation cost of the similar diesel unit costs $6.03 per hour. However, Takeuchi e210 costs only $0.14 per hour considering the overnight recharging electricity cost of $0.054/kWh in the United States. This indicates that Takeuchi e210 electric excavator uses less than 3% of the energy compared to the diesel unit.

While both of these excavators are small, Takeuchi recently demonstrated the Takeuchi 240e in the US and is marketing a mid-size excavator as The Green Machine. Comparing energy use in a similar diesel unit versus Takeuchi e240, the operation cost of the similar diesel unit costs $9.61 per hour. However, Takeuchi e210 costs only $0.42 per hour. This indicates that even a mid-size electric excavator uses less than 5% of the energy compared to the diesel unit. These figures, like some others presented above, come from the manufacturer, but they are in line with the dramatic differences between diesel and electric found in the mining applications and described in Yamamoto et al. 2009.

Overall, the main takeaway of this review construction equipment technology suggests that hybrid equipment results in moderate improvements in reducing GHG emissions, compared to conventional equipment, while battery electric seems to hold the potential for much more dramatic reductions, with the caveat that much less research has been published on the nascent battery electric equipment technology.

III. MEASURING GHG EMISSIONS IN THE CONSTRUCTION INDUSTRY

This section reviews past attempts at estimating GHG emissions from the construction industry, and then presents a new methodology and estimates at the national level. Studies that estimate GHG emissions from the construction industry range from economy-wide inventories, which attempt to provide comprehensive figures for nations or states as a whole, to firm and project-level inventories, which measure the GHG emissions produced by a company, individual projects (which may involve one or multiple firms) or laboratory evaluations. We focus on economy-wide inventories and address these other studies in less detail. The new methodology we develop, and then use to present updated estimates, draws on previous research, but takes advantage of advances in data collection efforts to provide not only more recent estimates, but also estimates that account for geographic variation (at the state-level) and that also disaggregate the construction industry into sub-industries, which will allow us to comment on those industries where advances in equipment technology are most likely to impact emissions.

Review of Methods of Estimating GHG Emissions from the Construction Sector

Many governments around the world routinely monitor GHG emissions produced within their borders. The US ratified the U.N. Framework on Climate Change (UNFCC) in 1997. Although the UNFCC does not have any emission reduction requirements, it does require all participating countries to report GHG emissions emitted within their country (UNFCC, 2014). As a result, the US has produced a “Greenhouse Gas Inventory” since the 1990s. The US EPA publishes these estimates that currently range from 1990 to 2014 (EPA, 2016a).

Inventories like those produced by the US EPA do estimate emissions by sector, but unfortunately their definitions are not very suitable for our purposes. For example, the most recent inventory combines construction and mining off-road emissions, combines construction with personal and other transportation for on-road emissions, and presents emissions from industries producing inputs used by construction (e.g. asphalt, cement) separately as well.

A more useful source, for the purposes of this report, comes from the Energy Information Administration, which each year releases the Annual Energy Outlook (AEO). This publication presents projections and analysis for a host of energy related variables. The 2016 report presented estimates of energy consumption by fuel source for three construction sub-industries, defined by the NAICS codes of 236 (Building Construction), 237 (Civil Engineering) and 238 (Trade). These figures are reproduced in Table 9 below. The 2016 AEO also included projections of GHG emissions from construction. These GHG figures are not reproduced below, but approximately 70 MMTCO2E GHG emissions were recorded in 2014, and approximately 80 MMTCO2E GHG emissions are projected in 2020 and thereafter. Thus, this indicates that emissions across all construction industries are expected to rise until 2020 and then stabilize. These projections rely on numerous assumptions, including some related to the future course of technological development.[47]

Table 9. Energy Consumption in Construction (NAICS 233, 234 and 235), Units are Trillion Btu

Energy Types	2014	2015	2020	2025	2030	2035	2040
Distillate Fuel Oil	297.4	291.4	375.7	383.6	387.0	395.9	406.9
Propane	136.6	102.7	127.2	131.3	133.0	136.2	139.8
Asphalt and Road Oil	792.6	834.8	892.6	933.4	1,046.3	1,176.7	1,311.8
Other Petroleum	46.8	63.1	84.5	98.1	101.5	102.9	104.6
Natural Gas	16.5	16.2	19.7	19.3	18.9	18.7	18.7
Purchased Electricity	217.0	207.7	294.9	317.3	327.7	339.7	353.2
Total	1,506.9	1,515.8	1,794.5	1,883.0	2,014.3	2,170.1	2,335.0

Source: http://www.eia.gov/forecasts/aeo/data/browser/#/?id=43-AEO2016&region=0-0&cases=ref2016&start=2013&end=2040&f=Q&sourcekey=0

Although the AEO includes emissions from several sources, and at the industry level, a major drawback for our purposes is the complexity of the model. Some policy analysts outside of the IEA and its contractors have utilized various versions of NEMS, but doing so requires a significant upfront investment in obtaining and running the data and simulations.[48] We therefore now explore other previous attempts at measuring GHG emissions in the construction sector which can be more readily extended with new data.

An EPA (2008) report titled *Quantifying Greenhouse Gas Emissions in Key Industrial Sectors* examined emissions from construction and several other industrial sectors, using different methodologies for the various sectors. For the construction sector, their method involved gathering data on fuel and electricity purchases from the Bureau of Economic Analysis' Economic Census, dividing the amount of purchases by prevailing prices (from the IEA) to estimate fuel quantities, and then multiplying these quantities by appropriate emissions factors to arrive at GHG emissions figures for the industry. This method is straightforward, and includes emissions produced from the main types of energy purchased in the construction industry. It does not include other direct impacts of construction activities, such as employee commuting, nor does it include emissions from indirect sources such as those embodied in the production of construction materials used, such as concrete or asphalt. Also, although it treats the construction industry at a less aggregate level, it still combines all construction activities into one industry.

In 2009, the EPA published a report titled *Potential for reducing greenhouse gas emissions in the construction sector* (EPA, 2009). This report attempted to apply the same methodology as the 2008 study, but to examine construction emissions in more detail at the sub-industry level. We have examined both the 2008 and 2009 EPA publications in detail and have replicated their results to ensure we can correctly replicate these methodologies.[49] Because we will build upon these methodologies in the next part of this chapter, we now present the details underlying this method. We begin by presenting all the "inputs" and carefully documenting the source of each.

The first input is nationwide expenditures on fuel for the construction industry. These were reported in the 2008 EPA report (in Table 20 of that document.) The original source, as noted above, is the Economic Census. The second column of Table 10 below reproduces these expenditures. In order to arrive at estimates of the quantity of fuel consumed, expenditures are divided by prices, which are reproduced in the third column of Table 10; these fuel prices were originally taken from EPA (2008, p. 5-3) for electricity, and from EPA (2008, Table 5-2) for the other sources. Next, the quantity of fuel consumed is multiplied by an emissions factor to arrive at emissions. These emissions factors are shown in the fifth column of Table 10; the factor for electricity was taken from the EPA (2008) report (Table 22), and the factors for the other sources were taken from EPA (2008, p. 5-3).

Thus, the "inputs" in Table 10, columns 2-4, were all taken from the sections of the EPA report documented above. The last column in the table, Emissions (the "output") was calculated based on the method described in the EPA report. These calculations involve a few additional complications glossed over in the paragraph above (for example, emissions associated with electricity consumption are increased slightly to account for transmissions and distribution losses) but we show all equations used in these calculations in a spreadsheet file available online.[50]

Table 10. Inputs and Outputs of EPA Method

	Expenditures on Fuel ($1,000)	Fuel Prices*	Quantity of Fuel**	Emissions Factors	Emissions (MMTCO2E)
Purchased electricity	2,325,050	0.049	47,450,000,000	1.36	31.91
Natural gas	977,067	4,365,110	223.84	0.053	11.86
On-highway petrol	6,280,391	10,658,510	791.12	0.071	57.75
Off-highway petrol	2,682,388	6,324,590	424.12	0.073	30.11

* For electricity, units are ($/kWh); for other three units are ($/Tbtu).
** For electricity, units are Kw/hr; for the other three units are Tbtus.

As shown in the Table 10, the quantity of electricity (Qe) is multiplied by the emissions factor of 1.36. In fact, the emissions associated with electricity generation vary considerably across the country. The EPA method involves calculating a weighted factor based on the share of total industrial emissions in each region. We have independently verified the 1.36 by using the information in the EIA861 publication and following the method outlined in the EPA report.[51]

By utilizing the EPA 2008 method with the final version of the Economic Census data which includes fuel expenditures by subsector, the EPA 2009 study shares the same beneficial features as the 2008 study in terms of transparency and replicability, with the added benefit of being able to present emissions estimates at the subsector level. Both reports share the limitation of being not fully comprehensive; for example, neither include emissions from inputs like cement, asphalt, employee commenting, or other factors.

All of the methods for estimating GHG emissions from construction reviewed so far were economy-wide inventories. Project-level inventories have also been conducted and present an alternative method of quantifying GHG emissions from the construction industry.

Although we do not take a project-level approach in the original analysis presented in this report, this review is meant to highlight some of the attempts that have been made to measure all the carbon impacts associated with construction activities. Thus, these represent an alternative approach with virtues and limitations. We also incorporate some elements of the project-based methods later in Chapter IV of this report.

There are various construction sectors such as buildings, roads, dams, tunnels, bridges, etc. Regardless of these construction project types, the construction process typically includes many activities or processes such as site-preparation, excavation, backfilling, landscaping, finishing, installation of materials requiring equipment operation. Although there have been several tools that enable the quantification of GHGs from one or more of these processes, there is no comprehensive tool capable of quantifying emissions that encompass a complete source category (Melanta et al. 2013). Through the literature review, Melanta et al. (2013) identified the most advanced GHG emissions estimation models developed for use in the construction sector and summarized utility and limitations of each tool. NONROAD2008 and OFFROAD2007 are designed to support the quantification of emissions from individual processes observed on a construction site.

NONROAD and OFFROAD are also used in a way that is closer to economy-wide inventory models, for example, to measure the effect of regulation. They take a bottom up approach in representing detailed descriptions of the diesel equipment population. We incorporate some of these inputs in Chapter IV. Thus these models represent an alternative method for calculating the GHG reductions from hybrid and electric vehicles that would be low cost to implement within a government agency where staff has in-house expertise using these models. On the other hand, both the URBan EMISsions (URBEMIS) model and the Pavement Life-cycle Assessment tool for Environmental and Economic Effects(PaLATE) model incorporate emissions from various sources, but only for one category of construction.[52]

Melanta et al. (2013) also developed a carbon footprint estimation tool (CFET) for the estimation of GHG emissions and other air pollutants from transportation infrastructure construction projects taking "a comprehensive approach to provide all-inclusive project-level emission estimates that incorporate effects from all stages of the construction project, including offsets generated by reforestation efforts, and accounts for recent and future GHG policies." CFET helps to quantify emissions from "all major processes observed on a construction project such as site preparation, equipment usage, on-site materials production, and environmental impact mitigation efforts, with the goal of meeting federally mandated programs such as the National Clean Diesel Campaign (NCDC)."

CFET consists of four major processes in construction projects: 1) site preparation, 2) operation of construction equipment, 3) materials production, and 4) environmental impact mitigation. In each category, a set of input data was entered and calculated in terms of GHG emissions. Melanta et al. (2013) illustrated the emission profile of the equipment usage by equipment type. The emission profiles of cranes, off-highway trucks, backhoes, dozers, and excavators were significantly higher than any other equipment in this case study. Using this case study, Melanta et al. (2013) concluded that estimating emissions using CFET directly help identify the major source of emissions. Based on the identified emission sources, the user can better understand the selection of the construction processes and improve their equipment fleet mix to reduce GHG emissions. In addition, CFET can help contractors determine their baseline GHG emissions for various project types. Another benefit of CFET is that regardless of the project size, this tool can be used by various parties such as contractors, design/build firms, and state transportation agencies.

Mukherjee et al. (2013) contributed to develop “a method for calculating project-level construction emission metrics and illustration of the method with the observed project.” In response to the need for addressing global climate change challenge, they developed the Project Emission Estimator (PE-2), a web-based tool that implements the project-based life-cycle framework, to help reduce the CO_2 footprints of highway construction projects. The PE-2 web-based tool is designed for both state transportation agencies and contractors and they can also implement the PE-2 to benchmark the carbon dioxide (CO_2) footprint of highway construction projects such as reconstruction, rehabilitation, and capital preventive maintenance projects.[53] In this study, the US EPA’s current official model, Motor Vehicle Emission Simulator (MOVES) was also used for estimating equipment emissions. In order to develop comprehensive project inventories of material and equipment usage, data collected from 14 highway pavement construction, rehabilitation, and maintenance projects in Michigan were included in this web-based tool. The collected data were organized based on material and equipment categories. Then, an assessment tool was prepared to identify standards that help reduce GHG emissions during the life-cycle of pavements. Finally, the GHG emissions for each project were calculated.

An Updated Method for Estimating GHG Emissions from the Construction Industry

This subsection outlines some modifications of the methods used in EPA (2008) and EPA (2009). We then present new emissions estimates using the improved method, for the construction industry overall in 2012, as well as for subsectors.

The most important innovation in method presented here is to utilize state-level data rather than US aggregate data. In addition to variation in fuel expenditures by construction firms across states, fuel prices and factors for electricity emissions also vary from state to state. Appendix Tables A7-A11 present state-level data on fuel expenditures, fuel prices, implied quantities of energy consumption by the construction industry in each state, as well as electricity emissions rates for each state. Table 30 presents the emissions estimates for each state and the US as a whole.

Before presenting emissions from the construction industry for each state, we first perform a calculation using nation-wide expenditure totals, and nation-wide prices and emissions factors. We do this for several reasons. First, the calculations for each state are identical to those we will perform for the national level estimate; thus it will facilitate describing our method. Second, presenting a national-level estimate will shed light on the magnitude of the bias that results from using aggregate data rather than disaggregate state-level data.

Expenditures for the nationwide, two-digit construction industry for natural gas, on-highway fuel, off-highway fuel and purchased electricity were $845,906, $14,748,424, $4,942,786, and $2,697,686 respectively. These are measured in thousands of dollars and are reported on the last row of Appendix Table 26. To determine the quantity of each of these fuels consumed by this industry, we divide expenditures by prices. Data on national average prices is contained in Table 27 and is taken from the IEA's SEPER. We thus find quantities of natural gas, off-road fuel, on-road fuel[54] and purchased electricity, measured in BTUs, of 157,248,008, 546,960,245, 196,712,853 and 134,144,486, respectively. These figures represent a 15% share of total energy consumption from natural gas, a 53% share for on-road fuel, 19% for off-road fuel and 13% for purchased electricity.

The last step in estimating national GHG emissions from the construction industry involves multiplying these quantities by emissions factors. Factors for homes and businesses are taken from the EIA. They are measured in pounds of CO_2 per million BTUs and are equal to 161.3 for Diesel Fuel (Distillate), 117 for Natural Gas and 157.2 for Gasoline.[55] For electricity we use the eGRID factor of 1,136.5 lbs/mWh for electricity, and convert into 333.1 lbs/million BTU by using the site conversion factor.[56]

It is noteworthy that the emissions factor for electricity is more than twice that of the factor for all other fuels considered in this analysis. One reason for this is that electricity is a secondary fuel. The eGRID factor measures emissions per net electricity output. In other words, it accounts for the energy used in generating electricity, which is greater than the electricity produced.

The EPA (2008) method accounted for emissions produced in generating electricity, as well as electricity lost during transmissions and distribution (or T&D). To account for T&D losses, they increased the quantity of electricity consumed by 9%, and we follow the same approach here with respect to electricity. However, the EPA (2008) method did not account for the fact that energy is also used in transporting gas, diesel or natural gas. We therefore follow Glaeser and Kahn (2010) and increase quantities of these other fuels consumed by 7% before applying the emissions factor.

National emissions, measured in pounds of CO_2, equal 19.7 billion for natural gas, 92 billion for on-road fuel, 34 billion for off-road fuel, and 48.7 billion for electricity (Appendix Table 30). These sum to 194.34 billion pounds, or 88.15 million metric tons of CO_2 ($MMTCO_2$).[57]

Our estimate of 88.15 $MMTCO_2$ is less than reported in EPA (2008) which used Economic Census data from 2007. As shown in Table 10, the sum of emissions from each fuel source there was 131.63 $MMTCO_2$. The difference is largely accounted for by the fact that our estimates of all types of energy consumption were lower than in EPA (2008), where natural gas and on-highway fuel consumption was some 30% higher than here, off-road fuel consumption was 54% higher, and electricity consumption 17% higher.[58] As mentioned earlier, macroeconomic conditions were largely the cause of the lower spending (see Figure 2 and surrounding discussion of construction employment in 2007 versus 2012).

Emissions estimates for the 50 states are also presented in Table 30. These figures use state-specific fuel prices, and for electricity, state-specific emissions factors. State-level emissions sum to 87.3 $MMTCO_2$, which is very close to what we found in our aggregate analysis. However, this aggregation masks sometimes large differences in state-level estimates, and, as we will see in the next chapter, knowing the particular energy profiles of the individual states could lead to surprising conclusions regarding the GHG reduction effect of certain types of new equipment, especially all electric.

Table 30 also includes emissions per dollar value of construction work (value of construction work for the 50 states was presented in the previous section). Here we also see substantial variation. Although it is beyond the scope of the present analysis to explore the determinants of this variation, common sense suggests that in states where comparable construction projects are more expensive to build (whether due to local regulations or other factors) the denominator of the emissions per dollar statistic (i.e. emissions intensity) will be larger thus intensity lower. Although this measure of emissions intensity is imperfect for this reason, it is a useful summary measure and future research could apply statistical methods to uncover some relationships in the data we have presented here.

Having described our methodological approach, and presented emissions estimates for the construction industry broadly conceived (i.e. the two-digit NIACS industry 23), in the remainder of this section we present and discuss results concerning state-level emissions for the construction subsector “highway, street, and bridge construction.” We present national-level estimates for all subsectors in a spreadsheet file we have made available online, but going through one subsector in detail provides the opportunity to point out important caveats for interpreting the subsector results.[59] For example, missing data for some states means GHG estimates are not available for all states for this and other subsectors.

The results in Table 11 show state-level emissions from the highway, street and bridge subsector for all states except Delaware, Hawaii, Nevada, and W. Virginia due to missing data (the District of Columbia) is also omitted from the estimates in this table.) New Jersey has the lowest emissions per dollar of value added, followed by Rhode Island, Connecticut, California, and Massachusetts. Meanwhile, Alabama has the highest emissions per dollar of value, followed by Wyoming, Idaho, N. Dakota, and Montana. It should be kept in mind that this ratio is sensitive to differences not only in emission but also in the value of construction work. Why are emissions per dollar of output lower in some states than others? This is an interesting and important question, and answering it is beyond the scope of this study. However, the figures we present can be used in future research to determine, for example, whether some of the policies we discuss in the conclusion (such as the presence of a green contracting strategy in the State’s DOT) may have a causal effect on lowering emissions from highway construction.

Table 11. Highway, Street, and Bridge Construction: Emissions in lbs

State	Natural gas emissions (lbs/MillionBTU)	On-highway emissions	Off-highway emissions	Electricity emissions	Total emissions	Value of construction work ($1,000)	e/$ ($1,000)
Alabama	268,544,250	158,958,952	132,027,481	101,781,327	661,312,011	1,166,959	566.7
Alaska	21,145,954	65,999,279	86,371,811	6,854,485	180,371,530	784,454	229.9
Arizona	7,431,774	143,920,984	87,583,094	40,212,626	279,148,478	1,582,921	176.4
Arkansas	20,898,014	51,787,689	49,854,183	37,497,586	160,037,473	534,869	299.2
California	115,170,376	424,509,297	424,820,513	89,601,405	1,054,101,592	8,295,408	127.1
Colorado	88,911,823	194,765,528	182,413,366	82,437,599	548,528,316	1,619,164	338.8
Connecticut	3,246,750	49,608,300	29,361,643	4,861,762	87,078,455	751,819	115.8
Delaware						277,649	
DC						330,246	
Florida	171,013,572	528,843,053	395,812,356	178,111,447	1,273,780,428	4,332,603	294.0
Georgia	122,592,238	253,303,848	136,505,063	121,897,261	634,298,410	2,096,774	302.5
Hawaii		12,125,305	12,267,363			394,953	
Idaho	109,075,117	85,811,155	53,111,173	11,104,071	259,101,516	508,098	509.9
Illinois	188,413,194	246,910,896	166,483,613	208,988,313	810,796,016	4,536,183	178.7
Indiana	306,981,426	189,483,821	173,263,342	114,697,893	784,426,483	2,447,815	320.5
Iowa	92,165,741	223,723,258	232,797,794	123,159,764	671,846,557	2,107,090	318.9
Kansas	147,503,658	181,868,798	205,107,361	63,724,260	598,204,077	1,863,109	321.1
Kentucky	100,152,000	110,461,496	90,669,614	100,109,566	401,392,676	1,285,985	312.1
Louisiana	133,936,151	127,935,111	110,277,166	97,385,401	469,533,829	1,954,584	240.2
Maine	373,330	51,968,515	45,012,009	3,667,785	101,021,640	243,388	415.1
Maryland	11,448,723	168,066,461	76,692,378	47,061,049	303,268,610	1,545,976	196.2
Massachusetts	12,848,447	138,001,624	68,045,283	25,102,623	243,997,978	1,769,553	137.9
Michigan	113,326,264	148,688,932	125,574,363	58,174,560	445,764,120	1,644,892	271.0
Minnesota	124,763,216	393,440,764	335,329,053	123,438,340	976,971,373	3,367,879	290.1
Mississippi	28,730,843	118,524,548	138,017,371	45,952,737	331,225,500	1,168,381	283.5
Missouri	18,468,309	122,389,231	145,033,005	89,309,998	375,200,542	1,697,683	221.0
Montana	18,217,186	143,842,769	89,384,425	21,574,323	273,018,704	628,800	434.2
Nebraska	15,869,155	79,778,534	69,452,036	20,923,367	186,023,092	765,695	242.9

State	Natural gas emissions (lbs/MillionBTU)	On-highway emissions	Off-highway emissions	Electricity emissions	Total emissions	Value of construction work ($1,000)	e/$ ($1,000)
Nevada		102,593,159	132,807,876			910,980	
New Hampshire	3,342,511	92,437,294	59,063,023	11,405,460	166,248,288	434,425	382.7
New Jersey	16,833,642	159,008,681	161,617,283	38,801,654	376,261,260	3,831,223	98.2
New Mexico	38,004,107	91,551,632	62,568,646	18,085,944	210,210,329	651,329	322.7
New York	28,121,037	312,771,388	253,600,244	92,277,493	686,770,163	4,936,513	139.1
N. Carolina	100,451,021	258,819,033	354,172,852	118,304,497	831,747,403	2,598,018	320.1
N. Dakota	140,058,171	104,766,363	106,546,360	26,533,154	377,904,049	761,519	496.3
Ohio	176,234,451	274,568,478	245,374,935	243,405,964	939,583,828	3,688,054	254.8
Oklahoma	48,217,579	132,548,089	99,200,271	105,074,333	385,040,273	1,235,294	311.7
Oregon	35,964,862	120,538,967	46,721,173	20,007,152	223,232,154	923,967	241.6
Pennsylvania	17,142,029	342,794,567	173,883,052	163,640,305	697,459,954	4,610,531	151.3
Rhode Island	2,796,658	23,308,137	4,779,861	1,543,458	32,428,114	284,417	114.0
S. Carolina	53,546,908	68,514,711	71,934,665	94,466,600	288,462,883	816,797	353.2
S. Dakota	9,294,409	45,611,682	20,798,010	15,735,137	91,439,239	468,469	195.2
Tennessee	141,076,534	151,878,967	145,422,530	186,227,441	624,605,472	1,936,205	322.6
Texas	134,770,867	746,602,477	798,789,951	345,207,693	2,025,370,989	9,261,235	218.7
Utah	9,228,929	120,577,836	107,183,088	18,240,233	255,230,086	1,018,686	250.5
Vermont	2,928,876	11,660,114	7,029,709	794,202	22,412,901	71,973	311.4
Virginia	144,887,213	287,458,503	135,417,018	201,072,448	768,835,182	3,441,474	223.4
Washington	33,148,901	250,541,706	184,739,975	93,544,724	561,975,305	2,559,800	219.5
W. Virginia		56,653,325	52,450,357	30,726,208		500,761	
Wisconsin	333,796,074	204,834,406	212,613,491	114,832,985	866,076,955	2,252,204	384.5
Wyoming	25,489,854	58,562,272	69,244,091	11,873,094	165,169,310	305,790	540.1

IV. QUANTIFYING THE ROLE OF GREEN EQUIPMENT IN REDUCING GHG EMISSIONS FROM CONSTRUCTION

In this chapter, we examine how shifts towards hybrid diesel and all electric equipment may impact emissions through the use of a methodology that combines fuel usage characteristics from Chapter II, with fuel consumption and GHG emissions factors from Chapter III. It also incorporates inputs regarding the characteristics of the heavy construction equipment fleet from some of the project-based models discussed in Chapter III, and technology adoption rates obtained from industry reports. The result is a methodology that is not only based on a realistic picture of the construction economy and emissions impacts, but which is also relatively simple, completely transparent, and can be used at relatively low cost to calculate new estimates as more information about these technologies comes to light, or, to produce new estimates with alternate configurations of the assumptions.[60]

The methods in this section differ depending on whether we are considering 1) the substitution of hybrid-diesel for conventional-diesel, or 2) the substitution of all-electric for diesel (either hybrid diesel or conventional.) In a nutshell, in measuring the reduction associated with a substitution of hybrid-for-diesel, the exercise boils down to calculating the resulting improvement in the average fuel economy of the national equipment fleet as newer equipment replaces old equipment.

When considering the substitution of all-electric for diesel, to arrive at net emissions reductions, we need to calculate both the reductions from reduced diesel emissions, and add to these the emissions associated with generating the electricity needed to carry out identical tasks. As we saw in the last chapter, the GHG emissions associated with electricity generation vary depending on the method of generation. Therefore, we know at the outset that the substitution of all electric for diesel will have a larger GHG reduction in some states (or eGrid regions) than in others. But an important open question is whether the GHG impact of electric equipment will be negative in some states, as has recently been shown in the case of electric automobiles,[61] a topic we discuss in the conclusion. Our analysis will produce answers to this question, as well as estimates of the magnitudes of the GHG reductions associated with the adoption of specific electric and hybrid technologies.

Hybrid Equipment

For hybrid equipment, we consider separately how the adoption of hybrid a) excavators and b) dozers (track-type tractors) will impact emissions, as these are the main types of hybrid equipment found in our review of the market in Chapter II. We purposely do not take into account factors such as growth in the economy or changes in relative prices for construction inputs such as fuel, as our objective is to provide an estimate of the pure effect of innovation adoption (measured as fleet greening, or fuel source swapping, for hybrid and all-electric equipment, respectively) on fuel use. The previous chapter focused on providing an accurate estimate of industry- (and sub-industry-) emissions, while the present chapter is instead concerned mainly with measuring the reductions that can be attributed to certain technological innovations.

Given hybrid equipment is already commercially available, its adoption has already started to improve the average fuel economy of the US heavy construction equipment fleet. We begin by presenting the necessary data, describing the calculations and then report estimates of the emissions reductions associated with hybrid excavators, after which we report the estimates for dozers.

We use the following equation for measuring emissions from hybrid excavators:

$$CO_2\ emissions\ from\ excavators = (Diesel\ consumed\ by\ excavators)\times(Emissions\ rate)$$

Where,

$$Diesel\ consumed\ by\ excavators = \sum_{i}^{number\ of\ excavators} hours\ operated_i \times avg\ fuel\ per\ hour_i$$

and an analogous equation for dozers.

The variables needed to estimate emissions with this equation are: emissions rate, number of machines, hours operated per machine, and average fuel per hour per machine. For the emissions rate, we use 22.4 lbs of CO_2 per gallon of diesel fuel consumed, the same rate used in Chapter III (though there it was expressed in lbs per million BTUs.) For the number of excavators, we use the figures from the US EPA's NONROAD model. For the distribution of the number of heavy construction machines by model year, as well as an estimate of activity (measured in annual machine hours) for equipment types by model year, we use inputs from California's OFFROAD model. Both NONROAD and OFFROAD were described in Chapter III.[62] Finally, we obtain average fuel per hour estimates from various sources, discussed below.

The age distribution of vehicles is taken from an OFFROAD technical document and includes all types of diesel construction equipment. The age profile of the California fleet is not likely to be identical to that of the national fleet for several reasons. As one example, California has stricter diesel regulations on equipment use by construction firms than other states (we discuss this in some detail in the final chapter on policy options) and this may result in a distribution that is skewed towards more newer equipment. However, on the other hand, using the 2009 California profile, which is as of this writing is eight years old, may be a reasonable approximation to the US distribution 2017, to the extent that other parts of the country may be trending towards newer fleets, due to various public and private pressures. In any case, "…the activity estimates in the NONROAD model do not currently take into account the effect of equipment age on activity," so for practical purposes we have little recourse other than using the California OFFROAD data in modeling activity.[63]

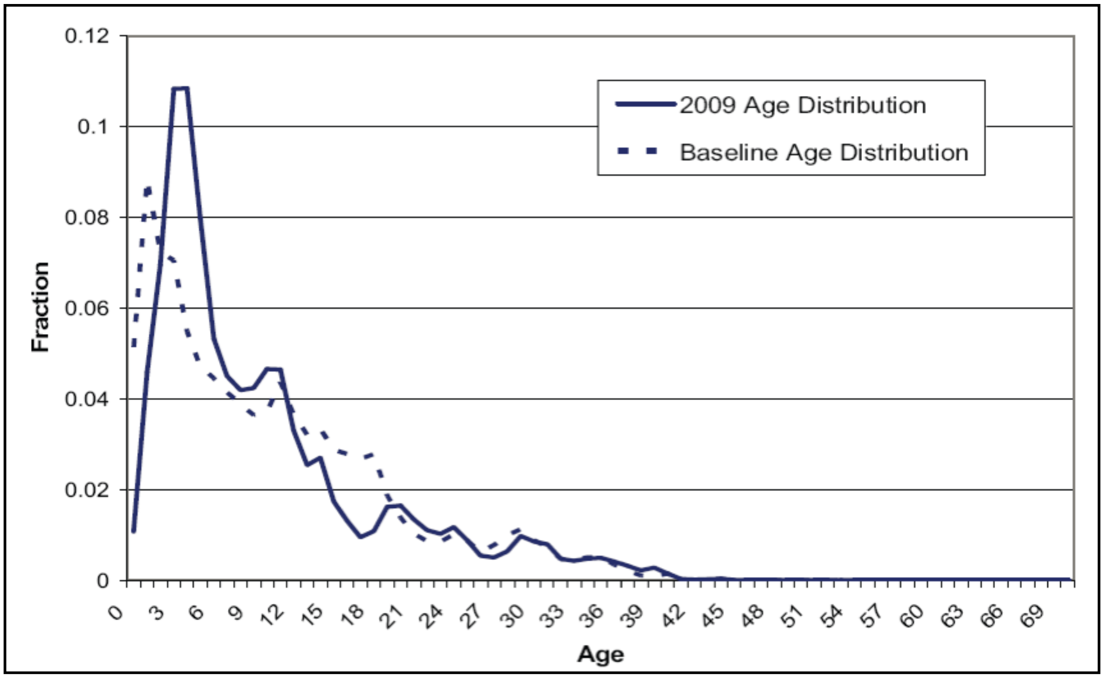

Figure 4. Age Distribution of Heavy Construction Equipment

Source: California Air Resources Board (2011) Appendix D of the Off-road emissions inventory: OSM and Summary of Off-road emissions inventory, page D-21.

We use a modified version of this distribution, which largely reflects the shape of the data from OFFROAD. This distribution could easily be adjusted if better information came to light regarding the age profile of the national equipment fleet.[64]

Next, we obtain activity estimates from OFFROAD for excavators and dozers. Different machines have different age-activity profiles. For example, for a new excavator, annual hours are assumed to be 786 but activity for a 13-year-old model is about half as much at 396 annual hours. Table 12 presents activity estimates for equipment up to 40 years of age, and this represents an assumption that the amount of equipment over year 40 years is trivial. This assumption may be warranted if very old equipment is retrofitted, and operates like a newer model year. Note the activity profile is assumed to not change after year 30 for both equipment types, for related reasons.

Table 12. Activity Estimates for Two Types of Construction Equipment, by Age

Age	Crawler Tractors	Excavators
0	667	786
1	649	756
2	630	726
3	612	696
4	593	666
5	575	636
6	557	606
7	538	576
8	520	546
9	501	516
10	483	486
11	465	456
12	446	426
13	428	396
14	409	367
15	391	337
16	373	307
17	354	277
18	336	277
19	317	277
20	299	277
21	281	277
22	262	277
23	244	277
24	225	277
25	207	277
26	189	277
27	170	277
28	152	277
29	133	277
30	133	277
.	.	.
.	.	.
.	.	.
40	133	277

To determine the population of equipment in the US fleet of excavators, we turn to the US EPA NONROAD model.[65] The estimated number of excavators by horsepower (HP) class is reported in Table 13; later we show population figures for dozers.

Table 13. Diesel Excavators

HP avg (a)	Population (b)	Fraction of excavator pop'n	HP-weighted-Pop (a) x (b)	% pop'n by HP (a) x (b) / 124,544
6	66	0.00	396	0.00
8	364	0.00	2,900	0.00
13	749	0.01	9,842	0.00
22	3,339	0.03	71,922	0.00
33	6,917	0.06	228,607	0.01
46	3,688	0.03	168,800	0.01
61	2,861	0.02	175,379	0.01
92	12,912	0.10	1,183,643	0.06
138	48,245	0.39	6,638,512	0.31
233	35,271	0.28	8,228,724	0.39
411	9,344	0.08	3,836,646	0.18
719	297	0.00	213,662	0.01
884	344	0.00	304,096	0.01
1,200	11	0.00	13,200	0.00
1,768	131	0.00	231,608	0.01
2,350	5	0.00	11,750	0.00
	124,544		21,319,687	

Source: NONROAD technical document, "Nonroad Engine Population Estimates" pp. A14-A15 and authors calculations.

From Table 13 it is apparent that the two most popular excavator sizes are those between the 138 and 233 average horsepower classes. Measured by number of machines, these two classes (100-175hp, and 175-300 HP) make up 39 and 28 percent of all machines, respectively. The sum of these is 68%, thus 2/3 of excavators fall in this horsepower range. We have also weighted the population counts by horsepower to proxy for fuel usage; along the dimension of HP-weighted populations, 89% of machines fall in the two classes between 100-300 HP classes. This is relevant because when we consider the Caterpillar 336EH excavator, which is rated at 308 HP, or the Komatsu HN215LC-1 and Kitachi ZH210-5, at 148 and 164HP, respectively, they are examples of hybrid equipment that are competitors in the most popular segments of the excavator market, and thus the potential exists for these products to contribute significantly to the greening of the US excavator fleet. We assume hybrid technology impacts 70% of excavator diesel consumption. This is the sum of the two HP-weighted shares (31 and 39) of the relevant HP classes.

The last component of the model concerns fuel consumption. First, how much fuel did excavators use in total? For the reason addressed in the preceding paragraph, 70% of this figure is the relevant amount of diesel consumption for this hybrid excavator analysis. Next, how much fuel on average is used by excavator from different model years? The answer depends on the age and activity distribution of excavators in the population.

Regarding the amount of diesel fuel consumed by excavators, we know construction industry-wide diesel fuel consumption was equal to 196,712,853 million BTUs in 2012 (from Table 28). Across 25 types of diesel construction equipment, the NONROAD model assumes 1.75 million pieces of construction equipment exist in the US fleet. From Table 13, 124,544 of these were excavators, or 7% of all pieces. In terms of HP-weighted population, the figure is 9.89%.[66] We round up slightly and assume that excavators make up 7% of the fleet by equipment, but use 10% of the total industry diesel consumption. As has already been mentioned, we are focusing on the excavator segment that makes up 70% of total excavator diesel consumption. We thus assume excavators in this HP class used 196,712,853*0.10*0.70 =13,769,900 million BTUs of diesel in 2012.

Turning to the average fuel used by equipment of different model years, in Chapter II we discussed some data from the Caterpillar performance handbook (this was shown in Figure 3). The numbers presented in that figure are a key component to our data for excavator fuel use rates. Surprisingly, the average fuel economy for excavators did not decline from 1990 to 2001 (these figures went from 8.58 to 9.00, respectively) but by 2017 both the conventional diesel and hybrid diesel excavators had fallen (to 6.75 and 4.9 gallons per hour, respectively.) These figures are only representative of Cat excavators of a specific class, however, and the apparent fall in fuel efficiency stands in contrast to recently published research.

A 2017 article by Lewis and Rasdorf, titled, “Fuel Use and Pollutant Emissions Taxonomy for Heavy Duty Diesel Construction Equipment,” examined data from 31 different types of heavy duty off-road equipment and conducted field tests involving standardized workloads. As a result of taking this controlled approach to measuring fuel use, the fuel consumptions values they report do not need to be adjusted for engine load and may therefore be more appropriate to use in calculating average fleet fuel efficiency. Their study presents average fuel consumption estimates by equipment type, and by engine “tier,” where the tiers refer to the federal standards for off-road diesel emissions. As of this writing, current model year off-road diesel engines are required to meet Tier 4 standards. Unfortunately, the equipment included in the LR study only went up to Tier 2. As a result, we combine data from both the Cat Performance Handbooks (PHs) and Lewis and Rasdorf (2017) to arrive at fuel use estimates for equipment by model year. The Cat PH data were presented in Figure 3 in Chapter II and are described in more detail in Appendix 2. The Lewis and Rasdorf (2017) figures on fuel use are presented below in Table 14.

Table 14. Average Fuel Consumption by Equipment Type

	Tier 0 (median age 1993)	Tier 1 (median age 2001)	Tier 2 (median age 2004)
Backhoe	0.09	0.07	0.06
Bulldozer	0.12	0.09	0.08
Excavator	0.13	0.1	0.08
Motor Grader	0.13	0.1	0.08
Off-road Truck	0.06	0.05	0.05
Truck Loader	0.16	0.12	0.09
Wheel Loader	0.09	0.07	0.06
Average	0.11	0.08	0.07

Source: Lewis and Rasdorf (2017, p. 6); median age by tier are authors’ calculations.

Using the information presented in the original article, we assign 1993, 2001 and 2004 to Tiers 1, 2 and 3, respectively, based on the median age of equipment of each tier.

Given the information on fuel efficiency from both of these sources, we assign fuel use rate (measured in liters per kWh) to older model excavators as follows: pre-1993, 0.13; 1993 to 2001, 0.10; and 2002 to 2010, 0.08. These figures come directly from Lewis and Rasdorf (2017) for excavators. For newer models, we choose fuel rates that embody several assumptions. The assumed fuel rates for all model years are presented in Table 15.

Table 15. Adoption and Fuel Use Assumptions for Excavator Analysis

Year	Adoption rate (a)	Hybrid fuel use (b)	Conventional fuel use (c)	Weighted average fuel use for model year (a x b) + (1-a) x c
Before 1993	0	na	0.130	0.130
1993-2001	0	na	0.100	0.100
2002-2010	0	na	0.080	0.080
2011	0.03	0.0435	0.077	0.076
2012	0.06	0.0435	0.074	0.072
2013	0.09	0.0435	0.071	0.069
2014	0.12	0.0435	0.069	0.066
2015	0.15	0.0435	0.066	0.062
2016	0.18	0.0435	0.063	0.059
2017	0.21	0.0435	0.060	0.057
2018	0.24	0.0435	0.060	0.056
2019	0.27	0.0435	0.060	0.056
2020	0.30	0.0435	0.060	0.055
2021	0.33	0.0435	0.060	0.055
2022	0.36	0.0435	0.060	0.054

We now describe the assumptions embodied in the weighted average fuel use rates listed in the last column of Table 15. We choose 2010 as the hybrid entry date to reflect the fact that the three hybrid excavators profiled in Chapter II were released in 2008 – 2013 period.[67] According to information presented in endnote 27 (in Chapter II), by the start of 2011 over 650 Komatsu hybrid excavators had entered the global excavator fleet. We don't know exactly what fraction of these were in the US fleet, but assume 25% of this figure, or 163 excavators were sold in the US by 2011; the assumption of 25% is based on the fact that this was the share of total Komatsu sales in North America in that year.[68] However given perhaps 5,763 excavators in this HP class are sold annually (this figure comes from adding 48,245 + 35,271, the population shown in Table 13 for the 138 and 233 HP classes, respectively, and then multiplying this sum by the distributional assumption that 6.9% of excavators are new), the sale of 163 hybrid excavators would represent a low adoption rate of 163/(5763), which is less than 3% of the relevant market. Thus, starting in 2011, we assume that 3% of sales were for hybrids and 97% were conventional diesel. We assume the adoption rate increases linearly to 2017 when we assume it is 21% (which is 7 years times 3%).

This yields the following equation for hybrid equipment adoption rates: Adoption rate = 3.00*t, where t=0 for 2010, t=1 for 2011, and so on to t=7 in 2017. After 2017 we will consider two scenarios in what follows, one where the adoption rate stays at 21%, and another where the adoption rate to continue to increase by the same formula. The lack of information on sales figures makes it necessary to make assumptions on adoption rates. These assumptions must be remembered when interpreting the eventual reduction estimates as the GHG reductions.

As discussed in Chapter II, the conventional diesel excavators also saw improvements in fuel economy between 1990 and 2017. The Cat Performance Handbook figures we presented there showed the excavator fuel use falling by 25% for conventional equipment and 45% for hybrid from 2001 to 2017. Thus in addition to assuming a straight line adoption rate for hybrid equipment, we also assume a straight line fuel economy improvement rate for conventional engines between 2011 and 2017, so that in 2017 fuel economy is 0.06 l/h for conventional diesel engines (which is 45% less than the LR 2017 estimates for Tier 2 excavators.) This assumption is made precise by the equation for fuel usage for conventional diesel of fuel use = 0.08-0.00286*t, where t=0 for 2010, t=1 for 2011, and t=7 for 2017.We assume fuel use is 0.0435 for all hybrids after 2010 (which is the fuel use figure for the Cat 336E-H.) All of these assumptions are embodied in Table 15 above.

We next show a very big table to illustrate a simple point: based on the assumptions describe above, the average fuel usage of excavators in 2012 was 0.085 liters per kWh, as shown in the lower right corner of Table 16. Seeing the full table may facilitate understanding these calculations. The calculation begins with activity estimates in column (b) multiplied by the number of excavators in the relevant HP class (which as mentioned above was 48,245+35,271=83,516), which are multiplied by the fraction of equipment of the listed model year in column (c) to arrive at number of machines in (d). The number of machines is multiplied by the activity in annual hours in (b) to arrive at annual machine hours by model year. Column (f) contains the fraction of machine hours for each model year by dividing (e) by total machine hours of 45,970,080 (which is shown on the last row of the table.) Finally, the fraction of hours in (f) is multiplied by fuel use rates in (g), for each of the 40 model years, and the product of these calculations are summed in the bottom of column (h) to produce the weighted average fuel use rate for this portion of the excavator fleet, which again is 0.085.

In unreported results, we calculated average fuel usage for 2017 using the same methodology (including the same fuel consumption figures shown above in Table 15). This involves updating the Table to reflect updated model years in the first column and their corresponding average fuel use rates. This resulted in a reduction in the average fuel usage to 0.0741. We also calculated average fuel usage in 2022 under two hypothetical scenarios: hybrid adoption continues at 3% per year, and hybrid adoption caps out at 25% in 2017. In the former, fleet fuel use is 0.0638 while without further increases in the adoption rate, we find an estimated fuel use rate that is only slightly higher at 0.0646.

Table 16. Calculating Average Fuel Use in Medium and Large US Excavator Fleet in 2012

Model year	Age (a)	Activity (b)	Fraction of Pop (c)	Machines of model year (d = c x 83,516)	Machine hours (e = b x d)	Fraction of hours (f = e/45,970,080)	Fuel use rate (liters per mWh) (g)	F times G (h)
2012	0	786.3	0.069	5,763	4,530,992	0.0986	0.072	0.0071
2011	1	756.3	0.069	5,763	4,358,210	0.0948	0.076	0.0072
2010	2	726.3	0.069	5,763	4,185,427	0.0910	0.08	0.0073
2009	3	696.3	0.069	5,763	4,012,645	0.0873	0.08	0.0070
2008	4	666.3	0.07	5,846	3,895,513	0.0847	0.08	0.0068
2007	5	636.4	0.07	5,846	3,720,226	0.0809	0.08	0.0065
2006	6	606.4	0.07	5,846	3,544,940	0.0771	0.08	0.0062
2005	7	576.4	0.07	5,846	3,369,653	0.0733	0.08	0.0059
2004	8	546.4	0.04	3,341	1,825,352	0.0397	0.08	0.0032
2003	9	516.4	0.04	3,341	1,725,189	0.0375	0.08	0.0030
2002	10	486.4	0.04	3,341	1,625,025	0.0353	0.08	0.0028
2001	11	456.5	0.04	3,341	1,524,861	0.0332	0.10	0.0033
2000	12	426.5	0.025	2,088	890,436	0.0194	0.10	0.0019
1999	13	396.5	0.025	2,088	827,834	0.0180	0.10	0.0018
1998	14	366.5	0.025	2,088	765,231	0.0166	0.10	0.0017
1997	15	336.5	0.025	2,088	702,629	0.0153	0.10	0.0015
1996	16	306.5	0.0125	1,044	320,013	0.0070	0.10	0.0007
1995	17	276.6	0.0125	1,044	288,712	0.0063	0.10	0.0006
1994	18	276.6	0.0125	1,044	288,712	0.0063	0.10	0.0006
1993	19	276.6	0.0125	1,044	288,712	0.0063	0.10	0.0006
1992	20	276.6	0.01	835	230,970	0.0050	0.13	0.0007
1991	21	276.6	0.01	835	230,970	0.0050	0.13	0.0007
1990	22	276.6	0.01	835	230,970	0.0050	0.13	0.0007
1989	23	276.6	0.01	835	230,970	0.0050	0.13	0.0007
1988	24	276.6	0.01	835	230,970	0.0050	0.13	0.0007
1987	25	276.6	0.01	835	230,970	0.0050	0.13	0.0007
1986	26	276.6	0.01	835	230,970	0.0050	0.13	0.0007
1985	27	276.6	0.01	835	230,970	0.0050	0.13	0.0007

Model year	Age (a)	Activity (b)	Fraction of Pop (c)	Machines of model year (d = c x 83,516)	Machine hours (e = b x d)	Fraction of hours (f = e/45,970,080)	Fuel use rate (liters per mWh) (g)	F times G (h)
1984	28	276.6	0.008	668	184,776	0.0040	0.13	0.0005
1983	29	276.6	0.008	668	184,776	0.0040	0.13	0.0005
1982	30	276.6	0.008	668	184,776	0.0040	0.13	0.0005
1981	31	276.6	0.008	668	184,776	0.0040	0.13	0.0005
1980	32	276.6	0.005	418	115,485	0.0025	0.13	0.0003
1979	33	276.6	0.005	418	115,485	0.0025	0.13	0.0003
1978	34	276.6	0.005	418	115,485	0.0025	0.13	0.0003
1977	35	276.6	0.005	418	115,485	0.0025	0.13	0.0003
1976	36	276.6	0.002	167	46,194	0.0010	0.13	0.0001
1975	37	276.6	0.002	167	46,194	0.0010	0.13	0.0001
1974	38	276.6	0.002	167	46,194	0.0010	0.13	0.0001
1973	39	276.6	0.002	167	46,194	0.0010	0.13	0.0001
1972	40	276.6	0.002	167	46,194	0.0010	0.13	0.0001
	sum of rows 1-40:				45,970,080	1.0000		0.0850

Using the fuel use rate for 2012 of 0.085 (which for some calculations below we will complete with a normalized value of 8.5 in order to facilitate working with more convenient units), we now calibrate machine hours returning to the equation from the beginning of this chapter:

$$Fuel\ consumption = machine\ hours \times avg\ fuel\ per\ hour$$

Industry-wide diesel fuel consumption for excavators in the relevant HP class was equal to 13,769,900 million BTUs in 2012, as shown earlier. Average fuel per hour for diesel equipment in 2012 was 0.085 liters per kWh. We divide 13,769,900 by (the normalized) 8.5 to arrive at a calibrated estimate of equipment hours equal to 1,619,988.[69] This number is quite far from the 45,970,080 machine hours estimated above in Table 16, but what is important here is not that these numbers agree—they shouldn't—because in the first case the goal was to calculate fleet average fuel usage, and here the goal is to calibrate the model so that the method returns the same estimate of diesel consumption from the 2012 Economic Census, given contemporaneous period assumptions. This set up enables varying the average fuel per hour estimate to reflect future conditions, and thus enables one to see how fuel consumption is predicted to fall with technological improvement, holding constant all other factors.

To clarify the calculations mentioned above we now show the calculation in the equation format below:

$$13{,}769{,}900 = 1{,}619{,}988 \times 8.5$$

Now according to our assumptions and analysis above, the average fuel use rate for excavators fell from 0.085 in 2012 to 0.0741 in 2017. This is because old equipment was phased out and replaced with more efficient conventional diesel engines and some (3% starting in 2011 and rising to 21% in 2017) hybrids. If machine hours also happened to equal in 2017, fuel consumption would fall from in 2012 to 12,004,111 in 2017, as shown below.

$$Fuel\ consumption = 1{,}619{,}988 \times 7.43$$

The left-hand side of this equation equals 12,004,111. Thus, we estimate that the greening of the excavator fleet between 2012 and 2017 would have, all else equal, caused diesel fuel consumption to fall from 13,769,900 to 12,004,111, which is a reduction of 1,765,789 million BTUs of diesel. Expressed as a percentage this is a 12.8% reduction. If we multiply this diesel consumption reduction by the emissions factor for CO_2 we find the same percentage reduction, but a rescaled amount that represents pounds of CO_2; emissions factors for homes and businesses are taken from the EIA and were given in Chapter II. For diesel fuel the factor is equal to 161.3 pounds of CO_2 per million BTUs, thus this hybrid equipment saved at least 284 million pounds of CO_2 (this figure is calculated as 1,765,789*161.3).

One can interpret the 12.8% figure to mean that emissions would be 12.8% higher today if not for these innovations, for example, in a counterfactual world where technology failed to advance since 2001. What are emissions associated with the use of excavators of this class? We have presented diesel consumption by this class as 13,769,900 million BTUs in 2012. Thus GHG emissions from this excavator class is 2,221 million pounds (this is 13,769,900*161.3) and 12.8% of this is the 284 million pound reduction reported above. But given construction activity increased from 2012 to 2017, while at the same time technology advanced, it is likely that total emissions are higher in 2017 than they were in 2012. And as a result, the adoption of this technology will have saved more than 284 million pounds.

With regard to determining a more accurate figure for the quantity of CO_2 saved as a result of the adoption of hybrid excavators, one could scale up GHG using, for example, the employment figures from Figure 1 to proxy for construction activity to arrive at what may be a more accurate estimate of GHG reductions from this equipment. For example, employment in construction is up about 18% from 2012 to 2017; thus one can correctly interpret the results of this analysis as meaning CO_2 emissions would be 335 million pounds higher today if hybrid excavator technology failed to advance (this is 284*1.18). In other words, total diesel consumption by excavators of this class in 2017 can be estimated to be 16,248,482 million BTUs in (this is 13,769,900*1.18), or in terms of GHG, 2,621 million pounds of CO_2 (16,248,482*161.3). Thus in 2017 a more accurate figure for the size of the reduction attributable to technology adoption in terms of pounds of CO_2 is 335 million pounds (0.128*2,621 million). These 335 million pounds of CO_2 are on par with two years of emissions that result from the entire construction sector in the District of Columbia, or with six months of emissions that result from the entire construction sector in Alaska. The reduction in emissions from improved excavator fuel efficiency (recall these calculations include the reduced fuel use from both hybrid and conventional excavators) is more than total emissions in the highway, street and bridge construction sector in the states of Massachusetts and Connecticut combined.[70]

We now use this approach to forecast how further replacement in the equipment fleet is anticipated to reduce emissions, again while holding machine hours constant. Above we presented two estimates of average excavator fleet fuel economy in 2022 — 0.0638 and 0.0646 — where the former reflected increasing adoption of hybrid equipment through 2022, and the latter reflected adoption rates that cap at 21% in 2017.

$$Fuel\ consumption = 1{,}619{,}988 \times 6.38$$

and

$$Fuel\ consumption = 1{,}619{,}988 \times 6.46$$

The left-hand sides of these equations are 10,335,523 and 10,465,122, respectively. Thus taking the 2017 figure of 12,004,111 BTUs of diesel fuel as a baseline, emissions are predicted to fall by either 13.9% or 12.8%, depending on whether the rate of adoption of hybrid equipment is higher or lower, respectively. This suggests society can reduce CO_2 emissions more if it can encourage firms to adopt hybrid equipment, but that the technology that has already been developed will yield continuing reductions, even if adoption does not increase, due to equipment being replaced with lower-emitting conventional equipment.

Turning now to dozers, and having gone through the excavator analysis in detail, we will be more concise in presenting the analysis, as the dozer analysis follows analogous steps. Activity estimates for dozers have already been reported in Table 12. And all equipment (excavators, dozers and loaders) is assumed to follow the same age distribution based on Figure 4. Fuel consumption estimates for older model dozers are from Lewis and Rasdorf (2017) and were reported in Table 14. As before with excavators, we calculate the average fleet fuel consumption rate by combining the Lewis and Rasdorf (2017) data with Cat PH data as well as assumptions concerning adoption and aforementioned factors.

Like the Komatsu HB215LC-1 excavator, the Cat D7E dozer was released in 2008. And as with excavators we did not find firm sales figures for hybrid dozers. However, one report indicates sales were 500 by 2011 and we use this source to form our adoption rate estimate.[71] According to Table 17, the population of dozers in the 255.5 HP class is 27,323. And as before the proportion that is new is 0.069. The product of these two produces an estimate of 1,885 new dozers sold annually in this HP class. Thus the 500 dozers sold by 2011, which assuming is over 2.5 years since its release, amounts to 200 dozers per year. Now given 200/1885=0.1061 or 10.61%, the adoption rate for dozers calculated in this way is higher than for hybrid excavators.[72] From this we form the adoption rate equation where adoption rate = 0.1*t, where t=1 in 2011 and so on. Thus by 2020 we assume the D7E dozer is fully adopted in this segment.

Table 17. Diesel Crawler Tractor/Dozers Population

HP avg (a)	Population (b)	Fraction of excavator pop'n	HP-weighted-Pop (a) x (b)	% pop'n by HP (a) x (b) / 124,544
25.75	0	0.00	0	0.00
42.5	0	0.00	0	0.00
57.98	485	0.01	28,120	0.00
87.86	13,961	0.15	1,226,613	0.05
136.1	31,552	0.33	4,294,227	0.17
235.5	27,323	0.29	6,434,567	0.26
425.3	13,835	0.14	5,884,026	0.24
707	5,458	0.06	3,858,806	0.16
923	1,129	0.01	1,042,067	0.04
1,065	1,964	0.02	2,091,660	0.08
1,473	9	0.00	13,257	0.00
	95,716		24,873,343	

Source: NONROAD technical document, "Nonroad Engine Population Estimates" pp. A14-A15 and authors calculations.

One notable difference between excavators and dozers is that the review of the Cat PH did not reveal much of an improvement in conventional diesel D7 dozers (the fuel consumption figures from Figure 2 for conventional D7 dozers are 7.5, 7.25 and 7.35 for 1990, 2001 and 2017 respectively, while the fuel use rate in Figure 2 for hybrid dozers is 5.9.) We thus use the Lewis and Rasdorf (2017; hereafter LR) estimates for Tier 2 engines for 2002 through 2022. We do assume that starting in 2011, 10% of new purchases are hybrids with the lower fuel use rate of 0.0651; this figure is arrived at as (5.9/7.25)*0.08, where 5.9 and

7.25 are the Cat PH fuel rates for a 2011 hybrid and 2011 conventional, respectively, and 0.08 is the LR figure for Tier 2 engines. Thus the fuel use rate for conventional dozers by age profile is: before 1993, 0.12 (LR, figures for Tier 0), 1993 to 2001 of 0.09 (LR figures for Tier 1) and 0.08 for 2002 through 2022 for conventional (LR figures for Tier 2.) For hybrid the figure is 0.0651 for all years after 2011.

Based on these assumptions concerning the age activity profile and the population of dozers, the adoption rate, and the fuel use rates by model year for conventional and hybrid equipment, we calculate that average dozer fleet fuel consumption is 0.0854 in 2012. This is very similar to what we found for excavators; it is also the case that excavators and dozers have similar fuel use rates in LR (2017), which of course informs our assumptions. When we update the fleet data to 2017, we find an average fleet fuel use rate of 0.079, and the 2022 estimate is 0.0725.

As with hybrid excavators, the 238 HP D7E Hybrid dozer is located in the second most popular HP class in the population of dozers, and is in the highest diesel consumption class, as measured by the HP-weighted population.[73] According to this data, there are 95,716 bulldozers in the population, which is 5.4% of the equipment population of 1,757,384 pieces of equipment. The HP-weighted population is 24,873,343 which is 11.54% of the HP-weighted population of all diesel equipment. (This is 24,873,343/ 215,466,525=0.1154, where the denominator on the left-hand side is the sum of HP times equipment population for all diesel equipment.) Thus while excavators represent around 10% of GHG emissions from diesel, bulldozers appear to be responsible for a somewhat higher amount at 11.5%.

The relevant HP-range for the D7E, the only hybrid dozer profiled in Chapter II, is narrower, at 26% of the HP-weighted population, compared to the 70% of the hybrid-relevant excavator market. Thus we assume the D7E is relevant for 0.26*0.1154*196,712,853 = 5,902,172 million BTUs. Recall construction industry-wide diesel fuel consumption was equal to 196,712,853 million BTUs in 2012. Now 0.26*0.1154=0.03, and so with the D7E dozer we are looking at potential savings from 3% of entire diesel emissions from construction. Therefore another way of arriving at the same figure is to multiply 0.03*196,712,853 which yields the same 5.902,172 million BTU (plus or minus due to rounding error.)

We now calibrate machine hours using the same equation from the excavator analysis:

$$Fuel\ consumption = machine\ hours \times avg\ fuel\ per\ hour$$

As described above, industry-wide diesel fuel consumption for dozers in the relevant HP class was equal to 5,902,172 million BTUs in 2012. Average fuel per hour for diesel equipment in 2012 was 0.0854 liters per kWh. We divide 5,902,172 by (the normalized) 8.54 to arrive at a calibrated estimate of equipment hours equal to 691,121. These calculations are shown in the equation below:

$$5{,}902{,}172 = 691{,}121 \times 8.54$$

Now, according to our assumptions and analysis above, the average fuel use rate for excavators fell from 0.0854 in 2012 to 0.079 in 2017 and 0.0725 in 2022. If machine hours also happened to equal 691,121 in 2017, fuel consumption would fall from 5,902,172 in 2012 to12,004,111 in 2017, as shown below:

$$Fuel\ consumption = 691{,}121 \times 7.9$$

The left-hand side of this equation equals 5,459,856. Thus, we estimate that the greening of the excavator fleet between 2012 and 2017 would have, all else equal, caused diesel fuel consumption from dozers in this HP class to fall from 5,902,172 to 5,459,856, which is a reduction of 442,316 million BTUs of diesel. Expressed as a percentage this is a 7.5% reduction. While for excavators the reduction was larger at 12.8%, the smaller reduction we find for dozers has mainly to do with the fact that we are aware of only one hybrid dozers in this HP class, while for excavators there were several across multiple HP classes.

As for GHG emissions, recall that for diesel fuel the CO_2 emissions factor is equal to 161.3 pounds of CO_2 per million BTUs, thus this hybrid equipment saved 71 million pounds of CO_2 (this figure is calculated as 442,316 *161.3).

As the hybrid dozers continue to be adopted by construction firms, the average fleet fuel use rate falls to and 0.0725 in 2022. Using the same equation this calculation is shown below.

$$Fuel\ consumption = 691{,}121 \times 7.25$$

The left-hand side of this equation equals 5,010,627. This is a projected reduction in 449,229 million BTUs of diesel, which is an 8.2% reduction from 2017 to 2022, all else equal. These estimates and projections can be modified if one wants to take into account the increased economic activity in the construction industry, as described in the earlier discussion of excavators. The figures we have presented for dozers represent "all else equal" estimates showing the effect of innovation on fuel use.

Battery-Powered Electric Equipment

Next, we turn to estimating the impact of substituting all-electric for diesel equipment. As discussed in Chapter II, battery-powered construction equipment is an emerging technology and at the moment only a few products are commercially available. Here we focus on an experiment that took a conventional JCR mini excavator and carried out 7 different tasks, then retrofitted it with a battery and electric motor and carried out the same tasks. The results were reported in an article titled, "Electrification of Excavator"[74] and are reproduced below in Table 18.

Table 18. Hybrid Electric Experiment and Energy Consumption

Task	Avg diesel consumption (g/hour)	Avg diesel consumption (kWh)	Avg electricity consumption (kWh)
1	0.36	14.02	2.96
2	0.34	13.16	2.55
3	0.39	15.09	3.76
4	0.51	20.03	5.59
5	0.41	16.15	3.10
6	0.30	11.64	1.35
7	0.13	5.32	0.46
	Averages:	13.63	2.82

With this data, a comparison of the GHG emissions is straightforward, using the emissions factors from Chapter III. For diesel fuel the emissions factor is 22.40 pounds of CO_2 per gallon. Thus from Table 18, Task 1 consumed 0.36 gallons, and this produced 0.36*22.4=7.99 lbs of CO_2.[75] However this same task took only 2.96 kWh of electricity, which means completing the task with the diesel power took 14.02/2.96=4.74 times more fuel. Given the national emissions factor of 1.1365 lbs of CO_2 per kWh, it produces 7.99/3.36=2.38 times more GHG emissions to complete this task with diesel rather than battery power.

The state-specific emissions factors reported in Chapter III had a mean of 1,095.9, and a min of 566.6 (in New York) and a max of 1,814.91 (in Colorado). Recall we calculated these state-level emissions factors ourselves and they are weighted averages of the eGRID subregions (and subregions exhibit even more variation than our state factors; they range from 408.8 in upstate NY to 1,822.65 in the WECC Rockies region (which includes Colorado and areas north).

Table 19. Hybrid Electric Experiment and GHG Emissions Under Three Scenarios

Task	Diesel CO2 emissions	Electric CO2 emissions (US factor)	Electric CO2 emissions (NY factor)	Electric CO2 emissions (CO factor)
1	7.99	3.36	1.68	5.37
2	7.52	2.90	1.45	4.63
3	8.64	4.27	2.13	6.82
4	11.42	6.35	3.17	10.15
5	9.23	3.52	1.76	5.63
6	6.63	1.53	0.77	2.45
7	3.02	0.52	0.26	0.83
Averages:	7.78	3.21	1.60	5.13

The results of this analysis show that the battery powered excavator produces fewer GHG emissions, regardless of in which state the electricity was generated. In Colorado the emissions from the diesel excavator are 7.78/5.13=1.5 times higher than emissions from the electric excavator. In NY, the emissions from the diesel excavator are 7.78/1.60=4.9 times higher than emissions from the electric excavator.

Although the example above is from a laboratory experiment rather than actual commercially available equipment, there is reason to believe these figures may be representative of electric excavator operations. For example, as discussed in Chapter II the mining industry has long used electric motors. Yamamoto et al. described how “fuel consumption is approximately one-fifth” in electric versus diesel operation. This is remarkably consistent with the data reported in the Electrification of Excavator article, where electric consumption measured in kWh was also exactly 1/5 that of diesel consumption measured in the same units.

V. CONCLUSION: ENCOURAGING DEVELOPMENT AND ADOPTION OF CLEAN TECH IN CONSTRUCTION

In the preceding chapters, we have described the construction and equipment manufacturing industries, new hybrid and battery electric technologies for off-road construction equipment, and methods for calculating current emissions from the construction sector. We then carried out an updated inventory of US emissions from construction. This updated inventory was the first to report emissions from construction by state. We argued that incorporating regional variation into the analysis is important, as when considering electric equipment, it is critical to ask how the electricity was generated, and the state-level electricity emissions factors created for this research varied considerably from state to state. Finally, we developed a methodology for calculating the reduction in emissions that are attributable to improved technology in construction equipment manufacturing, and carried out calculations for hybrid and battery electric construction equipment. We find big reductions in GHG emissions that we can be attributed partly to new hybrid technology, but it is important to note that improvements in conventional diesel technology also contributed to the greening of the US construction fleet. With regard to battery-powered electric equipment, this segment is still in its infancy, but in terms of GHG emissions, the substitution of electric for diesel fuel sources appears to result in impressive energy consumption reductions and thus significant GHG reduction possibilities, if it can be scaled up to compete with diesel equipment in the larger horsepower categories.

This final chapter considers ways public policy can encourage technological development and its adoption in the off-road construction equipment fleet. This will not be a formal policy analysis, for two main reasons. First, GHG emissions are important but are not the only factor policy makers should consider when setting policies. For example, although we have discussed public health impacts to some extent (for example in Chapter II when discussing higher NO_x emissions that was seen in some hybrid equipment) our focus has been almost exclusively on GHG emissions. Second, we have not attempted a full measurement of lifecycle carbon emissions and embodied carbon.[76] We discussed this briefly in terms of materials recycling and project-based models, but a fuel-based approach proved useful in answering our main question, and we did not consider these other impacts, which could be relevant in the area of electric technology given the recent attention on the environmental costs of battery production.[77]

A full-fledged policy analysis would take a broader perspective; in the paragraphs below, we only discuss general policy options and examples of encouraging the adoption and development of off-road clean tech, in order to stimulate discussion and pave the way for future more detailed analyses. This discussion will highlight seven key options:

- Green performance contracting for highway construction
- Regulating new engine technology
- Regulating equipment use
- Fuel taxes

- Regional air quality regulation and local ordinances
- Subsidizing the development of off-road clean tech
- Subsidizing the use of off-road clean tech equipment

Green Performance Contracting for Highway Construction

We begin with green performance contracting for highway construction. In Chapter II we described how state, local and federal governments were responsible for 71.9% of projects in the highway, street and bridge construction subsector. This important fact motivates examining contracting strategies as an environmental policy. A growing literature examines procurement practices which reward firms for having clean equipment. Such practices are alternatively referred to as “green contracting”, “green procurement”, “low carbon procurement” or “green performance contracting.”[78] This literature has examined both the road (Cui and Zhou, 2011; Zhu et al. 2014) and building (Liu and Cui, 2016) construction.

Cui and Zhu (2011) insisted that one of the best ways to reduce GHG emissions from highway projects is to implement contracting strategies regarding the construction contractor’s choice of equipment and materials. These authors surveyed 39 state departments of transportation (DOT) and through their results shed light on the state of green highway construction contracting practices in the United States. They defined four levels of green contracting strategies;

- Level I: Material-related strategies (e.g. material recycling; asphalt waste management);
- Level II: Equipment and energy efficiency (e.g. equipment retrofit, alternative fuels);
- Level III: Green life-cycle strategies (e.g. green road rating system, climate impact analyses);
- Level IV: Clean energy development (e.g. highway-based wind turbines solar panels).

Cui and Zhu’s (2011) survey results of state DOTs’ green contracting practices find, among 39 respondents, 14 states were not implementing any green strategies. However, the other 25 states were using the material-related green strategies (Level I). In addition, Level II green strategies for equipment and energy efficiency were implemented in 12 states. Cui and Zhu (2011) also identified the green highway rating system (which shares some traits with green building rating systems, such as the well-known LEED certification program[79]) as an important way to incorporate preferences for environmental outcomes into the contracting process. Among three green highway rating systems currently in use in the United States, the Green Leadership in Transportation Environmental Sustainability (GreenLITES) was officially recognized by the state highway agency in New York which required that all project Plans, Specifications & Estimates (PS&Es) submittals must be certified using the GreenLITES rating system. Greenroads has been used as pilot projects in Washington and Oregon and the Illinios-Livable and Sustainable Transportation (I-LAST) rating system was used in Illinois.

Zhu et al. (2014) further developed the Green Performance Contracting (GPC) strategy scorecard to identify appropriate GPC strategies for highway construction projects. Key inputs in optimizing contract terms are financial consideration, technological maturity, organizational readiness, and industrial and public acceptance. Meanwhile, the objectives of this analysis included emission reduction levels, project performance impacts, and project risk levels.

Interesting examples of green contracting abound. The Respiratory Health Association relates several examples from Illnois: “In May 2009, Cook County, Illinois became the first county in the Midwest to adopt a green construction ordinance aimed at limiting deadly diesel soot from its publicly financed construction projects. Previously, green contracting language was adopted for the Dan Ryan Expressway Reconstruction Project and the O’Hare Airport Modernization Project. The Illinois Tollway and Illinois Department of Transportation have also adopted green construction language for some projects” (lungchicago.org).[80] In addition to state and regional projects, an example of a local green contracting comes from the city of Chicago which in 2011 “…passed a clean construction ordinance…ensuring that progressively cleaner diesel equipment will be used on city projects over the next decade.”[81]

A more recent example of green contracting comes from construction of the California High-Speed Rail system, which is building the California bullet train as a “zero net” GHG project; contractors use cleaner Tier 4 equipment and recycle building materials. Remaining emissions produced during the project’s construction will be offset with things like tree planting. (CAHSR, 2015).[82] It is relevant to note that the California HSR project has an important mandate to reduce GHG emissions and a major portion of its funding is justified by the proposition that the project lowers GHG emissions.

It is likely that some government agencies across the country will continue to adopt green contracting techniques. To the extent that this encourages construction firms to maintain green fleets of equipment, this will in turn provide incentives to equipment manufactures to spend more resources developing green technology. Further research should focus on carefully evaluating the benefits of green performance contracting but also the costs and unintended consequences of these practices, and to compare these strategies with other cost-effective ways to improve environmental outcomes.

Regulating New Engine Technology

We have at various points in this report discussed the federal government’s regulatory program for non-road diesel engines (which culminated in the Tier 4 emissions standards.) These regulations have focused on criteria pollutants and have not targeted GHG emissions. An important open question remains regarding what effect these regulations have had on fuel consumption. For example, has designing engines to minimize PM and NO_x emissions made it easier or more difficult for manufacturers to improve fuel efficiency? Evaluating the causal effect of regulation is challenging because it is impossible to view a counterfactual with different levels of regulations and technology. Although equipment manufacturers have so far not been subject to fuel efficiency guidelines, a large regulatory program regulates corporate average fuel economy (CAFE) of automobiles.[83]

In addition to federal regulation of diesel emission standards, state governments also play a role in technological standards; as noted on an EPA information page, “the Clean Air Act allows California to seek authorization to enforce its own standards for new non-road engines and vehicles, despite the preemption which prohibits states from enacting emission standards for new non-road engines and vehicles. EPA must grant a waiver, however, before California’s rules may be enforced.”[84] Other states can then choose to follow the federal guidelines or California’s stricter rules. As in the case of automobiles, state-policy makers can thus influence technological standards of new construction equipment.

Regulating Equipment Use

In addition to regulating new technology, California is also unique among states in its regulatory policy for its In-Use Off-Road Diesel Fueled Fleets Regulation, adopted on July 26, 2007, by the California Air Resources Board (CARB) to reduce PM and NO_x emissions.[89] These regulations apply to self-propelled engines over 25 horsepower, including vehicles that are rented or leased, with some exceptions (for example for low-use vehicles, small fleets, and so on.) It imposes idling restrictions and requirements, equipment identification and reporting system (the DOORS, Diesel Off-Road Online Reporting System, which was one of the data sources used in Chapter IV), requires exhaust retrofits and retirements of noncompliance machines, and prevents construction firms from buying old vehicles. Specifically, as of this writing, no firms may add a vehicle with a Tier 1 engine and by 2023 this ban will be expanded to Tier II equipment.[85]

From a policy perspective, a complicating factor with regard to GHG emissions is that, if state regulation encourages construction firms to upgrade their fleet, what happens to the old equipment? The answer may be that it will be sold and used somewhere else. Considering GHG emissions are a global externality and it doesn’t matter where the emissions are produced, this speaks for such regulation to potentially have less of an impact than might be expected based on the results from reducing criteria pollutants.

Fuel Taxes

Green performance contracting, regulatory engine standards, and equipment use regulations are all associated with a complex administrative structure. Fuel taxes, while politically unpopular, represent a policy option that will jointly encourage construction firms to use less fuel (for example through decreased idling) and purchase more fuel-efficient equipment.

Thus, many economists argue the most straightforward way of reducing diesel consumption and facilitating the development of clean diesel technology is simply to raise federal and/ or state fuel taxes.[86]

Regional Air Quality Regulation and Local Ordinances

Regional air quality regulation and local ordinances can also serve to incentivize construction firms to adopt cleaner equipment, and this in turn encourages equipment manufacturers to innovate. Regional air quality management districts, like the Bay Area Air Quality Management District (BAAQMD) in California do not regulate mobile sources like the equipment we have profiled in this report, but BAAQMD does regulate stationary sources. In building construction, one of the more noticeable sources of emissions comes from on-site diesel generators. In principle, through enforcement of ambient air pollution thresholds, as well offering some incentives and support, regional air quality management districts could encourage construction firms to replace on-site generators with grid power. A 2007 EPA report titled, “Cleaner Diesels: Low Cost Ways to Reduce Emissions from Construction Equipment” indicated that the use of grid power is associated with fewer local emissions than the use of on-site diesel generators. “An uncontrolled 60 kilowatt generator operating at 40 percent load produces 73 grams of CO, 337 grams of NO_x, and 24 grams of PM per hour. If grid power can be accessed onsite and used instead, CO emissions per kilowatt hour can be cut by 91 percent, NO_x emissions by 75 percent, and PM emissions by 98 percent.”[87] The calculations we carried out in Chapter IV concerning diesel versus electric excavators also suggests switching to grid or battery power could be associated with substantially fewer CO_2 emissions.[88]

With regard to encouraging the development and adoption of battery-electric equipment, it is hard to overstate the importance of local government. As the quotations from the paragraph above reveal, supplying grid power has long been touted as a clean energy solution, but the logistical challenge of supplying grid electricity to construction sites remains a major challenge. Much like the chicken-and-egg question surrounding whether widespread adoption of electric automobiles will happen without a sufficient charging infrastructure, policy makers at all levels should examine what institutional challenges may stand in the way of making it easier for construction firms to use grid electricity. Doing so could cut down on the need for generators, and making it easier to recharge battery electric equipment would certainly encourage its development, adoption and use.

Subsidizing Development and Use of Off-Road Clean Technology

The final policy options we consider involve subsidies. Direct subsidies could be given to encourage manufacturers to develop off-road clean tech; for example, government could increase funding for basic research, or target subsidies in another way. The Chinese government has invested in research to produce low-emissions, fuel efficient vehicles, and Chinese cities like Wuhan subsidize firms producing electric cars by providing cheap land, capital and tax breaks.[89] Another form of subsidy involves encouraging the use of off-road clean tech. We have seen several US examples of this, including the Clean Diesel rebate.[90] Our conversations with experts in the construction industry indicated that these sorts of programs often come with various “strings” that make them unappealing. It may therefore be the case that in designing these subsidy programs more attention must be placed on understanding the constraints faced by construction firms.

The goal of this project was to evaluate the potential of hybrid and electric construction equipment in reducing GHG emissions from construction industries. We have found that the reductions in fuel consumption associated with new equipment—both new conventional diesel and especially hybrid equipment—will yield large gains in GHG reductions as these new products replace older models in the US construction equipment fleet. Regarding battery-powered electric equipment, the technology is still in its infancy, but our analysis suggests that if this industry shifts towards more electric power, this could also foster large GHG reductions. We have presented a framework for both measuring emissions, as well as designing policy to encourage greater adoption and development off off-road clean tech. At various points, we have cautioned the reader to remember the assumptions that enter in all calculations, and we have cautioned policy makers to take a holistic view that incorporates not only GHG impacts, but also public health and economic factors such as cost effectiveness in setting policy.

APPENDIX

Calculating State-Level Emissions Factors

This appendix describes how we calculated state-level emissions factors. The availability of state level data enables us to account for the fact that electricity generation varies in emissions intensity from region to region in a more satisfactory way compared to EPA (2008, 2009). Figure X below shows the eGrid (Emissions and Generation Resource Integrated Database) subregions defined as of 2012.

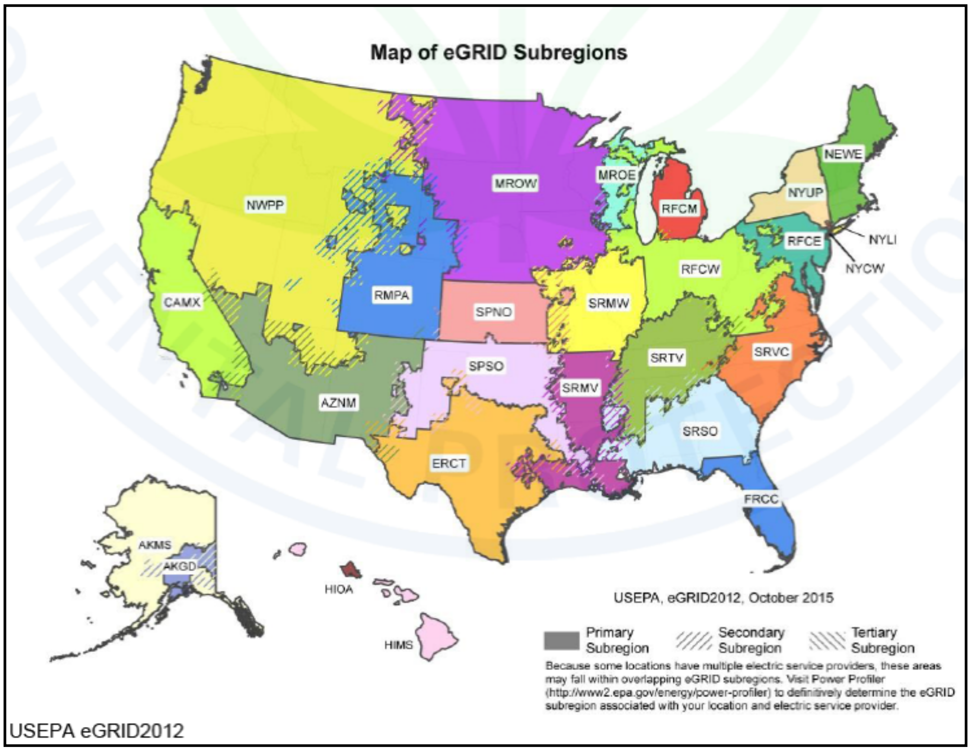

Figure 5. Map of eGRID Subregions

Source: USEPA.

Emissions intensity varies quite a bit across subregions. For CO_2, emissions (lb/MWh) ranges from a low of 408.8 in upstate New York (subregion NYUP) where 60% of electricity generation is hydroelectric, to 1,822 in the Rocky mountain west (subregion RMPA) with a resource mix featuring higher amounts of fossil fuels. Some states, like Maine (as can be noted in Figure X), fall entirely within an eGRID subregion, while many states are in multiple subregions. Due to the fact that subregions are not highly dependent on state political boundaries, and also because our primary source data is at the state-level, a state-level emissions factor would yield more accurate results compared to an identical emissions factor for all states (as in EPA 2008, 2009).

Table 20. NERC Subregions and Emissions Factors (lb/MWh)

SUBRGN	CO_2 factor	CH_4 factor	N_2O factor	CO_2E factor
AKGD	1,268.73	52.67	15.19	1,271.64
AKMS	481.17	37.31	7.10	482.66
AZNM	1,152.89	37.31	30.21	1,157.96
CAMX	650.31	62.23	11.35	652.72
ERCT	1,143.04	33.40	24.67	1,147.21
FRCC	1,125.35	80.09	23.71	1,129.86
HIMS	1,200.10	136.15	25.37	1,205.46
HIOA	1,576.38	180.81	43.10	1,584.96
MROE	1,522.57	48.61	51.11	1,531.00
MROW	1,425.15	55.19	48.52	1,433.25
NEWE	637.90	145.68	21.42	642.75
NWPP	665.75	25.19	20.75	669.23
NYCW	696.70	51.02	5.86	698.08
NYLI	1,201.20	156.40	19.74	1,205.90
NYUP	408.80	31.19	7.65	410.31
RFCE	858.56	52.89	22.97	862.68
RFCM	1,569.23	60.72	48.23	1,577.34
RFCW	1,379.48	34.22	43.33	1,386.55
RMPA	1,822.65	43.32	56.26	1,831.83
SPNO	1,721.65	40.43	54.29	1,730.49
SPSO	1,538.63	47.50	39.95	1,545.32
SRMV	1,052.92	41.91	21.21	1,056.65
SRMW	1,710.75	39.16	55.00	1,719.68
SRSO	1,149.05	45.32	30.98	1,154.33
SRTV	1,337.15	34.77	41.57	1,343.96
SRVC	932.87	47.90	29.20	937.90

Source: https://www.epa.gov/sites/production/files/2015-10/documents/egrid2012_ghgoutputrates_0.pdf

Our research did not reveal state-level emissions factors in standard use. We therefore produced our own using the 2012 eGRID database, which contains emissions figures for 7,286 electric power plants—essentially all power plants in the United States. The database indicates the state and eGRID subregion in which the plant is located, and also annual net generation, measured in MWh.

Our method of calculating state-specific emissions factors is to use a weighted average of the emissions factors of the subregions in which electricity is produced in each state. What is the most appropriate choice of weights? The answer depends on several factors. We use, as weight, the fraction of all electricity, measured by the variable PLNGENAN (Plant annual net generation, measured in MWh), generated in that state in that subregion. For example, in Alabama, 107,586,291 MWh of electricity was produced in subregion SRSO, and 45,518,925 MWh was produced in SRTV, for a total electricity production of 153,105,216 MWh. In other words, 70% of electricity was produced in SRSO and 30% was produced in SRTV. As can be seen from Table 20, the CO_2 emissions factors for SRSO and SRTV are 1,149 and 1,337, respectively. Thus our method assigns to Alabama an emission factor of 0.7*1,149 + 0.3*1,337, which equals 1,204.97. We perform identical calculations for all other states, and we reported the results in Table 29.

Other methods of weighting NERC subregions to arrive at state-specific factors are arguably more appropriate. For example, we could use eGRID to assign each county to a subregion's emissions factor, and use the fraction of state-level construction expenditures in the county as a weight. Our method has the benefit of computationally simpler, and arguably more suitable for future research studies, which may not focus on the construction industry. We include the factor for CO_2 equivalent (CO_2E) in the table for these future purposes, as the calculations we present below are in CO_2 not CO_2E.

Fuel Consumption Figures for Select Caterpillar Models, 1990-2017

Table 21. Average Fuel Consumption for CAT Excavators, 1990-2017

Year	CAT Dozers (a)	Power (HP) (b)	Average Fuel Consumption (Gal/Hr) (c)	Average Fuel Consumption Per HP (Gal/Hr) (d) = (c)/(b)
1990	E300	206	6.125	0.0297
1990	E450	276	8.5	0.0308
1990	E650	375	11.125	0.0297
2001	330B	222	7.5	0.0338
2001	345B	321	10.5	0.0327
2017	336E	300	6.75	0.0225
2017	336E H Hybrid	308	5.35	0.0174
2017	336F XE Hybrid	303	4.45	0.0147

Source: Caterpillar Performance Handbooks, various years.

Table 22. Average Fuel Consumption for CAT D7 Dozers, 1990-2017

Year	CAT Dozers (a)	Power (HP) (b)	Average Fuel Consumption (Gal/Hr) (c)	Average Fuel Consumption Per HP (Gal/Hr) (d) = (c)/(b)
1990	D7G	200	8	0.04
1990	D7H	215	7	0.0326
2001	D7G	200	7	0.035
2001	D7R	240	7.5	0.0313
2017	D7R	240	7.35	0.0306
2017	D7E Hybrid	238	5.9	0.0248

Source: Caterpillar Performance Handbooks, various years.

Table 23. Average Fuel Consumption for CAT Wheel Loaders, 1990-2017

Year	CAT Wheel Loaders (a)	Power (HP) (b)	Average Fuel Consumption (Gal/Hr) (c)	Average Fuel Consumption Per HP (Gal/Hr) (d) = (c)/(b)
1990	966E	216	6.75	0.0313
1990	980C	270	8.75	0.0324
2001	966G	235	6.75	0.0287
2001	972G	265	7.25	0.0274
2017	966M	278	3.75	0.0135
2017	966M XE (Hybrid-like)	298	3.3	0.0111

Source: Caterpillar Performance Handbooks, various years.

Construction Industry and Subsectors Economic Statistics

Table 24. Econ Census Data for Construction Industry and its Subsectors

Meaning of 2012 NAICS code	NAICS code	Number of firms	Number of employees	Construction workers	Other employees	Average wage, construction workers	Average wage, other employees	Average fringe benefits, all employees
Construction	23	598,065	5,669,623	4,136,743	1,532,880	$44,039	$58,954	$12,741
Construction of buildings	236	164,496	1,085,043	651,021	434,022	$41,992	$64,446	$11,001
Heavy and civil engineering construction	237	32,619	961,322	741,553	219,770	$53,413	$68,732	$15,882
Specialty trade contractors	238	400,950	3,623,257	2,744,169	879,088	$41,991	$53,798	$12,428
New single-family housing construction	236115	30,380	123,029	80,085	42,944	$34,497	$48,913	$7,019
New multifamily housing construction	236116	1,788	23,997	11,586	12,411	$51,363	$85,446	$12,420
New housing for-sale builders	236117	16,093	92,009	34,125	57,883	$45,243	$66,800	$9,951
Residential remodelers	236118	77,855	278,921	184,553	94,367	$30,165	$41,522	$6,162
Industrial building construction	236210	2,622	74,057	53,637	20,421	$53,857	$71,403	$15,056
Commercial and institutional building construction	236220	35,758	493,031	287,035	205,996	$48,704	$75,569	$14,250
Water and sewer line construction	237110	10,086	153,177	113,829	39,348	$48,147	$67,089	$13,525
Oil and gas pipeline construction	237120	2,101	174,432	136,639	37,794	$59,242	$71,792	$15,597
Power and communication line construction	237130	5,707	226,608	183,457	43,151	$51,997	$64,341	$14,201
Land subdivision	237210	2,448	17,357	8,743	8,614	$45,991	$61,305	$7,527
Highway, street, and bridge construction	237310	8,854	302,042	235,333	66,709	$51,816	$72,011	$17,489
Other heavy and civil engineering construction	237990	3,423	87,707	63,552	24,154	$61,331	$68,059	$21,029
Poured concrete foundation and structure contractors	238110	17,070	189,724	160,586	29,138	$35,602	$54,309	$8,776
Structural steel and precast concrete contractors	238120	3,248	62,247	51,800	10,447	$44,258	$63,399	$17,854
Framing contractors	238130	10,451	64,981	55,367	9,614	$29,022	$42,891	$6,328
Masonry contractors	238140	16,627	129,426	108,760	20,666	$33,357	$50,488	$10,242
Glass and glazing contractors	238150	4,693	42,935	29,034	13,902	$42,546	$53,621	$12,153

Meaning of 2012 NAICS code	NAICS code	Number of firms	Number of employees	Construction workers	Other employees	Average wage, construction workers	Average wage, other employees	Average fringe benefits, all employees
Roofing contractors	238160	16,615	162,763	121,490	41,273	$32,180	$54,899	$9,616
Siding contractors	238170	7,145	32,194	22,870	9,324	$29,167	$40,294	$6,293
Other foundation, structure, and building exterior contractors	238190	4,358	41,863	32,124	9,739	$45,009	$52,730	$11,077
Electrical contractors and other wiring installation contractors	238210	64,653	707,244	534,392	172,852	$48,800	$58,998	$15,466
Plumbing, heating, and air-conditioning contractors	238220	86,914	842,421	599,239	243,182	$47,461	$54,244	$14,381
Other building equipment contractors	238290	6,623	127,666	89,785	37,882	$59,138	$67,185	$22,207
Drywall and insulation contractors	238310	17,095	202,303	165,611	36,692	$37,914	$54,092	$13,307
Painting and wall covering contractors	238320	29,744	178,737	146,636	32,100	$31,488	$45,328	$8,070
Flooring contractors	238330	12,276	60,104	39,642	20,461	$33,724	$47,263	$7,918
Tile and terrazzo contractors	238340	8,448	47,089	34,362	12,727	$33,438	$43,697	$8,012
Finish carpentry contractors	238350	29,288	122,805	86,592	36,213	$33,078	$42,127	$7,632
Other building finishing contractors	238390	5,175	55,939	38,544	17,395	$36,961	$47,856	$10,085
Site preparation contractors	238910	34,217	334,140	265,460	68,680	$42,164	$53,508	$10,820
All other specialty trade contractors	238990	26,311	218,675	161,874	56,802	$37,291	$48,633	$8,106

Notes: Construction: Summary Series: General Summary: Detailed Statistics by Subsectors and Industries for US, Regions, and States: 2012 EC1223SG01.

Table 25. Econ Census Data for Construction Industry and Subsectors

Meaning of 2012 NAICS code	Total capital expenditure $	Cost of maintenance (machinery & buildings) $	Rental or lease payments for equipment $	Cost of materials and supplies $	Cost of power, fuels and lubricants $	Value of construction work $	% on federally owned projects	% state & local projects	% on privately owned projects
Construction	18,853,892	6,636,010	13,668,882	386,267,820	24,063,358	1,350,739,508	4.6%	17.5%	77.9%
Construction of buildings	2,811,183	897,620	1,776,582	117,449,856	3,057,630	503,311,159	4.5%	12.1%	83.4%
Heavy and civil engineering construction	6,624,085	2,281,869	5,203,510	72,086,430	6,421,027	252,425,713	5.7%	37.4%	57.0%
Specialty trade contractors	9,418,625	3,456,521	6,688,790	196,731,534	14,584,701	595,002,636	4.3%	13.6%	82.2%
New single-family housing construction	259,465	107,861	88,980	14,337,234	364,130	39,512,971	1.1%	1.2%	97.7%
New multifamily housing construction	101,115	16,355	50,944	3,945,150	59,742	19,042,551	2.1%	3.6%	94.3%
New housing for-sale builders	506,870	140,692	81,311	24,487,850	290,221	80,554,241	0.8%	0.3%	98.9%
Residential remodelers	458,448	133,384	241,937	15,134,142	811,492	51,982,363	0.7%	2.0%	97.2%
Industrial building construction	104,857	44,663	164,685	7,039,287	117,722	24,872,957	3.9%	6.4%	89.7%
Commercial and institutional building construction	1,380,429	454,664	1,148,726	52,506,194	1,414,323	287,346,076	6.8%	19.9%	73.3%
Water and sewer line construction	877,013	377,326	669,963	14,018,428	1,065,241	39,603,319	5.5%	50.5%	44.0%
Oil and gas pipeline construction	1,044,680	391,616	1,323,526	7,744,328	905,609	40,793,800	2.0%	2.8%	95.1%
Power and communication line construction	1,253,644	404,458	870,112	8,303,386	904,873	43,985,637	3.9%	6.8%	89.3%
Land subdivision	160,329	13,812	23,421	1,938,305	41,606	6,393,991	0.4%	2.3%	97.3%
Highway, street, and bridge construction	2,524,593	816,136	1,801,798	34,390,659	2,962,386	97,202,598	7.1%	64.8%	28.1%
Other heavy and civil engineering construction	763,826	278,521	514,690	5,691,324	541,312	24,446,368	11.0%	28.5%	60.5%

Meaning of 2012 NAICS code	Total capital expenditure $	Cost of maintenance (machinery & buildings) $	Rental or lease payments for equipment $	Cost of materials and supplies $	Cost of power, fuels and lubricants $	Value of construction work $	% on federally owned projects	% state & local projects	% on privately owned projects
Poured concrete foundation & structure contractors	432,282	189,104	400,473	10,824,757	673,272	29,198,829	3.4%	13.9%	82.7%
Structural steel and precast concrete contractors	143,203	50,497	247,706	2,811,813	160,594	9,776,237	6.0%	20.9%	73.1%
Framing contractors	75,202	38,841	86,707	2,988,858	149,575	8,687,631	3.4%	6.0%	90.6%
Masonry contractors	194,609	105,973	210,116	4,891,816	346,922	15,625,885	4.3%	16.6%	79.1%
Glass and glazing contractors	60,659	19,429	75,655	3,285,119	128,818	7,519,394	4.0%	13.6%	82.4%
Roofing contractors	292,694	117,739	183,863	11,019,762	541,942	28,128,487	3.4%	12.7%	83.9%
Siding contractors	49,557	19,000	31,350	1,876,367	109,685	4,868,840	1.5%	4.2%	94.3%
Other foundation, structure, and exterior contractors	89,688	32,665	100,126	1,859,098	128,957	6,570,739	3.2%	11.0%	85.8%
Electrical contractors & wiring installation contractors	1,644,529	442,891	995,390	41,828,011	1,895,768	123,113,207	5.0%	15.3%	79.6%
Plumbing, heating, and air-conditioning contractors	1,483,738	528,753	1,032,696	51,926,794	2,940,842	147,687,703	4.2%	12.3%	83.5%
Other building equipment contractors	211,842	79,036	255,513	6,213,826	355,810	24,357,668	3.6%	7.0%	89.4%
Drywall and insulation contractors	200,629	89,748	224,348	9,438,555	596,947	28,020,901	3.5%	10.7%	85.8%
Painting and wall covering contractors	185,943	73,377	221,578	3,977,872	442,394	18,719,025	4.4%	10.3%	85.3%
Flooring contractors	97,123	36,911	29,678	4,554,576	182,029	10,981,281	2.4%	8.3%	89.4%
Tile and terrazzo contractors	54,575	25,624	13,355	2,153,673	131,203	5,846,693	3.4%	8.4%	88.2%
Finish carpentry contractors	165,771	68,155	64,455	6,597,973	385,813	19,042,468	3.5%	6.6%	90.0%

Meaning of 2012 NAICS code	Total capital expenditure $	Cost of maintenance (machinery & buildings) $	Rental or lease payments for equipment $	Cost of materials and supplies $	Cost of power, fuels and lubricants $	Value of construction work $	% on federally owned projects	% state & local projects	% on privately owned projects
Other building finishing contractors	68,267	25,344	76,850	2,091,842	144,599	7,174,697	3.4%	11.7%	84.9%
Site preparation contractors	2,918,446	1,164,021	1,907,940	16,166,147	4,079,582	64,873,435	5.5%	22.4%	72.2%
All other specialty trade contractors	1,049,867	349,413	530,991	12,224,677	1,189,951	34,809,517	3.4%	12.1%	84.5%

Source: Economic Census, Detailed Construction Statistics, 2012. (EC1223SG01).

Notes: Values are in 1,000s.

State Specific: Fuel Expenditures, Emission Factors and Emissions

Table 26. Expenditures on Fuel, from 2012 Economic Census (in $1,000)

State	NAICS	natural gas	on-highway fuel	off-highway fuel	purchased electricity
Alabama	23	16,084	214,275	65,761	43,093
Alaska	23	5,352	45,720	35,958	9,366
Arizona	23	4,127	260,959	84,561	42,707
Arkansas	23	4,288	133,640	50,187	16,286
California	23	69,611	1,404,330	306,186	336,007
Colorado	23	27,692	304,384	121,617	57,294
Connecticut	23	9,388	172,708	39,740	26,724
Delaware	23	1,178	45,959	11,454	7,392
DC	23	1,351	13,871	1,924	2,742
Florida	23	23,613	760,735	253,467	159,106
Georgia	23	16,687	392,025	116,865	78,008
Hawaii	23	985	46,812	18,201	13,816
Idaho	23	9,108	97,856	25,899	13,058
Illinois	23	32,503	460,573	224,347	82,639
Indiana	23	45,586	315,651	112,555	45,123
Iowa	23	13,118	210,927	113,758	27,210
Kansas	23	12,411	173,914	78,151	29,161
Kentucky	23	9,028	187,330	69,488	26,838
Louisiana	23	5,680	287,929	114,517	40,637
Maine	23	6,024	96,030	30,998	11,734
Maryland	23	13,341	380,796	67,698	66,534
Massachusetts	23	21,301	316,329	73,069	51,431
Michigan	23	30,849	386,412	111,559	52,780
Minnesota	23	30,294	386,649	185,657	52,470
Mississippi	23	5,522	143,554	46,649	21,398
Missouri	23	10,721	247,533	94,085	49,315
Montana	23	4,217	101,586	46,435	10,023
Nebraska	23	10,440	129,212	48,884	17,224
Nevada	23	2,101	127,310	48,152	24,785
New Hampshire	23	9,679	86,970	27,935	11,936
New Jersey	23	17,551	343,611	97,994	62,074
New Mexico	23	4,687	112,621	35,939	12,961
New York	23	47,271	672,901	190,017	153,242
North Carolina	23	22,220	477,196	152,407	86,766
North Dakota	23	10,418	110,778	66,617	11,019
Ohio	23	40,828	454,345	160,493	81,404
Oklahoma	23	12,085	230,590	82,703	29,713
Oregon	23	8,297	185,063	37,003	29,971
Pennsylvania	23	43,884	656,237	187,752	96,726
Rhode Island	23	3,139	46,174	6,315	7,546
South Carolina	23	8,948	192,352	68,420	40,345

State	NAICS	natural gas	on-highway fuel	off-highway fuel	purchased electricity
South Dakota	23	4,001	76,344	20,771	11,970
Tennessee	23	14,472	252,780	81,949	118,714
Texas	23	66,246	1,460,493	575,653	279,182
Utah	23	9,909	188,465	71,642	26,035
Vermont	23	2,335	45,569	15,928	5,740
Virginia	23	24,420	479,966	131,167	94,755
Washington	23	11,166	363,212	106,727	58,658
West Virginia	23	3,193	86,139	45,819	10,251
Wisconsin	23	31,601	306,813	148,777	44,947
Wyoming	23	6,956	74,796	32,936	8,830
United States	23	845,906	14,748,424	4,942,786	2,697,686

Source: Economic Census, 2012.

Table 27. Fuel Prices (Dollars per Million Btu)

	natural gas	distillate fuel oil	motor gasoline	retail electricity
Alabama	4.28	24.21	27.57	18.24
Alaska	5.05	27.14	35.56	49.3
Arizona	5.66	25.87	28.27	19.14
Arkansas	6.32	24.68	27.69	16.9
California	5.66	26.03	31.59	30.74
Colorado	5.58	24.67	28.41	20.36
Connecticut	8.56	25.27	29.95	37.01
Delaware	11.29	23.47	28.95	24.49
DC*	4.91	25.06	30.5	16
Florida	6.83	25.13	27.71	23.55
Georgia	4.53	24.66	27.09	17.52
Hawaii	29.53	25.24	35.52	90.33
Idaho	5.64	25.49	29.72	16.05
Illinois	5.58	24.84	28.66	16.99
Indiana	6.12	24.9	27.68	18.58
Iowa	4.64	25.45	28.09	15.52
Kansas	3.86	25.52	27.73	20.78
Kentucky	3.84	25.45	28.86	15.68
Louisiana	2.92	24.21	27.56	13.95
Maine	10.06	24.95	29.73	23.39
Maryland	7.72	24.73	29.08	23.68
Massachusetts	9.5	25.25	29.05	36.83
Michigan	7.26	25.45	27.92	22.34
Minnesota	4.4	26.24	28.97	19.16
Mississippi	4.78	24.91	27.59	18.29
Missouri	7.87	25.02	27.29	17.27
Montana	7.36	23.97	29.43	14.96
Nebraska	4.26	25.33	28.67	20.54
Nevada	7.08	25.93	29.24	19

	natural gas	distillate fuel oil	motor gasoline	retail electricity
New Hampshire	10.15	23.76	29.01	34.68
New Jersey	7.66	25.18	28.38	30.82
New Mexico	4.76	24.47	27.8	17.09
New York	6.7	24.65	29.22	19.62
N. Carolina	6.28	24.84	29.11	18.82
N. Dakota	4.21	25.21	29.75	19.2
Ohio	5.3	25.33	28.45	18.27
Oklahoma	7.41	25.09	27.33	14.91
Oregon	5.74	24.27	29.99	16.37
Pennsylvania	9.18	25.38	29.77	21.18
Rhode Island	9.49	25.42	29.57	31.29
S. Carolina	4.22	25.13	27.25	17.65
S. Dakota	5.28	24.97	28.93	19.26
Tennessee	4.87	25.69	27.62	20.74
Texas	2.94	24.73	27.4	16.27
Utah	4.49	25.4	29.54	16.47
Vermont	4.83	25.19	30.06	29.25
Virginia	5.11	24.76	29.65	19.68
Washington	8.52	26.04	30.4	12.12
W. Virginia	3.29	25.13	29.47	18.55
Wisconsin	5.7	25.21	29.14	21.53
Wyoming	4.71	24.93	27.85	17.67
United States	4.91	25.13	28.82	19.59

Source: SEPER, Table E5. Industrial Sector Energy Price Estimates, 2012.
*Use US avg price for NG.

Table 28. Quantities (Million Btu)

	natural gas	on-highway	off-highway	electricity
Alabama	3,757,944	8,276,362	2,716,274	2,362,555
Alaska	1,059,802	1,458,373	1,324,908	189,980
Arizona	729,152	9,640,155	3,268,690	2,231,296
Arkansas	678,481	5,103,685	2,033,509	963,669
California	12,298,763	48,744,533	11,762,812	10,930,612
Colorado	4,962,724	11,468,877	4,929,753	2,814,047
Connecticut	1,096,729	6,255,270	1,572,616	722,075
Delaware	104,340	1,753,491	488,027	301,837
DC	275,153	499,316	76,776	171,375
Florida	3,457,247	28,793,906	10,086,232	6,756,093
Georgia	3,683,664	15,150,725	4,739,051	4,452,511
Hawaii	33,356	1,540,882	721,117	152,950
Idaho	1,614,894	3,544,865	1,016,046	813,583
Illinois	5,824,910	17,217,682	9,031,683	4,863,979
Indiana	7,448,693	12,006,504	4,520,281	2,428,579
Iowa	2,827,155	7,879,230	4,469,862	1,753,222

	natural gas	on-highway	off-highway	electricity
Kansas	3,215,285	6,531,981	3,062,343	1,403,321
Kentucky	2,351,042	6,898,545	2,730,373	1,711,607
Louisiana	1,945,205	11,123,392	4,730,153	2,913,047
Maine	598,807	3,512,436	1,242,405	501,667
Maryland	1,728,109	14,153,354	2,737,485	2,809,713
Massachusetts	2,242,211	11,651,160	2,893,822	1,396,443
Michigan	4,249,174	14,480,495	4,383,458	2,362,578
Minnesota	6,885,000	14,006,484	7,075,343	2,738,518
Mississippi	1,155,230	5,468,724	1,872,702	1,169,929
Missouri	1,362,262	9,464,080	3,760,392	2,855,530
Montana	572,962	3,804,719	1,937,213	669,987
Nebraska	2,450,704	4,785,630	1,929,886	838,559
Nevada	296,751	4,615,189	1,857,000	1,304,474
New Hampshire	953,596	3,296,191	1,175,715	344,175
New Jersey	2,291,253	12,830,881	3,891,739	2,014,082
New Mexico	984,664	4,309,202	1,468,696	758,397
New York	7,055,373	24,982,402	7,708,600	7,810,499
N. Carolina	3,538,217	17,690,306	6,135,548	4,610,308
N. Dakota	2,474,584	4,031,223	2,642,483	573,906
Ohio	7,703,396	16,896,430	6,336,084	4,455,610
Oklahoma	1,630,904	8,797,787	3,296,253	1,992,824
Oregon	1,445,470	6,821,342	1,524,639	1,830,849
Pennsylvania	4,780,392	23,798,259	7,397,636	4,566,856
Rhode Island	330,769	1,679,360	248,426	241,163
S. Carolina	2,120,379	7,344,483	2,722,642	2,285,836
S. Dakota	757,765	2,832,801	831,838	621,495
Tennessee	2,971,663	9,483,399	3,189,918	5,723,915
Texas	22,532,653	56,032,726	23,277,517	17,159,312
Utah	2,206,904	6,860,757	2,820,551	1,580,753
Vermont	483,437	1,649,557	632,314	196,239
Virginia	4,778,865	17,642,566	5,297,536	4,814,787
Washington	1,310,563	12,870,730	4,098,579	4,839,769
W. Virginia	970,517	3,155,275	1,823,279	552,615
Wisconsin	5,544,035	11,290,267	5,901,507	2,087,645
Wyoming	1,476,858	2,834,255	1,321,139	499,717
US	157,248,008	546,960,245	196,712,853	134,144,486
%	0.15	0.53	0.19	0.13

Table 29. State-Specific Emissions Factors (lb/MWh)

State FIPS	State Abb.	State Name	co_2 (lb/MWh)	co_2e (lb/MWh)	co_2 (lb/MBtu)	co_2e (lb/MBtu)
1	AL	Alabama	1,205.0	1,210.7	353.1	354.8
2	AK	Alaska	1,087.2	1,089.8	318.6	319.4
4	AZ	Arizona	1,151.2	1,156.2	337.4	338.9
5	AR	Arkansas	1,110.1	1,114.2	325.3	326.5
6	CA	California	665.4	667.9	195.0	195.8
8	CO	Colorado	1,814.9	1,824.0	531.9	534.6
9	CT	Connecticut	637.9	642.7	187.0	188.4
10	DE	Delaware	858.6	862.7	251.6	252.8
11	DC	DC	858.6	862.7	251.6	252.8
12	FL	Florida	1,126.4	1,131.0	330.1	331.4
13	GA	Georgia	1,148.5	1,153.8	336.6	338.1
15	HI	Hawaii	1,471.0	1,478.6	431.1	433.3
16	ID	Idaho	665.8	669.2	195.1	196.1
17	IL	Illinois	1,492.8	1,500.5	437.5	439.7
18	IN	Indiana	1,379.5	1,386.6	404.3	406.4
19	IA	Iowa	1,426.4	1,434.5	418.0	420.4
20	KS	Kansas	1,721.5	1,730.3	504.5	507.1
21	KY	Kentucky	1,340.0	1,346.9	392.7	394.7
22	LA	Louisiana	1,159.1	1,163.5	339.7	341.0
23	ME	Maine	637.9	642.7	187.0	188.4
24	MD	Maryland	887.2	891.5	260.0	261.3
25	MA	Massachusetts	637.9	642.7	187.0	188.4
26	MI	Michigan	1,532.3	1,540.3	449.1	451.4
27	MN	Minnesota	1,425.2	1,433.3	417.7	420.0
28	MS	Mississippi	1,188.4	1,193.7	348.3	349.8
29	MO	Missouri	1,703.7	1,712.5	499.3	501.9
30	MT	Montana	739.6	743.5	216.8	217.9
31	NE	Nebraska	1,425.2	1,433.3	417.7	420.0
32	NV	Nevada	990.1	994.5	290.2	291.5
33	NH	New Hampshire	637.9	642.8	187.0	188.4
34	NJ	New Jersey	847.3	851.3	248.3	249.5
35	NM	New Mexico	1,178.5	1,183.7	345.4	346.9
36	NY	New York	566.6	568.3	166.0	166.6
37	NC	N. Carolina	938.7	943.8	275.1	276.6
38	ND	N. Dakota	1,425.2	1,433.3	417.7	420.0
39	OH	Ohio	1,378.2	1,385.2	403.9	406.0
40	OK	Oklahoma	1,523.5	1,530.2	446.5	448.5
41	OR	Oregon	665.8	669.2	195.1	196.1
42	PA	Pennsylvania	1,012.4	1,017.4	296.7	298.2
44	RI	Rhode Island	637.9	642.7	187.0	188.4
45	SC	S. Carolina	932.9	937.9	273.4	274.9
46	SD	S. Dakota	1,428.8	1,436.9	418.7	421.1
47	TN	Tennessee	1,336.9	1,343.7	391.8	393.8
48	TX	Texas	1,180.1	1,184.5	345.8	347.1

State FIPS	State Abb.	State Name	CO_2 (lb/MWh)	CO_2e (lb/MWh)	CO_2 (lb/MBtu)	CO_2e (lb/MBtu)
49	UT	Utah	667.4	670.7	195.6	196.6
50	VT	Vermont	637.9	642.7	187.0	188.4
51	VA	Virginia	942.3	947.4	276.2	277.6
53	WA	Washington	665.8	669.2	195.1	196.1
54	WV	W. Virginia	1,327.6	1,334.4	389.1	391.1
55	WI	Wisconsin	1,444.5	1,452.2	423.3	425.6
56	WY	Wyoming	1,027.8	1,033.2	301.2	302.8
		US	1,136.5		333.1	

Table 30. GHG Emissions in lbs

State	Natural gas	On-highway	Off-highway	Electricity	Total emissions	Value of work (in thousands)	e/$
Alabama	470,457,000	1,392,117,115	468,804,492	909,405,504	3,240,784,111	17,730,507	182.8
Alaska	132,676,610	245,304,207	228,667,177	65,980,580	672,628,573	6,385,918	105.3
Arizona	91,282,532	1,621,512,657	564,146,407	820,525,855	3,097,467,452	26,006,452	119.1
Arkansas	84,939,038	858,460,285	350,965,337	341,737,934	1,636,102,594	8,900,343	183.8
California	1,539,682,171	8,199,025,454	2,030,155,510	2,323,585,658	14,092,448,793	146,865,780	96.0
Colorado	621,283,419	1,929,111,015	850,830,954	1,631,495,620	5,032,721,009	29,484,779	170.7
Connecticut	137,299,500	1,052,161,406	271,419,325	147,141,246	1,608,021,477	15,149,227	106.1
Delaware	13,062,340	294,944,206	84,229,114	82,783,403	475,019,063	3,773,728	125.9
DC	34,446,373	83,986,958	13,250,801	47,002,133	178,686,265	2,638,916	67.7
Florida	432,812,807	4,843,250,187	1,740,792,797	2,431,037,130	9,447,892,921	65,882,510	143.4
Georgia	461,157,954	2,548,412,487	817,917,568	1,633,561,501	5,461,049,509	36,347,780	150.2
Hawaii	4,175,826	259,182,543	124,458,351	71,870,005	459,686,725	7,871,733	58.4
Idaho	202,168,532	596,260,483	175,360,310	173,027,391	1,146,816,716	6,482,270	176.9
Illinois	729,220,532	2,896,083,024	1,558,787,161	2,319,444,694	7,503,535,411	53,632,061	139.9
Indiana	932,501,853	2,019,542,062	780,159,840	1,070,205,339	4,802,409,093	27,022,902	177.7
Iowa	353,931,556	1,325,318,084	771,458,034	798,850,340	3,249,558,015	15,239,001	213.2
Kansas	402,521,526	1,098,705,369	528,532,886	771,703,964	2,801,463,745	13,535,856	207.0
Kentucky	294,326,906	1,160,362,928	471,237,855	732,680,814	2,658,608,503	13,241,536	200.8
Louisiana	243,520,274	1,870,999,015	816,381,807	1,078,618,303	4,009,519,400	25,765,883	155.6
Maine	74,964,668	590,805,783	214,427,888	102,227,541	982,425,881	4,459,724	220.3
Maryland	216,341,942	2,380,650,823	472,465,245	796,327,527	3,865,785,537	37,114,022	104.2
Massachusetts	280,702,336	1,959,771,754	499,447,595	284,560,949	3,024,482,634	33,398,236	90.6
Michigan	531,954,037	2,435,677,124	756,545,358	1,156,479,583	4,880,656,102	32,208,855	151.5
Minnesota	861,933,150	2,355,946,691	1,221,140,522	1,246,739,115	5,685,759,477	32,482,160	175.0
Mississippi	144,623,259	919,861,220	323,211,464	444,126,770	1,831,822,713	8,735,447	209.7
Missouri	170,541,549	1,591,896,033	649,009,762	1,554,101,114	3,965,548,457	25,518,677	155.4
Montana	71,729,107	639,968,972	334,345,560	158,301,202	1,204,344,842	5,079,580	237.1
Nebraska	306,803,662	804,962,046	333,080,870	381,762,796	1,826,609,375	8,625,895	211.8
Nevada	37,150,309	776,293,320	320,501,420	412,569,125	1,546,514,175	12,209,043	126.7

State	Natural gas	On-highway	Off-highway	Electricity	Total emissions	Value of work (in thousands)	e/$
New Hampshire	119,380,691	554,432,514	202,917,912	70,136,820	946,867,936	5,115,593	185.1
New Jersey	286,841,996	2,158,205,551	671,679,208	545,172,894	3,661,899,648	39,551,802	92.6
New Mexico	123,270,069	724,825,050	253,483,774	285,520,002	1,387,098,896	6,888,631	201.4
New York	883,262,163	4,202,139,959	1,330,435,053	1,413,654,661	7,829,491,836	86,443,713	90.6
N. Carolina	442,949,331	2,975,580,203	1,058,940,279	1,382,465,726	5,859,935,540	35,636,050	164.4
N. Dakota	309,793,211	678,067,784	456,068,808	261,276,879	1,705,206,683	6,393,574	266.7
Ohio	964,388,174	2,842,047,095	1,093,551,021	1,961,609,653	6,861,595,942	42,400,586	161.8
Oklahoma	204,172,895	1,479,822,982	568,903,686	969,889,302	3,222,788,864	16,087,052	200.3
Oregon	180,958,437	1,147,376,957	263,139,051	389,372,959	1,980,847,405	16,425,776	120.6
Pennsylvania	598,457,294	4,002,962,406	1,276,765,383	1,476,931,244	7,355,116,328	54,483,722	135.0
Rhode Island	41,409,000	282,475,050	42,876,167	49,143,184	415,903,401	4,737,370	87.8
S. Carolina	265,450,265	1,235,371,356	469,903,550	681,189,450	2,651,914,622	15,065,933	176.0
S. Dakota	94,864,619	476,488,541	143,567,788	283,659,021	998,579,969	4,096,875	243.7
Tennessee	372,022,522	1,595,145,643	550,551,182	2,444,471,967	4,962,191,314	22,646,357	219.1
Texas	2,820,862,837	9,424,928,624	4,017,489,969	6,468,606,900	22,731,888,329	144,580,057	157.2
Utah	276,282,341	1,154,006,802	486,801,749	337,036,521	2,254,127,413	16,155,098	139.5
Vermont	60,521,460	277,462,012	109,131,776	39,988,772	487,104,020	2,980,208	163.4
Virginia	598,266,106	2,967,550,122	914,307,096	1,449,309,279	5,929,432,602	41,895,334	141.5
Washington	164,069,430	2,164,908,265	707,377,867	1,029,290,263	4,065,645,825	33,234,246	122.3
W. Virginia	121,498,988	530,729,830	314,681,537	234,355,919	1,201,266,274	4,871,594	246.6
Wisconsin	694,057,753	1,899,068,035	1,018,547,053	963,306,865	4,574,979,705	25,148,760	181.9
Wyoming	184,887,822	476,733,095	228,016,734	164,067,955	1,053,705,606	4,112,353	256.2
US-1	19,685,878,171	92,000,901,126	33,950,868,055	46,888,309,373	192,525,956,724	1,350,739,505	142.5
US-2	19,685,878,171	92,000,901,126	33,950,868,055	48,705,045,818	194,342,693,169	1,350,739,505	143.9

ACRONYMS AND ABBREVIATIONS

AEO	Annual Energy Outlook
BAAQMD	Bay Area Air Quality Management District
BTU	British Thermal Unit
CAFE	Corporate Average Fuel Economy
CARB	California Air Resources Board
CE-CERT	College of Engineering Center for Environmental Research and Technology
CFET	Carbon Footprint Estimation Tool
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CRs	Concentration Ratios
DOORS	Diesel Off-Road Online Reporting System
DOT	Department of Transportation
ECM	Engine Control Module
eGRID	Emissions and Generation Resource Integrated Database
EPA	Environmental Protection Agency
GHG	Greenhouse Gas
GreenLITES	Green Leadership in Transportation Environmental Sustainability
GPC	Green Performance Contracting
HHI	Herfindahl-Hirschman Index
HP	Horsepower
IEA	International Energy Agency
I-LAST	Illinios-Livable and Sustainable Transportation Rating System
IPCC	Intergovernmental Panel on Climate Change
LEED	Leadership in Energy and Environmental Design
LR	Lewis and Rasdorf
$MMTCO_2E$	Million Metric Tons of Carbon Dioxide Equivalent
MOVES	Motor Vehicle Emission Simulator
NAICS	North American Industry Classification System
NCDC	National Clean Diesel Campaign
NEMS	National Energy Modeling System
NMHC	Nonmethane Hydrocarbons
NO_x	Nitrogen Oxide
PaLATE	Pavement Life-cycle Assessment Tool for Environmental and Economic Effects
PH	CAT Performance Handbooks
PM	Particulate Matter
PS&Es	Plans, Specifications & Estimates

R&D	Research and Development
SEPER	State Energy Price and Expenditure Report
T&D	Transmissions and Distribution
UNFCC	U.N. Framework on Climate Change
URBEMIS	Urban Emissions Model

ENDNOTES

1. http://www.ucsusa.org/global_warming/science_and_impacts/science/CO2-and-global-warming-faq.html

2. EIA, International Energy Outlook, 2016, p. 139.

3. IPCC (2014, p. 4). http://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf

4. IPCC (2014). Historical temperature information taken from p. 2. Information on the causal effect of anthropogenic emissions taken from page 4. Projections and quotation taken from p. 10.

5. Figure 2: Total U.S. Greenhouse Gas Emissions in the U.S. by Economic Sector in 2014. Source: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2014.

6. According to the Bureau of Labor Statistics, in 2016 the U.S. construction industry employed a total of approximately 6.7 million workers (https://www.bls.gov/iag/tgs/iag23.htm). Total U.S. employment comprises 145,128,000, so construction industry employment as a percentage of total U.S. employment is 4.62%.

7. EPA, 2008, pp. 1-1 and authors' calculations.

8. Supplemental data files associated with this report are available for download at http://transweb.sjsu.edu/project/1533.html

9. Research projects originate in many ways. This one originated from discussion between personnel at Mineta Transportation Institute and US DOT and evolved under the guidance of the authors for the duration of the contract period. Although our choice of a focus on highways may therefore seem purely idiosyncratic, we find having a representative example to be useful for sharpening the discussion of specific policies, including green procurement, and technologies including hybrid diesel engines and all electric equipment. A focus on transportation can also be motivated by the large share of GHG emissions originating from transportation activities.

10. A scholarly literature on organizational management has studied innovation in equipment manufacturing. This literature complements the policy-focused approach of this report. See Murray R. Millson and David Wilemon, Innovation in Heavy Construction Equipment Manufacturing: An Exploratory Study, *International Journal of Innovation Management*, Vol. 10, No. 2 (June 2006) pp. 127–161.

11. Sources: http://www.cat.com/en_US/products/new/equipment/dozers/medium-dozers/1000000223.html, http://www.komatsu.com.au/Equipment/Pages/Excavators/HB215LC-1.aspx, https://www.deere.com/en/loaders/wheel-loaders/644k-wheel-loader/, https://www.greenmachineco.com/e240-electric-mini-excavator/ (see also: http://www.worldhighways.com/event-news/conexpo-con-agg/2017/news/battery-powered-excavator-from-takeuchi/) All links accessed August 9, 2017.

12. NAICS defines industries at various levels of specification. The subsectors of the construction industry include: Construction Buildings (NAICS code: 236), Heavy and Civil Engineering Construction (NAICS code: 237), and Specialty Trade Contractors (NAICS code: 238). These subindustries are further subdivided and we discuss these subsectors in more detail below.

13. Though one of their survey participants suggested hybrid equipment had potential to reduce fuel use; this quotation can be found on p. 55 of the report.

14. Hill, Nikolas, et al. "Reduction and Testing of Greenhouse Gas (GHG) Emissions from Heavy Duty Vehicles–Lot 1: Strategy," Final report to the European Commission–DG Climate Action. AEA Technology plc (2011).

15. Johnson et al. (2013). The equipment reviewed was the Caterpillar D7E and the Komatsu HB215LC-1 (HB215).

16. For example, Liu et al. 2014 analyze the life-cycle emissions of alternative pavement resurfacing designs, including the use of recycled pavement. They find that although use of recycled pavement results in up to 50% lower GHG emissions from the initial construction phase, from a life-cycle perspective, the performance of the recycled products is likely to have substantial weight from the use phase. Their life-cycle, or cradle-to-grave analysis includes the following six phases: site preparation, material production, equipment usage, traffic delay, use phase, and end-of-life. For an example of a government program see http://www.calrecycle.ca.gov/condemo/

17. A link to the survey form construction firms complete when responding to the Economic Census can be found here: https://www2.census.gov/programs-surveys/economic-census/2012/questionnaires/forms/cc23701.pdf

18. Whereas 33311 is divided into two: the larger is farm machinery and equipment manufacturing (333111) and the smaller component is lawn and garden tractor and home lawn and garden equipment manufacturing (333112), and 33313 is also divided into two: mining machinery and equipment manufacturing (333131) and oil and gas field machinery and equipment manufacturing (333132). The former subsector contains about 30% of the companies in 33313 and the latter about 70%.

19. HHI is a common concentration ratio and is calculated by summing the squared market share of each competing firm. The index can range from 0 to 1000 with the index increasing as market share per firm increases.

20. The Yellow Table is an annual table released by KHL through its International Construction magazine, ranking the top 50 construction equipment manufacturers by sales.

21. This comes from here: https://www.statista.com/statistics/280344/size-of-the-global-construction-machinery-market/ Here is another source of industry information from the same source: https://www.statista.com/topics/992/construction-equipment/

22. The full table is available at: http://www.khl-group.com/digital-mag/ICON/2015/ICON-April-2015/files/assets/basic-html/page14.html

23. "Final Rule for Determination of Significance for Nonroad Sources and Emission Standards for New Nonroad Compression-Ignition Engine At or Above 37 Kilowatts" 1994. https://www.gpo.gov/fdsys/pkg/FR-1994-06-17/html/94-13956.htm

24. Control of Emissions of Air Pollution From Nonroad Diesel Engines and Fuel, US EPA Final Rule. Federal Register / Vol. 69, No. 124 / Tuesday, June 29, 2004 / Rules and Regulations https://www.gpo.gov/fdsys/pkg/FR-2004-06-29/pdf/04-11293.pdf

25. Business Pathfinder, "Electric and Hybrid Construction Machinery for Low Emission and Cost Effective Equipment," https://www.linkedin.com/pulse/electric-hybrid-construction-machinery-low-emission-cost-on-fire?trk=mp-reader-card, Published on August 17, 2016.

26. Jixin Wang, Zhiyu Yang, Shaokang Liu, Qingyang Zhang and Yunwu Han, "A Comprehensive Overview of Hybrid Construction Machinery," *Advances in Mechanical Engineering*, Vol. 8(3) 1–15, DOI:10.1177/1687814016636809, SAGE, 2016.

27. In June 2008, Komatsu led the world by introducing the world's first hybrid hydraulic excavator, "PC200-8 E0 Hybrid" on the Japanese market. In fiscal 2009, Komatsu embarked on sales in China and test marketing in North America. As of October 31, 2010 over 650 units were in operation around the world." (http://www.komatsu.com/CompanyInfo/press/2010112911374014646.html)

28. JP Morgan, "Hybrid Equipment – Construction," Equipment Insight, Volume 11, February 2015. https://commercial.jpmorganchase.com/jpmpdf/1320706194621.pdf

29. Jixin Wang, Zhiyu Yang, Shaokang Liu, Qingyang Zhang and Yunwu Han, "A Comprehensive Overview of Hybrid Construction Machinery," *Advances in Mechanical Engineering*, Vol. 8(3) 1–15, DOI:10.1177/1687814016636809, SAGE, 2016.

30. Lin T, Wang Q, Hu B, and Gong, W., "Development of Hybrid Powered Hydraulic Construction Machinery," *Automation in Construction*, 2010; 19: 11–19.

31. J.P.Morgan, "Hybrid Equipment – Construction," Equipment Insight, Volume 11, February 2015.

32. Lewis, P., & Rasdorf, W. (2017). "Fuel Use and Pollutant Emissions Taxonomy for Heavy Duty Diesel Construction Equipment," *Journal of Management in Engineering*, Volume 33 Issue 2, 04016038

33. Nealon, S., "Hybrid Not Always Greener," UCR Today, https://ucrtoday.ucr.edu/18506, October 21, 2013.

34. Egelja, A., “Engineering a Groundbreaking Hydraulic Hybrid,” *Fluid Power World*, https://issuu.com/wtwhmedia/docs/fluid_power_world_september_2016/1?e=7799406/38953148, September 16, 2016.

35. Johnson, K., Burnette, A., Cao, T., Russell, R., and Scora, G., “Hybrid Off-Road Equipment In-Use Emissions Evaluation,” FY 2010-11 Air Quality Improvement Project, California Air Resources Board, 2013.

36. Lin T, Wang Q, Hu B, and Gong, W., “Development of Hybrid Powered Hydraulic Construction Machinery. *Automation in Construction*, 2010; 19: 11–19.

37. Tudor Van Hampton, T., “Cat Reveals Pricing of World’s First Hybrid Dozer,” http://www.enr.com/articles/9256-cat-reveals-pricing-of-world-s-first-hybrid-dozer?v=preview, June 24, 2009.

38. Caterpillar, “D7E Cuts Fuel Costs: D7E Delivers 50% Fuel Savings for Arkansas Landfill,” http://www.cat.com/en_US/articles/customer-stories/construction/d7e-cuts-fuel-costs.html, Retrieved on Jan 5, 2017.

39. Caterpillar, “Caterpillar Unveils First Hybrid Excavator,” Release Number: 335PR12, http://www.cat.com/en_US/news/machine-press-releases/caterpillar-unveilsfirsthybridexcavator.html, October 16, 2012.

40. IDTechEx Report, “Industrial and Commercial Electric Vehicles on Land 2017-2027,” IDTechEx, http://www.printedelectronicsworld.com/research/reports/industrial-and-commercial-electric-vehicles-on-land-2017-2027-000505.asp, 2016.

41. Peter Harrop “Electric Vehicles in Construction are the Future,” IDTechEx, http://www.idtechex.com/research/articles/electric-vehicles-in-construction-are-the-future-00010378.asp, 2016.

42. Yamamoto, H., Fujita, K., and Murata, H., “Product and Market Development of Large Electrically Driven Hydraulic Excavators Enjoying Strong Demand in Emerging Economies,” *Hitachi Review*, Vol. 58, No. 6, 2009.

43. Harrop, P., “Breakthrough Huddig Hybrid Wheel Loader in 2018,” IDTechEx research article, http://www.idtechex.com/research/articles/breakthrough-huddig-hybrid-wheel-loader-in-2018-00010379.asp, 2016.

44. Grayson, W., “Wacker Neuson is Quietly Building an Entire Line of Electric Loaders, Excavators and More,” *Equipment World Newsletter*, http://www.equipmentworld.com/wacker-neuson-is-quietly-building-an-entire-line-of-electric-loaders-excavators-and-more/, May 5, 2016.

45. http://www.takeuchi-us.com/www/blog/viewpost/43/takeuchi-introduces-worlds-first-fully-electric-hydraulic-excavator

46. http://www.takeuchi-us.com/www/docs/217.693/tb216h---hybrid-compact-excavator.html

47. We reviewed this model in detail in the course of our review of previous attempts and describe it here in order for the benefit of the more specialized reader. The GHG emissions and energy consumption figures cited above, and most other projections in the AEO, are model output from the National Energy Modeling System (NEMS), “an integrated model of the U.S. energy system linked to a macroeconomic model.” (https://www.eia.gov/forecasts/aeo/info_nems_archive.cfm) The Energy Information Administration published an overview of the NEMS in 2009 (http://www.eia.gov/forecasts/archive/0581(2009).pdf). This model is calibrated to a base year, using a variety of public and some proprietary data sources, and projections, currently to 2040, are made under baseline and alternative scenarios for use in public policy analysis and decision-making. The accuracy of current year and future projections depend on many factors, and the EIA assesses the quality of the forecasts annually through its “retrospectives” series. Within NEMS, construction is modeled as a part of the Industrial Demand Module (IDM) where “construction uses diesel fuel, gasoline, electricity and natural gas as energy sources. Construction also uses asphalt and road oil as a nonfuel energy source” (EIA, 2014, p. 64). These are the sources listed in the Table 9 above. Thus, in the Annual Energy Outlook estimates of GHG emissions from construction, NAICS codes define the scope of activities measured, and the variables listed above define the depth of what is measured in calculating energy consumption and emissions in construction. The most detail is provided in “Model Documentation Report: Industrial Demand Module of the National Energy Modeling System” August 2014. http://www.eia.gov/forecasts/aeo/nems/documentation/industrial/pdf/m064(2014).pdf. See pp. 54-57. And asphalt use in construction is discussed on p. 59.

    We now provide an overview of the process whereby the NEMS forms projections. A reader interested in full details could consult the Model Documentation Report cited above. The methodology used in AEO was also summarized in the 2009 EPA report on construction, as follows: “The AEO 2008 produces estimates as model output of the EIA National Energy Modeling System’s Industrial Sector Demand module, based on the following sources: DOE’s 2002 Manufacturing Energy Consumption Survey; aggregated construction sector data of the U.S. Department of Commerce, Census Bureau, Economic Census 2002: Construction Industry Series; the EIA’s Fuel Oil and Kerosene Sales 2002; and EIA’s 2006 release of State Energy Data System 2003. In order to calculate energy consumption, these estimates delineate fuel usage per value output as Unit Energy Consumption (UEC) ratios, since the source data relate to total energy consumption and provide no information on the processes or end-uses. For diesel, gasoline, and purchased electricity, CO2 emissions are calculated as the product of an EIA emissions factor and the modeled energy consumption.” The NEMS contains a Macro Activity Module (MAM) that produces “value of shipments” figures for all industries. The value of shipments is multiplied by “construction shipments from the MAM for region r and year y” is multiplied by a UEC to arrive at “quantity demanded in region r of fuel f for year y.” The UEC is “unit energy consumption” and is defined for each region r, fuel f and year y. The projections are then based on last year’s UEC, and a “technological possibilities curve" (TPC) which is calibrated to the expected level of innovation in this industry. The final step in calculating the GHG emissions in the AEO is to multiply the energy consumption, which is model output from NEMS, by the appropriate emissions factor. The latest carbon dioxide emissions components can be found on the EIA webpage at http://www.eia.gov/environment/emissions/co2_vol_mass.cfm. For example, for 2016 the emissions calculations involve multiplying 297.4, the NEMS estimate of distillate fuel oil used in this industry (shown in the Table 9 above) by 161.3 (the appropriate emissions factors for diesel fuel) to arrive at pounds of CO2 per million Btu, performing similar calculations for the other fuels, and summing up emissions. Note these factors are only for CO2 and exclude methane and other GHGs. As noted by EPA report, "methane (CH4) emissions from uncontrolled heavy-duty gasoline vehicles are estimated by the US EPA's NONROAD model to be 20 times the emissions from equipment with low-emissions vehicle technology. IPCC, 2006 National Guidelines for Greenhouse Gas Inventories, 2006, Table 3.2.3. Available online at: http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_3_Ch3_Mobile_Combustion.pdf.

48. Reference to Resources For the Future version of NEMS.

49. We have downloaded the 2002 Econ Census and applied the methodology described in the Appendix to the present report and calculated emissions in each sub industry for each fuel. We find that most of our calculations are identical to the numbers reported in the 2009 EPA report, with some minor differences which seem likely to be the result of analyst error.

50. A supplemental file, with the file name "Subsectors.xlsx" contains these calculations and is available for download at: http://transweb.sjsu.edu/project/1533.html

51. We arrived at a factor not exactly 1.36 but very close, suggesting this is indeed how this method works. What we did was take the EIA861 data on electricity sales to industrial customers for every electricity producer in the U.S. for which the government collects data, and determined the total industrial sales in each state. We then assigned each state to an eGRID region. This requires some judgment because some states are served by multiple regions. We used a simple visual method and assigned the state to the region in which most of the land area appeared. We then determined the fraction of total sales to industrial customers of each region, and calculated a weighted emissions factor using these weights. The emissions factor that resulted from this procedure was 1.37, which thus seems to be how the EPA arrived at their "national" emissions factor of 1.36.

52. Melanta, S., Miller-Hooks, E., and Avetisyan, H., "Carbon Footprint Estimation Tool for Transportation Construction Projects," *Journal of Construction Engineering and Management*, ASCE, ISSN 0733-9364, Vol. 139, No. 5, May 1, 2013.

53. Mukherjee, A., Stawowy, B., and Cass, D., "Project Emission Estimator: Tool for Contractors and Agencies for Assessing Greenhouse Gas Emissions of Highway Construction Projects," Transportation Research Record: *Journal of the Transportation Research Board*, No. 2366, pp. 3–12., DOI: 10.3141/2366-01, Transportation Research Board of the National Academies, Washington, D.C., 2013.

54. Following EPA (2008), we assume 50% of expenditures for on-road fuel is gasoline and 50% is diesel. In other words, we divide on-road expenditures by the average of the price of gasoline and the price of diesel.

55. http://www.eia.gov/environment/emissions/co2_vol_mass.cfm

56. 3,412,141.63 BTU converts to 1 MWh; thus 0.29307107 MWh coverts to 1 million BTUs.

57. To convert pounds to MMT, we first divide emissions in pounds by 2204.62 to convert to metric tons, and then divide this result by 1,000,000 to convert to MMT.

58. Not only fuel consumption, but even expenditures were higher in 2002; total expenditures on fuel were nearly twice as high in 2002, even without adjusting for inflation We will download the 2002 data ourselves, adjust them for inflation, and check to see whether these figures are the same as those presented in EPA 2008.

59. http://transweb.sjsu.edu/PDFs/research/1533_Holian_Pyeon_Subsectors.xlsx

60. To facilitate producing new estimates with alternative configurations of assumptions, we provide access to supplemental materials that implements the main calculations at this website: http://transweb.sjsu.edu/PDFs/research/1533_Holian_Pyeon_Calculations.xlsx

61. Stephen P. Holland, Erin T. Mansur, Nicholas Z. Muller and Andrew J. Yates (2016), Are There Environmental Benefits from Driving Electric Vehicles? The Importance of Local Factors, *American Economic Review* 2016, 106(12): 3,700–3,729.

62. Source: California Offroad Model, Input Tables, Activity/Cumulative Hours, https://www.arb.ca.gov/msei/off-road-emissions-inventory-v3-scenpop-and-hp.mdb

63. Median Life, Annual Activity, and Load Factor Values for Nonroad Engine Emissions Modeling. Page 7.

64. The distribution we use for equipment age given by, age range (Fraction of equipment): 0-4 (9.069), 4 to 8 (0.07), 8 to 12 (0.04), 12 to 16 (0.025), 16 to 20 (0.0125), 20 to 24 (0.01), 24 to 28 (0.01), 28 to 32 (0.008), 32 to 36 (0.005), 36 to 40 (0.002).

65. NONROAD technical document, “Nonroad Engine Population Estimates” pp. A14-A15 and authors calculations We also considered using to the California OFFROAD data. The CA population is shown in column two of Table 13 below. To produce the US population estimate, we multiply the California population by 9.19, which is the ratio of US construction output (reported as $1.35 trillion in Table 25) over the value of CA construction output (reported as $146.865 billion in Table 30). Another study from 1991 examined the population of heavy construction equipment in air quality nonattainment areas. Methodology to estimate nonroad equipment populations by nonattainment areas, prepared for the US EPA by Energy and Environmental Analysis. This highlights how much of the equipment in our table runs on gasoline not diesel.

66. This is 21,319,687 / 215,466,525, where the denominator is the sum of HP times equipment population for all diesel equipment.

67. As discussed in Chapter II, the Komatsu HB215LC-1 was the first to be released in 2008, followed by the Cat 336E-H in 2012 and the Hitachi ZH210 in 2013. References for the Cat date comes from page 5 of the document here: http://s7d2.scene7.com/is/content/Caterpillar/C10876416 Reference for the Hitachi date from: http://www.ferret.com.au/c/hitachi-construction-machinery/first-hitachi-hybrid-excavators-hit-australia-n2508458

68. In 2010 US sales represented 306.1 billion Yen, out of global sales of 1,268.5 billion. http://www.komatsu.com/CompanyInfo/ir/data/data07_y.html

69. Although the LR figures are measured in terms of liters per kWh and the Cat PH figures are measured in terms of gallons per hour, the units turn out not to matter here as ultimately our fuel use rates are just scalars for equipment hours. We assigned combined fuel use rates from these two sources based on percentage changes to arrive at a measure that can take on varying units.

70. If one were interested in only the effect of hybrid technology as opposed to advancement in conventional diesel technology, one could apply a figure of around 0.20 to the CO2 estimates reported here, where 0.20 is typical of the fuel reduction of hybrid equipment compared to new conventional diesel, as reported in Chapter II.

71. Cat Says 500 Hybrid D7E Dozers Save 1.4 Million Gallons of Diesel SOURCE: CATERPILLAR - CAT OCT 5, 2012 http://www.forconstructionpros.com/press_release/10798986/cat-says-500-hybrid-d7e-dozers-save-14-million-gallons-of-diesel

72. As before, we caution against using these figures independent from the analysis in this chapter, as they are based on news reports and old population estimates, not verified sales figures.

73. One source we found described the D7E as a mid-range model. Its predecessor the D7R sold 300 units in 2008, while the smaller D6 sold 2000 and the larger D8 sold 700. This appears consistent with the range we identified as the most important contributor to GHG emissions in the dozer population. http://gas2.org/2009/09/18/caterpillar-builds-worlds-first-hybrid-bulldozer/.

74. Vauhkonen, N., Liljeström, J., Maharjan, D., Mahat, C., Sainio, P., Kiviluoma, P., & Kuosmanen, P. (2014). Electrification of excavator. In 9th International DAAAM Baltic Conference” Industrial Engineering”-24-26 April.

75. The actual calculation without rounding error is =0.3566322*22.4

76. The approach taken in Hendrickson et al. (2000) involves using input-output matrices to model the life-cycle emissions of four construction subsectors. This approach is more data intensive than the one employed here and assumes reduced form linkages

between all industries, whereas the approach we have taken in this report describes more clearly some of the complex linkages between equipment manufacturers and construction firms. Hendrickson et al. 2000. Resource use and environmental emissions of U.S. construction Sectors. Journal of Construction Engineering and Management. January, 2000. pp. 38-44

77. See for example Amrakoon et al. (2013) which evaluated the potential environmental and health impacts of lithium-ion batters for electric vehicles. Amarakoon, S., Smith, J., & Segal, B. (2013). Application of life-cycle assessment to nanoscale technology: Lithium-ion batteries for electric vehicles (No. EPA 744-R-12-001).

78. These terms were used in Cui and Zhou, 2011, European Commission, 2011, Correia et al., and Zhu et al., 2014, respectively. See also UNDP Environmental Procurement Practice Guide (2008), Varnas et al. (2009) for the case of Sweden.

79. Details on the LEED certification program can be found at: http://www.usgbc.org/leed

80. http://www.lungchicago.org/diesel-pollution-construction/

81. CAHSR. press release: http://hsr.ca.gov/docs/newsroom/eblast/Tier_4_factsheet_FINAL_2014.pdf) See also https://yosemite.epa.gov/opa/admpress.nsf/d0cf6618525a9efb85257359003fb69d/8ac2e7081a8176fc85257d95007cfe72!OpenDocument and https://www.hsr.ca.gov/docs/programs/green_practices/sustainability/Sustainability_signed_policy.pdf

82. The economic analysis of these policies is mixed; some analysts have focused on the so-called “rebound effect” where, with more fuel-efficient cars, drivers drive more and this leads to more accidents, congestion and other socially undesirable outcomes. On the face of it seems unlikely that construction practices would lead to a large rebound-type effect, but this highlights that there remain many unsettled questions with regard to the effectiveness of regulatory policies. See for example Austin and Dinan (2005). Austin, David, and Terry Dinan. “Clearing The Air: The Costs and Consequences of Higher CAFE Standards and Increased Gasoline Taxes.” *Journal of Environmental Economics and Management* 50.3 (2005): 562-582.

83. https://www.epa.gov/state-and-local-transportation/vehicle-emissions-california-waivers-and-authorizations

84. https://www.arb.ca.gov/msprog/ordiesel/ordiesel.htm.

85. https://www.arb.ca.gov/msprog/ordiesel/faq/overview_fact_sheet_dec_2010-final.pdf

86. Although beyond the scope of the present report, the impact of fuel taxes on GHG emissions in construction could be readily measured if one obtained fuel demand elasticities for construction firms. We have not encountered any of such estimates in the course of conducting this research, and it may be the case that obtaining these elasticity estimates would require original empirical analysis. State fuel tax rates are available at the following link: https://www.eia.gov/tools/faqs/faq.cfm?id=10&t=10

87. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1009QEO.pdf See page 31.

88. This report also indicated grid power, at an average cost of $0.108 per kilowatt hour (presumably these were 2007 prices) is roughly half as expensive as the average cost of generator power under typical circumstances (which they calculated as $0.205). However it is important to note that this simple analysis ignores some important considerations. For example, construction firms may be able to take depreciation when they use their generators, which through the tax code may make the marginal economic cost of diesel use cheaper.

89. On these points see Kahn and Zheng (2016) p. 130, and also Sun (2012), Kahn, Matthew E., and Siqi Zheng, “Blue Skies over Beijing: Economic Growth and the Environment in China,” *Princeton University Press*, 2016. Lin Sun, 2012, “Development and Policies of New Energy Vehicles in China,” *Asian Social Science*, Vol. 8, No. 2, pp. 86-94.

90. https://www.epa.gov/cleandiesel/clean-diesel-rebates#2013co See also CARB’s Carl Moyer Program which provides grants for cleaner-than-required equipment. https://www.arb.ca.gov/msprog/moyer/moyer.htm

BIBLIOGRAPHY

Avetisyan, Hakob G., Elise Miller-Hooks, and Suvish Melanta. "Decision Models to Support Greenhouse Gas Emissions Reduction From Transportation Construction Projects." *Journal of Construction Engineering and Management* 138.5 (2011): 631-641.

BLS 2016a. "Industries at a Glance: Construction: NAICS 23". https://www.bls.gov/iag/tgs/iag23.htm

BLS (2017). Employment, Hours, and Earnings from the Current Employment Statistics survey (National) https://data.bls.gov/timeseries/CES2000000001?amp%253bdata_tool=XGtable&output_view=data&include_graphs=true

Business Pathfinder (2016). "Electric and Hybrid Construction Machinery for Low Emission and Cost Effective Equipment" https://www.linkedin.com/pulse/electric-hybrid-construction-machinery-low-emission-cost-on-fire?trk=mp-reader-card

California High-Speed Rail Authority. April 22, 2015. High-Speed Rail Utilizes Clean Construction Practices Celebrates Earth Day By Going Green. https://www.hsr.ca.gov/docs/newsroom/2015_HSR_Utilizes_Clean_Construction_Practices.pdf

Caterpillar (2012). "Caterpillar Unveils First Hybrid Excavator," Release Number: 335PR12, http://www.cat.com/en_US/news/machine-press-releases/caterpillar-unveilsfirsthybridexcavator.html

Caterpillar (2016). "D7E Cuts Fuel Costs: D7E Delivers 50% Fuel Savings for Arkansas Landfill," http://www.cat.com/en_US/articles/customer-stories/construction/d7e-cuts-fuel-costs.html Retrieved on January 5, 2017.

Census (2017). North American Industry Classification System (NAICS): 2012 NAICS. https://www.census.gov/cgi-bin/sssd/naics/naicsrch?chart=2012

Cui, Qingbin, and Xinyuan Zhu. "Green Contracting in Highway Construction: State of the Practice." *Transportation Research Record: Journal of the Transportation Research Board* 2228 (2011): 11-18.

Cui, Qingbin, et al. (2011). Innovative Contracting Strategies for Combating Climate Change. State Highway Administration Research Report.

Cui, Qingbin, Hakob Gevorg Avetisyan, and Xinyuan Zhu (2014). "Green Performance Contracting Strategy for Highway Construction Projects."

EC, 2011. Buying Green! A Handbook on Green Public Procurement. European Commission, Luxembourg.

Equipment World, 2014. http://www.equipmentworld.com/diesel-electric-and-other-hybrid-construction-equipment-are-waging-war-on-wasted-energy/

Egelja, A., “Engineering a Groundbreaking Hydraulic Hybrid,” Fluid Power World, https://issuu.com/wtwhmedia/docs/fluid_power_world_september_2016/1?e=7799406/38953148, September 16, 2016.

IPCC (2006). “National Guidelines for Greenhouse Gas Inventories.” http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_3_Ch3_Mobile_Combustion.pdf

IPCC (2014). “Climate Change 2014: Synthesis Report Summary for Policymakers.” http://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf

Harrop, Peter (2016). “Electric Vehicles in Construction are the Future,” IDTechEx, http://www.idtechex.com/research/articles/electric-vehicles-in-construction-are-the-future-00010378.asp

Hitachi Construction Machinery. “Battery Excavators.” https://www.hitachi-c-m.com/global/environment/showcase/battery.html

Holland, Stephen P., Erin T. Mansur, Nicholas Z. Muller and Andrew J. Yates (2016). Are There Environmental Benefits from Driving Electric Vehicles? The Importance of Local Factors. *American Economic Review* 2016, 106(12): 3,700–3,729.

Hong, J., Shen, G., Feng, Y., Lau, W., and Mao, C. (2015). “Greenhouse Gas Emissions During the Construction Phase of a Building: A Case Study in China,” *Journal of Cleaner Production*. http://dx.doi.org/10.1016/j.jclepro.2014.11.023

Horvath, A. (2004). “Construction Materials and the Environment”. Annu. Rev. Environ. Resour. 29: 181-204. http://isites.harvard.edu/fs/docs/icb.topic661271.files/Horvath_Constr%20Mat%20and%20the%20Environment.pdf

IDTechEx (2016). “Industrial and Commercial Electric Vehicles on Land 2017-2027.” IDTechEx, http://www.printedelectronicsworld.com/research/reports/industrial-and-commercial-electric-vehicles-on-land-2017-2027-000505.asp

Inoue, H. (2008). “Introduction of PC200-8 Hybrid Hydraulic Excavator,” Komatsu Technical Report, VOL. 54, NO. 161, 2008. http://www.komatsu.com/CompanyInfo/profile/report/pdf/161-E-05.pdf

Johnson, K., Burnette, A., Cao, T., Russell, R., and Scora, G., “Hybrid Off-Road Equipment In-Use Emissions Evaluation,” FY 2010-11 Air Quality Improvement Project, California Air Resources Board, 2013. https://www.arb.ca.gov/msprog/aqip/off-road%20hybrid/offrd_hybrid_final_report_executive%20summary.pdf

J.P.Morgan (2015). “Hybrid Equipment – Construction,” Equipment Insight, Volume 11, February 2015. https://commercial.jpmorganchase.com/pages/commercial-banking/services/hybrid-equipment-vol11

Krasnokutskaya, E., & Seim, K. (2011). Bid Preference Programs and Participation in Highway Procurement Auctions. *The American Economic Review*, 101(6), 2,653-2,686.

Lee, Jincheol, et al. “Building Environmentally and Economically Sustainable Transportation Infrastructure: Green Highway Rating System.” *Journal of Construction Engineering and Management* 139.12 (2013): A4013006.

Lewis, P., & Rasdorf, W. (2017). Fuel Use and Pollutant Emissions Taxonomy for Heavy Duty Diesel Construction Equipment. *Journal of Management in Engineering*, Volume 33 Issue 2, 04016038.

Lin, T; Wang Q; Hu B; and Gong, W. (2010). “Development of Hybrid Powered Hydraulic Construction Machinery. Automation In Construction; 19: 11–19. https://www.researchgate.net/publication/245136295_Development_of_hybrid_powered_hydraulic_construction_machinery

Liu, Xiaoyu, Qingbin Cui and Charles Schwartz. 2014. Greenhouse Gas Emissions of Alternative Pavement Designs: Framework Development and Illustrative Application. *Journal of Environmental Management* 132, pp. 313-322.

Liu, Xiaoyu, and Qingbin Cui. “Assessing the Impacts of Preferential Procurement on Low-Carbon Building.” *Journal of Cleaner Production* 112 (2016): 863-871.

Lu, Yujie, Peng Cui, and Dezhi Li. “Carbon Emissions and Policies in China’s Building and Construction Industry: Evidence from 1994 to 2012.” *Building and Environment* 95 (2016): 94-103.

Marion, J. (2007). Are Bid Preferences Benign? The Effect of Small Business Subsidies in Highway Procurement Auctions. *Journal of Public Economics*, 91(7), 1,591-1,624.

Melanta, Suvish, Elise Miller-Hooks, and Hakob G. Avetisyan. “Carbon Footprint Estimation Tool for Transportation Construction Projects.” *Journal of Construction Engineering and Management* 139.5 (2012): 547-555.

Naegelen, F., & Mougeot, M. (1998). Discriminatory Public Procurement Policy and Cost Reduction Incentives. *Journal of Public Economics*, 67(3), 349-367.

Mukherjee, Amlan, Brian Stawowy, and Darrell Cass (2013). “Project Emission Estimator: Tool for Contractors and Agencies for Assessing Greenhouse Gas Emissions of Highway Construction Projects.” *Transportation Research Record: Journal of the Transportation Research Board* 2366 (2013): 3-12.

Mukherjee, Amlan, and Darrell Cass (2014). “The Product Process Service Life Cycle Assessment Framework to Estimate GHG Emissions for Highways.” Climate Change, Energy, Sustainability and Pavements. Springer Berlin Heidelberg. 75-125. http://link.springer.com/chapter/10.1007%2F978-3-662-44719-2_3

Nealon, S. (2013). “Hybrid Not Always Greener.” UCR Today. https://ucrtoday.ucr.edu/18506

SRA International, “Report on the Analysis and Modeling Approach to Characterize and Estimate Fuel Use by End-Use Applications in the Agriculture and Construction Industries.” unpublished report prepared for the U.S Energy Information Administration, March 2011.

Statistica (2017). “Size of the Global Construction Equipment Market from 2014 to 2017.” https://www.statista.com/statistics/280344/size-of-the-global-construction-machinery-market/

Tudor Van Hampton, T. (2009). “Cat Reveals Pricing of World’s First Hybrid Dozer.” http://www.enr.com/articles/9256-cat-reveals-pricing-of-world-s-first-hybrid-dozer?v=preview

Union of Concerned Scientists (2008). Why Does CO_2 get Most of the Attention When There are so Many Other Heat-Trapping Gases (Greenhouse Gases)? http://www.ucsusa.org/global_warming/science_and_impacts/science/CO2-and-global-warming-faq.html

Rasdorf, William, et al. “Evaluation of On-Site Fuel Use and Emissions Over the Duration of a Commercial Building Project.” *Journal of Infrastructure Systems* 18.2 (2012): 119-129.

UNFCC (2014). Background on the UNFCCC: The International Response to Climate Change http://unfccc.int/essential_background/items/6031.php

U.S. EIA (2009). “The National Energy Modeling System: An Overview 2009.” http://www.eia.gov/outlooks/archive/0581(2009).pdf

U.S. EIA (2016a). “International Energy Outlook 2016.” http://www.eia.gov/outlooks/ieo/

U.S. EIA (2016b). Annual Energy Outlook 2016: Table: Nonmanufacturing Sector Energy Consumption. http://www.eia.gov/outlooks/aeo/data/browser/#/?id=43-AEO2016&cases=ref2016~ref_no_cpp&f=Q&sourcekey=

U.S. EIA (2016c). “Carbon Dioxide Emissions Coefficients.” http://www.eia.gov/environment/emissions/co2_vol_mass.cfm

U.S. EPA (1991). Nonroad Engine and Vehicle Emission Study- Report. EPA. https://www3.epa.gov/nonroad/documents/21a2001.pdf

U.S. EPA (2008a). Quantifying Greenhouse Gas Emissions in Key Industrial Sectors. Sector Strategies Division. https://archive.epa.gov/sectors/web/pdf/greenhouse-report.pdf

U.S. EPA (2008b). "2008 Sector Performance Report," Sector Strategies Division. https://archive.epa.gov/sectors/web/pdf/2008-sector-report-supplement.pdf

U.S. EPA (2009a). Potential for Reducing Greenhouse Gas Emissions in the Construction Sector. https://archive.epa.gov/sectors/web/pdf/construction-sector-report.pdf

U.S. EPA (2009b). Frequently Asked Questions About NONROAD2008. EPA. https://www3.epa.gov/otaq/models/nonrdmdl/nonrdmdl2008/420f09021.pdf

U.S. EPA (2010). Exhaust Emission Factors for Nonroad Engine Modeling—Spark – Ignition. EPA. https://www3.epa.gov/otaq/models/nonrdmdl/nonrdmdl2010/420r10019.pdf

U.S. EPA (2016b). Inventory of U.S. Greenhouse Gas Emissions and Sinks:1990–2014. https://www.epa.gov/sites/production/files/2016-04/documents/us-ghg-inventory-2016-main-text.pdf

Vauhkonen, N., Liljeström, J., Maharjan, D., Mahat, C., Sainio, P., Kiviluoma, P., & Kuosmanen, P. (2014). Electrification of Excavator. In 9th International DAAAM Baltic Conference." Industrial Engineering-24-26 April.

Wang, Jixin; Zhiyu Yang; Shaokang Liu; Qingyang Zhang; and Yunwu Han (2016). "A Comprehensive Overview of Hybrid Construction Machinery," Advances in Mechanical Engineering, Vol. 8(3) 1–15, DOI:10.1177/1687814016636809, SAGE, 2016. http://journals.sagepub.com/doi/abs/10.1177/1687814016636809

WRI (2008). Greenhouse Gas Protocol: Product Life Cycle Accounting and Reporting Standard. World Resource Institute and World Business Council for Sustainable Development. http://www.wri.org/our-work/project/greenhouse-gas-protocol/publications?page=1

Yamamoto, H., Fujita, K., and Murata, H. (2009). "Product and Market Development of Large Electrically Driven Hydraulic Excavators Enjoying Strong Demand in Emerging Economies." *Hitachi Review*, Vol. 58, No. 6, 2009. http://www.hitachi.com/rev/pdf/2009/r2009_06_103.pdf

Yi, Kyoo-Jin. "Modelling of On-Site Energy Consumption Profile in Construction Sites and a Case Study of Earth Moving." *Journal of Construction Engineering and Project Management* 3.3 (2013): 10-16.

ABOUT THE AUTHORS

MATTHEW HOLIAN, PhD

Matthew J. Holian is a professor in the Economics Department at SJSU. He joined the faculty at SJSU in 2008 after earning his PhD in Economics at Ohio State University. He currently teaches courses in Cost-Bene it Analysis, Econometrics, Industrial Organization and Regional Economics. His research focuses on environmental, public, urban and transportation topics, and his writing has appeared in scholarly journals such as the Journal of the Association of Environmental and Resource Economists, Ecological Economics, Public Choice, Environment and Urbanization Asia and the Journal of Housing Economics. In 2014, he received the Early Career Investigator Award from the SJSU Research Foundation. He lives in San Francisco with his wife and daughter.

JAE-HO PYEON, PhD

Jae-Ho Pyeon, PhD, is an associate professor in the Department of Civil and Environmental Engineering at San José State University. Dr. Pyeon received both his master's and doctoral degrees in Civil and Coastal Engineering from the University of Florida. Currently, Dr. Pyeon is a University Representative of the Transportation Research Board and a member of the Construction Research Council, Construction Institute, and American Society of Civil Engineers. Dr. Pyeon conducts research in the area of transportation construction engineering and management and teaches undergraduate and graduate courses in construction project management, construction information technology, construction scheduling and estimating, and heavy transportation construction equipment.

PEER REVIEW

San José State University, of the California State University system, and the MTI Board of Trustees have agreed upon a peer review process required for all research published by MTI. The purpose of the review process is to ensure that the results presented are based upon a professionally acceptable research protocol.

Research projects begin with the approval of a scope of work by the sponsoring entities, with in-process reviews by the MTI Research Director and the Research Associated Policy Oversight Committee (RAPOC). Review of the draft research product is conducted by the Research Committee of the Board of Trustees and may include invited critiques from other professionals in the subject field. The review is based on the professional propriety of the research methodology.

MTI FOUNDER

MTI BOARD OF TRUSTEES

Directors

Research Associates Policy Oversight Committee

MINETA TRANSPORTATION INSTITUTE
MTI

SAN JOSÉ STATE UNIVERSITY

Funded by U.S. Department of Transportation