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Review

Toward Environmentally Sustainable Construction Processes: The U.S. and Canada's Perspective on Energy Consumption and GHG/CAP Emissions

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Abstract: In the building and construction sector, most efforts related to sustainable development have concentrated on the environmental performance of the operation of buildings and infrastructure. However, several studies have called for the need to mitigate the considerable environmental impacts, especially air pollutant emissions and energy consumption, generated by construction processes. To provide a point of reference for initiating the development of environmentally sustainable construction processes, this article identifies energy consumption and air emissions resulting from construction activities and examines previous approaches utilized to assess such environmental impact. This research also identifies the opportunities and challenges to mitigate such environmental impact from construction processes, based on the investigation of current technology policies, regulations, incentives, and guidelines.

Keywords: sustainable construction; environmental management; construction processes

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1. Introduction

The built environment has a major share of environmental impact of our society, along with transportation and industrial processes. It accounts for approximately 40% of total energy use and associated greenhouse gas (GHG) emissions globally [1], and this places increasing pressure on the building and construction sector to address environmental issues. Most of the focus on this issue has centered on reducing energy consumption and its associated GHG emissions from the operation of the built environment. Conversely, the processes to construct the built environment have not drawn much attention to environmental issues, since their environmental impacts have been assumed to be fairly small compared to those from the operation of built environment [2]. The construction processes themselves, however, are significant economic activities; they contribute approximately 10% to the global gross domestic product (GDP) [1] and consume considerable energy and resources compared to other industrial processes.

Environmental impacts generated by construction processes include energy consumption and its associated air emissions, raw material use and waste generation, and water/land use. Of these, energy consumption and its associated air emissions need to be addressed most urgently because they are directly related to the demanding issues of global warming and the depletion of nonrenewable energy sources. The transformation of construction processes towards environmentally sustainable practices, in terms of energy consumption and associated air emissions, is at a relatively early stage. The first reason for this is that the significance of environmental impacts from construction processes has not been well understood because the decentralized nature of construction processes—employing a number of subcontractors—has hindered accurate quantification of their environmental impacts. In addition, the characteristics of construction processes—the uniqueness of each project and the high degree of fragmentation—make it difficult for firms to pursue a continuous improvement of their processes, and also limit the ability of governmental agencies to develop effective environmental regulations and incentives to regulate and stimulate the creation of environmentally sustainable construction processes.

In order to encourage the development of environmentally sustainable construction processes, this paper, firstly, investigates the energy consumption and associated air emissions of construction sectors in the United States and Canada, and explores various approaches to quantify the environmental impacts of a construction project. This paper also examines the efforts to manage these impacts at four management levels: environmental cooperation routines, environmental technology policies, environmental regulations, and environmental incentives. The United States and Canada generate around 20% of global GHG emissions from fossil-fuel burning [3]. They also lead the world in environmental legislation knowledge, and their environmental legislation is highly interconnected. The investigation of construction sectors in the United States and Canada thus provides insights into the opportunities and challenges for the reduction of energy consumption and air emissions for the construction industry globally.

2. Energy Consumption and Air Emissions from Construction Sectors in the United States and Canada

Table 1 summarizes the GDP, energy consumption, and GHG emissions from construction sectors in United States and Canada in 2006. Economic output from construction sectors accounts for 4.9% of the GDP of the United States and 6.0% of the GDP in Canada [4,5]; the actual impact of the construction industry on the economy is generally considered to be higher than the composition of GDP due to its effects on employment and investment. Construction's share of the GDP has steadily increased in Canada over the last decade, while it has fluctuated slightly in the United States.

Table 1. Energy use and GHG emissions from construction sectors in the United States and Canada in 2006 [4-8].

	GDP* (nominal billion $)	Share in national GDP	Energy Consumption (trillion Btu)	Share in national energy consumption	GHG emissions (Tg)	Share in national GHG inventories
US	649.4	4.90%	913.9	1.2%	67.2	1.2%
Canada	75.4	5.95%	57.5	0.7%	4.2	0.9%

* Adjusted based upon the nominal billion values of U.S. total GDP and Canada's total GDP in Fergusson's report [13].

Aggregate data on energy consumption and GHG emissions in the U.S. construction sectors can be found in the U.S. Environmental Protection Agency (EPA)'s inventory report for greenhouse gas emissions and sinks, which was submitted to the United Nations framework convention on climate change [6]. The report summarizes data for energy consumption and GHG emissions from the operation of off-road construction/mining equipment. It is reported that in 2006, construction equipment consumed 5,968 million gallons of diesel, equivalent to 827.8 trillion Btu at 138,700 Btu/gal, and 688 million gallons of gasoline, equivalent to 86.04 trillion Btu at 138,700 Btu/gal. As total construction industry use in 2006 was 913.85 trillion Btu, the industry represented 1.2% of total U.S. energy consumption. This level of energy consumption is higher than the combined total of all residential households in California, which is one of most populous states [9]. The GHG emissions resulted from this level of energy consumption were reported to be 67.2 Tg (Teragrams), corresponding to approximately 1.2% of total U.S. GHG emissions from fossil fuel use. Another report from the EPA states that the construction industry generates the third highest GHG emissions among U.S. industrial sectors [10].

However, this level of energy consumption and its associated GHG emissions did not account for on-site energy consumption from the use of electricity and natural gas. The share of electricity and natural gas in total energy consumption of the construction sector was estimated to be 10 to 25% and 13 to 15%, respectively in 2002 [11]. In addition, Sharrard *et al.* [11] offer useful insights that take into consideration the energy consumption of the on-road trucks employed in the construction sectors; they contend that the construction sector share could have been 2.6 to 3% of total U.S. energy consumption in 2002, if the use of on-road trucks was included (the construction sectors accounts for 6% of light on-road truck use and 17% of medium/heavy truck use in the U.S.).

Canada's annual inventory report for greenhouse gas emissions and sinks [12] states that construction sectors account for 0.2% of national energy consumption. This data, however, likely underestimates the actual energy consumption from construction sectors, since it has assigned the energy use of construction equipment to transportation sectors rather than construction sectors. The data in this report for transportation sectors does not give any guidance on disaggregating the energy use of construction equipment from other transportation sources. The available source on consumption for construction equipment use is the National Energy Use Database from the Office of Energy Efficiency [7]. This source reports that, in 2006, the Canadian construction sector consumed 57 trillion Btu of energy, accounting for 0.8% of Canada's total energy consumption, and generated 4.2 Tg CO_2 equivalent of GHG, accounting for 0.9% of Canada's total GHG emissions. This level of energy consumption and GHG emissions roughly corresponds to the electricity consumption of all residential households in British Columbia [13]. Unfortunately, this source also potentially underestimates the energy consumption and GHG emissions of the construction sectors, since the figures do not include the use of on-road trucks.

In addition to GHG, particulate matter (PM), sulphur oxides (SO_x), nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs) are regulated by governmental standards as Criteria Air Pollutants (CAPs) in the U.S. and as Criteria Air Contaminants (CACs) in Canada [14,15]; they are major contributors to smog, acid rain, and other health hazards. The CAP emissions from construction sectors in the United States and Canada in 2006 are summarized with their share in national CAPs inventories in Table 2. The NONROAD model of the U.S. EPA [16] provides data for these criteria air pollutants from construction equipment, based on an estimation of engine population and fuel consumption. Among criteria air pollutants, construction equipment causes a disproportionately high share of $PM_{2.5}$ and NO_x in national inventories, equivalent to 2.1% and 3.9% respectively, compared to its share in national GHG inventories. PM directly contributes to health problems such as asthma, lung cancer, and heart disease, and NO_x causes ozone and climate change problems.

Table 2. CAP emissions in metric tonnes from construction sectors in the United States and Canada [16,17].

		PM_{10}	**$PM_{2.5}$**	**SO_x**	**NO_x**	**VOC**	**CO**
US	Exhaust emissions	64,530	62,489	94,200	688,862	110,329	1,094,515
	Share in national total	0.4%	2.1%	0.7%	3.9%	0.6%	1.2%
Canada	Exhaust emissions*	9,365	8,988	5,141	141,482	12,943	71,457
	Share in national total	0.2%	0.7%	0.3%	5.5%	0.04%	0.6%
	Fugitive emissions	1,100,422	218,012	661	2,080	24	342
	Share in national total	18.1%	16.3%	0.0%	0.1%	0.0%	0.0%

* The amount of exhaust CAC emissions from construction processes is available upon request; this data is not revealed in annual NPRI reports.

As with the estimation of GHG emissions, if the use of on-road trucks in construction is included, the CAP emissions from this industry would increase by 32% for PM_{10}, 96% for NO_x and 125% for

VOC [11]. In addition, besides the emissions from fuel combustion for operating construction equipment, which are called exhaust emissions, construction operations in an outdoor and open space work environment directly generate a huge amount of CAP emissions, such as dust from soil erosion, rock crushing, and building demolition; these emissions released into the air from sources other than the tailpipes of construction equipment are called fugitive emissions. Fugitive emissions are not included in this estimation, however, since the inventory of fugitive emissions from construction operations has not been published.

In Canada, the National Pollutant Release Inventory databases (NPRI) [17] provide data on both exhaust and fugitive CAC emissions from construction processes. Exhaust emissions from Canadian construction sectors are assessed using an approach similar to that of the NONROAD model of the U.S. EPA; they cause a high share of NO_x in Canada's national inventories, equivalent to 5.5%. The estimation does not include the use of on-road trucks in the construction sector, however. Fugitive emissions resulting from construction operations are estimated using emission rates based on the construction area; they dominate nationwide PM emissions, accounting for 18% of PM_{10} and 16% of $PM_{2.5}$ in Canada's national inventories.

This investigation illustrates that energy consumption and air emissions from the construction industry in governmental estimates are significant when looked at from various perspectives and that construction processes in particular have been a major source of CAP emissions. Furthermore, governmental estimates of energy consumption and air emissions on the construction sectors may differ widely from the actual environmental impact of construction processes because they do not include several major sources of energy consumption and emissions. Therefore, more accurate inventories for construction processes must be acquired to understand the environmental impact of the construction industry relative to that of other industrial processes. To address these concerns, it is necessary to develop the reliable methodology to quantify emissions from a construction project, which will enable a bottom-up emission inventory, starting from each single construction project, to be developed.

3. Environmental Impact Assessment of Construction Processes

One approach to assess the total environmental impact of construction processes is to use life-cycle assessment (LCA). This method has been used widely for evaluating the total environmental effects over the life-cycle of commercial and residential buildings—from raw material extraction for manufacturing building components to maintenance and a building's end-of-life. Most current LCA tools for the entire life-cycle of a building overlook or improperly address the environmental impact from construction processes [18-20]. Conversely, only a few LCA analyses of construction processes have been attempted [2,21-23]. The process-based LCA utilizes a process-flow diagram for computing known environmental inputs and outputs at each process, such as energy, emissions and wastes [24]. The boundary of a process-flow diagram should include all the upstream environmental effects along the supply chain of materials and services for constructing built environment, in order to holistically assess the environmental effects of a process. However, due to data constraints, the boundary of process-based LCA is typically set at a level where some upstream effects are left out of the boundary. The I-O LCA method allows this problem to be simply addressed by using national sector-by-sector economic interaction data, which quantifies direct and supply-chain effects between sectors in an entire economy [25]. The I-O LCA provides average and general analysis of the environmental impacts generated by certain levels of economic demands in a sector, whereas the process-based LCA provides a process-specific analysis of environmental impacts. Therefore, a hybrid approach combining the advantages of both models is generally used in attempts to assess the environmental impact of construction processes.

Ochoa *et al.* [23] attempted to calculate the environmental impact of construction on a typical residence in Pittsburgh, PA, which is a two-story wood-frame building with 186 m^2 of living space. For this case study, Ochoa *et al.* [23] relied on the I-O LCA method using Carnegie Mellon University's Economic Life Cycle Assessment tool (EIO-LCA) [26]. With the results of a construction cost estimate of a case building, Ochoa *et al.* [19] mapped the cost for various materials and works to the EIO sectors of the EIO-LCA model. Construction processes for a typical residence thus were estimated to consume 550,000 MJ of energy, producing 43 CO_2 equivalent tonnes of GHG, 200 kg of NO_2, 300 kg of CO, and 100 kg of PM_{10}. Sharrard *et al.* [22] present the I-O-based hybrid LCA model for the construction industry; it allows users to create a modified direct supply chain for their custom products based on the current EIO-LCA matrix. Sharrard *et al.* [22] updated and reformulated the construction sector data in the current EIO-LCA model to account for 2002 benchmark of national-level environmental data; instead, the current EIO-LCA model employs 1997 data. Using this reformulated I-O-based hybrid model, Sharrard *et al.* [22] re-analyze Ochoa's case study, and estimate that it generated 95 CO_2 equivalent tonnes of GHG, 320 kg of NO_2, and 290 kg of PM_{10}—approximately 120%, 60%, and 190% larger than Ochoa's estimate, respectively.

Guggemos and Horvath [2] present an augmented process-based hybrid model for construction processes, which employs a process-based LCA with process description of a case project and uses EIO-LCA for estimating energy use and emissions from the production of the temporary materials for construction processes. Using this model, Guggemos and Horvath [2] estimate the environmental impact of the construction of the structural frame of a set of four-story office buildings in California with an area of 8,760 m^2. The project was estimated to consume approximately 4,180 GJ of energy and generate 291 tonnes of CO_2, 2,466 kg of NO_2, 1,997 kg of CO and 321 kg of PM_{10}. With a similar process-based hybrid model, Bilec *et al.* [21] analyze the environmental impact from the construction of a five-story precast concrete parking structure with 377 parking spaces in Pittsburgh. Unlike Guggemos and Horvath [2], Bilec *et al.* [21] include construction service sectors and the upstream production/maintenance effects of construction equipment in the boundary of the analysis; EIO-LCA is used for assessing their environmental impact. Bilec *et al.* [21] use as-built data for determining the input of analysis, whereas previous efforts mostly relied on as-planned data. This project is calculated as generating 682 tonnes of CO_2, 6,705 kg of NO_2, 3,540 kg of CO and 420 kg of PM_{10}. Bilec's hybrid model shows estimates of CO_2 emissions two times larger than Guggemos and Horvath's model for a case study on the construction of a steel frame; Bilec's estimate, however, is only about 17% of the estimates based on the EIO-LCA method [27].

Another approach focuses on estimating the emissions from operating construction equipment, whereas the LCA-based approach includes other environmental aspects of construction processes in its scope. These efforts are mostly based on off-road equipment emission inventory models such as NONROAD [16] and OFFROAD [28], and provide more reliable estimation on the emissions from operating construction equipment than the LCA-based approach by employing emission rates for each type of equipment. The road construction emission model developed by the Sacramento Metropolitan Air Quality Management District [29] calculates the amount of air pollutant emissions for four phases of road construction: (a) grubbing/land clearing, (b) grading/excavation, (c) drainage/utilities/ sub-grade, and (d) paving. The URBEMIS emission model [30] estimates air pollution emissions from land development projects such as building construction. In these emission estimation models, equipment fleet size and the operating hours of each equipment piece are estimated using a heuristic algorithm developed from historical project data. Consequently, the results of the models are determined mostly by the project size, regardless of the variations in construction process. In this context, authors of this paper [31] attempted to utilize construction simulation technologies that could incorporate various characteristics of construction operation plans for estimating emissions from construction processes. Using this approach, they estimate that a typical earthmoving operation under assumed conditions generates around 363 g of CO_2, 4.7 g of NO_x, 1.53 g of CO, and 0.037 g of PM for excavating 1 m^3 of dirt; further, the approach provides a comparison of the environmental impact of various operation scenarios by taking advantages of construction simulation technologies. This result shows a large disparity, around 80% less CO_2 emissions, from the results of previous efforts based on off-road equipment emission inventory models.

All these efforts have contributed to a better understanding of the environmental impact of construction processes, which previously had been underestimated, and have provided a decision-support tool for stakeholders to create an environmentally sustainable construction process. However, these efforts are still in development and need to improve the reliability of their results. Comparing the results of these efforts is difficult due to the unique qualities of each case study and the differences between each analysis boundary. In addition, even when a comparison is possible, there is little data on actual energy use and emissions in real-world scenarios to validate those comparisons. The use of rapidly advancing technologies for sensing the exhaust emissions from vehicles and monitoring on-site air quality could provide the necessary real-world data to enhance the development and validation of a robust emission simulation model.

4. Efforts to Enhance the Environmental Sustainability of Construction Processes

Many efforts have been implemented to enhance the environmental sustainability of the construction process at four management levels: environmental cooperation routines, environmental technology policies, environmental regulations, and environmental incentives. Table 3 summarizes the existing efforts to control the energy consumption and GHG/CAP emissions from construction processes in the United States and Canada. Thus far, governmental regulatory efforts rather than voluntary private sector efforts have led the way toward environmentally sustainable construction processes. Most of these regulatory efforts have focused on reducing CAPs from construction processes, since the environmental impact of CAP emissions from construction diesel equipment has been relatively well-recognized. In comparison, the efforts associated with reducing GHG emissions from construction processes are nascent, but have been increasing in demand recently. This is due to the recent definition of GHGs as air pollutants under Clean Air Act legislation in the United States and Canada [32,33].

Table 3. Current efforts on reducing energy consumption and air emissions from construction processes in United States and Canada.

Management Levels	**Current Efforts in North America**
Environmental Cooperation Routines	Green Building Certification—Leadership in Energy and Environmental Design (LEED) Environmental Management System—ISO 14001 certification
Environmental Technology Policies	Environmental Technology Verification Program U.S. EPA's SmartWay Transport Partnership
Environmental Regulations	Nonroad rules : "Tier 1", "Tier 2", "Tier 3", "Tier 4 transitional", and "Tier 4 Final"
Environmental Incentives	U.S. EPA's National Clean Diesel Campaign California Carl Moyer Program, Texas Emissions Reduction Plan Canada's Offset System for GHG Emissions

4.1. Environmental Cooperation Routines

The U.S. Green Building Council (USGBC)'s Leadership in Energy and Environmental Design (LEED) green building rating system [34] is a certification program that has been widely accepted as a benchmark for the design, construction, and operation of green and sustainable built environments in the United States. Canada also has its own LEED rating system, which has been tailored specifically for Canadian climates, construction practices, and regulations [35]. The LEED green building rating system is concerned mostly with the design of green buildings which require less energy for operation, and with the processes to implement the design properly. This rating system provides a list of credits measuring the environmental performance of construction processes in terms of sustainable site development, energy efficiency, and selection of materials [34]. However, with regards to energy consumption and the associated emissions from construction processes, this system is concerned only with fugitive dust emission prevention and the reduction of material transportation, which can be achieved from the use of regional materials, and the reuse of existing building components. It does not provide any credit to address directly exhaust emissions from operating construction equipment, which is the highest contributor of emissions from construction processes.

The adoption of Environmental Management Systems (EMS) allows an organization to identify opportunities for reducing the environmental footprint of its day-to-day operations. Many construction companies already have components of an EMS in place that they can develop further, such as written and unwritten procedures, best management practices, and regulatory compliance programs [36]; however, few construction companies in North America have a full EMS system [37]. The International Organization for Standardization (ISO) 14001 serves as the standard for developing and implementing an effective EMS. The ISO 14001 approach facilitates an organization-wide investigation of all the environmental aspects of its activities and builds the framework for continual improvement of environmental performance. This can lead to the reduction of environmental impact including waste generation, energy consumption, air emissions and material use. Also, by achieving ISO 14001 certification, an organization can enhance its reputation as an environmental leader and gain a competitive advantage in some markets. However, this standard has not been accepted widely by construction companies in the United States and Canada [36]; in contrast, many companies in the manufacturing sectors have achieved certification. The biggest challenge for implementing EMS to comply with the ISO 14001 standard is that the unique qualities of each construction project makes it difficult to pursue the continuous improvement of processes by monitoring environmental performance over time, that is suggested by the ISO 14001 standard [38]. Since none of construction processes are repeated under the same conditions, comparing the environmental performance of a construction process on one project with that of previous projects cannot provide a concrete basis to judge the improvement of its environmental management. Another challenge is that most construction firms are small, making it difficult to establish and maintain a company-wide ISO 14001 EMS [36].

4.2. Environmental Technology Policies

The U.S. EPA's Environmental Technology Verification (ETV) program provides the verification process for the performance of innovative environmental technologies in a particular application [39]. The ETV program ensures that state governments can be confident that the proposed emission reduction effect of new technologies is achieved when a state takes credit in a State Implementation Plan, which is imposed by the EPA for regulating emissions at the state level. In the construction sector, the ETV program has largely been concerned with the technologies for CAPs emission reductions, such as after-treatment technologies, use of cleaner fuel, and emission-reducing fuel additives. The amount of emission reduction achieved by these technologies in the real world is verified by the rigorous testing procedures of the ETV program. New technology that passes the EPA verification process is added to EPA's Verified Technology List.

This ETV process is essentially voluntary, and it can be initiated and paid for by manufacturers of environmental technologies. Manufacturers are motivated by purchase and lease agreements with contractors who are seeking environmental incentives at the national and state levels, as will be discussed below. Those incentives require contractors to verify the amount of emission reduction with EPA's Verified Technologies process. Canada's Environmental Technology Verification program offers a similar verification process under a license agreement with Environment Canada [40]. California, which is traditionally proactive in pioneering environmental initiatives, has its own verification process for diesel emission reduction technologies, called the Diesel Emissions Control Strategy Verification program [41]. It has some differences in comparison with the EPA program, such as with emission reduction classification and the test methods for measuring emission reduction. Only a few products have been verified by these programs for off-road use, however, even though there exist many verified products for on-road use.

The SmartWay Transport Partnership is a voluntary collaboration between the U.S EPA and various freight industry stakeholders [42]. SmartWay partners are committed to improving energy efficiency and reducing GHG and air pollutants emissions from their freight delivery operations; they benefit from the SmartWay brand to project the image of an environmental protector. To become a partner, owners must measure the current environmental performance of their vehicle fleets and improve their transportation emissions within three years. EPA has provided the Freight Logistics Environmental and Energy Tracking (FLEET) Performance model to assist stakeholders in measuring their current fuel use and emissions, as well as in evaluating the costs and effectiveness of emission reduction strategies that they might adopt in the future. One distinctive aspect of the strategies suggested by this partnership is that, besides technological strategies, operational strategies, such as idling reduction and productivity improvement, are considered significant. This program also provides financial support for the implementation of diesel emissions reduction technologies in transportation. Further, it can be applied to the vehicle fleets for transporting materials, waste, and equipment for construction processes; this is important since transportation incurs a large share of the environmental impact of construction processes, especially in cases where the job site is located in an isolated area. Under current circumstances, however, there is little motivation for contractors to employ a SmartWay partner for their transportation needs.

4.3. Environmental Regulations

The U.S. EPA's rules for off-road diesel engines are the regulations with the biggest impact on emissions from construction equipment. These rules classify off-road diesel engines by the year of manufacture and horsepower of engines, and they specify the allowable emission rates of combined NMHC + NO_x, PM, CO and HC for each group, named successively "Tier 1", "Tier 2", "Tier 3", "Tier 4 transitional", and "Tier 4 Final" [43]. The higher tiers address more recently manufactured engines with more stringent regulations. Equipment manufacturers are required to ensure their products comply with these regulations with a standardized certification test for their products. Canada also applies these rules to its off-road equipment, since all off-road diesel engines in Canada are imported, and about two-thirds of those are manufactured in the United States [44]. These rules have resulted and will continue to result in reductions of regulated air pollutants emissions. For example, under Tier 3 rates, which are effective from 2006 to 2010 for engines with horsepower range $175 \leq HP < 300$, typical of engines used in excavators and graders, engines are expected to reduce their emission rates by 63, 69 and 62 percent of PM, CO, and combined NMHC+NO_x, respectively, relative to engines designed to comply with Tier 1 rates [43].

However, these rules have several definite limitations in regard to the control of GHG/CAP emission from construction processes. First, these regulations do not have a rule for GHG emissions, since GHG, as mentioned, was not previously considered as an air pollutant under the Clean Air Acts. Although the EPA now is seeking a way to develop regulations for GHG emissions from off-road vehicles, even the rules that will be newly developed would not regulate all the construction equipment for a reason that will be described later. Another issue is that engines manufactured before 1996 were not affected by these regulations and many pieces of construction equipment manufactured before 1996 are still in use as the average lifetime of construction equipment is relatively long—15 to 20 years and sometimes even longer. Consequently, a large share of in-use construction equipment is not affected by these regulations. Thus, even after issuing regulations on GHG emissions, only newly manufactured equipment would be affected. Finally, these rules are concerned only with the emissions rate of engines, rather than the actual amount of emissions produced by construction processes. Even if the emission rate of construction equipment is reduced, the emissions from construction processes may be still considerable due to the increase of both engine populations and operating hours for construction equipment, which continue to grow as the economy expands.

4.4. Environmental Incentives

As addressed in the previous section, a large share of construction equipment is not affected by the governmental regulations. Voluntary innovation by the stakeholders in the construction sector on this issue, however, is rare since the cost for improving the environmental performance of equipment outweighs the short-term benefits. In this context, environmental incentives are required to spur the efforts of stakeholders. There are two types of environmental incentives for reducing emissions from construction processes: grant programs, which provide direct funding to equipment owners to replace old equipment with new and cleaner equipment, and tax incentives, which offer tax exemptions, tax deduction, or tax credits to spur the use of technologies for reducing emissions.

The U.S. EPA's National Clean Diesel Campaign (NCDC) is a nationwide grant program that provided $5 million in 2006 for supporting the adoption of cleaner diesel technologies and strategies, such as cleaner fuels and diesel retrofit devices (diesel oxidation catalysts, diesel particulate filters, engine replacement, *etc.*) [45]. Along with West Coast Collaborative [46], which provides additional funding resources, this grant program has reportedly resulted in effective emissions reductions in many case projects, such as the Central Artery/Tunnel Project (the Big Dig), the I-95 New Haven Harbor Crossing Improvement Program, and the South Ferry subway project. At the state level, California's Carl Moyer Program is the first successful statewide grant program, which has provided over $154 million of incentive grant funding—5 percent to construction equipment and 45 percent to on-roads (trucks)—since it began in 1998 [47]. This program has selected projects based primarily on the cost-effectiveness of emissions reduction. The Moyer program has focused on NO_x reductions; as a result, the projects funded by the Moyer Program are estimated to have reduced NO_x emissions by 5,100 tons per year in its first four years at an average cost-effectiveness of approximately $3,000 per ton [37]. The Texas Emissions Reduction Plan (TERP), modeled after the Moyer program, is also a state-level grant program focused on diesel emission reductions [48]. TERP provides a surcharge on the incremental costs associated with activities to reduce NO_x emissions for a project, which is selected in competition based on its cost-effectiveness. In its first three years, TERP has awarded more than $120 million in grants to approximately 280 projects—around one-third of the projects have involved construction equipment [48]. The cost-effectiveness of these projects averages about $5,700 per ton of NO_x emission reduced [37].

Regarding tax incentives, there have been some tax incentives at the state level for spurring the retrofit or repowering of diesel engines or promoting the use of alternative fuels. Oregon offers an income tax credit of up to 35 percent of the cost for purchasing and installing emissions reduction equipment [49]; Georgia offers an income tax credit of 10 percent of the cost (up to $2,500) of diesel particulate emission reduction equipment [37]. Tax incentives have explicit advantages over grants. They can be utilized at any time and are not subject to the exhaustion of funds; in contrast, grant programs require a company's business cycle to be synchronized with the granting schedule and can only be awarded to a limited number of projects due to funding constraints. However, tax incentives have not been used effectively, mainly because they are not large enough to cover the additional costs of adopting emissions reduction technologies [37]. Another issue regarding tax incentives is that small companies, which occupy a large share of the construction industry, do not make large profits and do not bear a large tax liability. Tax incentives for GHG emissions from construction processes have not yet been developed. However, support for a carbon tax (a tax on carbon dioxide emissions from the use of fossil fuels during the manufacturing process of a product) in the United States is increasing steadily among public officers and economists. If such a tax is introduced, there would be a high possibility of developing tax incentives that would be very effective for construction industry stakeholders, for example, by providing an exemption from the carbon tax for energy-efficient construction projects.

Environment Canada recently released draft guidelines for a proposed offset system for GHG emissions in July 2009 [50]. Under this cap-and-trade system, "offset credits" will be issued to the projects in Canada that reduce GHG emissions. Each offset credit will represent one tonne of GHG reduced, and the credits will be tradable and bankable. Project leaders who have achieved GHG emission reduction will benefit from selling offset credits to potential purchasers who must use the credits to offset their own emissions under a future federal cap-and-trade system. For a project to be eligible for registration and to receive offset credits, Environment Canada must have approved a "Quantification Protocol" for quantifying the GHG emissions reductions for the project type. The protocol will define the baseline of GHG emissions for the project type and only reductions achieved beyond this baseline will be eligible to receive credits. Construction projects may be required to offset their GHG emissions under a future cap-and-trade system. The issue is how to define the GHG emissions baseline for construction projects, in which it is difficult to apply simple historical baselines due to their unique qualities. This definition may decide whether the construction companies will be buyers or sellers in the carbon credit market. However, construction projects have great potential for enhancing their environmental performance on GHG emissions, as they have been relatively unregulated in the past.

5. Conclusions

Energy consumption and air pollutant emissions from construction processes have reached significant levels. Energy consumption in the U.S from the use of off-road construction equipment is equal to that of all residential households in California combined, while energy consumption in Canada is equal to the total electricity usage of all residential households in British Columbia. Criteria Air Pollutants (CAPs; Criteria Air Contaminants in Canada) from the use of construction off-road equipment, which have immediate and adverse effects on both the environment and human health, have an even higher share at the national level, compared to the share that construction processes hold national GHG inventories. Further, it should be noted that these amounts could be highly underestimated, since on-road vehicle use and on-site electricity/natural gas use are not included in estimation metrics. If all these sources in construction processes are considered, the national share for construction of energy consumption and GHG/CAP emissions may be approximately double [11].

The attempts to assess the environmental impact of construction projects have been based on LCA methods and off-road equipment emission inventory models. They have enhanced the understanding of the environmental impact of construction processes by analyzing various construction projects. Still, these efforts, especially the efforts for estimating in the pre-construction stage, remain in development, and the differences in assessing methodologies generates large deviations (up to two times bigger in each air pollutant emissions) between the assessment results. Therefore, continued efforts are necessary to develop reliable estimation methodologies that can assess the environmental impacts of construction processes; these will need to be validated by measuring real-world emissions through the use of emission sensors. This data then can provide the basis for decision-making regarding the management of the environmental impacts of construction processes.

The efforts to achieve environmentally sustainable construction processes have been implemented at different management levels: the LEED rating system and ISO 14001 certification at the environmental cooperation routine level; the Environmental Technology Verification (ETV) program at the environmental technology policy level; the NONROAD rules at the environmental regulation level; and the United States' National Clean Diesel Campaign and Canada's Offset System for GHG emissions at the environmental incentive level. Most of these efforts are focused on reducing CAP (CAC in Canada) emissions from construction equipment, since their immediate effects on human health and the environment have been relatively well-documented. Environmental regulations and environmental technology policies spur the technological development of construction equipment engines to reduce CAP emissions; environmental incentives encourage stakeholders to reduce emissions from construction equipment that is not controlled by environmental regulations. Meanwhile, efforts to reduce GHG emissions from construction processes have rarely been implemented, since GHG emissions have been recognized only recently as air pollutants that need urgent regulation. GHG emissions from construction processes are not inconsiderable compared to other industrial sources of GHG emissions; an immediate expansion of GHG emission technology policies, regulations, and incentives to levels corresponding to those for CAPs is required. Canada's carbon cap-and-trade market, predicted to be open in 2011, and the on-going discussion regarding U.S. carbon reduction legislation could be starting points for the creation of such efforts. Still, a number of issues under such carbon reduction systems, such as how to monitor the emissions from construction processes and how to set carbon offset baselines for construction projects, remain to be explored. In addition, current efforts have centered mostly on technological strategies such as employing diesel retrofit devices, replacing new engines and using cleaner fuels. Relatively little attention has been paid to operational strategies based on operation plan improvements for lower emissions. Such operational strategies have a great potential to reduce both GHG and CAP emissions, as well as energy consumption, with less additional cost compared to the technological strategies. For example, if robust environmental impact analysis of construction processes is integrated into decision-making processes at the planning stage, the selection of alternative operation plans with less energy consumption and emissions are possible; this can occur while letting other aspects (time, cost, and quality) of operations stay at the same or at a slightly higher level. To create and implement these strategies, cooperation between governmental, institutional, scientific, and commercial organizations is needed to research planning techniques and to estimate the environmental impact of construction operations, as well as to put the research results into practice.

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