RESOURCE USE AND ENVIRONMENTAL EMISSIONS OF U.S. CONSTRUCTION SECTORS

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ABSTRACT: Reducing the environmental effects of construction is a continuing professional and social concern to promote sustainable development. In this paper, we estimate the major commodity and service inputs, resource requirements, and environmental emissions and wastes for four major U.S. construction sectors as defined by the Department of Commerce: (1) highway, bridge, and other horizontal construction [0.6% of the 1992 U.S. gross domestic product (GDP)]; (2) industrial facilities and commercial and office buildings (1.5% of GDP); (3) residential one-unit buildings (1.9% of GDP); and (4) other construction (towers, water, sewer and irrigation systems, railroads, etc.) (2.4% of GDP). Our estimates include the entire supply chain of material, energy, and service suppliers for these sectors with the use of a detailed 1992 input-output model of the U.S. economy and publicly available environmental data. We find that in general, the four major U.S. construction sectors appear to use fewer resources and have lower rates of environmental emissions and wastes than their share of the GDP might suggest.

BACKGROUND

By its very nature, construction involves manipulation and use of large quantities of natural and man-made materials. Similarly, construction and infrastructure operations are large users of energy. As a result, it is a critical industry for the study of industrial ecology, the systematic analysis of resource and energy flows within the anthroposphere, the realm of man-made or managed resources (Graedel and Allenby 1995). With increased attention to issues of sustainable development, the industrial ecology of construction is a subject of considerable interest worldwide.

This paper estimates the resources and energy used, and emissions and wastes from U.S. construction. We quantify the major commodity, and the different mineral and energy inputs for the four major construction sectors defined by the U.S. Department of Commerce (DOC). To account not only for the environmental and economic effects of the sectors alone, but for the effects of the suppliers (both direct, or first tier, and indirect, or second, third, etc. tier) as well, our estimates include the entire supply chain of direct and indirect inputs. Finally, we estimate pollution emissions and waste generation. We do not examine issues of land use, impacts of facility placement and operation, or end-of-life management for constructed facilities. Similarly, we do not consider specific engineering decisions such as processes or materials in this paper (Hendrickson and Au 1989; Horvath 1997).

Our estimates may have several uses. First, many companies are developing environmental management systems with an explicit requirement to consider the environmental performance of their purchases and suppliers. The ISO 14000 environmental standards encourage this approach. Our estimates can provide a framework and benchmark data for such analyses. Second, systematic analysis of environmental effects is a means of identifying problems worthy of attention. For example, the concern for the health effects of particulate emissions has led to new regulatory requirements for heavy diesel engines common in construction applications (Phair 1998).

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Our model estimates are developed for the four construction sectors shown in Table 1, with the 1992 U.S. output for these sectors and the percentage of the gross domestic product (GDP) also listed (''Input-output'' 1997). These four construction sectors represent 6.5% of the U.S. GDP. Several additional construction sectors are identified by the Department of Commerce (''Input-output'' 1997), such as farm construction or apartment buildings, but these are considerably smaller than the four sectors examined here. (Assessment of additional construction sectors may be performed using *www.eiolca.net.)*

ECONOMIC INPUTS INTO CONSTRUCTION

A first step in identifying resource inputs and supply chain emissions and wastes for the construction sectors in Table 1 is to identify the economic inputs into construction. For this, our analysis is based upon the 1992 detailed economic input-output model of the U.S. economy, developed by the Department of Commerce (''Input-output'' 1997). The model includes 485 commodity sectors, and can be used to trace all of the supply chain inputs into construction (Hendrickson et al. 1998). We augment the DOC model with estimates of average pollution emissions and resource needs for each of the 485 commodity sectors by using emission and resource use factors calculated per dollar of output for each sector.

Our economic input-output analysis-based life-cycle assessment (EIO-LCA) model calculates the change in all commodity demands due to an increment in final demand. The direct supplier inputs for production in a sector can be obtained by multiplying a so-called direct requirements matrix by the dol-

TABLE 1. Sales of Four U.S. Construction Sectors in 1992

Construction sector (1)	Gross sales (millions of dollars, 1992) (2)	Fraction of gross domestic product (%) (3)
Highway, bridge, and other horizontal construction	33,596	0.6
Industrial facilities and commercial and office buildings	91,887	1.5
Residential one-unit buildings	115,450	1.9
Other construction (towers; water, sewer, and irrigation systems; railroads; power plants and power lines; flood control and marine construction; and so on)	142,393	2.4
[Total]	383,326	6.5

Source: ''Input-output'' (1997).

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lar amount of final demand (Lave et al. 1995; Cobas 1996; Hendrickson et al. 1998).

$$\mathbf{X}_{\text{direct suppliers}} = (\mathbf{I} + \mathbf{D})\mathbf{F} \quad (1)$$

where $\mathbf{X}_{\text{direct suppliers}}$ = direct supplier outputs (in dollars); $\mathbf{I}$ = identity matrix (to include the output of the sector itself); $\mathbf{D}$ = direct requirements matrix (a 485 $\times$ 485 matrix with rows showing the purchases from other commodity sectors for the production of a particular sector denoted in a column); and $\mathbf{F}$ = vector of final demand.

More generally, the entire supply chain for a product or service, including suppliers to a supplier (called indirect suppliers), should be taken into account. After all, we cannot have construction sectors without their extensive chain of suppliers. Thus, the second, third, fourth, etc. levels of suppliers are also important. The total output for the various stages can be calculated as

$$\mathbf{X} = (\mathbf{I} + \mathbf{D} + \mathbf{D}\cdot\mathbf{D} + \mathbf{D}\cdot\mathbf{D}\cdot\mathbf{D} + \ldots)\mathbf{F} \quad (2)$$

The supplier requirements series $(\mathbf{I} + \mathbf{D} + \mathbf{D}\cdot\mathbf{D} + \mathbf{D}\cdot\mathbf{D}\cdot\mathbf{D} + \ldots)$ is equal to $(\mathbf{I} - \mathbf{D})^{-1}$, so the total output including indirect suppliers is

$$\mathbf{X} = (\mathbf{I} - \mathbf{D})^{-1}\mathbf{F} \quad (3)$$

For example, a final demand might be a purchase of \$100,000,000 worth of residential construction. As a result of this demand, there are a series of additional transactions in the economy as purchases from suppliers are made. Purchases for each sector are found by survey of the companies involved, and then are summarized. Using (3) and the U.S. total require-

TABLE 2. Major Direct and Indirect Sector Inputs for \$100,000,000 in U.S. Construction (Highways and Commercial Construction)

New highways, bridges, and other horizontal construction (1)	Purchases (millions of dollars) (2)	New office, industrial, and commercial buildings construction (3)	Purchases (millions of dollars) (4)
Engineering, architecture, and surveying	6.4	Engineering, architecture, and surveying	9.3
Wholesale trade	6.3	Wholesale trade	8.4
Trucking and courier services (except air)	6.1	Retail trade	3.9
Ready-mixed concrete	4.7	Steel mills	3.7
Asphalt paving mixtures and blocks	4.1	Trucking and courier services (except air)	3.2
Crushed and broken stone	3.7	Pipe, valves, and valve fittings	3.0
Concrete products (except block and brick)	3.6	Real estate agents	2.6
Asphalt felts and coatings	3.5	Sawmills and planing mills	1.9
Petroleum refining	3.5	Plastic products	1.8
Crude petroleum and natural gas	3.1	Management services and public relations	1.8
Steel mills	2.3	Fabricated structural metal	1.7
Fabricated structural metal	2.2	Prefabricated metal buildings and components	1.7
Sand and gravel	2.1	Lighting fixtures	1.6
Plastic products	2.1	Electricity	1.6
Real estate agents	1.9	Banking	1.6
Management services and public relations	1.7	Sheet metal work	1.5
Electricity	1.7	Industrial inorganic and organic chemicals	1.4
Miscellaneous repair shops	1.6	Other business services	1.4
Banking	1.6	Telephone and other telecommunications services	1.3
Automotive repair shops and services	1.5	Crude petroleum and natural gas	1.2
[Total for largest 20 sector inputs]	63.7	—	54.6
[Other 465 sectors]	46.3	—	59.4
[Total direct and indirect transactions]	100 + 110 = 210	—	100 + 114 = 214

TABLE 3. Major Direct and Indirect Sector Inputs for \$100,000,000 in U.S. Construction (Residential and Other New Construction)

New residential one-unit structures construction (1)	Purchases (millions of dollars) (2)	Other new construction (3)	Purchases (millions of dollars) (4)
Wholesale trade	9.6	Engineering, architecture, and surveying	13.3
Retail trade (except eating and drinking places)	6.2	Wholesale trade	6.5
Trucking and courier services (except air)	4.3	Retail trade (except eating and drinking places)	3.2
Sawmills and planing mills	3.2	Steel mills	3.1
Plastic products	2.8	Trucking and courier services (except air)	2.8
Real estate agents	2.6	Real estate agents	2.6
Millwork	2.2	Plastic products	2.2
Logging	2.1	Management services and public relations	1.9
Steel mills	2.0	Nonferrous wiredrawing and insulating	1.8
Ready-mixed concrete	1.8	Concrete products (except block and brick)	1.7
Industrial inorganic and organic chemicals	1.8	Fabricated structural metal	1.6
Electricity	1.8	Other business services	1.6
Crude petroleum and natural gas	1.6	Banking	1.5
Management services and public relations	1.6	Sawmills and planing mills	1.4
Banking	1.6	Electricity	1.4
Reconstituted wood products	1.6	Miscellaneous repair shops	1.4
Refrigeration and heating equipment	1.5	Miscellaneous equipment rental and leasing	1.2
Veneer and plywood	1.5	Accounting, auditing, and bookkeeping	1.2
Petroleum refining	1.5	Telephone and other telecommunications services	1.2
Paints	1.5	Industrial inorganic and organic chemicals	1.2
[Total for largest 20 sector inputs]	52.8	—	52.8
[Other 465 sectors]	61.2	—	50.2
[Total direct and indirect transactions]	100 + 114 = 214	—	100 + 103 = 203

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ments matrix $(\mathbf{I} - \mathbf{D})^{-1}$ from the Department of Commerce, we find that there would be, on average, a total of $214,000,000 worth of commodity sales transactions in the economy, including the $100,000,000 of residential construction itself, plus the sales of direct and indirect suppliers to the construction sector.

Tables 2 and 3 show the major suppliers and amounts of economic activity for $100,000,000 in purchases for the four construction sectors. (Note that in input-output modeling, linearity is assumed: The inputs for $100,000,000 of commodity purchase are 100 times the inputs for $1,000,000 of demand of the same commodity). These commodity inputs include indirect suppliers, although direct suppliers to construction site activities dominate in Tables 2 and 3. Some sectors, such as electricity, would represent both a direct supplier to construction sites and an indirect supplier through purchases by material supplier plants. Labor used on-site for construction is not included in these tables (since it is not an industrial commodity).

As might be expected, construction material supply industries make up the bulk of purchases, with commodities such as steel, asphalt, and lumber prominent. Plastics products also appear; in past decades, plastics would not have been a major commodity input to construction. Services are important, with engineering, architecture, and surveying as the largest economic purchase for three of the four types of construction. However, services such as trade, trucking, and banking also appear. These fractions of different commodities tend to remain fairly stable over time, although there are changes, such as the increase in plastics and electronics purchases.

Regarding the different types of construction, the use of wood as a construction material is apparent for the residential housing sector. Sawmills, logging, reconstituted wood products, plywood, and paints all show up on the list of the 20 largest suppliers. Also, professional engineering, architecture, and surveying purchases do not even appear among the 20 largest suppliers for this sector.

RESOURCE INPUT REQUIREMENTS

For industrial ecology and environmental management, we are particularly interested in the resource requirements and environmental emissions resulting from construction. Tables 4 and 5 summarize the resource requirements for construction in the four different sectors shown in Table 1. Fuel, electricity, ore, and fertilizer use is based on 1992 data, while water use data are from 1982 (the latest year published). The requirements for $100,000,000 in new construction are shown, along with the total requirements for the sector, and the total requirements as an approximate percentage of total U.S. consumption.

Resource requirements and environmental emissions can be

TABLE 4. Resources Inputs into Major U.S. Construction Sectors (Highways and Commercial Construction)

	New Highways, Bridges, and Other Horizontal Construction			New Office, Industrial, and Commercial Buildings Construction		
Resource input (1)	Per $100,000,000 (2)	Per total sector output (3)	As percentage of U.S. use (4)	Per $100,000,000 (5)	Per total sector output (6)	As percentage of U.S. use (7)
Electricity (millions of kW·h)	33	11,087	0.4	34	31,242	1
(*a*) Total Fuels (Tons)						
Bituminous coal	15,328	5,149,595	0.6	14,967	13,752,727	1.7
Anthracite coal	21	7,055	0.2	20	18,377	0.6
Natural gas	7,358	2,471,994	0.7	3,592	3,300,581	0.9
Liquefied natural gas	811	272,464	0.3	302	277,499	0.3
Liquefied petroleum gas	1,247	418,942	0.6	692	635,858	0.9
Motor gasoline	1,721	578,187	0.2	1,067	980,434	0.3
Kerosene	0.8	269	0.01	1	919	0.03
Aviation fuel	77	25,869	0.8	70	64,321	1.9
Jet fuel	284	95,413	0.1	294	270,148	0.4
Light fuel oil	3,884	1,304,869	0.8	2,618	2,405,602	1.5
Heavy fuel oil	716	240,547	0.5	415	381,331	0.7
[Total energy (TJ)]	1,234	414,575	—[b]	856	786,553	—[b]
(*b*) Total Ores (Tons)						
Iron ore	3,446	1,157,718	—[b]	5,485	5,040,002	—[b]
Ferroalloy[a]	7,300	2,452,508	0.9	9,100	8,361,717	3
Copper	4,891	1,643,180	0.6	13,628	12,522,360	4.9
Lead and zinc[a]	16,500	5,543,340	2	31,800	29,220,066	11
Gold	1,453	488,150	0.1	3,197	2,937,627	0.7
Silver	25	8,399	0.3	51	46,862	1.6
Uranium and vanadium[a]	1,900	638,324	1.2	4,300	3,951,141	7.6
(*c*) Fertilizers (Dollars)						
Nitrogenous	100	33,596	0.2	100	91,887	0.5
Ammonium nitrate	8,500	2,855,660	0.1	3,700	3,399,819	0.2
Ammonium sulfate	4,800	1,612,608	0.08	5,900	5,421,333	0.3
Organic	15,700	5,274,572	0.3	12,900	11,853,423	0.6
Phosphatic	7	2,352	0.05	40	36,755	0.7
Superphosphate	1,400	470,344	0.08	4,400	4,043,028	0.7
Mixed	5,000	1,679,800	0.08	10,500	9,648,135	0.4
(*d*) Water (Billions of Liters)						
Water intake	1.1	356	—[b]	1.3	1,181	—[b]
Recycled and reused water	2.0	674	—[b]	2.1	1,912	—[b]

[a]Given in dollars.
[b]Not available.

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TABLE 5. Resource Inputs into Major U.S. Construction Sectors (Residential and Other New Construction)

	New Residential One-Unit Structures Construction			Other New Construction		
Resource input (1)	Per $100,000,000 (2)	Per total sector output (3)	As percentage of U.S. use (4)	Per $100,000,000 (5)	Per total sector output (6)	As percentage of U.S. use (7)
Electricity (millions of kW·h)	35	40,408	1.4	29	41,294	1.4
(a) Fuels (Tons)						
Bituminous coal	14,388	16,610,946	2.0	13,068	18,607,917	2.3
Anthracite coal	20	23,090	0.7	18	25,631	0.8
Natural gas	4,541	5,242,585	1.7	3,246	4,622,077	1.2
Liquefied natural gas	405	467,573	0.5	282	401,548	0.4
Liquefied petroleum gas	899	1,037,896	1.4	697	992,479	1.4
Motor gasoline	1,345	1,552,803	0.5	950	1,352,734	0.4
Kerosene	2	2,309	0.06	0.9	1,282	0.04
Aviation fuel	82	94,669	2.8	80	113,914	3.3
Jet fuel	300	346,350	0.5	249	354,559	0.6
Light fuel oil	3,313	3,824,859	2.4	2.658	3,784,806	2.4
Heavy fuel oil	522	602,649	1.2	370	526,854	1.0
Fuels (TJ)	958	1,106,011	—[b]	777	1,106,394	—[b]
(b) Ores (Tons)						
Iron ore	3,016	3,481,972	—[b]	4,623	6,582,828	—[b]
Ferroalloy[a]	8,100	9,351,450	3.3	7,200	10,252,296	3.6
Copper	10,103	11,663,914	4.6	13,667	19,460,851	7.6
Lead and zinc[a]	19,900	22,974,550	8.6	24,900	35,455,857	13
Gold	2,199	2,538,746	0.6	2,702	3,847,459	0.9
Silver	35	40,408	1.3	44	62,653	2
Uranium and vanadium[a]	2,600	3,001,700	5.9	3,100	4,414,183	8.5
(c) Fertilizers (Dollars)						
Nitrogenous	600	692,700	3.8	100	142,393	0.8
Ammonium nitrate	6,200	7,157,900	0.3	3,800	5,410,934	0.3
Ammonium sulfate	9,000	10,390,500	0.5	5,800	8,258,794	0.4
Organic	19,900	22,974,550	1.0	11,200	15,948,016	0.8
Phosphatic	60	69,270	1.5	30	42,718	0.9
Superphosphate	7,400	8,543,300	1.5	3,400	4,841,362	0.9
Mixed	17,500	20,203,750	0.9	11,400	16,232,802	0.8
(d) Water (Billions of Liters)						
Water intake	1.1	1,268	—[b]	1.1	1,563	—[b]
Recycled and reused water	2.0	2,271	—[b]	1.8	2,585	—[b]

[a]Given in dollars.
[b]Not available.

estimated from the economic output for each sector. Algebraically, a vector of resource requirements or environmental outputs can be obtained by multiplying the output of each supplier by its resource requirement, emission, or waste per dollar of output

$$\mathbf{B}_i = \mathbf{R}_i\mathbf{X} = \mathbf{R}_i(\mathbf{I} - \mathbf{D})^{-1}\mathbf{F} \tag{4}$$

where $\mathbf{B}_i$ = vector of environmental burdens (such as toxic emissions or electricity use); and $\mathbf{R}_i$ = matrix with diagonal elements representing the environmental effect per dollar of output for each stage. A large variety of resources and environmental burdens might be included in this estimation. In resource requirements quantification, the values of $\mathbf{R}_i$ are obtained from the U.S. Department of Commerce for individual resource purchases in each section. In particular, the following data sources are used:

- Electricity use calculations include manufacturing (''1992 Census of manufactures'' 1994) and mining (''1992 Census of mineral''1994) industries developed from the ''1992 Census of manufactures,'' and service and agricultural sectors estimated using the detailed workfiles of the DOC input-output (I-O) tables (''Input-output''1997) and average electricity prices for these sectors (''Annual'' 1996).
- Fuel, ore, and fertilizer use is calculated from commodity purchases (contained in the I-O workfiles) (''Input-output'' 1997) and average 1992 prices.
- Water intake, and recycled and reused water volumes are calculated using the ''1982 Census of manufactures'' (the latest water use data set available) (''1982 Census'' 1986).

Total resource use, including the chain of indirect suppliers, is reported in Tables 4 and 5. For example, electricity used to mine aggregate or to manufacture cement is included, as is petroleum required to manufacture the plastics products used in construction, and fertilizer used for agricultural products purchased in the supply chain.

The fuel, ore, and fertilizer consumption numbers in Tables 4 and 5 suggest that, in general, the four construction sectors use less resources than their economic activity might suggest. Exceptions are uses of some fuels and ores. For example, commercial building construction represents only 1.5% of the GDP, but consumes about 5% of U.S. copper ore demand and 11% of lead and zinc ore demand.

These resource uses are subject to greater uncertainty than the supplier fractions shown in Tables 2 and 3. The resource purchases in tons are calculated from an average price paid throughout the economy, but this average price might vary from place to place. Also, the water use is based on average intake and use in 1982, as these are the most recent data available for the U.S. manufacturing sectors.

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POLLUTION EMISSIONS DUE TO CONSTRUCTION

Of particular interest for policy purposes are the total amounts of pollutants and hazardous wastes generated in construction. Large emissions are likely to attract regulatory actions or motivate managerial attention for pollution prevention. Estimates of emissions for $100,000,000 in purchases, for the entire sector output, and the total sector output as a fraction of total U.S. emissions (where available) are shown in Tables 6 and 7. Again, these represent on-site construction emissions, but also emissions throughout the supply chain. As with economic and resource inputs, society cannot have construction sector activities without the extensive chain of suppliers and their associated emissions. The environmental effects are calculated using (4).

The environmental emission factors for our EIO-LCA model are developed from a variety of public data sets and assembled for the various sectors. The major environmental data sources are as follows:

- Toxic releases are derived from the U.S. Environmental Protection Agency's (EPA) ''1987–1995 Toxics release inventory'' (TRI) (1995) and the value of shipments for

TABLE 6. Pollution Emissions from Major U.S. Construction Sectors (Highways and Commercial)

	New Highways, Bridges, and Other Horizontal Construction			New Office, Industrial, and Commercial Buildings Construction		
Pollutant (1)	Per \$100,000,000 (2)	Per total sector output (3)	As percentage of U.S. total (4)	Per \$100,000,000 (5)	Per total sector output (6)	As percentage of U.S. total (7)
Sulfur dioxide (SO_2) (tons)	258	86,678	0.4	197	181,017	1
CO (tons)	419	141,767	0.2	367	337,225	0.4
NO_2 (tons)	373	125,313	—[c]	281	260,000	—[c]
Volatile organic compounds (VOC) (tons)	67	22,509	0.1	59	54,000	0.3
Particulate matter < 10 micrometers (tons)	402	135,056	—[c]	394	368,000	—[c]
Global warming potential (ton CO_2 equivalent)	84,485	28,383,581	2	63,949	58,760,818	3
Hazardous waste generated (RCRA)[a] (tons)	3,170	1,064,993	0.5	2,282	2,096,861	0.8
Toxic releases to air (TRI)[b]	13	4,367	0.6	18	16,540	2
Five largest toxic air emissions (TRI)[b] (tons)	Hydrochloric acid: 2.4 Chlorine: 2.0 Ammonia: 1.1 Methanol: 1.0 Toluene: 0.6	Hydrochloric acid: 806 Chlorine: 672 Ammonia: 370 Methanol: 336 Toluene: 202		Chlorine: 4.3 Hydrochloric acid: 1.4 Ammonia: 1.4 Xylene: 1.3 Methanol: 1.3	Chlorine: 3,951 Hydrochloric acid: 1,286 Ammonia: 1,286 Xylene: 1,195 Methanol: 1,195	
Total toxic releases (TRI)[b] (tons)	19	6,719	0.7	28	26,728	3
CMU-ET equivalent toxic air releases (ton H_2SO_4 equivalent)	5	1,680	1	10	9,189	6
CMU-ET equivalent total toxic releases (ton H_2SO_4 equivalent)	37	12,431	1	78	71,672	6

[a]Resource Conservation and Recovery Act.
[b]Toxics Release Inventory.
[c]Not available.

TABLE 7. Pollution Emissions from Major U.S. Construction Sectors (Residential and Other New Construction)

	New Residential One-Unit Structures Construction			Other New Construction		
Pollutant (1)	Per \$100,000,000 (2)	Per total sector output (3)	As percentage of U.S. total (4)	Per \$100,000,000 (5)	Per total sector output (6)	As percentage of U.S. total (7)
Sulfur dioxide (SO_2) (tons)	216	249,372	1	178	253,460	1
CO (tons)	413	476,809	0.6	363	516,887	0.7
NO_2 (tons)	325	375,213	—[c]	305	434,299	—[c]
Volatile organic compounds (VOC) (tons)	76	87,742	0.4	50	71,197	0.4
Particulate matter < 10 micrometers (tons)	466	537,997	—[c]	532	757,531	—[c]
Global warming potential (ton CO_2 equivalent)	69,388	80,108,446	5	57,900	82,445,547	5
Hazardous waste generated (RCRA)[a] (tons)	2,849	3,289,171	1	2,013	2,866,371	1
Toxic releases to air (TRI)[b]	21	24,245	3	14	19,935	3
Five largest toxic air emissions (TRI)[b] (tons)	Chlorine: 2.9 Ammonia: 2.3 Methanol: 2.2 Toluene: 1.7 Hydrochloric acid: 1.6	Chlorine: 3,348 Ammonia: 2,655 Methanol: 2,540 Toluene: 1,963 Hydrochloric acid: 1,847		Chlorine: 3.1 Hydrochloric acid: 1.4 Ammonia: 1.2 Methanol: 1.1 Toluene: 0.7	Chlorine: 4,414 Hydrochloric acid: 1,994 Ammonia: 1,709 Methanol: 1,566 Toluene: 997	
Total toxic releases (TRI)[b] (tons)	30	34,635	3	23	32,750	3
CMU-ET equivalent toxic air releases (ton H_2SO_4 equivalent)	8	9,236	6	8	11,391	7
CMU-ET equivalent total toxic releases (ton H_2SO_4 equivalent)	59	68,116	5	69	98,251	8

[a]Resource Conservation and Recovery Act.
[b]Toxics Release Inventory.
[c]Not available.

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TABLE 8. Direct Pollution Emissions from Major U.S. Construction Sectors As Function of Total Direct Plus Supply Chain Emissions (in Percentages)

Pollutant (1)	New highways, bridges, and other horizontal construction (2)	New office, industrial, and commercial buildings construction (3)	New residential one-unit structures construction (4)	Other new construction (5)
Sulfur dioxide (SO_2) (tons)	1	0.003	0.7	1
CO (tons)	18	22	23	32
NO_2 (tons)	30	39	33	49
Volatile organic compounds (VOC) (tons)	1	2	2	3
Particulate matter < 10 micrometers (tons)	62	92	86	94
Global warming potential (tons CO_2 equivalent)	3	5	5	8
Hazardous waste generated (RCRA)[a]	0	0	0	0
Toxic releases to air (TRI)[b] (tons)	—[c]	—[c]	—[c]	—[c]

[a]Resource Conservation and Recovery Act.
[b]Toxics Release Inventory.
[c]Not available.

sectors from the Department of Commerce (''1995 Annual'' 1997).

- The Resource Conservation and Recovery Act (RCRA) Subtitle C hazardous waste generation, management, and shipment was derived from the 1995 RCRA biennial survey (''National'' 1995).
- Conventional air emissions are estimated using the EPA's Aerometric Information Retrieval System database (''Aerometric'' 1999).

For the most part, the environmental data are self-reported and are subject to measurement error and reporting requirements gaps. For example, construction firms do not generally have to report to the ''Toxics release inventory.'' But while construction firms, just like all other companies, do have to report to the RCRA Subtitle C hazardous waste database, enforcement of this legislation is lax, and checking reported quantities is difficult.

Conventional pollutant emissions have been the subject of over three decades of regulatory attention. They represent the first six rows of Tables 6 and 7. In general, the construction sectors have lower releases of conventional pollutants than their share of GDP might suggest. Overall, global warming potential contributions are more significant (''Inventory'' 1998). Particulate matter (less than 10 micrometers) and total suspended particulate emissions appear to be substantial, although we do not have national totals for comparisons. As EPA moves to regulate these emissions more closely, construction activities may be affected. U.S. construction has a smaller contribution to hazardous waste generation than its share of GDP might suggest.

Toxic emissions are taken from the average emissions by sectors reporting to TRI in 1995, so nonmanufacturing sectors such as electricity generation are excluded (but electricity generation will soon be included in TRI reporting). The total emissions to air, water, land, and underground injection wells, the five largest toxic air emissions, and the toxicity-weighted emissions (CMU-ET) are reported in Tables 6 and 7. Our toxicity index called CMU-ET weights different chemical species of emissions using relative toxicity measures based on occupational safety threshold limit values (Horvath et al. 1995). Derived primarily from the supplier industries' emissions, the fraction of toxic emissions due to construction is larger than the construction sectors' share of economic activity.

The direct emissions of pollution are also of interest for regulatory and environmental performance reasons. Direct emissions result from construction activities themselves, excluding the emissions from suppliers. Table 8 summarizes the fraction of all emissions shown in Tables 6 and 7 that are realized directly by the four construction sectors. Most of the direct emissions are relatively modest. The exceptions are particulate matter emissions that reflect the dust common on construction sites, and NO_2 emissions due to burning fuel. Direct toxic release figures are not available because construction firms currently do not have to report to the TRI.

SUMMARY

We have developed estimates of resource consumption and environmental emissions for the four largest construction sectors in the United States. Results appear in Tables 2–8. These estimates can be used directly to gain a first approximation of the environmental effects of construction activities. Our estimates may be used for the development of environmental management systems, benchmarking with other industries, and for identifying problems worthy of attention both in the sector and in its extensive supply chain. We also provided estimates of direct pollution emissions for these sectors, which can be used to benchmark the performance of individual firms. We found that, in general, the four major U.S. construction sectors appear to use fewer resources and have lower rates of environmental emissions and wastes than their share of the GDP might suggest.

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