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Measuring Embodied Energy, Carbon, and Embodied Water of Construction Materials: A Case Study of University Building

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Buildings consume nearly 40% of the global energy supply and 16% of fresh water annually in their construction and operation, resulting in 39% of the global carbon emissions. Looking at the rate at which the global climate is changing, reducing energy and carbon impacts as well as water use of construction is essential. This paper presents input-output-based hybrid models to analyze embodied energy (EE), embodied carbon (EC), and embodied water (EW) of fourteen construction materials and a university building. The results indicate that the total EE, EC, and EW values of the university building are 4.5 MBtu/ ft^2, 528.7 $kgCO_2/ft^2$, and 1,049.6 gallon/ft^2, respectively. These results emphasize the extensive energy, carbon, and water impacts associated with building construction, which must be addressed. The intensities of total EE and EW of the construction materials vary in the range of 0.1-11.0 MBtu/ft^2 and 2.2-134.3 gallon/ft^2 indicating water use as an important indicator for material selection. The EC and EW values share a strong positive correlation at the building level, which weakens at the material intensity level. Findings highlight the significance of selecting materials based on not just energy and carbon impacts but also embodied water use.

Key Words: Embodied energy, embodied carbon, embodied water, life cycle energy, buildings

Introduction

Construction materials can play a pivotal role in reducing the energy and environmental impacts of the globe since buildings alone are responsible for over 40% of global annual energy use and nearly 40% of global carbon emissions (Nizam et al., 2018; Rasmussen et al., 2018; Venkatraj & Dixit, 2021). Although most of this energy use is due to operational energy consumption in air conditioning, heating, and lighting buildings and powering building equipment, embodied energy may share a significant portion of this energy consumption (Azari & Abbasabadi, 2018; Dascalaki et al., 2021). Embodied energy accrues over a building's life cycle due to the use of construction materials and processes (Crawford and Treloar, 2005). It includes all direct energy consumed in all onsite and offsite construction, installation, and transportation processes and energy used indirectly by using construction

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materials, which consume considerable energy is their manufacturing (Taffese & Abegaz, 2019). There are three approaches to measure embodied energy of a building (Nizam et al., 2018; Azari & Abbasabadi, 2018; Dixit & Singh, 2018): (1) process-based; (2) input-output-based and (3) hybrid. In a process-based method actual energy use data is collected from material manufactures and construction sites, whereas the national level monetary transactions between industry sectors are converted into energy flows in an IO-based technique. Consequently, process-based calculations are regarded as reliable but incomplete since not all energy inputs may be collected due to data confidentiality and unavailability (Nizam et al., 2018). On the other hand, IO-based energy results are considered complete because the IO system covers all inter-industry transactions. However, since monetary data is converted into energy inputs that requires energy process, IO calculations are plagued by fluctuations in energy and material prices as well as the assumptions of proportionality and homogeneity inherent in the IO system (Chang et al., 2014; Venkatraj & Dixit, 2021). Hybrid approach integrates the two methods to offer embodied energy calculations that are complete as well as reliable (Crawford and Treloar, 2005). One of the hybrid methods is input-out-based hybrid (IOH) technique that has the potential to offer enhanced completeness, specificity, and reliability of calculation (Crawford and Treloar, 2005). In addition to embodied energy, buildings and construction materials must also be analyzed for their carbon emission impacts since materials may have the same embodied energy but differing carbon emissions. Because each material is manufactured using different types of energy sources, its carbon dioxide emissions may be quite different from other materials (Hu, 2020; Hendriks et al., 1999).

Buildings also consume over 16% of global fresh water in their construction (Nizam et al., 2018; Rasmussen et al., 2018). Because fresh water availability is being threatened due to increased severity and occurrences of wildfire, extreme heat, and drought conditions, analyzing how much water is depleted by construction materials is essential to understand if an energy efficient and carbon neutral material is also water efficient (Chen et al., 2019). Like, EE, each building and its materials also have embodied water (EW) use that must be assessed (Dixit et al., 2022). EW is also comprised of a direct and an indirect EW component, which represent the fresh water used directly in construction processes and indirectly by using construction materials, respectively (Pullen et al.,2012; Mousavi et al., 2015; Bardhan and Choudhuri, 2016). Onsite construction operations may utilize between 0.5 and 7.5 kiloliters (kL) of water on a typical construction project (Choudhury and Roy, 2015; Choudhuri, 2015; Crawford and Treloar, 2005). Construction materials also deplete water in their raw material production, processing, transportation, and production, which must be covered under the indirect EW component. Materials such as structural steel may consume 0.6-2.6 cubic meters of water in each ton of their production (Strezov et al., 2013). Concrete, a material used in commercial buildings in bulk quantities, may deplete up to 180 liters of fresh water in each cubic meter of its production (Mellor, 2017). In addition to the direct and indirect EW, water may also be consumed indirectly by using different energy sources. Each energy source (e.g., natural gas, coal, electricity) used as embodied energy (EE) uses fresh water in its production, which must be considered as energy related embodied water (EREW). For instance, nearly 40% of water is drawn by thermos-electric power plants in the United States to produce electrical power (Wu & Chan, 2017). To produce one MWh of electricity, roughly 78 cubic meters of water is depleted by coal-fired power plants in Australia (Strezov et al., 2013). Primary energy sources such as coal, petroleum, and natural gas consumed roughly 0.37, 0.06, 0.03 cubic meters of water per GJ of energy produced (Grubert & Sanders, 2018). Surprisingly, the concentrated solar power (CSP) has one of the largest water footprints (4.7 liter/kWh) for producing electrical power (Li et al., 2012).

Multiple studies have evaluated EE, EC, and EW of buildings using different methods. Collinge et al. (2013), Krogmann et al. (2008), and Sharma et al. (2012) calculated and analyzed the EE of educational buildings and reported 5.1, 6.3, and 18 GJ/m^2 of EE use, respectively. Dixit and Singh (2018) applied an IO-based hybrid approach to compute the EE of higher educational buildings in the range of 30.6 and 50.1 GJ/m^2. Recently, Venkatraj and Dixit (2021) compared the EE of a renovated and a new construction building and reported 18.8 GJ/m^2 and 6.1 GJ/m^2 of EE, respectively. Studies by Treloar and Crawford (2004), McCormack et al. (2007), Bardhan (2011), and Bardhan and Choudhury (2016) computed EW of various commercial and residential buildings as roughly 54.1 kiloliters/m^2, 201. kiloliters/m^2, 27.0 kiloliters/m^2, and 19.4 kiloliters/m^2, respectively. In existing EW studies, the indirect EW was found to contribute to roughly 61-93% of the total EW of buildings, further highlighting the importance of construction material selection for lower EE, EC, and EW impacts (Dixit et al., 2022). Even though most of these studies quantified both direct and indirect EW of buildings, EREW was not evaluated (Hong et al., 2019). Figure 1 summarizes the EE and EW results of some previous studies.

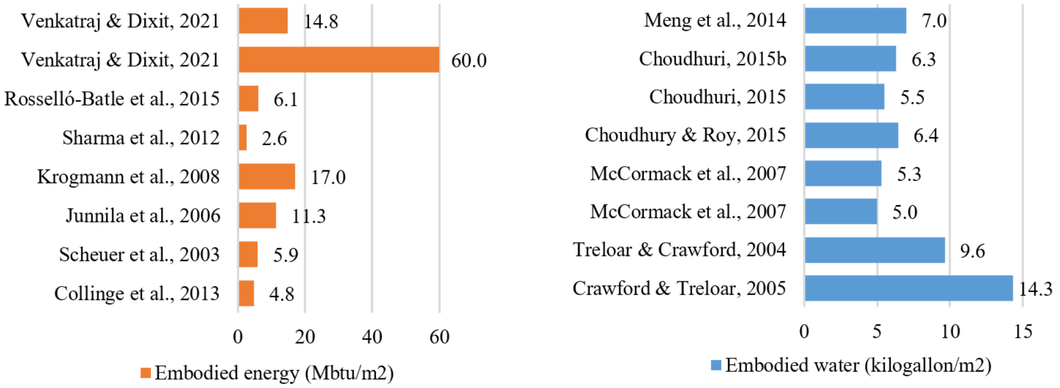

Figure 1. Summary of EE and EW values reported in the literature

Although several studies have quantified and analyzed EE and EW of buildings, research on construction materials' environmental impacts in terms of EE, EC, and EW remains limited. In this paper, two IOH models are presented to compute and analyze the amount of energy, carbon, and water embodied in construction materials. The aim is to underscore the significance of choosing construction materials that reduce not just EE and EC but also EW of buildings.

Research Methods

The main goal of this paper is to understand how different construction materials differ in their carbon and water footprints and how this may create environmental impact tradeoffs in design decisions geared towards improving environmental sustainability of buildings. Two research objectives are pursued:

- Develop IOH models using latest IO data of the United States economy to calculate embodied carbon (EC) and embodied water (EW) of construction materials
- Analyze the values of EC and EW of construction materials for potential interdependencies to highlight the significance of reducing not just carbon emission but also water use

Development of macroeconomic IOH models

Macroeconomic models to compute embodied carbon and water use are developed in three steps. In the first step, latest benchmark IO data of raw *Make* and *Use* tables was collected from the United States Bureau of Economic Analysis (USBEA). The *Make* table (industry-by-commodity 405 x 401 matrix) shows how commodities are manufactured by each industry sectors. The *Use* table (commodity-by-industry 401 x 405 matrix) lists the inputs of commodities required by each industry sector to produce their one unit of output. By adjusting the *Make* table for industry scrap and calculating the *Market Share* matrix, a commodity-by-commodity direct requirement matrix was computed that gives the monetary inputs of each commodity to manufacture one dollar worth of a commodity. Finally, using the Leontief's Inverse matrix approach, a commodity-by-commodity total requirement matrix was created that showed the amount of a commodity (in dollars) to produce one dollar output of each commodity.

The total requirement matrix shows the amount of energy and water commodities consumed by commodities representing construction materials in producing their one dollar of output. However, these energy and water inputs are in monetary units ($), which must be converted into physical units (MBtu and gallons) by acquiring sector-specific energy and water prices. Since prices of utilities fluctuate significantly, embedding energy use and water use data into the IO model in physical units is essential to avoid using prices. In the second step, the amount of energy and water consumed by industry sectors was collected by referring to federal sources such as, the United States Department of Agriculture (USDA), United States Department of Energy (USDOE), United States Census Bureau (USCB) and United States Geological Survey (USGS). A full methodology of data collection and processing can be read in Dixit et al. (2022). The amount (MBtu) of petroleum, natural gas, coal, and electricity used by the United States industry sectors was collected and embedded into the Use table to compute energy embodied in commodities' production in MBtu/$. Since the energy use data was inserted in the IO model in energy units (MBtu), the output of the model was in MBtu/$ of a commodity. By multiplying this EE intensity with the cost of a material or service from the schedule of values (SOV), the EE was calculated for the case study building. Likewise, water is supplied by the aggregated Water, Sewage and Other Systems industry sector, which represents not just the water commodities but also other commodities relating to waste water and sewage. Consequently, this aggregated commodity was broken down into a water use commodity and the other commodity that represents all remaining commodities lumped together. For disaggregation, the share of water utilities in the total annual revenue of the aggregated commodity was sourced and applied. Finally, the water use data was integrated into the Use table and EW intensities of different commodities were computed as million gallons/$. Like EE, the costs of materials and services from the SOV were multiplied with these EW intensities, to quantify the total EW. More details of the calculations can be found in Dixit and Singh (2018) and Dixit et al. (2022).

In the third step, the EC and EW of different construction materials were computed. For each of the four energy sources (petroleum, natural gas, coal, and electricity), the carbon emission factors (CEFs) were gathered from the Energy Information Administration (USDOE). Using these CEFs, the EC of commodities representing construction materials was quantified. To compute the final EC and EW, the EC and EW intensities of material commodities were multiplied with their cost obtained from the schedule of values (SOV) of the university building, a 178,380 square foot facility with 4-5 floors. The system boundary of EC and EW calculation was cradle-to-site that covered raw material extraction, transportation, manufacturing, and final delivery of a material to a site or a warehouse. The focus was on analyzing the EC and EW of 14 common construction materials as listed in Table 1.

Results

Table 1 lists the share of each of the 14 construction materials in the total construction cost ($63,562,421) of the university building. The initial embodied energy (EE) intensities of construction material ranges from 11.36 kBtu/$ for CMU to 43.35 kBtu/$ for aluminum. This is quite different from the EW intensities, which are computed in the range of 2.43 gallons/$ for damp-proofing/water-proofing material to 14.0 gallons/$ for carpet. This means that EE and EW intensities may not share a correlation, and a material selected for lower EE may not have a lower EW. This is particularly important for structural materials such as concrete and steel, which show that in terms of EE, concrete may be preferred, whereas in terms of EW, steel may be preferable. However, note that these intensities are in per unit of $ and a unit dollar can buy varying quantities of these materials. Likewise, common floor finishes such as carpet and ceramic tiles may not differ much in their EE intensities but the EW intensity of carpet in nearly 3.6 times that of ceramic tiles. Materials such as wood have the second largest EW intensity among the 14 materials.

Table 1

Construction cost share and EE and EW intensities of commodities representing materials.

Construction material	Share in total cost (%)	Cost/m^2	EE (kBtu/\$)	EW (gallons/\$)
Concrete	5.27%	\$18.77	18.67	5.28
CMU	3.24%	\$11.56	11.36	3.05
Cut Stone	0.18%	\$0.64	13.24	4.48
Structural Steel	10.50%	\$37.42	25.94	3.59
Wood	0.74%	\$2.62	19.00	10.06
Damp-/waterproofing	1.05%	\$3.76	24.02	2.43
Flashing	0.22%	\$0.80	14.23	2.75
Drywall/Gypsum Board	2.26%	\$8.05	43.02	7.58
Aluminum	2.44%	\$8.71	43.35	3.70
Glass	1.73%	\$6.16	21.70	4.41
Paint	1.33%	\$4.74	18.07	9.89
Flooring (Ceramic Tile)	0.60%	\$2.14	15.77	3.94
Carpet	1.01%	\$3.62	18.19	14.00
Insulation	3.07%	\$10.93	23.83	6.10

Table 2 lists comparatively the total EE, EC, and EW per unit area of these materials used in the case study building. Based on the quantities of different materials used in the building, the EE, EC, and EW values vary significantly across the building. The total EE, EC, and EW values of the case study building are 802,940 MBtu, 94,305 ton CO_2, and 708,745 liter of water, respectively. The top three materials in term of the largest share in total EE and EC are structural steel, aluminum, and concrete, which are some of the most commonly and frequently used bulk construction materials in commercial buildings. The top three materials in terms of their share in the total EW include structural steel, concrete, and insulation. Surprisingly, aluminum, a highly energy and carbon-intensive material, ranks 8th in terms of its share in the total EW of the building. This further highlights the fact that even though the EW intensities of materials such as carpet, wood, and paint are the top three, materials that make up the most EW are steel, concrete, and insulation. Again, this is due to their bulk use in most commercial buildings.

Table 2

Total embodied energy (EE), embodied carbon (EC), and embodied water (EW) values of construction materials installed in the university building

	Concrete	CMU	Cut Stone	Structural Steel	Wood	Damp-proofing	Flashing	Drywall	Aluminum	Glass	Paint	Ceramic Tile	Carpet	Insulation
EE (MBtu/m^2)	0.35	0.13	0.01	0.97	0.05	0.09	0.01	0.35	0.38	0.13	0.09	0.03	0.07	0.26
EC (kg/m^2)	38.71	15.30	0.98	115.03	5.02	7.06	1.51	33.74	60.17	14.63	8.09	3.34	7.25	31.53
EW (liter/m^2)	0.38	0.13	0.01	0.51	0.10	0.03	0.01	0.23	0.12	0.10	0.18	0.03	0.19	0.25

Figure 2 demonstrates how each material differs in terms of EC for the same unit of EE. This further makes a strong case for considering energy- and non-energy-related carbon emissions when selecting construction materials. The results of EREW calculation show that each material also differs in its share of EREW in the total EW. The EREW's share in the total EW of the fourteen construction materials varies from 2.5% to 27%. This emphasize making design decisions of material and layout selection on the basis of EE, EC, and EW to ensure long-term holistic sustainability.

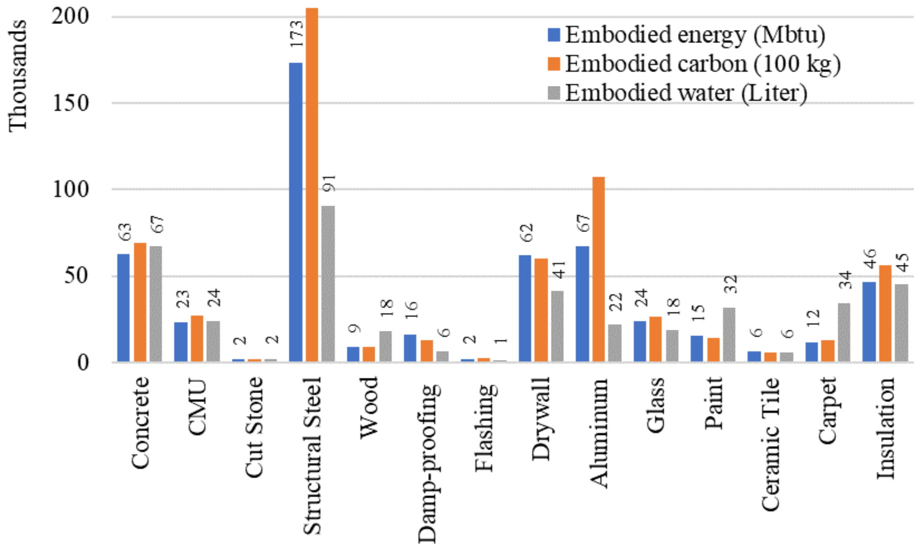

Figure 2. Total EE, EC, and EW values of construction materials installed in the university building

Discussion

The findings of this paper highlight three important aspects of the environmental sustainability of buildings. First, saving EE through material selection may help reduce EC but it may not decrease EW. Figure 3 shows two scatter plots. In the first scatter plot (left-hand side), the total EW of materials at the building level seems to share a strong positive correlation with the materials' EC. Due to this seemingly strong positive correlation, a regression analysis was run to test the correlation. An extremely small *Significance of F* (0.00042) indicated the unlikeliness that the correlation was random. Further, a smaller *p-value* (0.00042) indicated that the EC and EW demonstrate a high positive correlation with $r^2 = 0.66$. According to Chan (2003) and Taylor (1990), a coefficient of determination in the range of 0.64-0.81 indicates a strong correlation. This may lead us to believe that saving EC may result in saving EW, which may be true. However, not all EW may be reduced by decreasing the EC of materials since only 2.5%-27% of the total EW can be attributed on EREW. This means that additional design strategies may be needed to lower the total EW of a building and its materials. Note that the strong positive EC-EW correlation in the left-hand side scatter plot in Figure 3 may be driven by the one point at the far end. More detailed correlation analysis may be needed to further study this correlation. The second scatter plot (right-hand side scatter plot in Figure 3) shows that the strong positive correlation becomes extremely weak at the material intensity level. Since the correlation seemed weaker, a regression analysis was not run for this correlation. This weaker correlation may get stronger at the building level due to material quantities; a lower EW material may cause more EW use at the building level simply because its quantity used in the building is higher. Second, at the whole building level, the indirect components of EE and EW represent a significant portion of the total EE and EW. The fourteen materials that represented roughly 1/3rd of the total construction cost of the university building contribute to nearly 65% of the total EE and 60% of the total EW of the building. This point to the huge role construction materials may play in reducing the energy and resource burdens of buildings. This information is critical to design decision making by designers, especially during material and layout selection. Third, a building design optimized for EE may not have the least EW. In other words, optimizing a building's environmental performance from EE, EC, and EW standpoint is a multi-objective problem with conflicting objectives achieving which may need computational algorithms such as multi-objective genetic algorithm (MOGA).

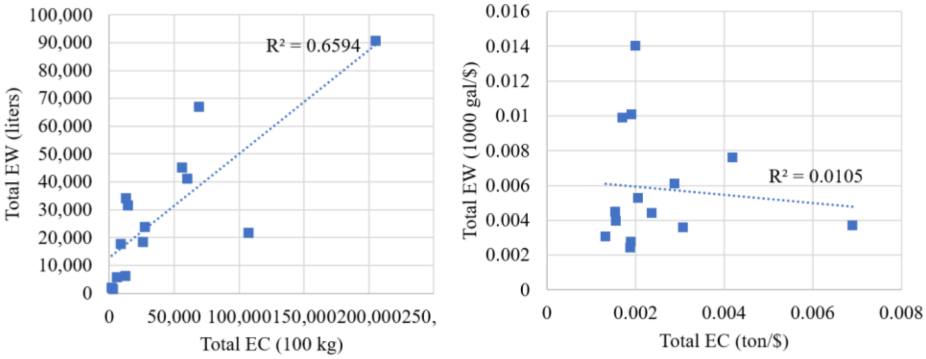

Figure 3. Correlation of EC and EW at the whole building and per $ intensity levels

Conclusions

The main goal of this paper was to understand the EE, EC, and EW impacts of construction materials and compare their impacts at the building level. Two IOH macroeconomic models were designed using the latest IO data for the United States economy to compute EE and EW intensities of construction material commodities. Using the SOV of a university building project, the EE, EC, and EW of fourteen major construction materials conventionally used in commercial building construction were computed. The results indicate that the total EE, EC, and EW values of the case study building are 4.5 MBtu/ ft^2, 528.7 $kgCO_2/ft^2$, and 1,049.6 $gallon/ft^2$. Moreover, the total EE and EW of the fourteen construction materials vary in the range of 0.1-11.0 $MBtu/ft^2$ and 2.2-134.3 $gallon/ft^2$. This means that two materials with the same function in a building must be analyzed by the architects and engineers not just for energy impacts but also for carbon emission and water use impacts. For instance, concrete and steel both can be used as structural material but the two have different energy and water footprint that must be carefully analyzed before selecting one material over the other. The findings further suggest that EE savings may convert to proportional savings in EC. However, reducing EE may not decrease EW, and decreasing EW of a building may require specific design strategies involving the selection of low EW materials. This shows that optimizing all three dimensions of energy use, carbon emissions, and water use at the building level may be complicated and may require generating most possible alternatives to create a population of design alternatives and select the most optimal solution. This underscores the significance of designing computational algorithms such as a multi-objective optimization (MOO) that help find design solutions with not just low EE and EC but also the least amount of EW. The results have clear educational implications. Undergraduate and graduate students are future construction managers, entrepreneurs, policymakers, constructors, and homebuilders. They must learn how their professional decisions may influence the energy, carbon, and water flows in the construction sector influencing its environmental footprint.

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