**PAPER** • **OPEN ACCESS**

# Analyzing Embodied Energy and Embodied Water of Construction Materials for an Environmentally Sustainable Built Environment

To cite this article: M K Dixit and P Pradeep Kumar 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1122** 012045

View the article online for updates and enhancements.



# Analyzing Embodied Energy and Embodied Water of Construction Materials for an Environmentally Sustainable Built Environment

**M K Dixit[1] and P Pradeep Kumar[2]**

[1] Associate Professor, Department of Construction Science, Texas A&M University, College Station, TX, USA – 77843
[2] PhD Researcher, Zachry Department of Civil and Environmental Engineering, Texas A&M University, College Station, TX, USA – 77843

E-mail: mdixit@tamu.edu

**Abstract**. Buildings consume over 40% of global energy in their construction and operations contributing to over 39% of global carbon emission each year. This huge environmental footprint presents an excellent opportunity to reduce energy use and help deliver an environmentally sustainable built environment. Most of the energy is consumed by buildings as embodied energy (EE) and operational energy (OE). EE is used directly and indirectly during buildings' initial construction, maintenance and replacement, and demolition phases through construction products and services. OE is used in the processes of heating, cooling, water heating, lighting, and operating building equipment. Most environmental optimization research has been centered on energy and carbon emission overlooking another critical sustainability aspect, water use. Each building also consumes a significant amount of freshwater as embodied water (EW) or virtual water in its initial construction, maintenance and replacement, and demolition phases. Since each primary and secondary energy source depletes water in its extraction, refinement or production, there is also a water expense associated with EE and OE use that must also be included in total EW use. The total EW, therefore, includes both non-energy and energy related water use. Research suggests that there are tradeoffs between EE and EW that may complicate design decisions such as material selection for environmental sustainability. In other words, a material selected for its lower EE may have higher EW and selecting such a material may not help reach environmental sustainability goals since water scarcity is becoming a grave problem. In this paper, we created an input-output-based hybrid (IOH) model for calculating and comparing EE and EW of building materials frequently used in building construction. The main goal is to examine and highlight any tradeoffs that may exist when selecting one material over another. The results reveal that there is a weak correlation between EE and total EW that is the sum of energy and non-energy water use, which means that a design decision made solely based on EE may conflict with EW. The share of energy related water use in total EW of construction materials also varies significantly (2.5%-31.2%), indicating that reducing energy use alone may not be sufficient to reduce freshwater use; additional efforts may be needed to decrease the use of materials and processes that are water intensive. The results of this study are significant to achieving the goal of creating a truly sustainable built environment.

## 1. Introduction

Approximately 40% of the entire annual energy supply of the world is consumed by the building sector during the extraction and processing of raw materials, building construction, operation, and demolition phases of a building [1]. Non-renewable energy resources such as fossil fuels are primarily consumed during the various construction processes making the construction sector responsible for the emission of *ca.* 40% greenhouse gases [2,3]. Making a building more efficient during its operation may lead to increased material use resulting in higher embodied energy consumption [4]. Additionally, over 16% of the water consumption across the globe is caused by building construction activities [3]. However, this water consumption has not been fully studied, which is important to monitor for reducing pressure on the natural capital. Embodied water (EW) is consumed in direct construction activities and indirectly during the extraction of raw materials of the finished products installed in the buildings [5–8]. Also, it is important to account for the water consumed by different energy sources [9]. Often the energy related EW is intrinsically included in the indirect water component. Several studies [9,10] have highlighted the importance of a holistic assessment of energy related water that is consumed in the production of energy sources. In this paper, an input-output based hybrid (IOH) model is developed and applied to compute the direct, indirect, and total embodied energy (EE) and embodied water (EW) intensities of different building materials. A correlation between the EE and EW of building materials is also presented to understand the trade-off between the two.

## 2. Literature Review

Embodied energy consumption stemming from manufacturing and construction sectors includes all non-renewable energy sources consumed directly in construction processes and indirectly through building materials [11–14]. There is tremendous burden on fossil fuels that are consumed during initial construction as initial embodied energy, during use phase as recurring embodied energy (e.g., maintenance, repair, and replacement) and operational embodied energy [15–17]. To alleviate the greenhouse emissions and the pressure on these finite resources, assessing and targeting the use of these energy sources is essential. While process-based models of embodied energy (EE) and embodied carbon (EC) calculations are reliable and product-specific since they gather data from manufacturing and construction sectors, they cover a narrower system boundary, which may result in underestimation of EE and EC [18–21]. On the other hand, the input output (IO)-based calculations cover a wider system boundary but lack reliability since product and energy prices are used to convert monetary flows into energy flows [22–24]. The timely updates to IO data also affect the IO model since the data is influenced by temporal representation [21]. Factors that may lower the data representativeness include technological variations occurring from the time when data was collected, which may range from 5-23 years [25,26]. An input output-based hybrid (IOH) model combines the advantages of the process-based and the input output models to capture reliability and boundary completeness.

Both process- and IOH-based models are employed for quantifying EW components associated with the construction of a building [8]. Three components of embodied water are essential to cover, i.e., direct, indirect, and implied, for reaching sustainability goals for built environments [27–30]. The computation must take into account the water consumption during the construction phase (direct and indirect) as well as the use of water for energy related purposes (e.g., water used for generating and delivering energy sources used as EE) [7,9]. It should be noted that water consumption takes place not only in the manufacturing and construction processes but also during the extraction and processing phases [31–33]. Both the direct and indirect EE components tend to put pressure on fresh water resources [2,4,34]. In fact, 61-93 percent of the total initial embodied water (EW) is due to the indirect consumption of water [7,35–37]. The generation of electrical power has a huge embodied water footprint, irrespective of whether it is generated from renewable or nonrenewable energy [27,38]. Among the common construction materials that are used in bulk, steel and concrete are estimated to be highly water intensive. The current research seems to focus more on the individual components of the embodied water and tend to not capture the interdependency that may exist between the three components of embodied water – direct, indirect, and energy related. This study quantifies and examines the interrelationship of the three EW components using an IOH-based model. Recent work by the authors [8] studied the three components in conjunction using an input-output based hybrid model and highlighted that the aggregated computation of embodied water may not be as accurate as the disaggregated approach. The study also highlighted the contribution of energy related water use for different materials.

## 3. Methodology

### *3.1. Research Objectives*
The goal of this paper is to apply the Input-Output-based Hybrid (IOH) model to determine the direct and indirect components of EE and EW as well as the energy related embodied water (EREW). The following are the key objectives:

1. Apply IOH model to compute and compare EE and EW intensities of commonly used building materials.
2. Analyze and compare the direct and indirect components of EE and EW and determine the contribution of energy related EW.
3. Analyze any potential correlation between EW and EE intensities of the building materials.

### *3.2. System Boundary*
The system boundary of the present research is *cradle-to-site* gate i.e., it includes the extraction and processing of raw materials, production and manufacturing of building materials, transportation of materials to the site and on-site construction and installation covering stages A1 through A3 as defined by EN 15804:2012 and EN 15978:2011 [39,40]. The system boundary for the IOH model covers the direct, indirect, and total EE and EW of different building materials.

### *3.3. IOH Model*
Three steps are involved in the development of the IOH Model. In the first step, the United States benchmark input-output data in the form of *Use Table* (405x405 commodity-by-industry) and *Make Table* (405x405 industry-by-commodity) are used to create an Input-Output (IO) model. The Use table (commodity-by-industry) represents the consumption of a commodity by an industry to produce a unit output*, whereas* the Make table (industry-by-commodity) the production of commodities by an industry. Make table is adjusted to account for industry scrap [41,42]. The total market share values are then used to determine the Use and Make coefficients. Using each industry's total output and total market share values, the *Use* and *Make* monetary values are converted to *Us*e and *Make* coefficients that are then used to determine the direct, indirect, and total requirements [42–45].

In the second step, the total amount of energy and water used by each commodity produced by these industries is collected, processed, and disaggregated to account for the total energy and water consumed by each commodity of the national economy. Energy use by different commodities are obtained from various national databases [46–48] and the energy prices for each energy source is obtained from the annual energy reviews [49,50] reported by the United States Energy Information Administration (USEIA). Using these data, the total energy source specific energy requirements (MBtu/$) were determined.

Primary energy factors were used to convert the source specific energy values to primary energy units. Similar to embodied energy, for the embodied water requirements, the *Use* and *Make* coefficients are used to calculate the total embodied water (BGal.) [8]. The water use data by different industries are collected from different national databases such as United States Geological Survey [51,52] and United

States Census Bureau [46]. Total revenue ($) per year of water systems (NAICS 221310) is used to disaggregate the water systems from the broader commodity category of water, sewage, and other systems (NAICS 221300). Using the monetary and water use data, the total water requirements (BGal./$) are determined for different commodities. To calculate the energy related embodied water, the energy values are not converted to primary units since the water factors are determined for secondary (onsite) energy.

Finally, the IOH model is developed by replacing the monetary data of the energy and water use by different commodities by the energy and water use data in their respective physical units. To avoid double counting, all inputs to energy providing sectors including water are kept at zero. We, instead, used primary energy factors and water factor of different energy sources to compute EE and EW in primary energy terms.

*3.3.1. Computation of Embodied Energy (EE) and Embodied Water (EW) Intensities.*

The Leontief's inverse matrix is used to calculate the direct and total EE (MBtu/$) and EW intensities (BGal./$) using the IOH model. The *Use* coefficients along with the industry scrap adjusted *Make* coefficients were used to determine the commodity-by-commodity (401x401) direct energy requirement matrices. Likewise, the Leontief's matrix is used to determine the commodity-by-commodity (402x402) direct and total embodied water intensity (BGal./$) matrices.

One additional commodity is the result of the disaggregation of the *Water, Sewage and Other Systems* commodity into: (1) *Water Systems;* and (2) *Sewage* and *Other Systems* sub-commodities. The indirect energy and water requirements are determined using the total and direct energy requirement matrices. Along with the direct and indirect embodied water components, the energy related embodied water (EREW) intensities are also computed using the embodied energy values to account for total water consumed by different energy sources. In general, the energy related water is considered as indirect water. However, for this study, the indirect embodied water is obtained by separating the energy related water use to avoid double counting of energy related water.

## 4. Results and Findings

Figure 1 shows the distribution of 12-upstream stages of indirect EE and EW requirements of different building materials. The distribution of EE of building materials is quite different than EW. For most materials (carpet, concrete, cut stone, insulation, paint, and plaster), there is a higher indirect EW requirement in stage 2 as compared to stage 1, whereas indirect EE requirements decrease from stage 1 to stage 2. This highlights the importance of IOH model in capturing most upstream stages of the indirect EE and EW requirements, which helps understand different way in which indirect EE and EW are consumed. Figure 1 also indicates how some materials have higher EE intensity than other materials but have lower EW intensity. For instance, concrete has the highest stage 1 indirect EE intensity, whereas wood has the highest stage 1 indirect EW intensity. This indicates that the indirect usage of EE and EW for building materials are not the same and may not be directly correlated to the usage of each other. This also shows that if stage 2 indirect inputs are excluded, which is the case with a process-based analysis, EW may be more adversely impacted than EE.

Figure 2 presents the contribution of direct and indirect EE and EW components for the 14 building materials. The contribution of direct EE component in total EE is comparatively higher than the contribution of direct EW component to total EW for most materials with the exception of concrete, CMU, and flashing. The direct EE is attributed to be over 50% of the total EE intensity for 9 out of the 14 materials (cut stone, structural steel, wood, membrane, plaster, aluminum, glass, flooring, and insulation), whereas EW for only 5 out of the 14 materials (CMU, membrane, glass, flooring, and insulation). Paint has the lowest direct EE proportion (17%), whereas wood the lowest direct EW proportion (8%). Overall, the direct and indirect EE and EW components vary significantly for different materials and, therefore, using a disaggregated approach to determine EE and EW intensities is important. This helps in capturing and understanding the upstream stage distribution of the indirect energy and water requirements for different materials.

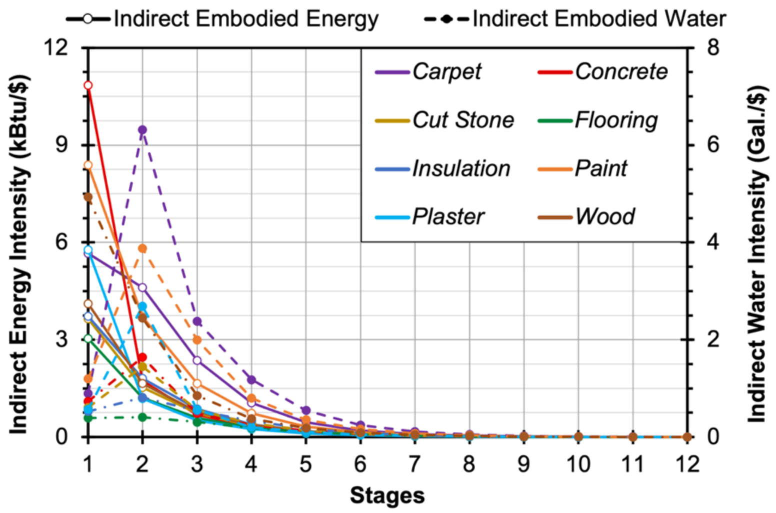


**Figure 1.** 12-stage indirect embodied energy and water intensities for selected building materials.

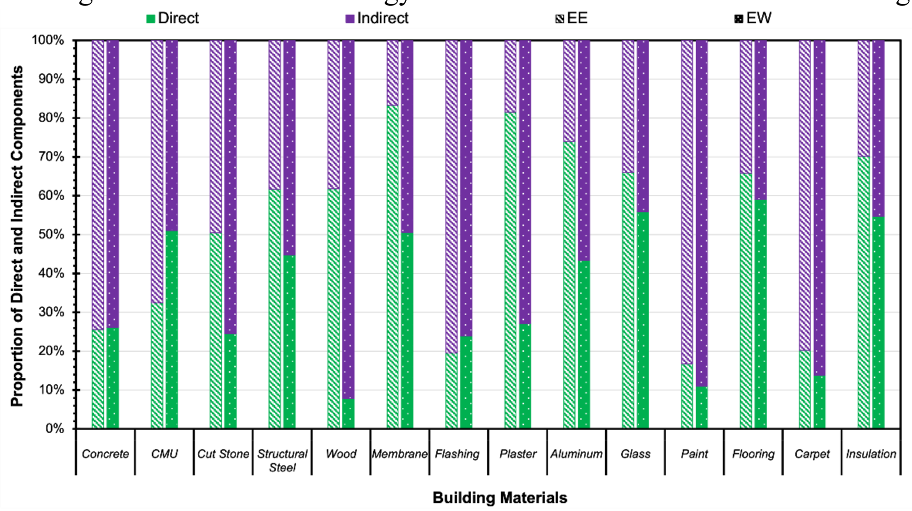


**Figure 2.** Contribution of direct and indirect components of embodied energy (EE) and embodied water (EW) for building materials.

Figure 3 presents the percentage of energy related embodied water (EREW) use in the total EW of different building materials. The contribution of energy related water varies from 2.5%-31.2% for different building materials which is quite significant. Materials such as aluminum (31.2%), structural steel (27.3%), and plaster (23.2%) have the highest share of EREW, whereas carpet (2.5%), paint (3.0%) and wood (3.2%) the lowest. This variation in EREW proportions for different building materials may be due to the differences in the processes involved in their production. Concrete and structural steel have EREW up to 13.6% and 27.3% of their embodied water values, respectively. With these two materials being the two most widely used building materials, their share of EREW is significant for the environmental sustainability of building structures.

Figure 4 demonstrates the correlation between the EE and EW intensities of different building materials. The EE and EW values show almost no correlation ($R^2 = 0.022$). Carpet has the highest EW intensity (14.73 Gal./$) among all the building materials, whereas aluminum has the highest EE intensity (43.35 kBtu/$) among the materials. Materials such as carpet, paint and wood have relatively higher EW intensity as compared to aluminum and plaster that have relatively higher EE intensities.

IOP Conf. Series: Earth and Environmental Science 1122 (2022) 012045 doi:10.1088/1755-1315/1122/1/012045

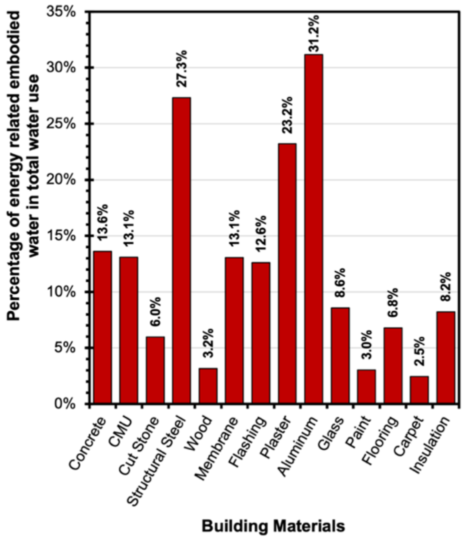


Figure 3. Percentage of energy related embodied water (EREW) in total embodied water (EW).

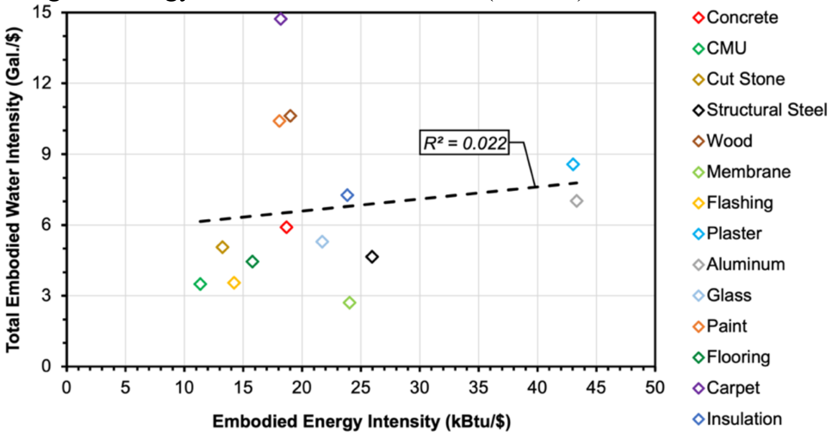


**Figure 4.** Correlation of total embodied water (EW) intensities of building materials with embodied energy (EE) intensities of all energy sources.

## 5. Discussion

This study developed an IOH model to determine the embodied energy (EE) and embodied water (EW) of 14 commonly used building materials. The IOH model is used to determine the direct component, which includes the energy and water consumed in the manufacturing of different construction materials as well as the indirect component that covers the energy and water embedded in raw materials, equipment, and services used in building construction. The IOH model is able to capture most indirect energy and water requirements associated with indirect upstream stages. In this study, 12 upstream stages of indirect energy and water component are calculated and compared. Each upstream stage for a material and a service includes the energy and water consumed by the machinery and services during the extraction and processing of raw materials, production and manufacturing of the materials, transportation of the materials to the site, on-site construction, and installation. The results show how the indirect embodied energy intensities decrease from stage 1 to 12 while indirect embodied water intensities of most building materials increase from stage 1 to 2 and then decreases gradually from stage 2 to 12. This clearly shows that the indirect EE and EW components for different materials may not be the same. The fact that the second upstream stage of EW contains more EW than the first stage further shows the importance of capturing most embodied indirect requirements.

The direct and indirect component analysis results, as shown in Figure 2, demonstrate that the direct and indirect components of EE and EW vary among the 14 materials. Results indicate that, for some materials like wood, the EW is predominantly consumed indirectly (92%) while the EE is consumed directly (62%). Similarly, the direct consumption of EE varies from 17% to 83%, whereas the direct consumption of EW from 8% to 59%, clearly showing that for most materials EE is consumed directly compared to EW. This variation also shows that water is consumed in the production and extraction of not only raw materials but also energy required to produce different materials. Glass uses more water directly than indirectly, which is mainly due to its raw material (sand). CMUs consume more water directly during the curing process, whereas wood indirectly due to the machinery and equipment required for wood production.

Though the indirect component of EW is larger than direct EW for most building materials, it is important to account for the embodied water consumed by the energy sources. The energy related embodied water (EREW) varies drastically across the study materials. Most commonly used building materials have EREW more than 10% of their total EW indicating a significant concern on how important it is to save energy in order to save freshwater use. The large share of energy related embodied water for aluminum and structural steel may arise because the production of these commodities involves higher usage of electricity that is highly water intensive. Materials such as concrete and structural steel consume 13% and 27% of their respective EW, indicating the need to improve building energy efficiency to save both energy and water. These results, however, indicate that decreasing EE may not always mean reducing EW.

The correlation between the embodied water and embodied energy, is shown to be weak. This suggests that a design decision made solely based on EE may conflict with EW. Therefore, it is important to improve the production of energy sources such as electricity that are known to consume approximately 52% of the total energy related embodied water which translates into 3-5% of the total embodied water of a building. In the United States, about 40% of water is consumed by thermoelectric power plants to generate electricity. Additional measures may also be required to improve the production, manufacturing and construction processes of different materials that are water intensive.

## 6. Conclusions

This paper presented the results of embodied energy (EE) and embodied water (EW) intensities for 14 building materials frequently used in building construction. The results highlighted the importance of performing separate embodied energy and water analysis to compare the tradeoffs between the two parameters in selecting sustainable materials for building construction. The results showed that there is a weak correlation between EE and total EW and EE and EW intensities of building materials may differ significantly. This further strengthens the argument that design decisions to enhance environmental sustainability must consider energy use, carbon emissions as well as water use. This study also analyzed the contribution of energy related embodied water (EREW), which showed that the share of EREW in total EW varies significantly (2.5%-31.2%) across the study materials, indicating that efforts may be needed to decrease the use of materials and processes that are water intensive. The results also underscore the importance of an input-output based Hybrid (IOH) model's ability to capture most indirect impacts in the computation of both EE and EW. This study signifies the importance of both EE and EW in selecting building materials that help create a truly environmentally sustainable built environment.

## References

[1] Gan V J L, Wong H K, Tse K T, Cheng J C P, Lo I M C and Chan C M 2019 Simulation-based evolutionary optimization for energy-efficient layout plan design of high-rise residential buildings *J. Clean. Prod.* **231** 1375–88

[2] Venkatraj V and Dixit M K 2021 Life cycle embodied energy analysis of higher education buildings: A comparison between different LCI methodologies. *Renew. Sustain. Energy Rev.* **144** 110957

[3] Dixit M K, Fernández-Solís J L, Lavy S and Culp C H 2010 Identification of parameters for embodied energy measurement: A literature review *Energy Build.* **42**

[4] Venkatraj V, Dixit M K, Yan W and Lavy S 2020 Evaluating the impact of operating energy reduction measures on embodied energy. *Energy Build.* **226** 110340
[5] Pullen S, Chiveralls K, Zillante G, Palmer J, Wilson L and Zuo J 2012 Minimising the impact of resource consumption in the design and construction of buildings *Aust. New Zeal. Archit. Sci. Assoc. Annu. Conf.*
[6] Mousavi S, Kara S and Kornfeld B 2015 Assessing the impact of embodied water in manufacturing systems *Procedia CIRP* **29** 80–5
[7] Bardhan S and Choudhuri I R 2016 Studies on virtual water content of urban buildings in India. *Indian J. Sci. Technol.* **9**
[8] Dixit M K, Pradeep Kumar P and Haghighi O Embodied water analysis of higher education buildings using an input-output-based hybrid method. *Submitt. to J. Clean. Prod.*
[9] Hong J, Zhong X, Guo S, Liu G, Shen G Q and Yu T 2019 Water-energy nexus and its efficiency in China's construction industry: Evidence from province-level data. *Sustain. Cities Soc.* **48**
[10] Fang D, Fath B D, Chen B and Scharler U M 2014 Network environ analysis for socio-economic water system. *Ecol. Indic.* **47** 80–8
[11] Krogmann U, Minderman N, Senick J and Andrews C 2008 *Life-Cycle Assessment of the New Jersey Meadowlands Commission Center for Environmental and Scientific Education Building.* (New Brunswick, New Jersey, USA)
[12] ASMI 2009 Life Cycle Assessment Study of Embodied Effects for Existing Historic Buildings. *Athena Sustain. Mater. Institute, Ontario, Canada*
[13] Dixit M K, Culp C H and Fernández-Solís J L 2013 System boundary for embodied energy in buildings: A conceptual model for definition. *Renew. Sustain. Energy Rev.* **21** 153–64
[14] Lützkendorf T, Foliente G, Balouktsi M and Wiberg A H 2015 Net-zero buildings: Incorporating embodied impacts. *Build. Res. Inf.* **43** 62–81
[15] USGBC A 2008 *National Green Building Research Agenda.* (USA)
[16] Ghattas R, Gregory J, Olivetti E, Greene S and Hub C S 2013 *Life Cycle Assessment for Residential Buildings: a Literature Review and Gap Analysis, a Publication of Concrete Sustainability Hub.*
[17] Monteiro H, Fernández J E and Freire F 2016 Comparative life-cycle energy analysis of a new and an existing house: The significance of occupant's habits, building systems and embodied energy. *Sustain. Cities Soc.* **26**
[18] Lenzen M 2000 Errors in conventional and input-output-based life-cycle inventories. *J. Ind. Ecol.* **4** 127–48
[19] Crawford R H 2004 *Using Input-Output Data in Life Cycle Inventory Analysis.* (Deakin University, Victoria, Australia)
[20] Acquaye A C, Duffy A P and Basu B 2008 *Development of a construction sub-sector embodied energy hybrid analysis.*
[21] Dixit M K 2015 A Framework for an Improved Input-output-based Hybrid Method for Embodied Energy Calculation. *51st ASC Annual International Conference Proceedings*
[22] Rauf A and Crawford R H 2015 Building service life and its effect on the life cycle embodied energy of buildings. *Energy* **79** 140–8
[23] Stephan A and Stephan L 2016 Life cycle energy and cost analysis of embodied, operational and user-transport energy reduction measures for residential buildings. *Appl. Energy* **161** 445–64
[24] Dixit M K 2017 Embodied energy analysis of building materials: An improved IO-based hybrid method using sectoral disaggregation. *Energy* **124** 46–58
[25] Chang Y, Ries R J, Man Q and Wang Y 2014 Disaggregated I-O LCA model for building product chain energy quantification : A case from China. *Energy Build.* **72** 212–21
[26] Dixit M K 2017 Life cycle embodied energy analysis of residential buildings: A review of literature to investigate embodied energy parameters *Renew. Sustain. Energy Rev.* **79** 390–413
[27] Li X, Feng K, Siu Y L and Hubacek K 2012 Energy-water nexus of wind power in China: The

balancing act between CO 2 emissions and water consumption. *Energy Policy* **45** 440–8
[28] Sfakianaki E 2015 Resource-efficient construction: Rethinking construction towards sustainability. *World J. Sci. Technol. Sustain. Dev.*
[29] McManus C 2016 *Education for Sustainable Development-The Irish Construction Sector and the Need for a Sustainable Approach.* (Technological University Dublin)
[30] Rios F C 2018 *Beyond Recycling: Design for Disassembly, Reuse, and Circular Economy in the Built Environment.* (Arizona State University)
[31] El-Hameed A K M A 2018 Towards an Egyptian Benchmark for Water Efficiency During the Core Manufacturing Processes of Building Materials. *Am. J. Civ. Environ. Eng.* **3** 37–42
[32] Netz J and Sundin J 2015 *Water footprint of concrete.*
[33] Chang Y, Huang Z, Ries R J and Masanet E 2016 The embodied air pollutant emissions and water footprints of buildings in China: A quantification using disaggregated input-output life cycle inventory model. *J. Clean. Prod.* **113** 274–84
[34] Dixit M K 2019 Life cycle recurrent embodied energy calculation of buildings: A review. *J. Clean. Prod.* **209** 731–54
[35] Crawford R H and Treloar G J 2005 An assessment of the energy and water embodied in commercial building construction. *4th Australian Life Cycle Assessment Conference* (Sydney, Australia) pp 1–10
[36] Choudhuri I R 2015 Assessment of Embodied Water of Construction: Case Study of a Four Star Rated Hotel in New Delhi, India. *Int. J. Emerg. Eng. Res. Technol.* **3** 195–9
[37] Choudhuri I R and Roy S 2015 Significance of Pre-operational Embodied Water of Buildings in Innovative & Sustainable Design Practices. *Inst. Eng. Local Centre, Tech. J.* **39** 74–8
[38] Grubert E and Sanders K T 2018 Water Use in the United States Energy System: A National Assessment and Unit Process Inventory of Water Consumption and Withdrawals. *Environ. Sci. Technol.* **52** 6695–703
[39] BSI 2012 Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method. *BS EN 159782011*
[40] BSI 2013 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products. *BS EN 158042012+A12013*
[41] Horrowitz K J and Planting M A 2009 *Concepts and Methods of the U . S . Input-Output Accounts*
[42] Dixit M K, Culp C H and Fernandez-Solis J L 2015 Embodied energy of construction materials: Integrating human and capital energy into an IO-based hybrid model *Environ. Sci. Technol.* **49** 1936–45
[43] Dixit M K, Culp C H and Fernandez-Solis J L 2014 Calculating primary energy and carbon emission factors for the United States energy sectors *RSC Adv.* **4** 54200–16
[44] Dixit M K and Singh S 2018 Embodied energy analysis of higher education buildings using an input-output-based hybrid method *Energy Build.* **161** 41–54
[45] Pradeep Kumar P, Venkatraj V and Dixit M K 2021 Evaluating the temporal representativeness of embodied energy data: A case study of higher education buildings *Energy Build.* 111596
[46] USCB 2020 Economic Census Data *United States Census Bur.*
[47] USDA 2020 Quick Stats Tool *United States Dep. Agric.*
[48] USDOE 2020 Manufacturing Energy Consumption Survey (MECS) *United States Dep. Energy*
[49] EIA 2014 *Annual Energy Outlook 2014 - With Projections to 2040*
[50] EIA 2020 *Monthly Energy Review, June 2020*
[51] Diehl T H and Harris M A 2014 *Withdrawal and Consumption of Water by Thermoelectric Power Plants in the United States , 2010*
[52] Harris M A and Diehl T H 2019 *Withdrawal and consumption of water by thermoelectric power plants in the United States, 2015: U.S. Geological Survey Scientific Investigations Report 2019–5103*