Research Article

Life Comparative Analysis of Energy Consumption and CO₂ Emissions of Different Building Structural Frame Types

Sangyong Kim, Joon-Ho Moon, Yoonseok Shin, Gwang-Hee Kim, and Deok-Seok Seo

1 School of Construction Management and Engineering, University of Reading, Reading RG6 6AW, UK
2 Department of Plant & Architectural Engineering, Kyonggi University, Gwanggyo-sun-ro, Yeongtong-gu, Suwon-si, Gyeonggi-do 443-760, Republic of Korea
3 Department of Architectural Engineering, Halla University, Wonju-si 220-712, Republic of Korea

Correspondence should be addressed to Gwang-Hee Kim; ghkim@kyonggi.ac.kr

Received 9 August 2013; Accepted 6 September 2013

Copyright © 2013 Sangyong Kim et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The objective of this research is to quantitatively measure and compare the environmental load and construction cost of different structural frame types. Construction cost also accounts for the costs of CO₂ emissions of input materials. The choice of structural frame type is a major consideration in construction, as this element represents about 33% of total building construction costs. In this research, four constructed buildings were analyzed, with these having either reinforced concrete (RC) or steel (S) structures. An input-output framework analysis was used to measure energy consumption and CO₂ emissions of input materials for each structural frame type. In addition, the CO₂ emissions cost was measured using the trading price of CO₂ emissions on the International Commodity Exchange. This research revealed that both energy consumption and CO₂ emissions were, on average, 26% lower with the RC structure than with the S structure, and the construction costs (including the CO₂ emissions cost) of the RC structure were about 9.8% lower, compared to the S structure. This research provides insights through which the construction industry will be able to respond to the carbon market, which is expected to continue to grow in the future.

1. Introduction

The greenhouse gas (GHG) emissions reduction policy, driven by European Union (EU) members, took effect in 2008 and has been implemented for the past 5 years [1]. This policy is a result of the adoption of the Kyoto Protocol by the United Nations Framework Convention on Climate Change (UNFCCC) in 1997. A Post-Kyoto Regime is now emerging, including within it countries classified as developing (such as Korea and Mexico), and within which enforcement of relevant provisions will commence after 2013 [2]. Aside from participating on a voluntary basis in the UNFCCC, developing countries are required to actively respond to the carbon market. In addition, the parties to the UNFCCC are activating carbon trading as a new market-based growth engine to cost-effectively manage their reduction commitments. Furthermore, with the rise of green protectionism, which is the imposition of trade sanctions on countries not participating in the UNFCCC [2], participation in the latter becomes necessary to sustain economic growth, particularly for countries like Korea that have a strong dependence on trade. According to Korea’s Ministry of Environment, in 2009, Korea voluntarily submitted to the UN a forecast target of 30% reduction in GHG emissions by 2020; the country also issued advance notice of a GHG emissions trading scheme [3]. Furthermore, all sectors, including the construction industry, have been pursuing research on CO₂ reduction technology and energy efficiency. The reduction of CO₂ is particularly essential in the construction industry, a large-scale consumption field, which accounts for more than 40% of natural resource consumption, 30% of energy consumption, and 30% of CO₂ emissions, and which is in turn based on the steel, petrochemical, and cement industries, which are all major sources of CO₂ emissions [4].

Few studies have been conducted on the economic aspects of energy consumption and CO₂ emissions, to enable companies to actively and economically respond to environmental policies, such as those resulting from the UNFCCC.
and emissions trading schemes. If a country or a company does not actively respond to the UNFCCC provisions, it risks having to pay a large CO₂ emissions cost. This damages the image of a country or company and eliminates its competitiveness in overseas exports. Notwithstanding, awareness of environmental issues and efforts to resolve them in the private sector have been insufficient. In a survey by Korea’s Ministry of Environment, large companies that consume a significant amount of energy were questioned in terms of the necessity of a new economic order due to climate change. However, only 30.8% of respondents replied that this was certainly necessary. Only 6.0% of participating companies were carrying out a GHG reduction program at the time [5].

There are studies [5, 6] that show the energy consumption and CO₂ emissions of different constructional methods and building materials. Kim et al. [7] quantitatively assess environmental load through calculating energy consumption and CO₂ emission of building material in apartment construction. Lee et al. [8] compare construction costs, including CO₂ emission costs of masonry wall. Their study found that CO₂ emission costs were highest for fire brick walls, followed by concrete brick walls. Some studies [9–15] have been explicitly dedicated to life-cycle analysis (LCA) of material and component combinations. Cole and Kernan [9] examined total life-cycle energy use, including initial embodied energy, recurring embodied energy (associated with maintenance and repair), and operating energy. Wu et al. [11] present a method, which categorizes environmental impacts, using materials’ environmental profiles to assess their environmental impacts based on the LCA framework. Gustavsson and Sathre [13] study changes in energy and CO₂ balances, caused by the variation of key parameters in the manufacture and use of materials which make up a wood and a concrete-framed building. Other research on the LCA of the whole process of construction is ongoing. This includes (i) research that analyzes initial, recurring, demolition, and operating embodied energy of proposed timber, steel, and concrete buildings, by dividing work phases as follows: site work, structure, envelope, finishes, services, and construction of the building [16]; (ii) research that quantifies the total amount of energy consumption and CO₂ emissions caused by construction, operation, maintenance [17], and renovation of office buildings in Japan; (iii) research to estimate CO₂ emissions in the life-cycle of residential buildings [18]; (iv) research to measure the life-cycle energy and environmental performance of a new university [19]; (v) research to estimate the environmental load of wood and steel reinforced concrete housing construction [20]; and (vi) a detailed analysis of environmental load for each of the three types of residential buildings in Beijing across their whole life-cycle, focusing on energy consumption and CO₂ emissions during the phases of embodied materials, construction, operation, and disposal [21].

Although many studies are being conducted, and Korea has been required to cope with a carbon market since its participation in the UNFCCC, its research on CO₂ emissions costs, as an element of construction costs, has been insufficient. Therefore, this study aims to measure and compare energy consumption, CO₂ emissions, and construction costs for different structural frameworks, with this analysis also including the CO₂ emissions cost of input materials. This research has thus included an analysis of the environmental loads of six office buildings with different building structural frame types during the construction stage, using I/O analysis [6], measurement of environmental loads [22], estimation of energy consumption and CO₂ emissions [7], and qualitative analysis of energy consumption and CO₂ emissions.

As per this outline of the structure of the research, this paper first considers previous research and functional unit estimation approaches for energy consumption and CO₂ emissions. Next, energy consumption, CO₂ emissions, and CO₂ emission costs of input materials of different structural frame types will be analyzed and compared. Finally, key conclusions will be drawn.

2. Research Methodology

This research has been conducted using I/O analysis, based on an interindustry relation table. The I/O table published by the Bank of Korea in 2010 was adapted for this research. By comparing the characteristics of estimation approaches [23], it was found that I/O analysis was more efficient than any other approach in terms of operating hours, scope, and cost. An outline of the research is presented in Figure 1. First, energy consumption and CO₂ emissions were estimated by functional unit, using I/O analysis. Functional unit approaches for estimating energy consumption and CO₂ emissions costs across the life-cycle are divided into three: (i) I/O analysis, directly employing the I/O table; (ii) survey-based approaches that directly track and investigate the same; and (iii) hybrids that combine both approaches [24, 25]. The units of energy consumption and CO₂ emissions used were TOE (ton of oil equivalent, 107 kcal) and T-CO₂, respectively. Second, total energy consumption and total CO₂ emissions of input materials were estimated for each structural frame type. In this research, input materials of four constructed buildings were analyzed, comprising two short and two tall
buildings with RC and S structures. Finally, construction costs were estimated, taking into account the CO$_2$ emissions cost. CO$_2$ emissions cost was measured using the trading price of CO$_2$ emissions on the International Commodity Exchange (ICE) and applying the basic rate of exchange of the Korea Exchange Bank. Additionally, modified construction costs were estimated, including estimated CO$_2$ emissions cost, and existing construction cost, consisting of material costs, labor costs, and expenses.

### 3. Comparison of Energy Consumption, CO$_2$ Emissions, and CO$_2$ Emission Costs

#### 3.1. Description of Cases

Table 1 provides an outline of the different case study buildings and summarizes the quantity of input materials used for each type of structural frame. All case study buildings are located in Seoul, and all are office buildings. Cases A and B have similar gross floor area (GFA), as do cases C and D. Analyzed input materials include cement, sand, gravel, shape steel, steel sheet, and steel plate.

#### 3.2. Estimation of Energy Consumption and CO$_2$ Emissions

Table 2 shows estimates for consumed energy and CO$_2$ emissions involved in the production of input materials for each structural frame type, as per the I/O analysis.

The energy consumption by unit area ($m^2$) was estimated at an average of 0.10 TOE/$m^2$ for the RC structure and 0.14 TOE/$m^2$ for the S structure. The analysis of energy consumption by input materials showed that steel manufacture has higher energy consumption than the manufacture of any other material used in structural frameworks.

In the RC structure, “rebar” accounted for about 74% (case A) and 76% (case C) of the total energy consumption. In contrast with the S structure, however, “shaped steel” only accounted for about 4% (A) and 1.9% (C) of total energy consumption. For the S structure, the sum of section “rebar” and “shaped steel” accounted for 37% and 39% (B) and 26% and 54% (D), respectively.

CO$_2$ emissions by unit area ($m^2$) were estimated at an average of 0.41 T-CO$_2$/m$^2$ and 0.55 T-CO$_2$/m$^2$ for the RC structure and the S structure, respectively. The analysis of CO$_2$ emissions by input materials concluded that rebar for the RC structure accounted for the highest portion of total CO$_2$ emissions, at 75% (A) and 77% (C), whereas the sum of section shaped steel and rebar for the S structure accounted for 76% (B) and 80% (D). In contrast, sand and...
3.3. Construction Costs Including CO₂ Emissions Cost. As shown in Table 3, the cost of CO₂ emissions by unit area (m²) was estimated at an average of 8,669 KRW/m² (7.6 USD/m²) for the RC structure and an average of 11,759 KRW/m² (10.31 USD/m²) for the S structure, with both of these accounting for about 4%–5.3% of existing construction costs. Additionally, by analyzing the rate of increase for modified construction costs (including CO₂ emissions cost against existing construction costs for different structural frame types), it was noted that the RC structure increased to an average of 4.17% and the S structure to an average of 5.15%. Existing construction costs per unit area (m²) were estimated at an average of 208,183 KRW/m² (182.62 USD/m²) for the RC structure and at an average of 228,662 KRW/m² (200.58 USD/m²) for the S structure. As for modified construction costs, the RC structure and the S structure were estimated at 216,852 KRW/m² (190.22 USD/m²) and 240,421 KRW/m² (210.9 USD/m²), respectively.

3.4. Results and Discussion. The RC structure showed lower energy consumption and CO₂ emissions than the S structure. Results for the RC structure indicated about 29% less energy consumption and 26% lower CO₂ emissions per unit area (m²) than the S structure. A large portion of emissions is attributable to the steel manufacturing process.

The CO₂ emissions cost by unit area (m²) of the S structure was 26% higher than that of the RC structure. Additionally, by comparing the modified construction cost, it was found that the RC structure reduces costs by about 10% compared to the S structure. The RC structure reduces costs by about 9% compared to existing construction costs, but the cost-saving effect becomes magnified when considering the high CO₂ emission cost of the S structure.

Therefore, when selecting a structural frame type, it is advantageous to select the RC structure over the S structure, in terms of reducing energy consumption, CO₂ emissions, and CO₂ emissions cost. Furthermore, it is more advantageous to select constructional methods or materials that minimize the use of steel, provided that they meet required design conditions.

It is reasonable to consider the CO₂ emissions cost as part of construction costs, because this cost has an influence on whether it is possible to respond cost-effectively to the

| Construction costs | A        | B        | C        | D        |
|--------------------|----------|----------|----------|----------|
| Existing Subtotal (α) (Million won) | 4,138.36 | 4,576.31 | 10,037.09 | 11,074.34 |
| Per area (Million won/m²) | 0.2194  | 0.2405  | 0.1970   | 0.2168   |
| CO₂ emissions Subtotal (β) (Million won) | 168.05   | 227.01   | 429.47   | 591.81   |
| Per area (Million won/m²) | 0.0089  | 0.0119  | 0.0084   | 0.0116   |
| Modified Total (α + β) (Million won) | 4,306.42 | 4,803.32 | 10,466.55 | 11,666.15 |
| Per area (Million won/m²) | 0.2283  | 0.2524  | 0.2054   | 0.2284   |

Rate of increase (β/α) | 4.06 | 4.96 | 4.28 | 5.34

...
various constructional methods, using LCA, and thus taking into account the production of construction materials, as well as construction, maintenance, and demolition phases.

**Conflict of Interests**

The authors declare that there is no conflict of interests in this paper.

**References**

[1] UNFCCC, Kyoto Protocol Reference Manual on Accounting of Emissions and Assigned Amount, UNFCCC Secretariat, Bonn, Germany, 2008.

[2] H. C. Kang, CEO Information (UNFCCC, Opportunity or Crisis To Korean Companies), Samsung Economic Research Institute, 2009.

[3] Ministry of Environment, Q&A Emissions Trading System, Ministry of Environment, 2011.

[4] Z. Li, “A new life cycle impact assessment approach for buildings,” *Building and Environment*, vol. 41, no. 10, pp. 1414–1422, 2006.

[5] Y. Takebayashi, T. Oka, and T. Konya, “Application of input output analysis to buildings: part 2. Effects to the environment due to construction of office buildings,” *Transactions of AII*, vol. 431, pp. 129–136, 1992.

[6] T. Yashiro and N. Yamahata, “Energy use and CO₂ emission by construction houses,” in *Proceeding of the 1st CIB TGS Environmental Assessment of Buildings International Conference*, pp. 16–20, Watford, UK, 1994.

[7] J. Y. Kim, S. E. Lee, and J. Y. Sohn, “An assessment of the energy consumption and CO₂ emission during the construction stage of apartments,” *Korea Institute of Building Construction*, vol. 21, no. 4, pp. 199–206, 2005.

[8] B. Y. Lee, B. R. Kim, and G. H. Kim, “Comparison of construction costs of masonry wall types, including CO₂ emission costs,” *Journal of the Korea Institute of Building Construction*, vol. 10, no. 3, pp. 83–90, 2010.

[9] R. J. Cole and P. C. Kernan, “Life-cycle energy use in office buildings,” *Building and Environment*, vol. 31, no. 4, pp. 307–317, 1996.

[10] J. Seppälä, S. Koskela, M. Melanen, and M. Palperi, “The Finnish metals industry and the environment,” *Resources, Conservation and Recycling*, vol. 35, no. 1-2, pp. 61–76, 2002.

[11] X. Wu, Z. Zhang, and Y. Chen, “Study of the environmental impacts based on the ‘green tax’: applied to several types of building materials,” *Building and Environment*, vol. 40, no. 2, pp. 227–237, 2005.

[12] A. K. Petersen and B. Solberg, “Environmental and economic impacts of substitution between wood products and alternative materials: a review of micro-level analyses from Norway and Sweden,” *Forest Policy and Economics*, vol. 7, no. 3, pp. 249–259, 2005.

[13] L. Gustavsson and R. Sathre, “Variability in energy and carbon dioxide balances of wood and concrete building materials,” *Building and Environment*, vol. 41, no. 7, pp. 940–951, 2006.

[14] C. Koroneos and A. Dompros, “Environmental assessment of brick production in Greece,” *Building and Environment*, vol. 42, no. 5, pp. 2114–2123, 2007.

[15] B. Nebel, B. Zimmer, and G. Wegener, “Life cycle assessment of wood floor coverings: a representative study for the German flooring industry,” *International Journal of Life Cycle Assessment*, vol. 11, no. 3, pp. 172–182, 2006.

[16] M. Suzuki and T. Oka, “Estimation of life cycle energy consumption and CO₂ emission of office buildings in Japan,” *Energy and Buildings*, vol. 28, no. 1, pp. 33–41, 1998.

[17] S. Seo and Y. Hwang, “Estimation of CO₂ emissions in life cycle of residential buildings,” *Journal of Construction Engineering and Management*, vol. 127, no. 5, pp. 414–418, 2001.

[18] C. Scheuer, G. A. Keoleian, and P. Reppe, “Life cycle energy and environmental performance of a new university building: modeling challenges and design implications,” *Energy and Buildings*, vol. 35, no. 10, pp. 1049–1064, 2003.

[19] G. P. Gerilla, K. Teknomo, and K. Hokao, “An environmental assessment of wood and steel reinforced concrete housing construction,” *Building and Environment*, vol. 42, no. 7, pp. 2778–2784, 2007.

[20] X. Gong, Z. Nie, Z. Wang, S. Cui, F. Gao, and T. Zuo, “Life cycle energy consumption and carbon dioxide emission of residential building designs in Beijing: a comparative study,” *Journal of Industrial Ecology*, vol. 16, no. 4, pp. 576–587, 2012.

[21] H. K. Lee and B. H. Kang, “A study on the variable factor of cost in the multi-story office buildings,” *Architectural Institute of Korea*, vol. 11, no. 6, pp. 203–209, 1995.

[22] K. H. Lee and C. U. Chae, “A study on the amount of the energy consumption and CO₂ emission of public buildings using the input-output analysis,” *Korea Institute of Building Construction*, vol. 18, no. 5, pp. 99–108, 2002.

[23] Bank of Korea, 2000 Input-Output Table, Bank of Korea, Seoul, South Korea, 2003.

[24] F. Bazzazan, M. Alavinasab, and A. A. Banouei, “Construction of regional Input-Output table and its applications: the case of Yazd Province,” in *Proceedings of the 15th International Conference on Input-Output Techniques*, Beijing, China, June 2005.

[25] K. H. Lee and J. H. Yang, “A study on the functional unit estimation of energy consumption and carbon dioxide emission in the construction materials,” *Architectural Institute of Korea*, vol. 25, no. 6, pp. 43–50, 2009.