International Journal of Structural and Civil Engineering Research Vol. 5, No. 4, November 2016

Life Cycle Assessment of Post Disaster Prefabricated & Container Housings

A. Atmaca and N. Atmaca
Vocational School of Technical Sciences, Gaziantep University, Gaziantep, Turkey
Email: {aatmaca, atmaca}@gantep.edu.tr

***Abstract*—About 40% of all primary energy is used in buildings all over the world. This paper analyses the life cycle energy demand of case study prefabricated (PRE) and container (CON) housings in Turkey using a comprehensive Input-Output based Hybrid (IOHA) analysis. The proposed research focused on building construction and operation phases to calculate total energy use. The primary operational energy demands of the assessed case study housings are calculated to be 24.8 GJ/m^2 and 33.5 GJ/m^2 respectively. Embodied Energy (EE) demand, calculated as per the input-output based hybrid analysis is about 3 times higher than in previous studies which rely on process based data. It is found that the operation phase is dominant over the buildings' lifetime and contributes about 62% of the primary energy requirements.**

***Index Terms*—life cycle assessment, input-output based hybrid analysis, embodied energy, post disaster housings**

I. INTRODUCTION

The construction of a building is one of the most resource intensive and economically significant decisions made by designers. A detailed analysis of the resource intensity of a housings requires a life cycle perspective which includes materials production, construction, operation, and demolition phases [1]. (Life Cycle Assessment (LCA) is the investigation and evaluation of environmental impacts of a given product, system or service, over its entire life cycle. It quantifies resource use and environmental emissions associated with the system evaluated [2], [3].

Assessing the energy consumption of a building over its lifetime is a complex exercise. Due to the large immigration and natural disasters affecting significant number of people, the construction and use of post disaster housings have been growing rapidly in the last decades and expected to increase in the future. Thus, post disaster temporary housings are an important area to represent a major opportunity for reducing energy and cost requirements. Many past LCA studies have used traditional inventory analysis methods. Recently, hybrid inventory analysis methods have been developed, combining these two traditional methods to reach more reliable results. In process data analysis, indirect inputs are traced in the upstream of the main manufacturing process. All indirect inputs are counted by going into the upstream of building construction. Owing to the extensive efforts required to categorize each input of the complicated upstream processes, tracing energy inputs becomes increasingly difficult after a certain stage in the upstream [4]. Crawford [5] has expressed that the truncation associated with process analysis can be up to 87%. He emphasized that the capital inputs account for up to 22% of the total inputs to a specific material. Hybrid analysis associates the benefits of process-based and input-output based methods to ensure accurate results and to minimize their respective errors. In this study, a detailed IOHA method [6] is used to ameliorate the way process analyses are conducted.

This paper addresses the primary life-cycle energy consumption for the construction and use of typical post disaster temporary housings in Turkey. The investigation includes the entire set of home subsystems and components, including wall systems, flooring, roof and ceiling systems, foundation and basement, doors and windows, appliances and electrical systems. The methodology for such a detailed analysis is provided including the quantity of each construction element in terms of mass, process based and hybrid embodied energy values. The results and the information obtained from this study will be very valuable for improving the design and operational conditions of housings.

II. CASE STUDY POST DISASTER HOUSINGS

Two typical post-disaster temporary housings were analyzed to represent the majority of the housings constructed after a disaster. Detailed architectural, functional and operational data of the houses were obtained from working drawings, utility bills and reports provided by The Disaster and Emergency Management Presidency of Turkey (AFAD). Technical and characteristic specifications of the housings are presented in Table I. Fig. 1 and Fig. 2 show photos of PRE and CON, respectively.

Figure 1. Photo of prefabricated housing

Manuscript received October 26, 2015, revised May 5, 2016.

doi: 10.18178/ijscer.5.4.323-328

Figure 2. Photo of container housing.

TABLE I. CHARACTERISTIC AND TECHNICAL SPECIFICATIONS OF PREFABRICATED AND CONTAINER HOUSINGS

Specifications	PRE	CON
Number of floor	1	1
Base area (m^2)	Four types of housings with different base areas; 50 (5mx10m), 60 (6mx10m), 70 (7mx10m) and 80 (8mx10m)	Four types of housings with different base areas; 10 (5mx2m), 21 (7mx3m), 24 (6mx4m) and 30 (6mx5m)
Total height (m)	2.8	2.6
Space heating	Separate coal burner	Separate coal burner
Lighting (W/m^2)	3	2 W/m^2
Equipment (W/m^2)	2	2 W/m^2
HVAC	NA	NA
Life span (years)	15	15
Occupancy	4 person/prefabric	4 person/container
Structural system	Steel profiles and wall panels	Steel profiles and wall panels
Exterior and interior walls insulation	40 mm thickness Inflammable glasswool insulation (40 mm) board between precast concrete and plasterboard panels	35 mm thickness sandwich plasterboard panels with glasswool (40 mm)
Floors	16 mm thickness precast concrete panels and wood, tile or PVC coatings	16 mm thickness precast concrete panels and 3 mm PVC coatings
Roof Covering	Structural steel trusses, OSB, 100 mm thickness glass-wool, tiles, sandy membranes	Galvanized roller steel sheets, OSB, 80 mm thickness glass-wool
Doors	900x2100 mm steel framed for exterior door 800x2100 mm PVC framed for interior doors	900x2100 mm steel framed for exterior door 800x2100 mm PVC framed for interior doors
Windows	100x110 mm PVC framed with single 4 mm single glazing.	100x110 mm PVC framed with single 4 mm single glazing.
Exterior surface coatings	Polymer vinyl siding	Sandwich plasterboard panels

III. ASSUMPTIONS AND UNCERTAINTIES

LCA of building contains many simplifications and assumptions related with the energy requirements of buildings in construction, operation and demolition phases, the estimated lifespan of the building and the EE associated with materials used in the future. There is important uncertainty associated with energy consumption and emissions in the demolition phase. Vehicle fuel consumption (as measured in liters of fuel consumed per kilometer traveled) of new vehicles was reduced considerably in the 90s due to fuel economy standards. An integrated policy package that combines fuel economy standards might reduce the overall fuel consumption and greenhouse gas emissions of the light-duty vehicles by 32% up to 50% in 30 years [7].

The location of a building, construction materials and systems used, material manufacturing processes, and other factors will influence its total energy demand and variations in any of these factors has the potential to vary the findings of this study. The following assumptions were made during the calculations:

- The life cycle of the building was assumed to be 15 years.
- Standard building construction methods and materials were assumed to be the same over the next 15 years.
- The building design and materials were obtained mainly from original project documents.
- Energy mix and intensities were considered constant over the next 15 years.
- The service lives for the structural components were assumed to be equal to the service life of the house.
- It was assumed that all final product manufacturing took place in the city Gaziantep, within a 40 km radius of which most of the resources are located.
- Predictions over energy consumption during use phase of the building life cycle (15 years) are highly uncertain. Energy use in operational phase is strongly related with the future changes of prices, inhabitant behavior, regulations and environmental concerns. We assumed a constant consumption rate based on data from 2010 and 2015.
- Energy required for the provision of thermal comfort was quantified on a yearly basis for heating and cooling seasons and assumed to be constant over the 50-year life span of the buildings.
- We assumed an average occupancy of 4-5 persons per dwelling unit.
- It is assumed that the building will be demolished 15 years later. The demolition of the buildings depends on heavy equipment such as excavators, loaders, and trucks, the end-use demolition energy is assumed to be diesel.
- The weight of the disposal of the building is calculated to be about 1,866 tons. The loading capacity of the trucks, the distance of the recycling facility and the fuel economy of the trucks are assumed to be 20 tons, 200 km and 15 L/100 km respectively.
- EE associated with demolition and removal of building materials was assumed to be insignificant, and excluded from the study.

- Some environmental qualities such as indoor air quality are not included, environmental impacts are assumed to be constant over time.

IV. EMBODIED ENERGY CALCULATIONS

In this study, PDA and IOHA were used to calculate the EE associated with the initial construction of the housings. In order to calculate a building's hybrid EE intensities, the first step is to calculate the hybrid energy intensity of the most common basic materials. In the case of Turkey, there is no existing EE energy database for building materials. The most well-known publication about EE values is the Inventory of Carbon and Energy (ICE), which is a generic database which is published by Building Services Research and Information Association. The database which was produced by the University of Bath in England provides average values for materials taken from a range of assessments. The economic structure of Turkey is similar to the other EU countries. Even though it is not specific to Turkey, using the ICE database is acceptable [8], [9].

Treloar & Crawford [10] have been developed a hybrid database of construction materials used in Australia. Disaggregated energy-based I-O model of the Australian economy has been used to calculate the energy associated with the transport of materials and on-site construction processes [11]. In this study, the most recent and comprehensive Australian I-O data developed by the Australian Bureau of Statistics (ABS) in 1996-1997 were used. Despite the fact that using Australian data might induce some errors in the results, there are no equivalent hybrid coefficients for building materials in Europe. This database has an extensive system boundary and includes capital investments in the input-output framework but excludes personal consumption. In order to calculate the amount of non-material inputs the currency exchange ratio of 2 [12] is used to convert Turkish liras (TR) to Australian dollars (AUD) for the building and construction materials [13].

The primary step of the hybrid analysis is to perform an IOA to determine the direct and total energy intensities of the appropriate sector for the product being studied. In order to determine the total energy intensities (*TEI*) of the products, the economic sectors of the products have been analyzed.

In order to calculate the EE of a specific product, in gigajoules (GJ), the retail price of the product was obtained from the supplier and the price of the product was then multiplied by the *TEI* of the appropriate sector [14].

$$EEt = TEIn \; x \; (\$BP/1000) \qquad (1)$$

where EEt is the total embodied energy through IOA, $TEIn$ is the total energy intensity of input output sector n and \$BP is the total price of the basic product.

IOA results, combined with the results from the PDA, will be very useful to estimate the gap between this method and traditional PDA. The I-O data component of the analysis was calculated using (2), using 1996-97 I-O data and added to the PDA figure. The hybrid energy intensity (*EIM*) of the basic material is calculated by using eqn. (3):

$$EIM = PEIM+(TEIn-TEIM)x(\$M/1000) \qquad (2)$$

where $TEIn$ is the total energy intensity of I-O sector n, $TEIM$ is the total energy intensity of the I-O path of the basic material, $PEIM$ is the material process energy intensity and $\$M$ is the total price of the basic material. Total EE through IOHA is calculated by using eqn. (3):

$$EEt = QMxWxEIM+(TEIn - TEIM)x(\$BP/1000) \qquad (3)$$

PDA and IOHA intensities of basic materials used during the study are shown in Table II and Table III respectively [15]. The total energy intensities of "Housings" sector and related pathways representing the material production processes are calculated from Ref. [16]. Inventory of Carbon and Energy (ICE) Version 2.0 [8], [9] is used for the calculation of primary energy requirements.

The ICE includes the EE intensity values for a large number of materials. The life cycle EE of the buildings has been calculated by considering REE which is obtained by multiplying the material quantities by their number of replacements over the life of the building and their energy intensity values. A replacement factor, which is the ratio of service life of a building to average service life of a building material, could be decisive in determining the amount of REE [17]. In most previous studies the REE represented about 23% of the life cycle EE [5]. It is noticed that, the EE is nearly evenly split between the initial and recurrent demands [18]-[20].

TABLE II. MATERIAL QUANTITIES AND EE INTENSITY VALUES FOR PREFABRICATED HOUSING

No	Sections	PRE Materials	Amount (kg)	EE (MJ/kg)	Total EE (MJ)	Total IOHA (MJ)
1	Foundation	Concrete	36,400	0.78	28,392	74,620
		Mesh reinforcement	2,100	28.5	59,850	204,750
2	Structure	Steel profiles	1,994	21.6	43,070	194,415
3	Roof	Oriented Strand Board	1,929	15	28,935	86,805
		Steel profiles	85	21.6	1,836	8,288
		Glass wool	455	16.6	7,553	12,922
		Tile	2,530	10	25,300	37,318
		Sandy membrane	250	1.28	320	1,125
4	Walls and floor	Polymer vinyl siding	320	13.7	4,384	14,400
		PVC doors	50	77.2	3,860	2,250
		Steel doors	125	21.6	2,700	12,188
		PVC windows	150	77.2	11,580	6,750
		Wood flooring	293	12	3,516	6,534
		Tile flooring	71	10	710	1,047
		Plasterboard	484	6.75	3,267	2,212
		Precast concrete panel	614	2.33	1,431	1,259
	Total		46,388		226,704	666,881

V. RESULTS AND DISCUSSIONS

A. *Construction Phase*

The life-cycle inventories for the building based on PDA and IOHA, including the quantity of each construction elements in terms of mass and EE are presented in Table II and Table III respectively.

TABLE III. MATERIAL QUANTITIES AND EE INTENSITY VALUES FOR CONTAINER HOUSING

No	Sections	CON Materials	Amount (kg)	EE (MJ/kg)	Total EE (MJ)	Total IOHA (MJ)
1	Foundation	Concrete	10,080	0.78	7,862	20,664
		Mesh reinforcement	630	28.5	17,955	61,425
2	Structure	Steel profiles	1,135	21.6	24,516	110,663
3	Roof	Oriented Strand Board	600	15	9,000	27,000
		Steel profiles	115	21.6	2,484	11,213
		Glass wool	25	16.6	415	710
4	Walls and floor	Plasterboard	350	6.75	2,363	1,600
		PVC doors	50	77.2	3,860	2,250
		Steel doors	125	21.6	2,700	12,188
		PVC windows	115	77.2	8,878	5,175
		Precast concrete panel	443	2.33	1,032	908
		PVC flooring	20	77.2	1,544	900
	Total		13,688		82,609	254,694

The life cycle EE of each raw material used during construction phase for the housings based on IOHA are presented in Tables II and III. Some hybrid embodied intensity values of the housings are presented in Table IV. Most of the EE is contributed from steel (62.9-76.8%) and concrete (24.4-19.1%). The higher amount of EE for steel and concrete compared to other materials results from the larger amount of steel and concrete used per square meter. In addition, the EE intensity of steel is quite high compared to the other building materials.

TABLE IV. HYBRID ENERGY INTENSITIES OF SOME BUILDING MATERIALS

Building material	Value*	Unit
Concrete	4.461	GJ/m^3
Steel	97.458	GJ/t
Brick	0.935	GJ/m^2
Plaster	0.160	GJ/m^2
Painting	0.068	GJ/m^2
Tile and ceramic	0.236	GJ/m2
Laminate	0.167	GJ/m2
Timber	5.386	GJ/m^3
Insulation- Fiberglass	0.183	GJ/m^2
Bitumen	5.627	GJ/m^3
Roof tiles	1.027	GJ/m2
PVC	45	GJ/t
Aluminum	259.1	GJ/t
Glass	2.048	GJ/m^2

* Intensity values are extracted from Ref. [16].

The choice of the building materials can have noteworthy effects on a building's energy consumption over 15 year life span. The EE coefficients of "secondary" materials like bricks and PVC are higher by an order of magnitude than those of "mass" materials like concrete.

The EE of PVC is calculated to be 9-7.4 GJ for PRE and CON respectively. PVC contributes 1.3 and 2.9% of EE respectively.

The life cycle EE percentages of each section of the housings are presented in Fig. 3. Most of the concrete and steel are used during construction of foundation. As a consequence, the foundation contributes more than 41.9 and 32.2% of EE for PRE and CON respectively.

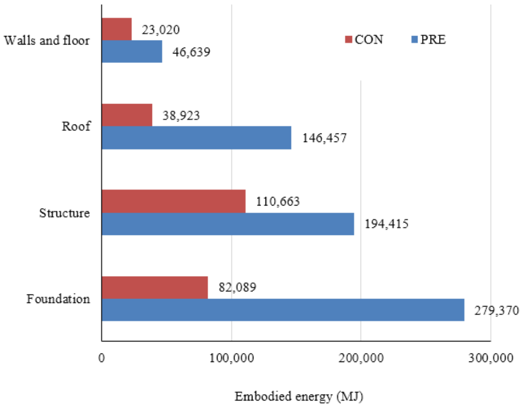

Figure 3. Life cycle EE of PRE and CON in construction phase.

B. *Operation Phase*

Post disaster housings in Turkey typically utilize coal for heating. The life cycle primary operational energy demand of the assessed case study PRE and CON housings are calculated to be 15.3 and 20.8 GJ/m^2. This primary energy demand is mostly due to appliances, heating, cooling, lighting and cooking. Fig. 4 presents the operational energy demand of the residential house. The primary energy demand is mostly due to space heating (12-16 GJ/m^2) followed by lighting (1.4-1.1 GJ/m^2).

The most energy intensive appliances are those operated on electricity. This is due to the high primary energy conversion factor for electricity (2.5), caused by losses in the grid as well as the efficiency of current power plants in Turkey.

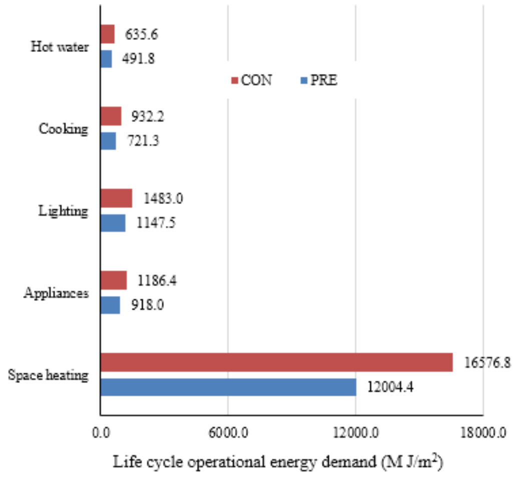

Figure 4. Life cycle operational energy requirements of the case study post disaster housings over 15 years, per m^2 of usable floor area. Note: figures may not sum due to rounding.

VI. CONCLUSION

The life cycle energy demand of the housings, combining embodied and operational energy is presented in Fig. 5. The primary energy requirement of the housings are calculated to be 24.8 and 33.5 GJ/m^2 respectively. PDA is associated with lower energy demand while IOHA has about 23.4% higher energy requirements. The construction phase accounts for 38.4-38% of energy requirements for PRE and CON respectively. The EE of construction phase is calculated to be 9.5-12.7 GJ/m^2 for the housings, while this value is 3.1-4.2 GJ/m^2 using PDA. The operation phase has the greatest primary energy demand for both of the analysis, representing 61.6 and 62 % of energy for PRE and CON, respectively. Another interesting result is about the demolition phase.

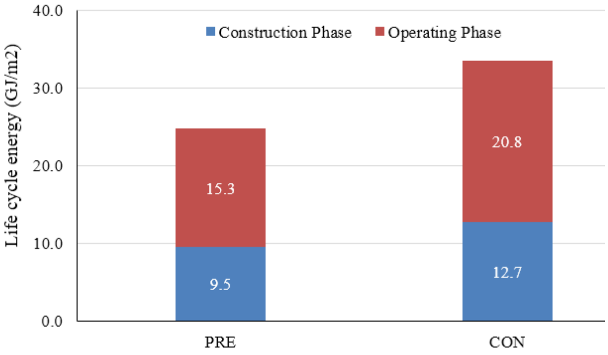

Figure 5. Total life cycle energy demand of the post disaster housings.

The life cycle energy demand of a case study housings constructed in South East of Turkey have been evaluated using a traditional method named Process Data Analysis (PDA) and a comprehensive Input-Output based Hybrid Analysis (IOHA).

For the energy analysis building construction and operation phases were considered. This study does suffer from a number of limitations. Due to the unavailability of comparable data for Turkey, Australian hybrid database for EE was used for the housings constructed in Gaziantep, Turkey. Therefore, EE figures may vary due to the inappropriateness of the data and adopted useful lives of materials. More comprehensive EE figures are needed, notably through the development of a hybrid embodied energy coefficient database for Europe. The main finding of the study is that the EE demand, calculated as per the IOHA using Australian database [4], [13], [16], [21]-[23] is much higher (about 3 times) than in previous studies which rely on a PDA.

The contribution of the EE was found to be 3.1-4.2 GJ/m^2 for PRE and CON, using PDA. The EE was quantified using IOHA, its contribution to the total life cycle energy of the housings was calculated to be 9.5-12.7 GJ/m^2. It is clear that the use of the input-output-based hybrid analysis is therefore necessary for a more comprehensive quantification of EE. The foundations represent the largest EE requirements when considering the construction phase.

The operation phase was dominant over the building's lifetime. The life cycle primary operational energy demands of the assessed case study housings are calculated to be 15.3-20.8 GJ/m^2 respectively. The operation phase has the greatest primary energy demand for both of the analysis, representing 61.6-62% of life cycle energy for PRE and CON, respectively. The energy consumption of the housings during operation phase are strongly related to the net dwelling area heated during winter season.

The life cycle energy demand of a building should be reduced by decreasing its operational energy and EE significantly through the use of passive and active technologies even if it leads to a minor increase in EE. Reducing the requirements for operational energy seems to be the most important aspect in the design of buildings that are energy efficient throughout their life cycle.

REFERENCES

[1] A. Utama and S. H. Gheewala, "Indonesian residential high rise buildings: a life cycle energy assessment," *Energy and Buildings*, vol. 11, pp. 1263–8, 2009.

[2] ISO 14040, Environmental Management – Life Cycle Assessment–Principles and Framework, 2006.

[3] ISO 14044, Environmental Management–Life Cycle Assessment – Requirements and Guidelines, 2006.

[4] J. A. Alcorn and G. Baird, "Use of a hybrid energy analysis method for evaluating the embodied energy of building materials," Center for Building Performance and Research, Victoria University of Wellington, 1996.

[5] R. H. Crawford, "Validation of a hybrid life-cycle inventory analysis method," *J. Environ Manage*, vol. 88, pp. 496-506, 2008.

[6] G. J. Treloar, "Extracting embodied energy paths from input-output tables: Towards an input-output-based hybrid energy analysis method," *Economic Systems Research*, vol. 9, pp. 375-391, 1997.

[7] EPA, United States Environmental Protection Agency, Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2014, EPA 420-S-14-001.

[8] G. Hammond and C. Jones, "Inventory of carbon and energy," Version 1.6 Sustainable Energy Research Team, Department of Mechanical Engineering, University of Bath, UK, 2008.

[9] G. Hammond and C. Jones, "Inventory of carbon and energy," Version 2.0 Sustainable Energy Research Team, Department of Mechanical Engineering, University of Bath, UK, 2011.

[10] G. J. Treloar and R. H. Crawford, "Database of embodied energy and water values for materials," The University of Melbourne, 2010.

[11] M. Lenzen and S. Lundie, "Input-Output model of the Australian economy based on published 1996-97 Australian input-output data," University of Sydney, Australia, 2002.

[12] World Bank. World development indicators. World Bank. (2015). [Online]. Available. http://data.worldbank.org/indicator/PA.NUS.FCRF?page=3

[13] A. Stephan and L. Stephan, "Reducing the total life cycle energy demand of recent residential buildings in Lebanon," *Energy*, vol. 74, pp. 618–37, 2014.

[14] A. Rauf and R. H. Crawford, "Building service life and its effect on the life cycle embodied energy of buildings," *Energy*, vol. 79, pp. 140-8, 2015.

[15] R. H. Crawford and A. Stephan, "The significance of embodied energy in certified passive houses," *World Academy of Science, Engineering and Technology*, vol. 78, pp. 473-479, 2013.

[16] R. H. Crawford, "Using input-output data in life cycle inventory analysis, PhD thesis, Deakin University, 2004.

[17] C. K. Chau, F. W. H. Yik, W. K. Hui, H. C. Liu, and H. K. Yu, "Environmental impacts of building materials and building services components for commercial buildings in Hong Kong," *Journal of Cleaner Production*, vol. 15, pp. 1840–1851, 2007.

[18] R. H. Crawford, G. J. Treloar, B. D. Ilozor and P. E. D. Love, "Comparative greenhouse emissions analysis of domestic solar hot water systems," *Building Research and Information*, vol. 31, pp. 34-47, 2003.

[19] G. J. Treloar, "Environmental assessment using both financial and physical quantities," in *Proc. 41st Annual Conference of the Architectural Science Association ANZAScA*, Geelong, November 2007.

[20] B. G. Majeau, A. H. Strømman, and E. G. Hertwich, "Evaluation of process- and input-output-based life cycle inventory data with regard to truncation and aggregation issues," *Environmental Science & Technology*, vol. 5, pp. 1170-1177, 2011.

[21] A. Stephan, R. H. Crawford, and K. Myttenaere, "Towards a comprehensive life cycle energy analysis framework for residential buildings," *Energy and Buildings*, vol. 55, pp. 592–600, 2012.

[22] A. Stephan and R. H. Crawford, "A multi-scale life-cycle energy and greenhouse-gas emissions analysis model for residential buildings," *Archit. Sci. Rev*., vol. 57, pp. 39-48, 2014.

[23] G. J. Treloar, "A comprehensive embodied energy analysis framework, PhD thesis, Geelong, Deakin University, 1998.

Adem Atmaca is a lecturer at the Energy Systems Engineering Department at The University of Gaziantep, Turkey. He has obtained his PhD from Mechanical Engineering Department in the same institution in 2014. His study covers the efficiency improvement and pollutant reduction concepts in the cement industry. His main areas of research are thermodynamics, renewable energy and heat transfer, energy conversion and conservation, the optimal use of energy resources, analysis and optimization of energy processes, sustainable energy systems and life cycle energy efficiency of buildings and embodied energy.

Nihat Atmaca is working as an Assistant Professor at University of Gaziantep, Turkey. He obtained his PhD from Mechanical Engineering Department of the same university, in 2007. He studied on Artificial Neural Networks (ANN), fracture mechanics and vibration analysis. Currently, his main area of research is life cycle assessment (LCA) in buildings.