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A Study on Life Cycle Assessment of Energy Retrofit Strategies for Residential Buildings in Turkey

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Abstract

In this study based on life cycle energy and environmental performance, the alternatives related to energy retrofit strategies were evaluated in order to improve the energy performance of the existing residential buildings. In this context, the effect of each measure on life cycle energy consumption and CO_2 emission was determined by using the "Life Cycle Energy (LCE)" and "Life Cycle CO_2 ($LCCO_2$)" analyses developed based on life cycle assessment (LCA) method.

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Keywords: Residential buildings; Energy retrofit; Life cycle approach; Energy consumption; CO_2 emission.

1. Introduction

Globally, the building energy use accounts for approximately 40 percent of total primary energy use during the product stage as embodied energy and the use stage in the form of operational energy. Also, the energy consumption in residential buildings contributes significantly to their negative environmental impact such as climate change and ozone depletion, and the implication for carbon dioxide emissions reductions in buildings during the product stage as embodied carbon and the use stage in the form of operational carbon are widely acknowledged. The investment on creating the sustainable built environment especially through energy retrofit strategies for buildings has been progressively increasing over the last decade. There are many studies which have methodological differences such as the building lifetime, the life cycle stages considered, whether final or primary energy is taken into account and the final energy conversion factor [1-3]. These studies have revealed the importance of a life cycle approach to understand the environmental impacts related to the buildings.

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To identify the optimum energy retrofit strategies for reducing both energy consumption and CO_2 emissions, this paper presents a simplified life cycle model and implements this to a case study focused on hot humid and cold climate zones of Turkey. The objective of this study is to develop effective strategies on the improvement of building energy performance for hot humid and cold climate zones, which is important for optimum use in the sense of country resources and decision makers; and also the energy and the environmental performances of the residential buildings regarding these strategies are assessed on the basis of a comparative method in the framework of life cycle.

2. Methodology

LCA structure includes four main stages: goal and scope definition, life cycle inventory, impact assessment and interpretation [4]. LCA method can also be implemented for life cycle energy (LCE) and life cycle CO_2 ($LCCO_2$) analysis regarding only the energy use and CO_2 emission as the criteria for the environmental impact. These analyses are aimed at enabling to make the necessary decisions about the energy and environmental efficiency of buildings during the life cycle [5]. Therefore, as it is the aim of this study to assess the life cycle energy performance and the environmental performance considering the life cycle CO_2 emissions of the residential buildings, the life cycle energy and CO_2 emission analyses were carried out to help determining the optimum alternative for the improvement of the present state of the residential buildings.

2.1. Goal and scope definition for LCE and $LCCO_2$ analyses

LCE and $LCCO_2$ analyses are focused on the assessment of the effect of different alternatives regarding the energy retrofit strategies for the hot humid and the cold climate zones of Turkey on the life cycle energy consumption and CO_2 emission of the building. The analyses in accordance with this purpose enable to quantitatively assess the energy consumption (embodied energy, operational energy) and CO_2 emission (embodied carbon, operational carbon) concerning the life cycle stages of the building in the framework of life cycle inventory. As to the impact assessment, the total life cycle energy consumption (primary energy) and the total CO_2 emissions are taken into account.

According to CEN TC 350 Standard, the life cycle stages of a building are product stage, construction process stage, use stage and end-of-life stage [6]. As there is not sufficient data about demolition and the end-of-life stage of materials, these stages are rarely considered in the framework of life cycle studies [7]. In the studies handling the stages of construction, end-of-life and relative transportation of materials clearly, it is stated that the necessary energy for these stages is at the negligible level or approximately 1% of the total energy consumed during the life cycle of building [8]. Therefore, in this study, the system boundaries include the product stage and use stage in the framework of life cycle energy and CO_2 emission analyses. The building lifetime stated by [9] is taken into account in this study, and the building lifetime is accepted as 30 years.

2.1.1. Building model and energy retrofit strategies

In this study, a mass housing project constructed by the Housing Development Administration of Turkey (TOKI) which has a significant role in dwelling production in Turkey has been chosen; this project involves common construction technologies and design criteria. One of the housing blocks in the mass housing project is taken as the building case and is treated as if it is in Antalya and Erzurum which are the representative cities of hot humid and cold climate zones of Turkey respectively.

The residential building (the orientation and the form given in Fig. 1) is a 17-storey building and floor to floor height is 2.79 m. The shape factor (the ratio of building length to building depth) is 1.37, A/V (the ratio of the total façade area to building volume) is 0.19, the ground floor area is 573 m^2 and the total height of the building is 48.28 m. The data related to the residential building envelope components are given in Table 1. The indoor comfort temperature is accepted as 21ºC for the period required heating, and 25ºC for the period required cooling. Natural gas is used for the heating system and the individual water heater system, and the electric energy is used for cooling as fuel.

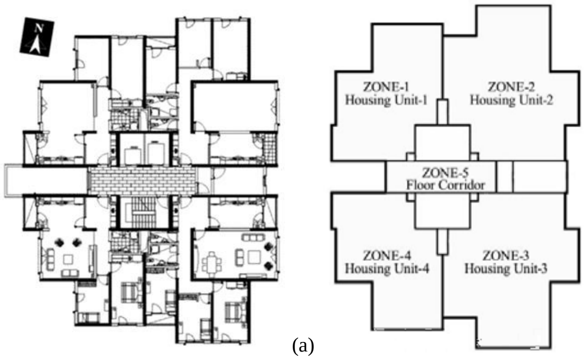

Fig. 1. Plan view of the residential building (a) and conditioned zone areas (b).

Table 1. Main characteristics of building components, including embodied energy (EE) and embodied carbon (EC).

Component	Material (outside-inside)	Thermal conductivity (W/mK)	Thickness (m)	Density (kg/m^3)	Area (m^2)	Embodied energy (kWh/kg)	Embodied carbon ($kgCO_2/kg$)
Exterior wall ($type_1$)	Cement rendering	1.60	0.03	2000	2120.30	0.16	0.09
	Extruded polystyrene (XPS)	0.035	0.05	28	2120.30	23.60	2.51
	Aerated concrete block	0.193	0.20	580	2120.30	0.96	0.43
	Gypsum plaster	0.51	0.02	1200	2120.30	0.56	0.12
Exterior wall ($type_2$)	Cement rendering	1.60	0.03	2000	1839.60	0.16	0.09
	Extruded polystyrene (XPS)	0.035	0.05	28	1839.60	23.60	2.51
	Reinforced concrete	2.50	0.20	2400	1839.60	0.55	0.20
	Gypsum plaster	0.51	0.02	1200	1839.60	0.56	0.12
Ground floor	Reinforced concrete	2.50	1.00	2400	552.57	0.55	0.20
	Concrete	1.65	0.03	2200	552.57	0.36	0.19
	Extruded polystyrene (XPS)	0.035	0.04	35	552.57	23.60	2.51
	Concrete	1.65	0.03	2200	552.57	0.36	0.19
	Screed	1.40	0.05	2000	552.57	0.44	0.18
	Parquet	0.08	0.01	600	552.57	7.78	1.46
Roof	Gravel	0.36	0.01	1840	510.00	0.01	0.00
	Roofing felt	0.19	0.0017	960	510.00	21.60	1.92
	Expanded polystyrene (EPS)	0.033	0.05	30	510.00	354.00	39.30
	EPDM	0.30	0.006	1200	510.00	27.40	3.08
	Concrete	1.65	0.04	2200	510.00	0.36	0.19
	Reinforced concrete	2.50	0.14	2400	510.00	0.55	0.20
	Gypsum plaster	0.51	0.02	1200	510.00	0.56	0.12
Window	Clear glazing	1.00	0.004	2500	800.36	4.42	0.96
	Air	-	0.012	1.29	-	-	-
	Clear glazing	1.00	0.004	2500	800.36	4.42	0.96
	PVC frame	0.17	0.060	1390	239.07	39.8	7.23

The application of thermal insulation in the exterior wall components and the application PV systems are considered as the energy retrofit strategies in the framework of the study. For the application of thermal insulation in the exterior wall components, it is assessed whether the thermal insulation layer matches the overall heat transfer coefficient (U, W/m^2K) stated in Turkish Standard (TS) 825 [10] besides the other cases enabling lower U coefficients. Within the framework of the application of PV systems, PV system application on the terrace roof and the southern façade of the opaque areas is taken into consideration. The data regarding the alternatives improved in this context are given in Table 2.

2.2. Life cycle inventory for LCE and $LCCO_2$ analyses

LCE and $LCCO_2$ inventories include the determination of the energy consumption and CO_2 emission amount related to product and use stages of the residential building. In the framework of this study, in order to determine the

Table 2. The alternatives related to the energy retrofit strategies.

Alt. No.	Description	U_{wall1}, U_{wall2} (W/m^{2}K)	U_{roof} (W/m^{2}K)	$U_{ground\ floor}$ (W/m^{2}K)	U_{window} (W/m^{2}K)
A_1	No thermal insulation layer in the exterior wall components	0.79, 3.25	0.55	0.51	2.60
A_2	Thermal insulation value = base case	0.37, 0.58	0.55	0.51	2.60
A_3	Thermal insulation value ≥ U value in TS 825	0.34, 0.49	0.55	0.51	2.60
A_4	Thermal insulation value ≥ U value in TS 825	0.31, 0.43	0.55	0.51	2.60
A_5	Thermal insulation value ≥ U value in TS 825	0.28, 0.39	0.55	0.51	2.60
A_6	Thermal insulation value ≥ U value in TS 825	0.26, 0.35	0.55	0.51	2.60
A_7	Thermal insulation value ≥ U value in TS 825	0.24, 0.32	0.55	0.51	2.60
A_8	Thermal insulation value ≥ U value in TS 825	0.20, 0.25	0.55	0.51	2.60
A_9	Thermal insulation value ≥ U value in TS 825	0.18, 0.22	0.55	0.51	2.60
A_{10}	Thermal insulation value ≥ U value in TS 825	0.16, 0.18	0.55	0.51	2.60
A_{11}	Thermal insulation value ≥ U value in TS 825	0.14, 0.17	0.55	0.51	2.60
PV system					
A_{12}	Mono crystalline silicon module for terrace roof (190Wp)	PV surface area:148.36 Wp/m^2			
A_{13}	Amorphous silicon module for opaque areas of south façade (340 Wp)	PV surface area: 55.30 Wp/m^2			

product stage energy requirement and CO_2 emission of the residential building related to both base case and the energy retrofit strategies handled, per unit embodied energy and embodied carbon values were derived for main building components using the GABI 6.0 LCA software and the Inventory of Energy and Carbon (ICE) version 2.0 [11,12] and for PV system components such as PV module, balance of system (BOS, including inverter, array support and cabling), obtaining directly from literature [13-15]. In the determination of embodied energy and embodied carbon values, the process analysis method taking into the account the production process from the level of raw material extraction to building materials within the scope of "cradle to gate" approach is taken as a basis. As no renovation related to the strategies is predicted during the building lifetime described in the study, recurring embodied energy and carbon values are not considered in the calculations. For the calculation of energy consumption related to use stage, the primary energy consumption depending on the final energy consumption and the primary energy savings depending on the final energy generation are taken into consideration. The final energy consumption (including heating, cooling, lighting, domestic hot water, auxiliary energy) (kWh/a) of the alternatives related to the base case of the residential building and the thermal insulation application in the exterior wall components is calculated by DesignBuilder simulation program. The final energy generation (kWh/a) of the alternatives related to the application of PV systems on the terrace roof and opaque areas of southern façade of the residential building is calculated by PV*SOL Expert simulation program. The primary energy conversion factors for the fuel types consumed in Turkey are given as 1.00 for natural gas and 2.36 for electrical energy [16]. Regarding the primary energy conversion factor for electrical energy generated by the PV system, depending on the efficiency level of the grid; it is accepted that in order to obtain 1kWh energy, 3.23 kWh primary energy is consumed [17,18]. CO_2 emissions regarding the use stage of the residential building can be calculated according to the estimation methods provided by the Intergovernmental Panel on Climate Change (IPCC) 2006 [19]. In this study, among these estimation methods, the Tier 2 method concentrates on estimating the emissions from the carbon content of fuels supplied to the country with the country specific emission factors being used. For Turkey, the emission factors for natural gas and electricity were taken as 0.2 and 0.55 kg eq.CO_2/kWh respectively [20]. The conversion factor for the CO_2 emission avoided is taken as 0.88 kgCO_2/kWh [21].

2.3. Impact assessment for LCE and LCCO$_2$ analyses

Impact assessment for LCE and $LCCO_2$ analyses consists of a classification and evaluation of potential environmental impacts for each energy retrofit strategy during the life cycle inventory. Thus, in order to determine the building energy retrofit strategy with the lowest energy consumption and CO_2 emission over the assumed lifetime of the building, the results of life cycle inventory analysis are assigned to the total life cycle energy consumption and CO_2 emission as the environmental indicators.

3. Findings and Results

The life cycle assessment related to the energy retrofit strategies for the cities representing the hot humid and cold climate zones is carried out by the help of the analyses results of LCE and $LCCO_2$ and showed in Tables 3-4.

Table 3. LCE and $LCCO_2$ analyses results for Antalya, the representative city of hot humid climate zone.

Alt. No.	Embodied energy (MWh)	Embodied carbon ($tonCO_2$)	Final energy consumption (MWh/a)	Operational energy (MWh/a)	Operational carbon ($tonCO_2$/a)	Life cycle energy consumption (MWh)	Life cycle CO_2 emission ($tonCO_2$)
A_1	7,401.80	2,291.84	547.12	873.22	193.35	33,598.44	8,092.25
A_2	7,542.01	2,306.76	437.62	754.79	169.15	30,185.63	7,381.19
A_3	7,570.05	2,309.74	428.06	738.44	165.49	29,723.33	7,274.44
A_4	7,598.10	2,312.72	424.24	734.35	164.66	**29,628.56**	**7,252.38**
A_5	7,626.14	2,315.71	426.17	742.76	166.71	29,909.00	7,317.00
A_6	7,654.18	2,318.69	423.71	740.19	166.19	29,859.99	7,304.40
A_7	7,682.23	2,321.67	421.64	738.04	165.75	29,823.40	7,294.29
A_{12}	7,786.22	2,354.34	386.61	590.03	123.96	**26,027.76**	**6,220.27**
A_{13}	7,699.97	2,336.75	422.27	705.21	155.55	29,018.80	7,047.79

Table 4. LCE and $LCCO_2$ analyses results for Erzurum, the representative city of cold climate zone.

Alt. No.	Embodied energy (MWh)	Embodied carbon ($tonCO_2$)	Final energy consumption (MWh/a)	Operational energy (MWh/a)	Operational carbon ($tonCO_2$/a)	Life cycle energy consumption (MWh)	Life cycle CO_2 emission ($tonCO_2$)
A_1	7,401.80	2,291.84	1,600.56	1,824.57	377.76	6,2139.03	13,624.73
A_2	7,542.01	2,306.76	1,051.90	1,280.03	269.09	4,5942.80	10,379.43
A_5	7,626.14	2,315.71	992.29	1,221.31	257.40	4,4265.59	10,037.65
A_6	7,654.18	2,318.69	979.50	1,208.72	254.89	4,3915.92	9,965.45
A_7	7,682.23	2,321.67	968.76	1,198.17	252.79	4,3627.23	9,905.39
A_8	7,766.36	2,330.62	944.84	1,174.66	248.11	4,3006.30	9,774.04
A_9	7,822.44	2,336.58	933.38	1,163.41	245.88	4,2724.79	9,712.84
A_{10}	7,906.57	2,345.53	920.31	1,150.58	243.32	4,2423.91	9,645.20
A_{11}	7,962.66	2,351.50	913.51	1,143.91	242.00	**4,2279.91**	**9,611.37**
A_{12}	7,784.67	2,353.04	1,009.04	1,141.60	231.12	**4,2486.73**	**9,411.14**
A_{13}	7,699.97	2,336.75	1,038.93	1238.14	257.60	4,4981.54	10,102.41

From among the described alternative group related to the thermal insulation application in the exterior wall components, the alternative with an optimum performance for Antalya is A_4 alternative by which the thermal insulation thickness for 7 cm is implemented, and U_{wall1}: 0.31 W/m^{2}K and U_{wall2}:0.43 W/m^{2}K values are obtained. The alternative with an optimum performance for Erzurum is A_{11} alternative by which the thermal insulation thickness for 20 cm is implemented, and U_{wall1}:0.14 W/m^{2}K and U_{wall2}:0.17 W/m^{2}K values are obtained. According to the results of LCE and $LCCO_2$ analyses, when A_4 alternative for Antalya is compared with A_1 in which there is no thermal insulation layer in the exterior wall components, it is observed that there is an increase in embodied energy and embodied carbon values respectively with the ratio of 3% and 1%, and there is a decrease in per year final energy consumption as 22%, in per year operational energy as 16%, in per year operational carbon as 15%, in the life cycle energy consumption as 12% and in the life cycle CO_2 emission as 10% (Table 3). When A_{11} alternative for Erzurum is compared with A_1 in which there is no thermal insulation layer in the exterior wall components, it is observed that there is an increase in embodied energy and embodied carbon values respectively with the ratio of 8% and 3%, and there is a decrease in per year final energy consumption as 43%, in per year operational energy as 37%, in per year operational carbon as 36%, in the life cycle energy consumption as 32% and in the life cycle CO_2 emission as 29% (Table 4).

From among the described alternative group related to the PV system application, the alternative with an optimum performance for Antalya and Erzurum is A_{12} alternative by which roof PV system is dealt with. According to the results of LCE and $LCCO_2$ analyses, when A_{12} alternative is compared with A_2 in which there is no PV system, it is observed for Antalya that there is an increase in embodied energy and embodied carbon values respectively with the ratio of 3% and 2%, and there is a decrease in per year final energy consumption as 12%, in per year operational energy as 22%, in per year operational carbon as 27%, in the life cycle energy consumption as 14% and in the life cycle CO_2 emission as 16% (Table 3). As to Erzurum, it is observed that there is an increase in embodied energy and embodied carbon respectively with the ratio of 3% and 2%, in per year final energy consumption as 4%, in per year operational energy as 11%, in per year operational carbon as 14%, in the life cycle energy consumption as 8% and in the life cycle CO_2 emission as 9% (Table 4).

4. Conclusion

The aim of the maximum benefit from the energy saving potential in the residential buildings highlights the improvement of a life cycle approach based on the optimization of energy and environmental performances. Therefore, in this study, the impacts of energy retrofit strategies aimed at improving the energy performance of a residential building on the life cycle energy consumption and the life cycle CO_2 emission of a residential building are assessed by considering an existing residential block including the construction technologies and the design criteria widely used in Turkey. The calculation results of LCE and $LCCO_2$ analyses indicate differences depending on the energy retrofit strategies and the climate zones. A limited number of energy retrofit strategies are studied in the framework of the study. Consequently, the results of this study compared with the previous studies show that this approach can be used for the similar climate zones and also point the importance of assessing the strategies effective in improving the residential energy performance with their effects on the energy and environmental performances of residential buildings based on the life cycle principle within an integrated framework. However, in order to reach acceptable general results, a larger number of energy retrofit strategies should be studied and assessed.

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