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Life cycle assessment of energy retrofit strategies for an existing residential building in Turkey

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Abstract

Energy consumption in residential buildings contributes significantly to negative environmental impacts such as climate change and ozone depletion, and the implication for carbon dioxide emissions reductions in buildings during the construction phase as the embodied carbon and the operation phase in the form of operational carbon are widely acknowledged. Investment on creating a sustainable built environment especially through energy retrofit strategies for buildings has been progressively increasing over the last decade. To identify 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 different climate regions of Turkey. The objective of this study is to develop effective strategies on the improvement of building energy performance for different climate regions, which is important for optimum use in the sense of country resources and decision makers. Also the energy and environmental performances of the residential buildings regarding these strategies are assessed on the basis of a comparative method in the framework of life cycle. 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 emissions was determined by using the "Life Cycle Energy (LCE)" and "Life Cycle CO_2 ($LCCO_2$)" analyses developed based on the life cycle assessment (LCA) method.

Keywords
Residential buildings, Energy retrofit, Life cycle approach, Energy consumption, CO_2 emissions.

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1. Introduction

Globally, the building energy use accounts for approximately 40% of total primary energy use during the product stage as embodied energy and the usage stage in the form of operational energy. Also, the energy consumption in residential buildings contributes significantly to negative environmental impacts such as climate change and ozone depletion, and the implication for carbon dioxide emissions reductions in buildings during the product stage as the embodied carbon and the use stage in the form of operational carbon are widely acknowledged. The investment on creating a 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 (Adalberth, K., 1997; Norman, J., MacLean, H.L., ASCE, M., Kennedy, C.C., 2006; Bastos, J., Batterman, S.A., Freire, F., 2014).

First of all, the life cycle approach in building energy analysis was applied by Bekker (Bekker, P.C.F., 1982). It was demonstrated that it was appropriate to deal with the problem of limited resources in terms of buildings by means of a life cycle approach. Adalberth studied about life cycle energy use of three dwellings in Sweden, and analysed the construction, use and end-of-life phases of a residential building (Adalberth, K., 1997). Fay et al. (Fay, R., Treloar, G., Iyer-Raniga, U., 2000) suggested alternative designs with additional insulation with the help of a study on primary energy use of a detached house in Melbourne, Australia. The life cycle energy and greenhouse gas emissions of a standard house and an energy efficient house, both in Michigan, USA were calculated by Keoleian et al. (Keoleian, G., Blanchard, S., Reppe, P., 2001). Asif et al. (Asif, M., Muneer, T., Kelley, R., 2007) focused their investigations on embodied energy and other environmental impacts of a semi detached house in Scotland. Citherlet and Defaux (Citherlet, S., Defaux, T., 2007) made a comparative analysis on a family house by changing its insulation thickness and type. Blengini (Blengini, G.A., 2009) studied an apartment building in Turin, Italy. The primary energy, GHG emissions and other environmental impacts, with alternative end-of-life scenarios, have been studied in detail. Thanks to Gustavsson and Joelsson (Gustavsson, L., Joelsson, A., 2010), the life cycle primary energy balance of residential buildings (single family house, row house unit and apartment block) in Sweden was simulated for a period of 50 years. Also, potential life cycle energy improvements were discussed in terms of the influence of building material selection and a different energy supply. Nemry et al. (Nemry, F., Uihlein, A., Colodel, C.M. et al., 2010) estimated different lifespans in their study, and observed that the existing building types had a minimum residual service life (time from assessment to end-of-life) of 20 years, and the new building types generally had a 40-year lifespan.

The study of Malmqvist et al. (Malmqvist, T., Glaumann, M., Scarpellini, S. et al., 2011) looked into the reasons of limited application of life cycle assessment in the building sector, and a simplified methodology facilitating the assessment process was proposed. Blom et al. preferred to use life cycle assessment (LCA) to calculate the environmental impact of gas and electricity consumption in dwellings in their study (Blom, I., Itard, L., Meijer, A., 2011). Ramesh et al. (Ramesh, T., Prakash, R., Shukla, K.K., 2012) made an assessment of ten residential building designs with energy saving features, e.g. heat insulation on walls and roof, double pane glass for windows, in the Indian context in terms of the life cycle energy (LCE) demand. One of these buildings was selected to further assess LCE performance with an on-site power generation. In the analyses of Bastos et al. (Bastos, J., Batterman, S.A., Freire, F., 2014), life cycle energy and greenhouse gas (GHG) of three representative residential building types in Lisbon were examined. It was focused on building construction, retrofit and use stages with the life cycle model, applying an econometric model to estimate energy use in Portuguese households. Two functional units were considered. A hybrid model for assessing the life cycle energy and GHG emission impacts of retrofitting residential building stocks comprising a process based approach was presented in the study of Famuyibo et al. (Famuyibo, A.A., Duffy, A., Strachan, P., 2013). In order to estimate the performance along retrofitting, operational, maintenance and disassembly stages of the three selected house retrofit scenarios, the representative archetypes were used.

These studies have revealed the importance of a life cycle approach to understanding the environmental impacts related to the buildings. In the analysis of the studies about the evaluation of residential building performances, the differences between the evaluation methods were found because of the effects of many different variables and interactions on the energy and environmental effectiveness levels of residential buildings. However, certain effective strategies should be determined in order to improve the building performance and the priorities need to be classified as the residential buildings have a complicated structure from the viewpoint of either architectural and mechanical, or environmental and social.

It is also acknowledged that residential buildings in Turkey, just as all over the world, are highly responsible for the energy consumption and CO_2 emissions due to energy consumption. In the design of new residential buildings or the improvement of existing residentials, it is obvious that energy consumption and environmental impact assessments have not been taken into consideration. However, the improvement of energy efficiency levels of residential buildings plays a significant role in solving the energy and environmental problems encountered within the framework of the sustainable development goals of Turkey. For the improvement of energy efficiency levels of residential buildings, it is necessary to minimise energy consumption, increase energy efficiency by integrating energy producing systems, thereby improving the building's energy performance. It is well known that in this way, a considerable amount of energy savings can be provided in the residential buildings which can then be turned into high-performance buildings that have fewer CO_2 emissions and energy expenses.

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 relates this to a case study focused on three different climate regions of Turkey. The objective of this study is to develop effective strategies for the improvement of building energy performance for temperate humid, hot humid and cold climate regions, which is important for optimum use in the sense of country resources and decision makers. 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.

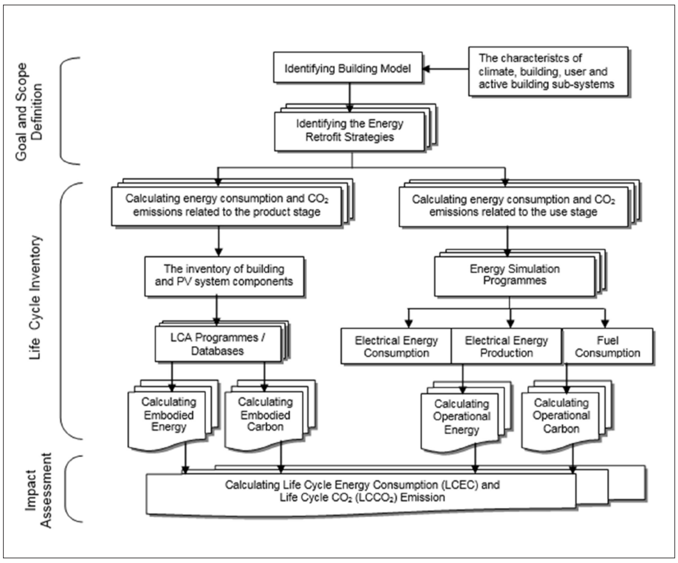

Figure 1. *The schematical explanation of LCE and $LCCO_2$ analyses.*

2. Methodology

The LCA structure includes four main stages: goal and scope definition, life cycle inventory, impact assessment and interpretation (ISO 14040, 2006). The 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 emissions as the criteria for the environmental impact. These analyses are aimed at enabling the making of the necessary decisions about the energy and environmental efficiency of buildings during the life cycle (Fay, R., Treloar, G., Iyer-Raniga, U., 2000). Therefore, as it is the goal 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 determine the optimum alternative for the improvement of the present state of the residential buildings (Figure 1).

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

LCE and $LCCO_2$ analyses are focused on the assessment of the effects of different alternatives regarding the energy retrofit strategies for the temperate humid, hot humid and the cold climate regions of Turkey, on the life cycle energy c$_o$nsumption and CO2 emission of the building. The analyses in accordance with this purpose enable quantitatively assessing the energy consumption (embodied energy, operational energy) and CO_2 emissions (embodied carbon, operational carbon) concerning the life cycle stages of the building in the framework of the 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 the CEN TC 350 Standard, the life cycle stages of a building are the product stage, the construction process stage, the use stage and the end-of-life stage (CEN/TC 350, 2008). As there are 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 (Wallhagen, M., Glaumann, M., Malmqvist, T., 2011). 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 a building (Sartori, I., Hestnes, A.G., 2007). Therefore, in this study, the system boundaries include the product stage and use stage in the framework of life cycle energy and CO_2 emissions analyses, and these are defined in Table 1.

Table 1. *Life cycle stages of a building according to CEN/TC 350 (2008) and the stages which are included in this study.*

Stage	Module	Stages included
Product Stage	Raw material supply	yes
	Transport	yes
	Manufacturing	yes
Construction Process Stage	Transport	no
	Construction-installation on-site processes	no
Use Stage	Maintenance	no
	Repair and replacement	no
	Refurbishment	no
	Operational energy use: heating, cooling, ventilation, hot water and lighting	yes
	Operational water use	no
End-of-life stage	De-construction	no
	Transport	no
	Recycling/Re-use	no
	Disposal	no

Table 2. *Characteristics of the climate regions.*

Climate region	Representative city	Latitude-longtitude (°)	Heating degree days	Cooling degree days	Global horizontal radiation (kWh/m²y)
Temperate humid	Istanbul	40.97-28.82	1886	2152	1465
Hot humid	Antalya	36.70-30.73	972	3345	1798
Cold	Erzurum	39.95-41.17	4785	856	1555

The energy values were defined in primary energy (kWh) for LCE and $LCCO_2$ analyses. The $kgCO_2$ unit was used for CO_2 emissions values related to the different stages. As the general application widely accepted related to the building lifetime is 30-50 years (Sartori, I., Bergsdal, H., Müller, D.B., Brattebø, H., 2008). The building lifetime stated by the Official Journal of the European Union (2012) is taken into account in this study, and the building lifetime is accepted as 30 years.

2.1.1. Building model

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 Istanbul, Antalya and Erzurum which are the representative cities of temperate humid, hot humid and cold climate regions of Turkey, respectively (Table 2).

The residential building (the orientation and the form given in Figure 2) is a 17-storey building and floor to floor

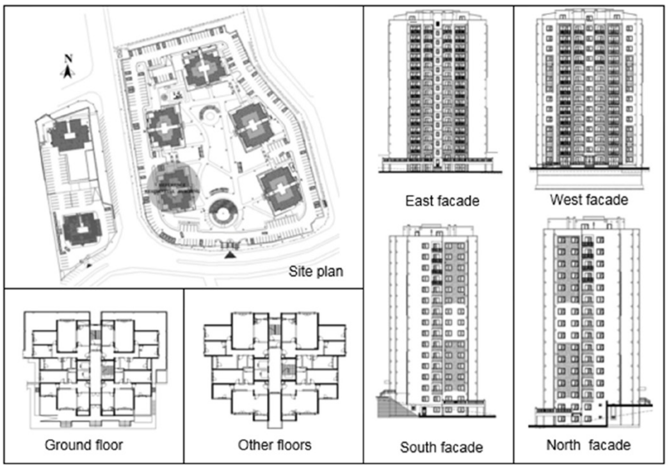

Figure 2. *Site plan, floor plans and elevations for the residential building.*

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 facade 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 3.

The indoor comfort temperature is accepted as 21°C for the period requiring heating, and 25°C for the period requiring cooling. The heating system of the residential building is the penthouse condensing boiler type central system, and the fuel used is natural gas. It is assumed in the study that there is a cooling system and the electric energy is used for cooling. The hot water system of the residential building is the individual water heater system, and the fuel used is natural gas.

Table 3. *Main characteristics of building components, including embodied energy (EE) and embodied carbon (EC).*

Component	Material layers (from outside to inside)	Thermal conductivity (W/mK)	Thickness (m)	Density (kg/m³)	Area (m²)	EE (kWh/kg)	EC ($kgCO_2$/kg)
External wall (type$_1$)	Cement rendering	1.60	0.03	2000	2120.30	0.16	0.09
	Extruded polystyrene	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
External wall (type$_2$)	Cement rendering	1.60	0.03	2000	1839.60	0.16	0.09
	Extruded polystyrene	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	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
Flat 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	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

2.1.2. Energy retrofit strategies

The building envelope affects heat transfer from the external environment to the internal environment in order to improve the existing residential building performance as energy effective and to minimise the use of active building sub-systems. It has an important impact on providing indoor thermal comfort requirements. In this respect, it is aimed to improve the building envelope as energy effective passive system elements with optimum performance. In line with this aim, the improvement measures are taken into account as:

- The application of heat insulation in the exterior wall components,
- Improvement of glazing systems and
- The application of a photovoltaic (PV) system.

These retrofit strategies consider the current regulation related to the existing situation and the design flexibility of the reference residential building alongside the minimum performance necessities which are successful in the building effectiveness. For the application of heat insulation in the exterior wall components or improvement of glazing systems, it has been assessed whether the heat insulation layer or the glazing type matches the overall heat transfer coefficient (U, W/m^2K) stated in Turkish Standard (TS) 825 (TS 825, 2013) along with 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 facade of the opaque areas are taken into consideration. The data regarding the alternatives improved in this context are given in Table 4.

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 amounts related to product and use stages of the residential building.

Process analysis, input-output analysis and hybrid analysis are used to quantify the production energy and CO_2 emissions of a material. Process

Table 4. *Characteristics of the alternatives related to the energy retrofit strategies.*

Alt. No.	Descriptions	U_{wall_1}, U_{wall_2} (W/m²K)	U_{roof} (W/m²K)	U_{g_floor} (W/m²K)	U_{window} (W/m²K), SHGC*
A_1	No insulation for external walls	0.79, 3.25	0.55	0.51	2.60, 0.74
A_2	Insulation level = Base case	0.37, 0.58	0.55	0.51	2.60, 0.74
A_3	Insulation level ≥ U value in TS 825	0.34, 0.49	0.55	0.51	2.60, 0.74
A_4	Insulation level ≥ U value in TS 825	0.31, 0.43	0.55	0.51	2.60, 0.74
A_5	Insulation level ≥ U value in TS 825	0.28, 0.39	0.55	0.51	2.60, 0.74
A_6	Insulation level ≥ U value in TS 825	0.26, 0.35	0.55	0.51	2.60, 0.74
A_7	Insulation level ≥ U value in TS 825	0.24, 0.32	0.55	0.51	2.60, 0.74
A_8	Insulation level ≥ U value in TS 825	0.20, 0.25	0.55	0.51	2.60, 0.74
A_9	Insulation level ≥ U value in TS 825	0.18, 0.22	0.55	0.51	2.60, 0.74
A_{10}	Insulation level ≥ U value in TS 825	0.16, 0.18	0.55	0.51	2.60, 0.74
A_{11}	Insulation level ≥ U value in TS 825	0.14, 0.17	0.55	0.51	2.60, 0.74
A_{12}	Clear single glazing (4mm)	0.37, 0.58	0.55	0.51	4.90, 0.85
A_{13}	Low-E (heat cont.) e2=0.04(4+12air+4mm)	0.37, 0.58	0.55	0.51	1.80, 0.44
A_{14}	Low-E (heat cont.) e2=0.04(4+12argon+4mm)	0.37, 0.58	0.55	0.51	1.50, 0.44
A_{15}	Low-E (heat cont.) e3=0.03(4+12 air+4mm)	0.37, 0.58	0.55	0.51	1.80, 0.51
A_{16}	Low-E (heat cont.) e3=0.03(4+12argon+4mm)	0.37, 0.58	0.55	0.51	1.50, 0.51
A_{17}	Low-E (heat-solar cont.) e2=0.02(4+12 air+4mm)	0.37, 0.58	0.55	0.51	1.80, 0.30
A_{18}	Low-E (heat-solar cont.) e2=0.02(4+12 argon+4mm)	0.37, 0.58	0.55	0.51	1.50, 0.30
PV systems					
A_{19}	Monocrystalline silicon module (190Wp) for roof	PV surface area:148.36 Wp/m²			
A_{20}	Amorphous silicon module (340 Wp) for south facade	PV surface area: 55.30 Wp/m²			

*SHGC : Solar heat gain coefficient.

analysis systematically analyse the energy inputs to the actual material production process which is based on the reliable energy consumption for particular processes (Pearlmutter, D., Freidin, C., Huberman, N., 2007; Rossi, B., Marique, A.F., Glaumann, M., Reiter, S., 2012). A wide range of studies (Börjesson, P., Gustavsson, L., 2000; Chen, T.Y., Burnett, J., Chau, C.K., 2001; Scheuer, C., Keoleian, G.A., Reppe, P., 2003; Huberman, N., Pearlmutter, D., 2008; Bribián, I.Z., Usón, A.A., Scarpellini, S., 2009; Ramesh, T., Prakash, R., Shukla, K.K., 2012; Baek, C., Park, S.H., Suzuki, M., Lee, S.H., 2013) related to the calculation of embodied energy values of the building envelope commonly use this method. The national statistical information compiled by the governments is utilised in input-output analysis for the purpose of analysing the national economic flows between the sectors. These economic flows can be turned into energy flows by the average energy tariffs (Fay, R., Treloar, G., Iyer-Raniga, U., 2000). Compared with the process analysis, this method is seen as less accurate (Treloar, G.J., 1997). A certain number of researchers propose hybrid analysis combining the strengths of process analysis with those of input-output analysis in order to avoid a truncation and an aggregation error which are encountered based on these two methods (Fay, R., Treloar, G., Iyer-Raniga, U., 2000; Treloar, G.J., 1997; Stephan, A., Crawford, R.H., 2014).

In the framework of this study, in order to be able to determine product stage energy requirements and CO_2 emissions of a reference building related to both base case and the improvement measures dealt with, per unit embodied energy and embodied carbon values were derived for major building components, such as external walls, roof, ground floor, windows using the GABI 6.0 LCA software and the Inventory of the Energy and Carbon (ICE) version 2.0 (GABI Software, 2014; Hammond, G., Jones, C.,2011), and for PV system components such as PV modules, balance of system (BOS, including inverter, array support and cabling), obtaining directly from literature (Alsema, E.A., 1998; Alsema, E.A., de Wild-Scholten, MJ., 2006; Alsema, E.A., de Wild-Scholten, M.J., 2007). The GABI 6.0 software programme is a widely-used LCA programme developed through the partnership of Stuttgart University, Chair of Building Physics Life Cycle Engineering and the PE International GMBH, used to evaluate the environmental impacts of building materials during the course of the building's life and to generate data for artificial and environmental product declaration. ICE database 2.0, with which energy density and carbon values related to many building materials are defined, is an open source database developed by Prof. Geoffrey Hammond and Dr. Craig Jones (Bath University,

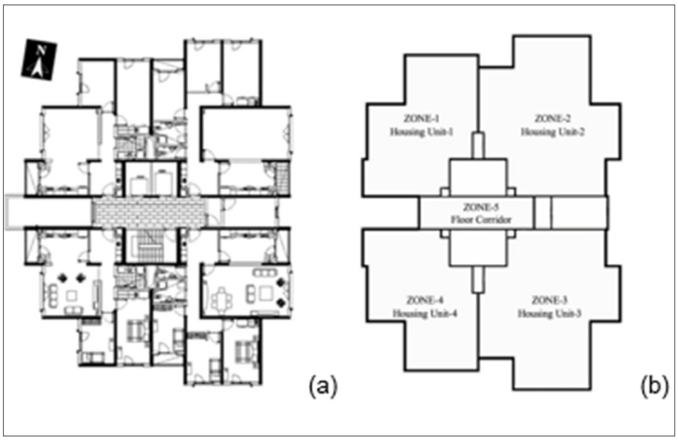

Figure 3. *Plan view of the reference residential building (a) and conditoned zone areas (b).*

Department of Mechanical Engineering). These values were later multiplied with building envelope quantities that were calculated by using original drawings and other project documents, and the component amounts determined related to PV systems designed in the fields of roof and facade. Therefore, the process analysis method was taken as a basis as it takes into account the production process for the determination of embodied energy and carbon values in the framework of the "cradle to gate" approach from the level of raw material extraction to building materials. As no renovation related to the strategies is predicted during the building's lifetime described in the study, recurring embodied energy and carbon values are not considered in the calculations.

In the calculation of energy consumption relating to the use stage, primary energy consumption depending on final energy consumption and primary energy savings depending on final energy production should be considered. The operational energy (*OE*) values (kWh/a) of the alternatives defined for the current situation of the reference residential building and the considered measures can be calculated by the equation below (CEN/BT/WG 173, 2006):

$$OE = \sum\left(E_{cons,fuel} \times f_{p,fuel}\right) - \sum\left(E_{PV} \times f_{p,PV}\right)$$

(1)

where $E_{cons,fuel}$ is the energy consumption per fuel type (kWh/a), E_{PV} is the energy generated by the PV system (kWh/a), $f_{p,fuel}$ is the primary energy conversion factor for each fuel type and $f_{p,PV}$ is the primary energy conversion factor for electrical energy generated by the PV system.

The final energy consumptions (including heating, cooling, lighting, domestic hot water, auxiliary energy) ($E_{cons,fuel}$) of the variables defined related to the current situaton of the reference residential building and energy saving measures are calculated by using the DesignBuilder simulation programme representing the detailed dynamic calculation method. In the simulation carried out by using the DesignBuilder programme, the housing units and the floor halls of the reference residential building are accepted as independent zones in terms of zoning criteria (Figure 3).

Physical properties of the various building materials (density, conductivity and specific heat) were input to the DesignBuilder programme based on the values from the Turkish Standard (TS) 825 (TS 825, 2013), supplemented by the software database (DesignBuilder Programme, 2013) when appropriate.

The final energy production (E_{PV}) of the alternatives defined relating to PV implementation on the roof and facade areas of the reference residential building are calculated by using the PV*SOL Expert simulation programme representing the detailed dynamic calculation method.

Based on Eq. 1, 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 (The Official Gazette of Turkish Republic, 2010). 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 1 kWh energy, 3.23 kWh of primary energy is consumed (Alsema, E.A., de Wild-Scholten, M.J., 2005; IEA, 2006; Swiss Ecoinvent database, 2013; TETC, 2013).

The use stage environmental performance related to the reference residential building, meaning the energy related to CO_2 emissions, can be calculated according to the estimation methods provided by the IPCC 2006. According to the aim of 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. In the framework of the Tier 2 method, the operational carbon related to the reference residential building (OC) ($_{k}$gCO2/a) is calculated by the following equation (IPCC (2006):

$$OC = \sum\left(E_{cons,fuel} \times f_{CO_2,fuel}\right) - \sum\left(E_{PV} \times f_{CO_2,PV}\right) \tag{2}$$

where $E_{cons,fuel}$ is the energy consumption per fuel type (kWh/a), E_{PV} is the energy generated by the PV system (kWh/a), $f_{co_2,fuel}$ is the country specific emission factor per fuel type ($kgCO_2$/kWh) and $f_{co_2,PV}$ is the conversion factor for the CO_2 emissions avoided concerning the electrical energy generated by the PV system ($kgCO_2$/kWh).

For Turkey, the emission factors for natural gas and electricity were taken as 0.2 and 0.55 $kgCO_2$/kWh respectively (MEU, 2013). The conversion factor for the CO_2 emissions avoided is taken as 0.88 $kgCO_2$/kWh (GEMIS, 2013).

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 emissions over the assumed lifetime of the building, the results of life cycle inventory analysis are assigned to the total life cycle energy consumption (LCEC) and CO_2 ($LCCO_2$) emissions as the environmental indicators. Certain studies demonstrate that the LCEC is calculated by adding the embodied energy concerning the product stage and the total operational energy over a 30 year lifetime (both values given in terms of primary energy) (Fay, R., Treloar, G., Iyer-Raniga, U., 2000). As to the $LCCO_2$ it is calculated by adding the embodied carbon concerning the product stage and the total operational carbon over a 30 year lifetime (Taea, S., Shina, S., Wooc, J., Roha, S., 2011; Baek, C., Park, S.H., Suzuki, M., Lee, S.H., 2013).

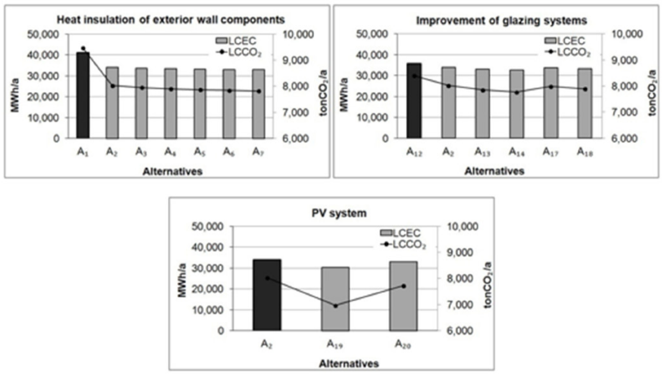

Figure 4. *LCE and $LCCO_2$ analyses results for Istanbul.*

3. Findings

The life cycle assessment related to the energy retrofit strategies for the cit-

Table 5. *LCE and $LCCO_2$ analyses results for Istanbul.*

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	877.30	1124.61	239.11	41,140.23	9,465.06
A_2	7,542.01	2,306.76	627.66	880.51	190.60	33,957.24	8,024.86
A_3	7,570.05	2,309.74	615.09	867.81	188.06	33,604.49	7,951.46
A_4	7,598.10	2,312.72	606.60	859.61	186.43	33,386.40	7,905.70
A_5	7,626.14	2,315.71	599.76	853.01	185.13	33,216.57	7,869.54
A_6	7,654.18	2,318.69	594.09	847.55	184.05	33,080.58	7,840.06
A_7	7,682.23	2,321.67	589.36	842.99	183.14	**32,971.80**	**7,815.98**
A_{12}	7,188.25	2,229.92	704.56	956.03	205.63	35,869.19	8,398.78
A_{13}	7,542.01	2,306.76	613.31	855.77	185.06	33,215.20	7,858.58
A_{14}	7,542.03	2,306.76	597.90	840.88	182.11	**32,768.36**	**7,770.10**
A_{17}	7,542.01	2,306.76	630.30	876.81	189.50	33,846.43	7,991.79
A_{18}	7,542.03	2,306.76	614,93	861.56	186.46	33,388.84	7,900.48
A_{19}	7,781.56	2,352.45	581.28	730.71	149.51	**30,194.46**	**6,972.70**
A_{20}	7,699.97	2,336.75	613.67	835.32	178.21	32,907.95	7,723.70

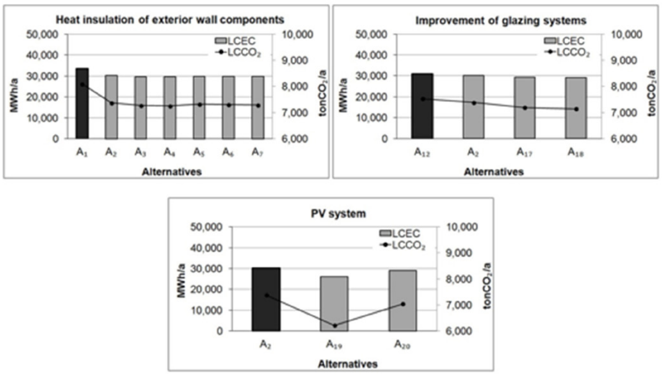

Figure 5. *LCE and $LCCO_2$ analyses results for Antalya.*

ies representing the temperate humid, hot humid and cold climate regions is carried out with the help of the analyses results of LCE and LCC_O2 and are shown in Figures 4-6 and Tables 5-7.

From among the described alternative group related to the heat insulation application in the exterior wall components, the alternative with an optimum performance for Istanbul is A_7 alternative by which the heat insulation thickness of 10 cm is implemented, and U_{wall1}: 0.24 W/m^{2}K and U_{wall2}:0.32 W/m^{2}K values are obtained. The alternative with an optimum performance for Antalya is A_4 alternative by which the heat 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 heat 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_7 alternative for Istanbul is compared with A_1 in which there is no heat 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 4% and 1%. There is a decrease in per year final energy consumption of 33%, in per year operational energy of 25%, in per year operational carbon of 23%, in the life cycle energy consumption of 20% and in the life cycle CO_2 emissions of 17% (Figure 4, Table 5). When A_4 alternative for Antalya is compared with A_1 in which there is no heat 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%. There is a decrease in per year final energy consumption of 22%, in per year operational energy of 16%, in per year operational carbon of 15%, in the life cycle energy consumption of 12% and in the life cycle CO_2 emissions of 10% (Figure 5, Table 6). When A_{11} alternative for Erzurum is compared with A_1 in which there is no heat 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 of 43%, in per year operational energy of 37%, in per year operational carbon of 36%, in the life cycle energy consumption of 32% and in the life cycle CO_2 emissions of 29% (Figure 6, Table 7).

From among the described alterna-

Table 6. *LCE and $LCCO_2$ analyses results for Antalya.*

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}	7,188.25	2,229.92	467.97	790.38	176.57	30,899.57	7,526.91
A_{17}	7,542.01	2,306.76	439.89	730.50	162.77	29,457.15	7,189.82
A_{18}	7,542.03	2,306.76	432.46	722.41	161.11	**29,214.47**	**7,140.15**
A_{19}	7,786.22	2,354.34	386.61	590.03	123.96	**26,027.76**	**6,220.27**
A_{20}	7,699.97	2,336.75	422.27	705.21	155.55	29,018.80	7,047.79

tive group related to the improvement of glazing systems, the alternative with an optimum performance for Istanbul is A_{14} alternative by which the glazing system defined as Low-E (heat control, e2=0.04) coating filled with argon gas is used, and U_{window}: 1.50 W/m^{2}K and SHGC: 0.44 values are obtained. The alternative with an optimum performance for Antalya is A_{18} alternative by which the glazing system defined as Low-E (heat and solar control, e2=0.02) coating filled with argon gas is used, and U_{window}: 1.50 W/m^{2}K and SHGC: 0.30 values are obtained. The alternative with an optimum performance for Erzurum is A_{16} alternative by which the glazing system defined as Low-E (heat control, e3=0.03) coating filled with argon gas is used, and U_{window}: 1.50 W/m^{2}K and SHGC: 0.51 values are obtained.

According to the results of LCE and $LCCO_2$ analyses, when A_{14} alternative for Istanbul is compared with A_{12} in which a clear single glazing system is defined, it is observed that there is an increase in embodied energy and embodied carbon values respectively with the ratio of 5% and 3%, and there is a decrease in per year final energy consumption of 15%, in per year operational energy of 12%, in per year operational carbon of 11%, in the life cycle energy consumption of 9% and in the life cycle CO_2 emissions of 8% (Figure 4, Table 5). When A_{18} alternative for Antalya is compared with A_1 in which a clear single glazing system is defined, it is observed that there is an increase in embodied energy and embodied carbon values respectively with the ratio of 5% and 3%, and there is a decrease in per year final energy consumption of 8%, in per year operational energy of 9%, in per year operational carbon of 9%, in the life cycle energy consumption and the life cycle CO_2 emissions of 5% (Figure 5, Table 6). When A_{16} alternative for Erzurum is compared with A_1 in which a clear single glazing system is defined, it is observed that there is an increase in embodied energy and embodied carbon values respectively with the ratio of 5% and 3%, and there is a decrease in per year final energy consumption of 18%, in per year operational energy of 15%, in per year operational carbon of 14%, in the life cycle energy consumption of 12% and in the life cycle CO_2 emissions of 11% (Figure 6, Table 7).

From among the described alternative group related to the PV system

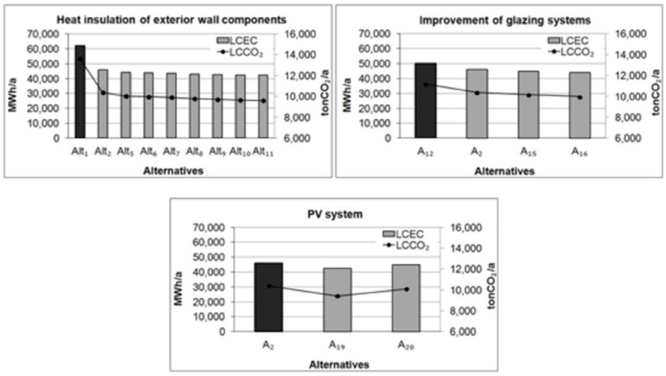

Figure 6. LCE and $LCCO_2$ analyses results for Erzurum.

Table 7. LCE and $LCCO_2$ analyses results for Erzurum.

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}	7,188.25	2,229.92	1,199.55	1,424.96	297.92	4,9936.96	11,167.49
A_{15}	7,542.01	2,306.76	1,018.46	1,246.43	262.36	4,4934.91	10,177.59
A_{16}	7,542.03	2,306.76	984.79	1,213.43	255.80	**4,3944.82**	**9,980.70**
A_{19}	7,784.67	2,353.04	1,009.04	1,141.60	231.12	**4,2486.73**	**9,411.14**
A_{20}	7,699.97	2,336.75	1,038.93	1238.14	257.60	4,4981.54	10,102.41

Table 8. Summary of LCE and LCCO$_2$ analyses results (increase in EE and EC).

Measure	Representative city	Embodied energy (%)		Embodied carbon (%)	
		min	max	min	max
Heat insulation in the exterior wall components	Istanbul	18	23	24	30
	Antalya	22	26	28	32
	Erzurum	12	19	17	24
Improvement of glazing systems	Istanbul	20	23	27	29
	Antalya	23	26	30	32
	Erzurum	14	17	20	23
PV system	Istanbul	24	26	30	34
	Antalya	27	31	33	39
	Erzurum	17	19	23	25

application, the alternative with an optimum performance for Istanbul, Antalya and Erzurum is A$_{19}$ alternative by which roof PV system is dealt with.

According to the results of LCE and LCCO$_2$ analyses, when A$_{19}$ alternative is compared with A$_2$ in which there is no PV system, it is observed for Istanbul 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 of 7%, in per year operational energy of 17%, in per year operational carbon of 22%, in the life cycle energy consumption of 11% and in the life cycle CO$_2$ emissions of 13% (Figure 4, Table 5). As to Antalya, there is an increase in embodied energy and embodied carbon values respectively with the ratio of 3% and 2%. There is a decrease in per year final energy consumption of 12%, in per year operational energy of 22%, in per year operational carbon of 27%, in the life cycle energy consumption of 14% and in the life cycle CO$_2$ emissions of 16% (Figure 5, Table 6). 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 of 4%, in per year operational energy of 11%, in per year operational carbon of 14%, in the life cycle energy consumption of 8% and in the life cycle CO$_2$ emissions of 9% (Figure 6, Table 7).

Table 9. Summary of LCE and LCCO$_2$ analyses results (decrease in LCE and LCCO$_2$).

Measure	Representative city	Life cycle energy consumption (%)		Life cycle CO$_2$ emission (%)	
		min	max	min	max
Heat insulation in the exterior wall components	Istanbul	17	20	15	17
	Antalya	10	12	8	10
	Erzurum	26	32	24	29
Improvement of glazing systems	Istanbul	5	7	4	6
	Antalya	2	5	2	5
	Erzurum	8	12	7	11
PV system	Istanbul	3	11	4	13
	Antalya	4	14	5	16
	Erzurum	2	8	3	9

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 optimisation 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$_2$ emissions of a residential building are assessed by considering an existing residential block including construction technologies and 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 regions are summarised in Tables 8-9.

Consequently, the results of this study compared with the previous studies show that this approach can be used for similar climate regions and also point out 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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