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BUILDING COMPONENTS AND BUILDINGS

Life-cycle assessment and cost analysis of residential buildings in South East of Turkey: part 2—a case study

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Abstract

Purpose Residential buildings play an important role in consumption of energy resources. About 40 % of all primary energy is used in buildings all over the world. This paper is the second part of the study on the life-cycle energy (LCEA), emissions (LCCO$_2$A) and cost (LCCA) assessment of two residential buildings constructed in urban and rural areas.

Methods In the first part, the methodology, formulations and procedure for such a comprehensive analysis are provided, while this paper provides an application of the methodology that considers two actual buildings located in Gaziantep, Turkey. The proposed model focused on building construction, operation and demolition phases to estimate energy use, carbon emissions and costs per square meter over a 50-year lifespan. The optimum thickness of insulation used to reduce energy consumption and emissions per square meter is determined.

Results and discussion It is found that the operating phase is dominant in both urban and rural residential buildings and contributes 87–85 % of the primary energy requirements and 88–82 % of CO_2 emissions, respectively. Life-cycle greenhouse gas emissions were 5.8 and 3.9 tons CO_2 eqv. for BT1 and BT2, respectively. It is calculated that the life-cycle energy consumption and CO_2 emissions of the residential buildings can be reduced by up to 22.8 and 23.4 %, respectively, by using a proper insulation material for the external walls. The life-cycle cost, consisting of mortgage, energy, maintenance, service and demolition payments are calculated to be 7.28 and 1.72 million USD for BT1 and BT2, respectively.

Conclusions Building envelope developments, such as better wall insulation, provide noteworthy potential energy savings and contribute to the reductions from cooling and space heating. Therefore, primary strategies and technologies needed for efficient buildings include optimal insulation of external walls. The economic insulation thickness of the residential buildings in Gaziantep is determined to be 80 mm by using a life-cycle cost analysis. The results show that because of the differences in building structures and living standards, life-cycle energy intensity and CO_2 emissions in urban residential buildings are 29 and 25 % higher than in rural conditions.

Keywords Greenhouse gas emissions · Life-cycle cost analysis · Life-cycle energy analysis · Residential buildings

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1 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 residential building requires a life-cycle perspective which includes materials production, construction, operation and demolition phases (Keoleian et al. 2001).

World energy demand is estimated to increase by up to 71 % between 2003 and 2030 (EIA 2006; Dincer and Acar 2015). The majority of this energy consumption is based on fossil fuels, and despite remarkable advances in renewable energy technology, it is questionable whether such a demand trajectory can be met in an ecological manner. In order to

Table 1 Specifications of XPS foam board

Properties	Standard	Unit	XPS
Thickness	–	mm	50
Bulk density	EN 1602	kg/m^3	>30
Thermal conductivity λ_D (ageing process without gas-tight lamination)	EN 13164	W/(mK)	0.036
Compressive strength and/or compressive stress at 10 % compression	EN 826	N/mm^2	>0.25
Change in dimension under 70 °C temperature and 90 % relative humidity	EN 1604	%	≤5
Vapour diffusion resistance factor μ (dependent on the thickness)	EN 12086	–	200–60
Water absorption on long-term immersion	EN 12087	%	≤1
Linear thermal expansion coefficient	–	mm/(mK)	0.07
Fire behaviour	EN 13501-1	Class	Euroclass E
Working temperature	–	°C	−50/+75

avoid a severe reduction in accepted standards of living, it is necessary to increase the energy efficiency of systems and applications (Langston and Ding 2011; Wade 2002; Atmaca 2016).

There are three major groups of life-cycle assessment (LCA) studies in the literature aimed to increase the efficiency and reduce the environmental impacts and total costs of residential buildings (Chau et al. 2015). These are: life-cycle energy assessment (LCEA), life-cycle carbon emissions assessment (LCCO_2A) and life-cycle cost assessment (LCCA; see Introduction in part 1). A detailed literature review is presented in Table 1 in part 1 (Utama and Gheewala 2009; Thormark 2002; Shukla et al. 2009; Atmaca and Atmaca 2015; Grant and Ries 2013). This paper addresses the primary life-cycle energy consumption and the corresponding release of greenhouse gases for the construction and use of two typical residential houses in Turkey. This investigation addresses 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 (Norman et al. 2006; Frischknecht et al. 2015; Gustavsson and Joelsson 2010; Aye et al. 2012; Sartori and Hestnes 2007; Treloar et al. 2000). The life-cycle costs of the buildings were determined by considering home finance payments, construction costs, utility payments, maintenance, service and end-of-life costs for a period of 50 years. In part 1, the methodology for such a detailed analysis is provided including the quantity of each construction element in terms of mass, embodied energy and CO_2 intensity values. In this part 2 of the study, the developed methodology is applied to existing buildings located in Gaziantep, using the actual operational, material and cost data.

The purpose of this study is to reveal the effects of differences in living standards and building specifications in life-cycle energy consumption and related emissions. The study will identify opportunities in construction sector in Turkey to

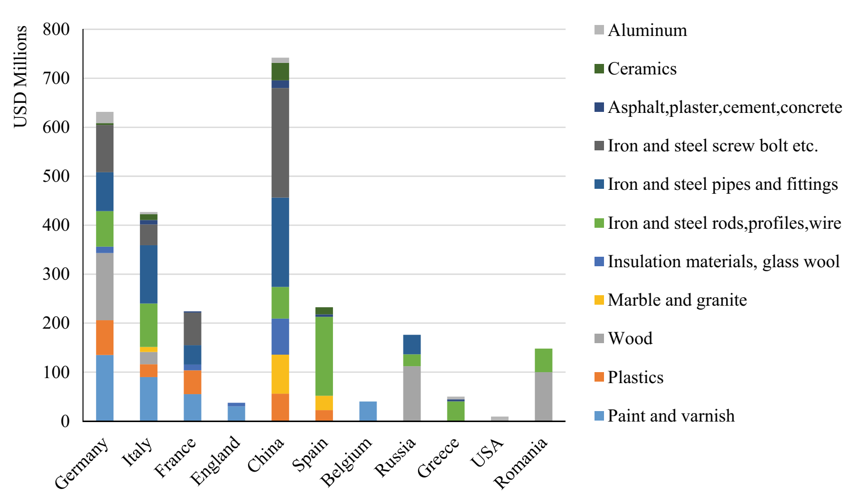

Fig. 1 Turkey construction material import, leading suppliers by country

improve energy efficiency and reduce emissions. The results and the information obtained from this study will be very valuable for improving the design and operational conditions of buildings. In section 2 of the study, the appropriateness of existing method for the construction sector in Turkey is discussed. In section 3, detailed information about the case study buildings are provided. Section 4 includes the results of LCEA and $LCCO_2A$ of the case study buildings. The construction, operating and demolition phases are investigated in detail. The effect of insulation thickness on life-cycle energy and emissions of the case study buildings are discussed in this section. The overall results are provided in section 5. In section 6, the life-cycle cost assessment results are presented. Finally, the conclusions of the study are discussed in section 7.

2 Description of the data

The analysis compares two residential buildings constructed in urban and rural areas in Gaziantep, Turkey in 2014. Detailed architectural, functional and operational data of the buildings were obtained from working drawings, utility bills and reports provided by Gaziantep Municipality and Edacan Construction Company. Complete details of the buildings' physical characteristics are presented in Tables 3 and 4.

In the case of Turkey, there is currently no existing EE energy database for building materials. Due to the different industrial processes and differences in economic structure of each country, the use of ICE data for the determination of EE of materials used in Turkey can result in errors. Even though it is not specific to Turkey, using the ICE database globally is justified by the two following reasons:

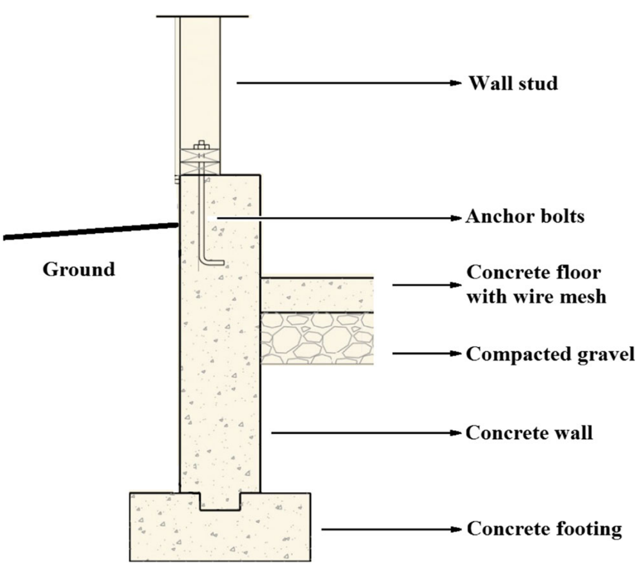

Fig. 2 Conventional foundation

Table 2 Specifications of perlite roof insulation

Properties	Unit	Perlite
Thickness	mm	50
Conductance	W/(m^2 °C)	1.02
Water absorption, % by volume, 2 h	%	1.5 max.
Compression resistance 10 % consolidation	kPa	276
Laminar tensile strength	kPa	48
Density	kg/m^3	144
Flexural strength	kPa	448

- Most of the EE of the case study buildings, which is representative of recent apartment buildings in Turkey, comes from imported materials mostly from EU counties (Fig. 1).

- Regardless of the origin of the database, EE results calculated in this study using ICE data are comparable with other studies in Turkey and other EU countries. The EE of houses is largely underestimated in the literature with numbers within 3.1–7.6 GJ/m^2 (see Table 1). The EE of BT1 and BT2 are calculated to be 4.3 and 3.9 GJ/m^2, respectively.

Figure 1 shows the origin of the construction materials of the case study buildings. Most of the building materials are mainly sourced from Europe and China, especially: the steel elements including profiles, rods, wires and screw. Other suppliers include Romania and Russia for wood, England and Belgium for paint and varnish, Spain for plastics, China for insulation materials and the USA for paint ingredients. This list obviously illustrates the global nature of the supply chain of recent residential buildings in Turkey. For this reason, the comprehensive ICE data database is used as it is one of the most comprehensive databases for building materials, globally. The world average data of each construction element have been collected and used during the calculations.

3 Case study

Detailed information about the case study buildings, including their construction characteristics, bill of material quantities and operational energy data are provided in this section. All building construction projects include some elements in common (design, financial, legal considerations etc.). During construction process, the construction company (Edacan Construction Company) has made detailed plans and maintained careful oversight during the project to ensure a positive outcome. Residential building construction technologies must conform to local building authority regulations. Generally, readily available construction materials in the area are preferred by the construction company. Based on site conditions and local regulations, the cost of a construction on a per-square-meter basis can vary dramatically.

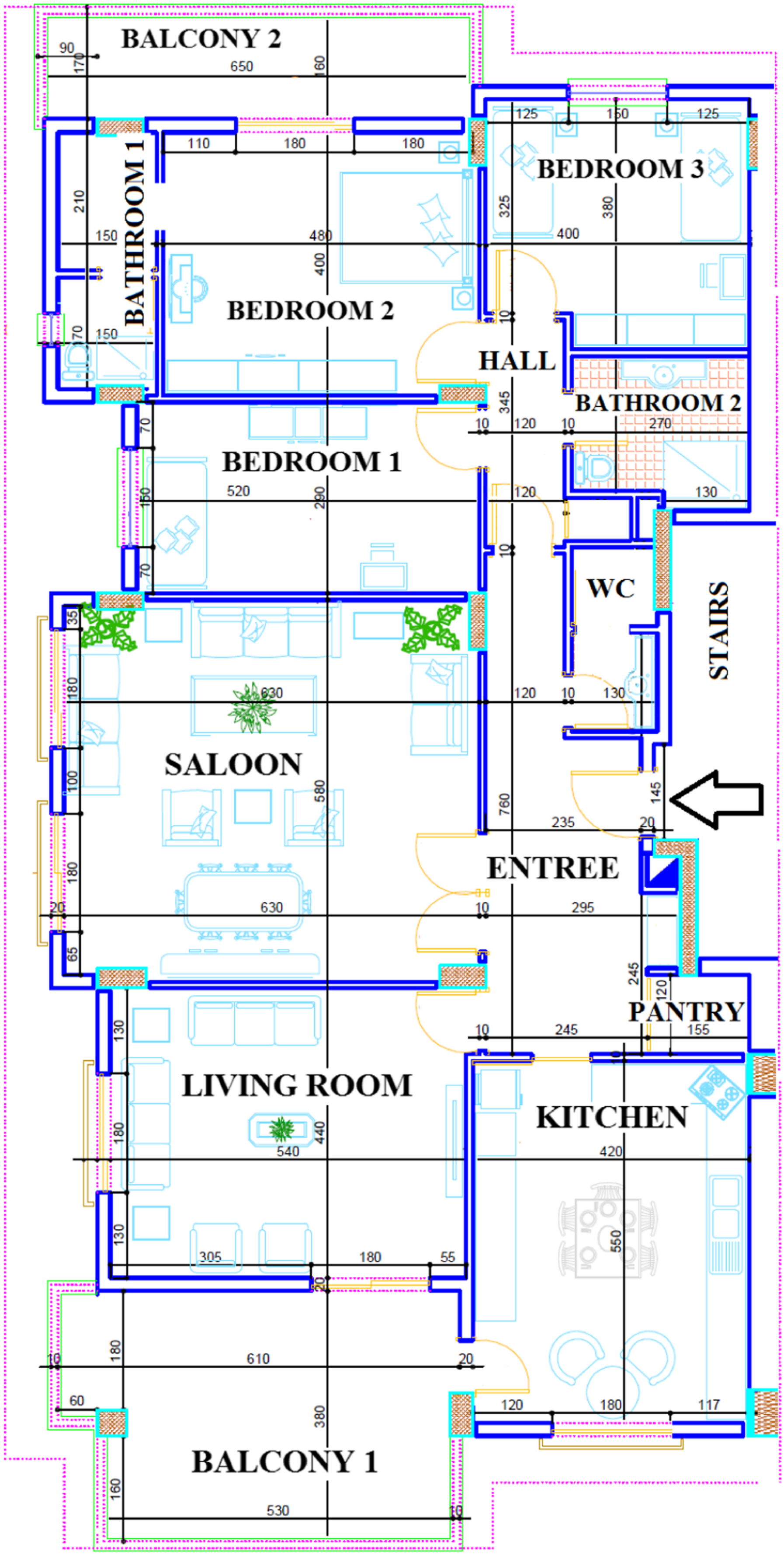

Fig. 3 Detailed floor plan of BT1

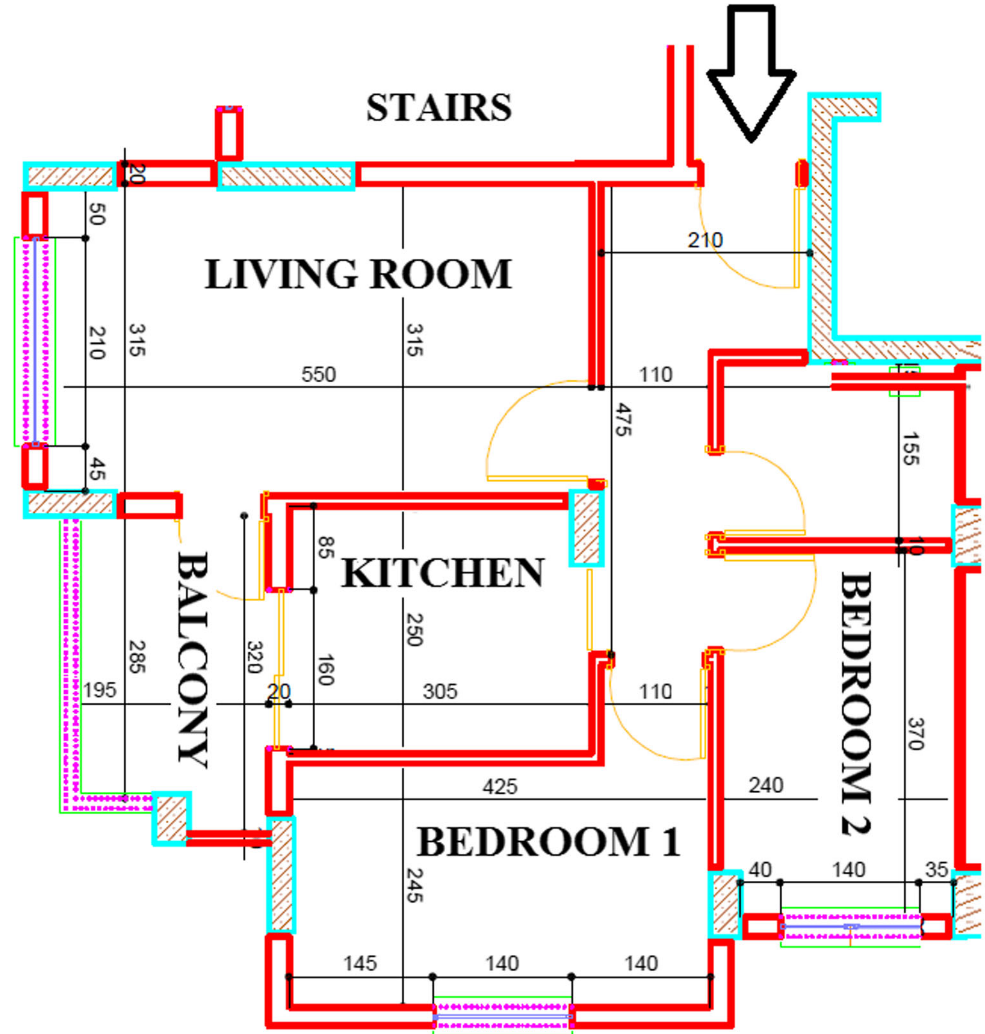

Fig. 4 Detailed floor plan of BT1

The most popular method of residential construction in Turkey is concrete construction. Typical construction steps for the case study residential buildings are:

– Floor plans are prepared and government building approval is obtained.
– Building site preparation, excavation and foundation work using a backhoe and a bulldozer.
– Wooden forms are picked up to serve as a template for the foundation, the holes and trenches are dug out.
– Footings (structures where the house interfaces with the earth that supports it) are installed.
– The hole is dug (for the house with full basement), the footings are formed and poured and the foundation walls are formed and poured.
– Concrete is poured into the holes and trenches.

Table 3 Sections of the buildings

Sections	Sub-sections	Components
Foundations	Basement	Concrete and steel
Mansory units	Internal and external walls (façade)	Plaster, painting, and insulation
Floor structures	Columns, beams, slabs, and stairs	Concrete and steel
Flooring	Tile, seramic, marble, and wood	Moulding and plaster
Roof structures	Insulation and roof tiles	Concrete and steel
Doors and windows	Frames and panels	Wood, steel, aluminum, and PVC

- The concrete floor systems, walls and roof systems are completed.
- Brickworks
- Windows and exterior doors are installed.
- Siding and roofing are installed.
- Insulation materials are installed in side walls, attics, roof and basements.
- Spackle and paint exterior and interior walls and ceilings.
- Tiling for wet areas, such as the bathroom and kitchen backsplash
- Final floor covering, such as floor tile, carpet, vinyl or wood flooring, is installed.

Both of the case study buildings are supported by a cast in situ-reinforced concrete structure like most residential buildings of this type in Turkey. The ground in Gaziantep is almost rocky and provides high-bearing capacity; therefore, the foundations are relatively small compared to the size of the buildings. Conventional foundation is used for both of the building types. To prevent a water penetration through the foundation wall, outside of the foundation wall is coated with a water-resistant coating. In order to divert water away from the buildings, drain pipes are also installed (Fig. 2).

The main reinforced concrete columns and beams which bolster the slabs are supported by the foundation. The thickness of the slabs for BT1 and BT2 are 150 and 120 mm, respectively. Primary beams placed on the reinforced concrete columns support the secondary beams (ribs). The width of the beams varies between 600 and 800 mm. The outer walls are

Fig. 5 Floor plan and picture of BT1

double concrete blocks walls with an air blade in between. They are rendered with a concrete mortar and painted on the outside and inside. The double-glazed windows are installed on an aluminum frame. The external walls of the buildings are insulated with 50 mm of extruded polystyrene (XPS) foam board. The specifications of the XPS are provided in Table 1. The roofs of both of the buildings are insulated with 50 mm of perlite. Perlite roof insulation is a homogeneous board composed of expanded perlite particles, cellulose fibers and selected binders. The specifications of the perlite roof insulation are indicated in Table 2. The interior finishes are of medium standard with large ceramic tiles in the living room, tiled walls to the ceiling in bathrooms, wet closets and kitchens. The detailed floor plans of the buildings are presented in Figs. 3 and 4, respectively.

The sections of the buildings are indicated in Table 3. Figures 5 and 6 present the floor plan and photos of Building Type 1 (BT1) and Building Type 2 (BT2),

Fig. 6 Floor plan and picture of BT2

respectively. BT1 is constructed in an urban area and BT2 is constructed in a rural area. The building life was assumed to be 50 years. There are significant differences in number of floors, number of dwellings, construction areas, net areas and the height of buildings. BT1 has a gross area of 250 m^2 per story, five stories, and two dwellings per story, four bedrooms and a large saloon per dwelling unit. BT2 is a small building with a gross area of 100 m^2, which has 13 stories, 4 dwellings per story and a common staircase. Each dwelling unit has two bedrooms and a living room. Complete details of the buildings' physical characteristics are presented in Table 4.

The number of rooms in a dwelling, divided by the number of persons living there, indicates whether residents are living in crowded conditions. The number of households in Turkey is over 19 million, average household size is 3.8. Dense living conditions have a negative impact on physical and mental health of the habitants. In addition, overcrowded places are habitually a sign of inadequate water and sewage supply. In the OECD, the average home contains 1.8 rooms per person. In Turkey, 20 % of the households reside in the dwellings located in buildings which have one floor, 25.5 % of the households in buildings which have four to five floors and 23.1 % of the households reside in the dwellings located in buildings which have six or more floors. Number of occupants per room is 1.1. Average occupancy for Gaziantep is assumed to be four to five persons per dwelling (see Table 4). About 25.6 % of the households use central heating in Gaziantep; the proportion of the households that use central heating for one or more building is 11.4 % and the proportion of the households that use electric heater, air conditioner and other systems is 5.9 % (TUIK 2013).

4 LCEA and $LCCO_2A$ results

4.1 Construction phase

The approach and data used for the analysis are given in part 1 of this study in more detail (Tables 2, 3, 4, 5, 6, and 7 in part 1). The life-cycle inventories for both of the building types, including the quantity of each construction elements in terms of mass, embodied energy and CO_2, are presented in Tables 5 and 6. High-rise residential buildings are more energy intensive. It is calculated that BT2 has higher EE (5,932 GJ) and CO_2 (562 ton) emissions. In comparison, BT1 attains a reduction of about 50 % in EE (2,987 GJ) and CO_2 (279 ton) in construction phase.

The life-cycle EE and CO_2 amounts of each raw material used during construction phase for the BT1 and BT2 are presented in Figs. 7 and 8 respectively. Most of the EE is contributed from steel (31–32 %)

Table 4 Specifications of BT1 and BT2

Specifications	BT1	BT2
Number of floor	5	12
Number of dwellings	10	48
Construction area (m^2)	7445	2110
Base area (m^2)	814	570
Net area (m^2)	240	95
Floor height (m)	2.8	2.8
External walls	150 mm concrete block and 24 mm of plaster inside and outside	150 mm concrete block and 20 mm of plaster inside and outside
Internal wall	100 mm concrete block and 24 mm of plaster inside and outside	100 mm concrete block and 20 mm of plaster inside and outside
Roof	30 mm polyurethane and 150 mm concrete	140 mm perlite and 150 mm concrete
Windows	160 × 140 cm double reflective glass.	200 × 160 cm single reflective glass
Doors	90 × 220 cm wood framed and 80 × 220 cm PVC framed	90 × 220 cm wood framed
Space heating	Natural gas	Natural gas
Lighting	6 W/m^2	3 W/m^2
Equipment	3 W/m^2	2 W/m^2
HVAC	Mono split air conditioner	NA
Hot water	Individual solar water heaters	Individual solar water heaters
Life span	50 years	50 years
Occupancy	4 person/dwelling	5 person/dwelling

and concrete (28–29 %). 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 (21.6 MJ/kg) is quite high compared to the other building materials. It is determined that concrete is responsible for about 43–44 % of CO_2 emissions. One thousand seventy-one tons of concrete is used for construction of BT1 which corresponds to 81 % of overall mass of the building.

The choice of the building materials can have noteworthy effects on a building's energy consumption and CO_2 emissions over the 50-year life span. It is recognized that the EE coefficients of "secondary" materials like bricks and PVC are higher by an order of magnitude than those of "mass" materials like concrete.

Most of the doors and windows of buildings are made of PVC, as a result the EE based on PVC is 150.8 GJ for BT1 and 281.4 GJ for BT2. PVC contributes 5.1–4.7 % of EE and 2.1–1.8 % of CO_2 emissions for BT1 and BT2, respectively. Total EE and CO_2 emissions during construction process, bricks accounted for 7.8–9.5 and 6.7–8.1 % for BT1 and BT2, respectively.

The life-cycle EE and CO_2 emissions percentages of each section of BT1 and BT2 are presented in Figs. 9, 10, 11, and 12. Most of the concrete and steel are used during the construction of floors. As a consequence, the floors contribute more than 50–54 % of EE and 59–61 % of CO_2 emissions, respectively.

4.2 Operating phase

Operating energy in both BT1 and BT2 is dominant and varies from 89 to 87 % of LCE, respectively. BT1 consumes more energy in operating phase (35.2 GJ/m^2) compared to BT2 (26.7 GJ/m^2). Residential buildings in Turkey typically utilize natural gas and coal for heating. The use of natural gas offers a number of environmental benefits over other sources of energy,

Table 5 EE, CO_2, and construction material quantities of each section of BT1

No.	Sections	Materials	Amount (kg)	EE (MJ/kg)	CO_2 (kg CO_2/kg)	Total EE (MJ)	Total CO_2 (kgCO_2)
1	Foundation	Concrete	192,888	0.8	0.11	150,452	21,796
		Steel	6,120	21.6	1.86	132,192	11,383
2	Walls	Brick	24,249	6.9	0.55	167,316	13,336
		Plaster	59,361	1.8	0.13	106,849	7,716
		Painting	616	10.5	0.87	6,466	535
3	Floors	Concrete	803,700	0.8	0.11	626,886	90,818
		Steel	32,640	21.6	1.86	705,024	60,710
4	Flooring	Tile and ceramic	8,000	12	0.78	96,000	6,240
		Marble	25,981	2	0.13	51,961	3,377
		Wood flooring	8,100	12	0.87	97,200	7,047
5	Roof	Concrete	75,012	0.8	0.11	58,509	8,476
		Steel	2,040	21.6	1.86	44,064	3,794
		Insulation (perlite)	14,400	0.7	0.03	9,504	432
		Bitumen	2,016	51	0.43	102,816	866
		Roof tiles	23,040	6.5	0.48	149,760	11,059
6	Façade	Plaster	19,787	1.8	0.13	35,616	2,572
		Painting	205	10.5	0.87	2,155	178
		Insulation (XPS)	3,880	16.8	1.05	65,180	4,073
		Bricks (Bims)	9,699	6.9	0.55	66,926	5,334
7	Others	Wood doors	4,900	11	0.72	53,900	3,528
		PVC doors	750	77.2	2.81	57,900	2,107
		Steel doors	2,200	21.6	1.9	47,520	4,180
		PVC windows	1,200	77.4	2.79	92,880	3,348
		Al Railing	693	214	12.5	148,263	8,660
		Glass	1,038	18	0.85	18,684	882.3
	Total		1,321,476			2,987,527	279,329

Table 6 EE, CO_2 and construction material quantities of each section of BT2

No	Sections	Materials	Amount (kg)	EE (MJ/kg)	CO_2 (kg CO_2/kg)	Total EE (MJ)	Total CO_2 (kgCO_2)
1	Foundation	Concrete	397,028	0.78	0.113	309,681	44,864
		Steel	12,597	21.6	1.86	272,095	23,430
2	Walls	Brick	54,271	6.9	0.55	374,472	29,849
		Plaster	144,724	1.8	0.13	260,502	18,814
		Painting	1,531	10.5	0.87	16,080	1,332
3	Floors	Concrete	1,654,283	0.78	0.113	1,290,340	186,934
		Steel	67,184	21.6	1.86	1,451,174	124,962
4	Flooring	Tile	10,400	12	0.78	124,800	8,112
		Marble	77,531	2	0.13	155,061	10,079
		Wood flooring	6,669	12	0.87	80,028	5,802
5	Roof	Concrete	154,400	0.78	0.113	120,431	17,447
		Steel	4,199	21.6	1.86	90,698	7,810
		Insulation (perlite)	11,400	0.66	0.03	7,524	342
		Bitumen	1,596	51	0.43	81,396	686
		Roof tiles	18,240	6.5	0.48	118,560	8,755
6	Façade	Plaster	72,362	1.8	0.13	130,251	9,407
		Bricks (Bims)	27,136	6.9	0.55	187,236	14,925
		Insulation (XPS)	14,472	16.8	1.1	243,135	15,196
		Painting	766	10.5	0.87	8,040	666
7	Others	Wood doors	9,360	11.0	0.7	102,960	6,739
		PVC doors	1,560	77.2	2.8	120,432	4,384
		Steel doors	2,650	21.6	1.9	57,240	5,035
		PVC windows	2,080	77.4	2.8	160,992	5,803
		Al railing	1,292	214.0	12.5	276,525	16,152
		Glass	5,124	18	0.85	92,232	4,355
	Total		2,747,730			5,932,659	562,148

particularly other fossil fuels. BT2 has a 24 % decrease in CO_2 emissions while BT1 releases more emissions (5,227 kg CO_2/m^2). The difference is mostly based on the emissions released during construction phase of the buildings. The type and amounts of construction materials affect the emission rates considerably. For BT1, natural gas presents 68 % and electricity is 21 % of total LCE. The primary energy requirement and CO_2 emissions of the operating phase for BT1 and BT2 are presented in Figs. 13 and 14, respectively.

Table 7 The total energy requirement and CO_2 emissions per building type in demolition phase

Total energy and CO_2 emissions	BT1	BT2
Total energy consumption (MJ/m^2)	78.7	61.1
Total emissions released (kg CO_2/ m^2)	19.7	41.1

4.3 Demolition phase

In order to find the total emissions released during the demolition stage, Eq. (4) in part 1 is used for both of the buildings. The 0.2 % of total life-cycle primary energy consumption of the buildings is calculated to estimate the total energy consumed during demolition phase. Table 7 shows the total primary energy requirement and CO_2 emissions per building type in demolition phase. The demolition of structurally massive generally buildings constructed in urban places including more steel and concrete requires more energy than buildings constructed in rural places.

4.4 Effect of insulation thickness on life-cycle energy and emissions

The building envelope serves as a thermal barrier. It has a crucial role in determining the amount of energy necessary to maintain a comfortable environment inside the

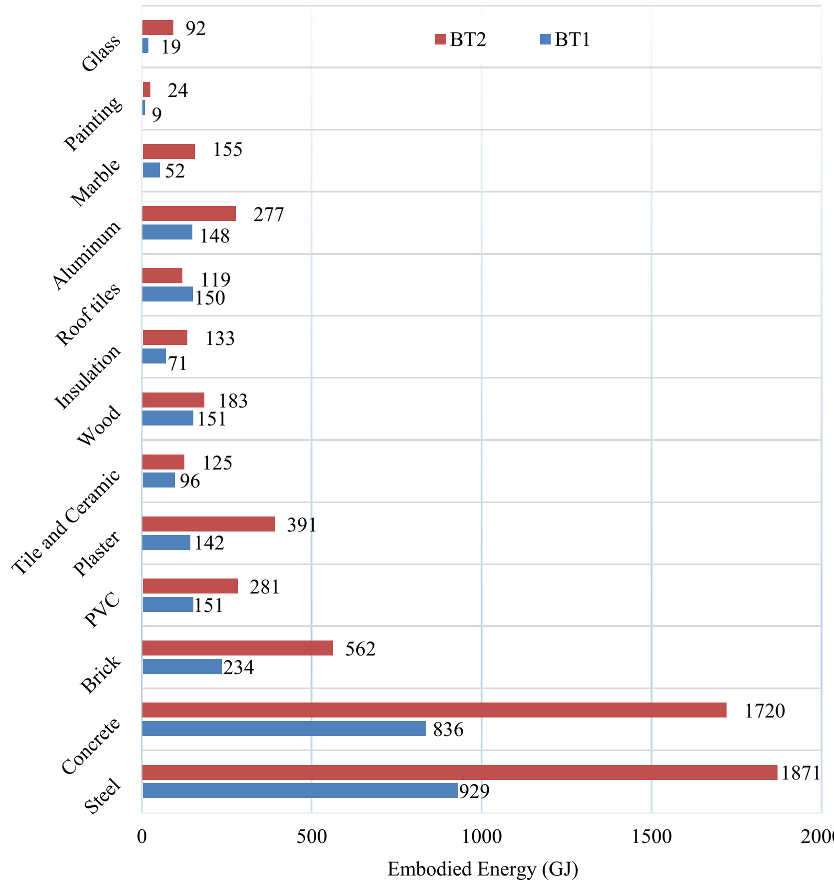

Fig. 7 Life-cycle EE amounts of each raw material used during construction phase of the BT1 and BT2

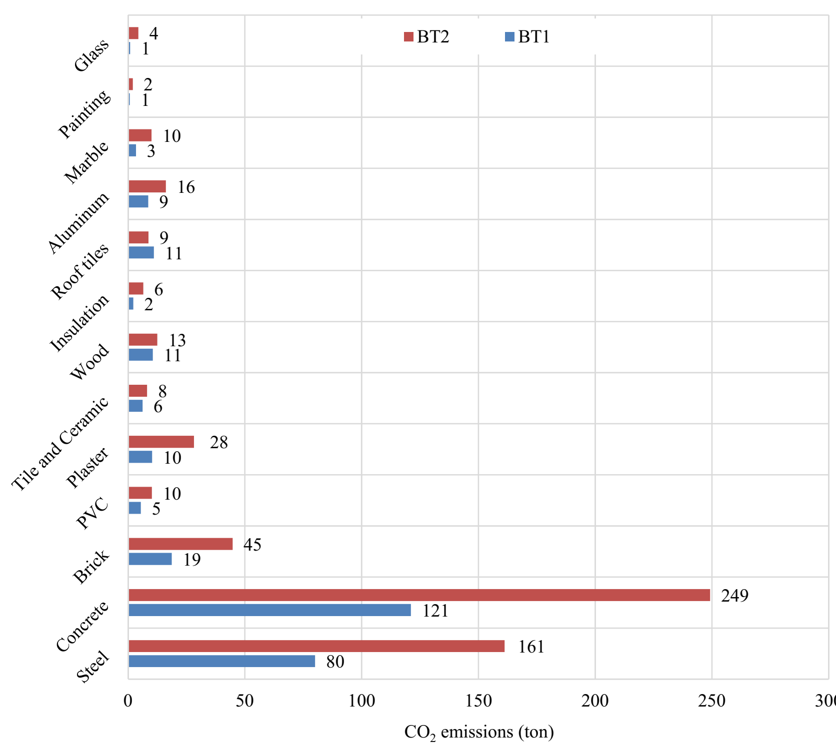

Fig. 8 Life-cycle CO_2 emissions of each raw material used during construction phase of the BT1 and BT2

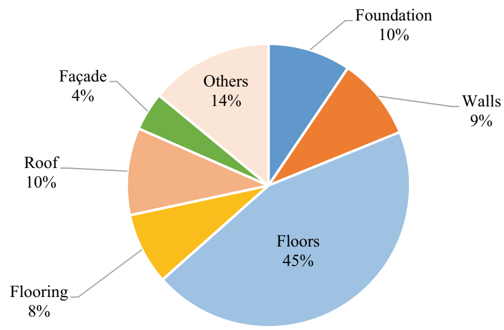

Fig. 9 Life-cycle EE percentages of each section of BT1

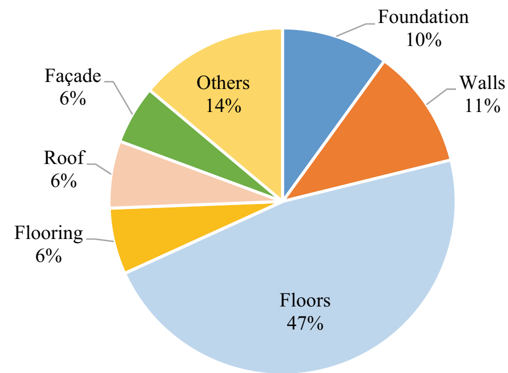

Fig. 11 Life-cycle EE percentages of each section of BT2

building relative to the outside environment. Insulation can reduce the amount of energy required for heating and cooling in the buildings. The effects of external wall insulation on the energy consumption and emissions release of residential buildings were analysed in this section. The parameters used during the calculation of optimum insulation thickness are indicated in Table 8. Chemical combination and chemical formula of natural gas are given in Table 9.

The annual heating and cooling requirements of buildings can be obtained by using heating degree-day concept. Increasing the insulation thickness reduces heat losses in a building. Besides, the fuel consumption and air pollution are brought down. By using the eqns. 5 to 20 in part 1 of this study, the energy requirements and emissions of the buildings have been calculated. The economic insulation thickness is determined to be 80 mm by using a life-cycle cost analysis. The results show that the energy consumption and CO_2 emissions of the residential buildings can be reduced by up to 22.8 and 23.4 %, respectively, with the insulation thicknesses vary from 20 to 100 mm (see Figs. 15 and 16).

5 Overall results

The primary energy requirements and CO_2 emissions per building type on a per-square-meter basis are presented in Figs. 17 and 18. The primary energy requirement and CO_2 emissions of BT1 is calculated to be 39.4 GJ/m^2 and 5,809 kg CO_2/m^2, respectively. BT2 is associated with lower energy demand and CO_2 emissions, while BT1 has 29 and 25 % higher-energy requirements and emissions, respectively. The difference is likely related to the differences in the characteristics of habitants living in urban and rural areas. The construction phase accounts for 11–13 % of energy and 10–15 % of emissions, respectively.

The EE of construction phase of BT1 is calculated to be 4.1 GJ/m^2, while this value is 3.9 GJ/m^2 for BT2. It is recognized that the difference was originated from the type of the concrete used. The 30/40 MPa high-strength concrete is used for BT2, while 20/30 MPa of concrete which has less strength is used for BT1. Due to variation of cement strength, the concrete made from these cement will also have variable strength. The strength of cement is heavily influenced by raw meal grinding, precalcination, burning process in rotary

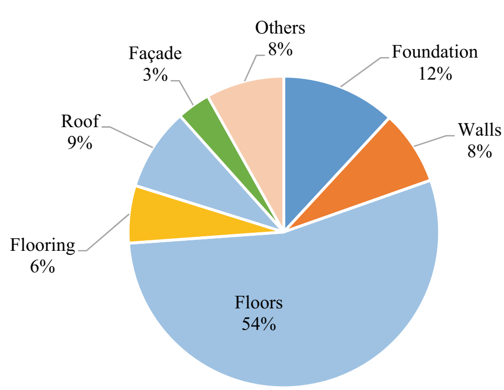

Fig. 10 Life-cycle CO_2 emissions percentages of each section of BT1

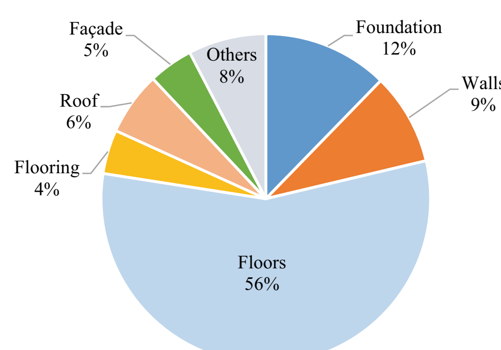

Fig. 12 Life-cycle CO_2 emissions percentages of each section of BT2

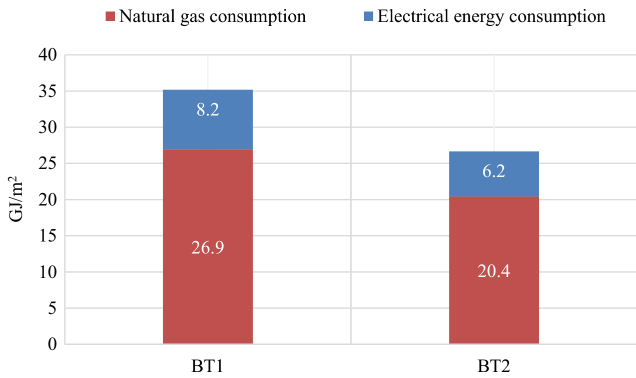

Fig. 13 The primary energy requirements of *BT1* and *BT2* during the operating phase

Table 8 Parameters used to calculate the optimum insulation thickness

Parameters	Value
DD for Gaziantep city	2009
Fuel	Natural gas
Hu	34.526 kJ/m^3
Cf	0.3025 \$/m^3
H	0.85
PWF	9.61
i	9.85 (for the first quarter of 2015)
g	8.84
Insulation	XPS
k	0.032 W/mK
Ci	84.5 \$/m^3
Rt (Ri + Rw + Ro)	0.51 m^2 K/W (0.13 + 0.34 + 0.04)

kilns and finish grinding technology in cement mills. This long-manufacturing process affects the EE and CO_2 emissions intensity of concrete considerably (Atmaca and Yumrutas 2014; Atmaca et al. 2012).

The operating phase has the greatest primary energy demand and CO_2 emissions for both of the building types, representing 89–87 % of energy and 90–85 % of emissions, respectively, for BT1 and BT2.

It is interesting to note that even though there is a low occupancy and there is a difference in the number of dwellings, the energy requirement and CO_2 emissions of BT1 are 32 % more in operating phase. The consumption of more natural gas for heating repurpose in BT1 releases more CO_2 to the atmosphere.

Comparison with other life-cycle studies, as noted in section 4 in part 1, is affected by assumptions, methodological choices, climate, the uniqueness of each building and consumption habits of occupants. These differences lead to a large range of life-cycle results (Gurung and Mahendran 2002).

For example, Ramesh et al. (2010) calculated the LCE of conventional residential buildings ranged from 0.54 to 1.44 GJ/m^2 per year, while Sartori and Hestnes (2007) estimated a range from 1.04 to 4.25 GJ/m^2 per year. It is noticed that the EE demand of a building, calculated by using hybrid analysis techniques, is much higher than in all previous studies that rely on process data. For example, Stephan et al. (2013) calculated the initial EE of a house to be 19.17 GJ/m^2, which is much higher than in the previous studies. They indicated that using Australian process data produces similar initial embodied energy figures to previous studies relying on European process data. Most of the LCA studies have been completed in developed countries, only a few of them have been completed in southern Europe and none comparing existing buildings.

Ortiz-Rodríguez et al. (2008) compared the LCE of dwellings in Spain and Colombia. For Colombia and Spain, the construction energy and GHG emissions are calculated to be 4,940–4,180 MJ/m^2 and GHG 238–192 kg CO_2eq/m^2, respectively.

Monteiro and Freire (2011, 2012) focused on a single-family house in Portugal with seven alternative exterior wall

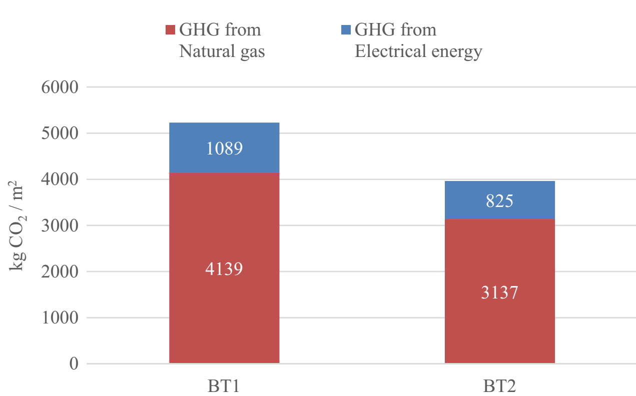

Fig. 14 CO_2 emissions of *BT1* and *BT2* during operating phase

Table 9 Chemical combination and formula of natural gas

Natural gas	Values
CH_4 (%)	91.22
C_2H_6 (%)	5.9
C_3H_8 (%)	0.06
C_4H_{10} (%)	0.02
CO_2 (%)	1.7
N_2 (%)	1.1
Chemical formula	$C_{1.05}H_4O_{0.034}N_{0.022}$

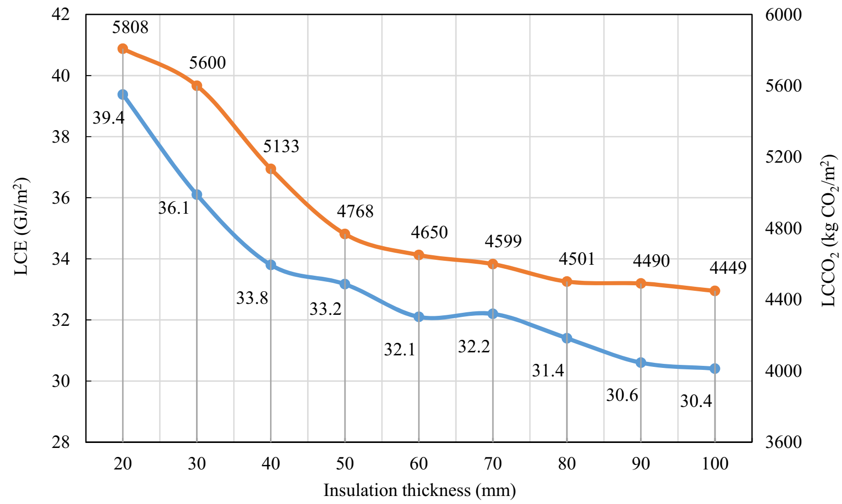

Fig. 15 Effect of insulation thickness on energy consumption and emissions release of BT1

types. They calculated the LCE of buildings with respect to different occupancy and comfort levels. LCE and emissions of the buildings were calculated to be 182 MJ/m^2 and 13 kg CO_2eq/m^2 per year, respectively.

In this study, two residential buildings of the same topology and materials constructed in different places in Gaziantep City have been described. The primary energy requirement and emissions of the buildings range from 25.8 to 33.2 GJ/m^2 and 3,956 to 4,872 kg CO_2/m^2 per year, respectively.

The results of the LCA studies are affected especially by the uniqueness of each building, consumption habits of occupants and differences in climate. Thus, it is highly relevant to provide comparative studies of existing buildings in different countries and regions. The energy consumption of the building during operation phase is strongly related with the fuel used for heating (Crawford et al. 2003; Sterner 2000). LCE and GHG emissions results of our study are higher compared to the other Southern EU countries. This is due to the fact that most of the population in Turkey spends most of their times in homes and the number of occupants per dwelling is higher compared to the other EU countries. This increases the energy consumption in operational phase. Although the uncertainty and variability are associated with life-cycle analyses, the calculated energy and emission values are comparable to the range of results provided by the studies in south European context.

6 LCCA results

Equations 21, 22 and 23 in part 1 are used to calculate both the discounted present value and the undiscounted cumulative

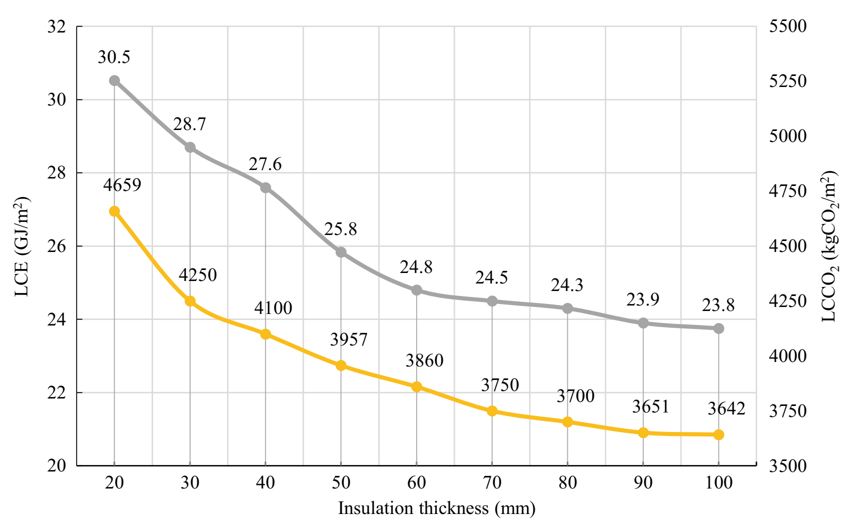

Fig. 16 Effect of insulation thickness on energy consumption and emissions release of BT2

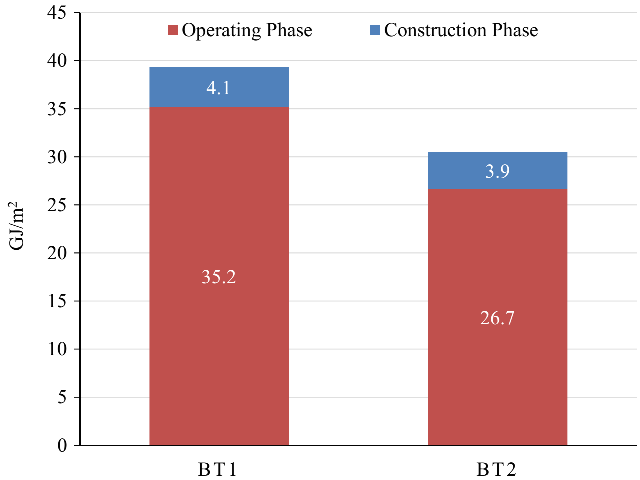

Fig. 17 Primary energy requirements of *BT1* and *BT2*

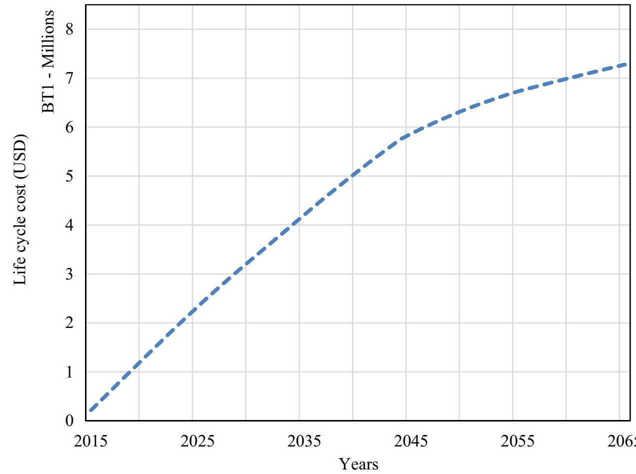

Fig. 19 Accumulated life-cycle costs of BT1

life-cycle costs for the buildings. Life-cycle costs in this study consist of project, utility, maintenance, service and end-of-life costs over the assumed 50-year life of the homes. It is noticed that natural gas and electricity costs rise annually between 2005 and 2015. It is assumed that energy costs continue to escalate annually thereafter until 2065. The accumulated undiscounted costs for the buildings are presented in Figs. 19 and 20.

Even though totaling undiscounted costs is not a rigorous calculation, it does indicate the relative amounts a habitant could expect to pay. The life-cycle cost elements for BT1 and BT2 are presented in Figs. 21 and 22, respectively.

The study outcomes for life-cycle costing approach depend on system boundary considered, building typology and construction methods used in buildings. Making correct assumptions and choosing the right system boundary are important to achieve meaningful results.

The total life-cycle costs are calculated to be 7,276,931 USD for BT1 and 1,717,581 USD for BT2 over the 50-year lifetime. The analyses indicated that project and utility costs contributed the most (90 %) to the life-cycle cost. Maintenance and service contributed relatively little. The project cost of BT2 (836,134 USD) is quite low compared to the project cost of BT1 (3,775,505 USD). The difference may be attributed to the differences in house design, location and material price.

The main study outcomes are the construction phase (51.9–48.7 %) that has the highest contribution to LCC, followed by utility (38.5–44 %), maintenance (6.6–3.2 %) and then service (1.8–1.9 %) and end-of-life costs (1.2–2.2 %). The contribution of different life phases varied widely depending on assumptions and system boundaries. It is also recognized that the

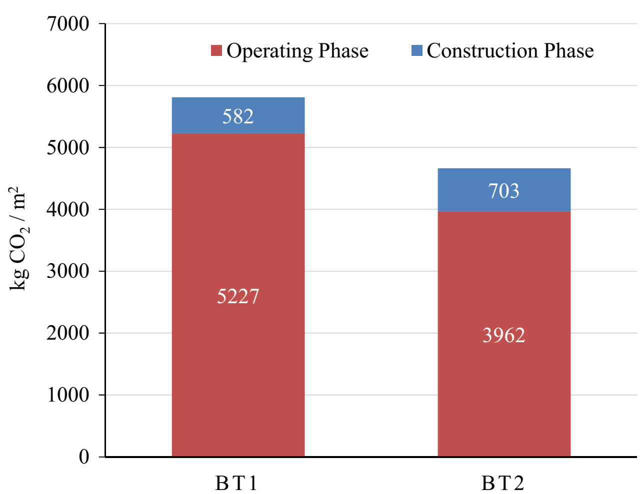

Fig. 18 The CO_2 emissions of *BT1* and *BT2*

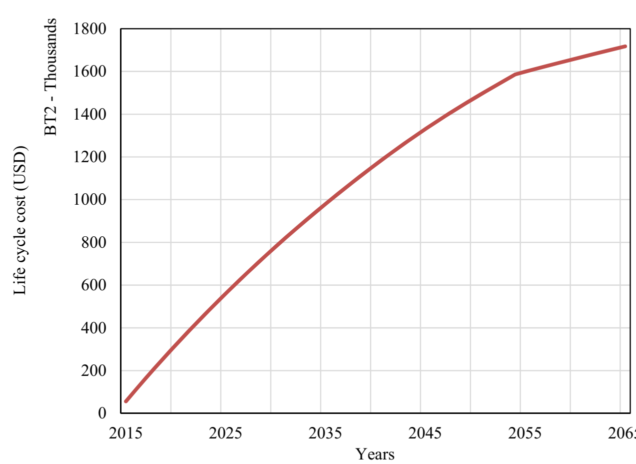

Fig. 20 Accumulated life-cycle costs of BT2

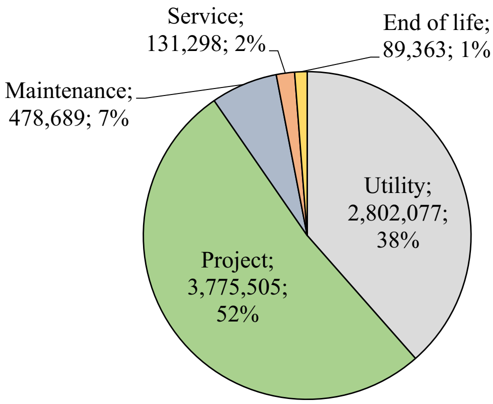

Fig. 21 LCC elements of BT1

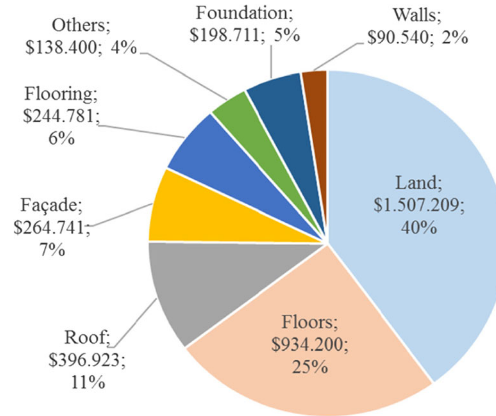

Fig. 23 Project costs of BT1

LCCA is sensitive by the changes of discount rate which affects the future maintenance, service and end-of-life costs significantly. Figures 23 and 24 show the individual costs of each project items of the construction process of BT1 and BT2, respectively.

The allocation of a building's purchase price between land and construction is different from one type of building to another. In the absence of specific valuations, a general rule of thumb for real property is 70 % to buildings and 30 % to land. However, every commercial property is likely to be unique and land acquisition costs differ among urban and rural places in Turkey. It is recognized that 40 and 32 % of the project costs are based on land acquisition costs for BT1 and BT2, respectively. It is calculated that floors accounted for 25–24 % and roofs accounted for 11–26 % of the total life-cycle costs of BT1 and BT2, respectively. Roofing cost is based on the cost of roofing materials, roof pitch and labor.

The cost of shingles and the labor to install shingles or other roofing materials increases as their quality and weight increases. Roofing installation labor increases dramatically as the pitch of the roof increases. It is recognized that the difference in total roof cost percentages are because of the pitch height of the BT2. Wood is used mainly for the roofing of BT2. It is a renewable resource which is recyclable and less expensive than steel. It has also a lower-embodied energy than steel. The analyses reveal the significance of achieving a reduction in energy consumption by the residential home sector. The life-cycle energy profiles for BT1 and BT2 indicated that most of the energy consumption is in the use phase, whereas the economic incentives to conserve energy are relatively weak. Special government energy policies can also be implemented to encourage energy efficiency in residential buildings in Turkey. The life-cycle operating costs and percentages of BT1 and BT2 are presented in Table 10.

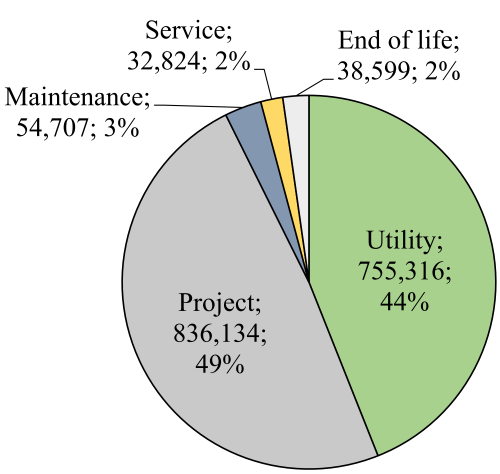

Fig. 22 LCC elements of BT2

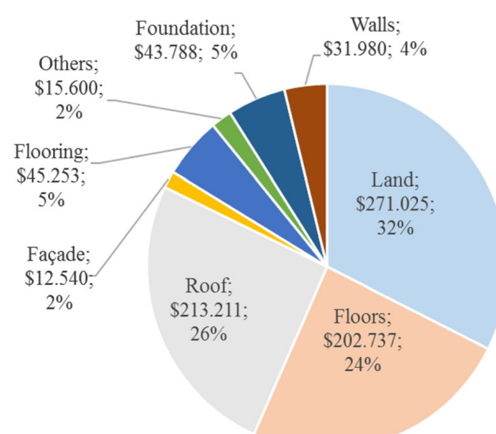

Fig. 24 Project costs of BT2

Table 10 Life-cycle operating costs and percentages of BT1 and BT2

Operating expenses	BT1 (USD)	Percentage (%)	BT2 (USD)	Percentage (%)
Electricity	1,528,216	54.5	357,730	47.4
Natural gas	1,273,862	45.5	397,586	52.6
Total	2,802,077	100	755,316	100

7 Conclusions

LCEA, $LCCO_2A$ and LCCA of two common residential buildings in Gaziantep, Turkey are investigated in detail and the following conclusions have been drawn from the study.

- The operating phase was dominant over the buildings' 50-year lifetime. The floors represent the largest EE requirement and CO_2 emissions when considering the construction phase.
- The life-cycle energy demand and CO_2 emissions of a building should be reduced by decreasing its operating energy significantly through use of passive and active technologies even if it leads to a minor increase in EE.
- Reducing the requirements for operating energy seems to be the most important aspect for the design of buildings that are energy efficient throughout their life cycle.
- The results showed that the BT1 has higher energy and CO_2 emissions per square meter basis during the whole life cycle. The primary energy use of BT1 and BT2 falls in the range of 23.8–39.4 GJ/m^2 and CO_2 emissions in the range of 3,956 to 5,809 kg CO_2/m^2 which is higher compared to the other EU countries. It is found that the life-cycle energy intensity and CO_2 emissions in urban residential buildings are 29 and 25 % higher than in rural conditions.
- The results show that the energy consumption and CO_2 emissions of the residential buildings can be reduced by up to 22.8 and 23.4 %, respectively, by using proper insulation. The economic insulation thickness for the external walls of the residential buildings in Gaziantep is determined to be 80 mm (for XPS) by using a life-cycle cost analysis.
- The total life-cycle costs are estimated at 7.28 million USD for the BT1 and 1.72 million USD for the BT2 over the 50-year lifetime. The project costs contribute 52–49 % to the total LCC with the foundation and floors being the most expensive items. The costs in the use stage contribute 48–51 % to the total life-cycle costs of BT1 and BT2, respectively.
- Building more energy-efficient homes will obviously diminish all life-cycle costs considerably. If the overall objective had been to minimize both life-cycle cost and life-cycle energy, then a different set of improvement methods would have been selected. Several energy-reducing approaches could not be employed because of the shape, layout, and orientation of the residential buildings. It is investigated that the payback period for energy-efficient applications are much longer based on the prospect of lowering future energy costs. Adjusting the effective energy prices would shorten the payback period and lead to a quick implementation of green construction technologies.
- It is obvious that improving energy efficiency and reducing the dependency on fossil fuels to reduce energy demand, and environmental impacts will be the main concerns of building industry in the near future. Moreover, the inequality between the construction costs and house market prices will need to be considered to ensure that access to house ownership do not become the privilege of a few.
- Using simulation tools to minimize energy consumption, designing an efficient air-conditioning system, incorporating renewable energy use, increasing durability of products, increasing the recycling rate of products at the end of their life cycle, eliminating hazardous materials, minimizing material and land use by considering potential impacts to the environment on a life-cycle basis are the basic steps in designing an energy efficient and environmental friendly building.
- Further studies are needed to investigate more about the use of different building materials and climatic and socio economic perspectives, including cost analysis of more residential buildings, mostly in southern European countries, especially in Turkey.

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