CLIMA 2022
Eye on 2030
Towards digitalized, healthy, circular and energy efficient HVAC
REHVA 14th HVAC World Congress
22nd – 25th May, Rotterdam, The Netherlands

Embodied Energy and Carbon of Residential Buildings: Towards an Actual nZEB Concept

Nazanin Moazzen [a], *Touraj Ashrafian* [b]

[a] Faculty of Architecture and Design, Maltepe University, Istanbul, Turkey, nazaninmoazzen@maltepe.edu.tr

[b] Faculty of Architecture and Design, Özyeğin University, Istanbul, Turkey, touraj.ashrafian@ozyegin.edu.tr

Abstract. Over the past few decades, energy efficiency policies have concentrated more on buildings' energy consumption and performance. EU established strategies by energy performance of buildings directive and its amendments for all new and retrofitted buildings to achieve nearly Zero Energy Buildings (nZEBs). Most of the studies and approaches cover the operation phase of the building life cycle, while, by observing the building's whole life cycle, it is determined that buildings are accounted for energy consumption during not just the operation phase and also the construction and demolishing stages. Consequently, the most prominent buildings should progress towards nearly Zero Energy Buildings by evaluating the energy consumption during the whole life cycle and not just during the operation. The embodied energy that covers the energy consumed in the process and manufacturing of the material, transportation, and installations on-site, is intensive energy consumed in a short period compared to the operation energy.

Residential buildings are accounted for extensive energy consumption among different building typologies due to their size and number. According to various studies on residential buildings, in conventional and low energy buildings, the share of embodied energy has varied between 6 and 20%, and 26 and 57%, respectively. It means that embodied energy of the buildings is not negligible.

Consequently, a logical method for residential buildings to reach the nZEB level using energy-efficient measures and proper materials considering the life cycle of buildings is inevitable. The paper aims to investigate the possibility of obtaining nearly zero energy levels in residential buildings reflecting the whole life cycle. The paper has concentrated not only on the operation energy but also on the embodied energy and carbon commencing from applying various measures to the building. The embodied energy and carbon data for building materials have been obtained from the Intergovernmental Panel on Climate Change (IPCC) database. All primary energy consumption of the building and improvement measures during the operation phase are computed with dynamic simulation tools, EnergyPlus and DesignBuilder. The life cycle energy consumption and CO_2 emissions of various measures have been calculated. Optimum alternatives have been proposed in the temperate-dry climatic zones of Turkey.

Keywords. Life Cycle Energy, Embodied Energy, Embodied Carbon, Residential, Nearly Zero Energy Buildings.
DOI: https://doi.org/10.34641/clima.2022.290

Abbreviations

ACH – Air Change per Hour
CFL - Compact Fluorescent Lamp
EC – Embodied Carbon
EE – Embodied Energy
GHG – Greenhouse Gas
LCA – Life Cycle Analysis
LCE – Life Cycle Energy
LCEA – Life Cycle Energy Assessment
LCEC – Life Cycle Energy Consumption
LCCO2E – Life Cycle CO_2 Emissions
LCI – Life Cycle Inventory
nZEB – nearly Zero Energy Building
RB – Reference Building
PEC – Primary Energy Consumption

1. Introduction

Buildings are responsible for a significant share of energy use. Improving the buildings' energy efficiency, reducing carbon emissions and increasing renewable energy uses are essential to cope with climate change [1]. The buildings sector is in charge of about 35% of worldwide energy consumption. Assessment of building during operational energy use is crucial; nevertheless, the energy used for production, transportation of building materials, construction, and demolition should be considered. The construction sector's Embodied Carbon (EC) is accountable for 11% of global GHG emissions, equal to 28% of the building sector's GHG emissions.

The whole life cycle of building construction has generated environmental impacts. Life Cycle Energy Analysis (LCEA) is a widespread and popular method for assessing energy uses and CO_2 emissions during buildings' lifespans. LCEA is comprised of manufacturing, operational, and demolition energy. The manufacturing energy includes the energy content of all materials and components entitled the embodied energy and the transportation energy. Operational energy consists of the whole energy used for HVAC, domestic hot water, lighting, and home appliances during the building operation. Demolition energy is the energy required to demolish a building at the end of its useful life and transport the material to storage areas or recycling facilities [2].

The proportion of embodied energy and carbon of energy-efficient buildings in whole life cycle energy consumption (LCEC) is high enough not to be neglected. Most researchers have addressed the operational energy, but less attention is on embodied energy and embodied carbons. The growing building renovation towards nearly zero energy building standards is expected to lead to a relative increase in embodied energy and embodied carbon emissions. All the new construction has critical roles in embodied carbon and energy. This paper focuses on the life cycle of nearly zero energy residential buildings. The environmental impact and embodied energy and carbon are evaluated during the life cycle framework.

2. Literature review

There are several works of literature on LCE of different building typologies. Ramesh et al. [2] identified 73 case buildings across 13 countries, including residential and office buildings. They concluded that operating energy has about 80–90%, the embodied energy (10–20%), and the demolition energy is negligible with a little percentage share in LCE. Mangan et al. [3] have investigated residential building performances for different climatic zones of Turkey regarding LCE and life cycle cost efficiency. More recent evidence highlights the importance of embodied energy and embodied carbon. Some studies have concentrated on LCE and cost-efficiency. Ferrari et al. [4] assessed the existing office building by some representative retrofit options for achieving zero buildings. Pikas et al. [5] considered energy efficiency and cost optimality of office building fenestration design. The investigation evaluated different measures to achieve the nZEB level. Sicignano et al. [6] have investigated identifying the construction system with the lowest embodied energy and carbon. Thormark [7] studied that the embodied energy was 40% of the total energy needed for a life expectancy of 50 years. The embodied energy can be decreased by approximately 17% through material adjustment.

However, few studies have focused on LCE terms and embodied energy and carbon of materials simultaneously. Chastas et al. [8] have shown an increasing share of embodied energy in the transaction from conventional to passive, low energy, and nZEB. The share of embodied energy in low energy buildings is 26%-57%, and nearly zero energy buildings are 74%-100%, respectively. In passive buildings, the percentage of embodied energy varies between 11% and 33%. Shirazi et al. [9] evaluated that up to 30% of a building's life cycle energy (LCE) and emissions are associated with the embodied phase. Ohta [10] investigated that the material added for better energy efficiency and CO_2 emissions generated during the manufacturing and construction periods positively affected reducing the Life Cycle CO2 Emission (LCCO2E) of homes. The ratio of LCCO2E for a zero-energy home becomes relatively high compared with a conventional home. Cabeza et al. [11] discussed the Low carbon and low embodied energy materials. Different materials are defined as cement and concrete, wood, bricks, rammed earth, and sandstone as low carbon materials referred. Xiaodong Li et al. [12] evaluated the embodied carbon impacts of three types of residential buildings in China. Morini et al. [13] indicated that it is possible to use reliable software with embodied energy and carbon footprint metrics to assess the environmental problem early in development and materials selection. Khadra et al. [14] considered three different renovation packages used in multi-family buildings from an economic perspective.

3. Methodology

Four stages should be considered in the LCA of energy-related building renovation. These stages define the scope, life cycle inventory, impact assessment, and interpretation. The methodology of this paper was also divided into four parts. The first stage was the definition of the scope of study and the initial analyses. A residential building was selected to be the reference building (RB). The energy modelling was conducted. It includes calculating operational energy use and emissions. The energy model was made in DesignBuilder and then transferred to the EnergyPlus to calculate the operational energy and carbon emissions.

The second step of the LCA outlines the methodology used to analyze embodied energy and embodied CO_2eq emissions arising from the production of building materials. The Life Cycle Inventory (LCI) phase is generally considered the most significant obstacle since the data collection process is very time-consuming. As there are no LCI databases available in Turkey, in the study, the LCI database of the University of Bath's Inventory of Carbon and Energy has been used [15].

The third step outlines the various alternatives to improve the RB. Different envelope, lighting, mechanical components, and renewable energy alternatives are determined in this step. The LCE and LCCO2E have been calculated for individual and combined single measures during the building life cycle. The building lifespan is considered 50 years. The fourth step is related to interpreting the LCEC, LCCO2E and EE of all parameters and evaluating them.

4. Reference Building

The five-story apartment building, which represents a detached apartment located in Ankara, is a case building. This city has a tempered-dry climate. This 6-floor building (5 occupied floors and an unoccupied underground floor) has a gross area of about 2752.1 m^2; from this amount, 440 m^2 belongs to the sloped roof area that is unoccupied. The building has four dwelling units with about 85 m^2 and 90 m^2 areas on each floor. Each unit has two bedrooms and one living room. Each unit's height is 2.8 m from above to below the floor. Most of the living areas are faced to the south. Other physical information about the reference building is presented in table 1.

Tab. 1 - RB's physical properties.

Physical properties of the RB.	
Location	Ankara-39.93°N-32.85° E
Orientation	0°
Floor area (m^2)	440
Total floor area (m^2)	2312.1
Floor height (m)	3.20
Facade surface area (m^2)	1557
Elevation (m)	752
Roof area (m^2)	442.54
Glazing area (m^2)	327.40
Glazing ratio (%)	20
Number of floors	6 (1+5 typical floor)
Number of apartments	20
Number of the apartment on the floor	4

The building energy modelling is done by dynamic simulation tools design-builder and energy plus. Figure 1 shows the floor plans drawings and 3D views of the Reference Building (RB).

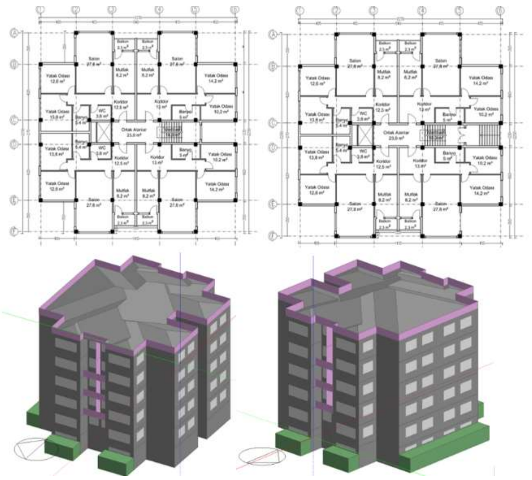

Fig. 1 - Drawings of floor plans and 3D views of 5-story reference building apartment.

The building envelope materials are chosen based on TS825-2013 standards [16]. According to TS825-2013, Ankara is located in third-degree day zones. The U-values of reference building for walls, roofs, and ground floor are 0.48, 0.28, and 0.43 W/m^2°K, respectively. Also, the minimum U-value of the glazing system is 1.8 W/m^2°K. The Visible transmittance of glazing and the solar heat gain coefficient are 0.56 and 0.32, respectively. Table 2 indicates the primary characteristics of the building components and their materials, including embodied energy and embodied carbon.

Tab. 2 - Thermo-physical properties of the RB.

	Material layers (from outside to inside)	E.E. (kWh/kg)	EC (kgCO2/kg)	U value (W/ m^2°K)
External Wall	Cement rendering	0.37	0.21	0.48
	Extruded polystyrene	24.61	2.55	
	Brick	0.83	0.24	
	Gypsum Plastering	0.50	0.12	
Roof	ceramic	3.33	0.74	0.28
	cement mortar	0.37	0.21	
	Reinforced concrete	0.31	0.16	
	water insulation	14.17	0.38	
	Extruded polystyrene	24.61	2.55	
	water barrier	14.17	0.38	
	concrete	0.24	0.10	
	Reinforced concrete	0.31	0.16	
	Gypsum Plastering	0.50	0.12	
Ground Floor	Hardcore	0.13	0.02	0.43
	Concrete	0.24	0.10	
	Water insulation	14.17	0.38	
	Cement mortar	0.37	0.21	
	Extruded polystyrene	24.61	2.55	
	Water barrier	14.17	0.38	
	Dry pine	0.02	0.00	
	Parquet	4.44	1.05	
Glazing	Clear glazing	4.17	0.85	1.8
	PVC frame	597.23	110.00	

Like the envelope, the interface part of buildings, the renovation measures on envelope measures affect the building's energy use. Thus, construction elements like internal walls or floors do not affect the building's energy performance. Based on Turkey's Building Energy Performance (BEP-TR) [17], the setpoint temperature for cooling and heating is set to 26°C and 20°C, respectively. The reference building's heating system is a natural gas-based combi boiler with an internal radiator (Baseboard Hot Water Convector). In contrast, the cooling system is an individual system with a packaged terminal air-conditioner in each case. A mechanical ventilation system is not used in the building, and natural ventilation works solely. The boiler produces the Domestic Hot Water (DHW) system. Also, all lamps are 40W Compact Fluorescent Lamp (CFL). There are lighting controls in living spaces. It is estimated that during occupancy hours, except for sleeping hours, one of the bedrooms can be used as a study room and living room. When the illumination level provided by natural lighting is below the required amount (200 LUX for the bedroom and 150 LUX for the living room), the lighting system is on; otherwise, the system is off in those rooms. Table 3 includes the features of building HVAC systems.

Tab. 3 - Energy systems' characteristics.

Heat production	Boiler efficiency = 0.8 COP (Coefficient of Performance)
Heat distribution	Hot water radiator-Natural gas
Domestic Hot Water (DHW)	Boiler – Natural Gas
Cooling Generator	Individual System
Cooling System	Air Conditioning (Electricity)
Ventilation System	Natural Ventilation
Heating & Cooling Setpoints	Heating Periods=20 °C, Cooling Periods =26 °C
Lighting System	Compact fluorescent- Lighting Control
Infiltration Rate	0.5 Air Change per Hour (ACH)

4.1 Definition of the Energy Efficiency Improvement Measures.

Different measures on envelope, lighting, and mechanical systems are defined to reach the nZEB level. Three thermal insulation levels on walls, roof, and ground floor are used at the first, second, and third stages. The primary material of third measures on walls is Autoclaved Aerated Concrete (AAC) blocks. In other measures and the ERB, the primary wall material is brick. Two different improvement measures are defined for glazing systems. The first measure is double glazing with a 1.3 W/m^{2}K U-value, and the second measure is a triple glazing system with 1.3 W/m^{2}K U-values. Another measure on the envelope is added Polyethylene wick for reducing air filtration from 0.5 ACH to 0.3 ACH. For improving the lighting systems, all CFL lamps were replaced with LED lamps.

Besides, the mechanical system is modified for improving the heating system. At the first level, boiler modification with central systems by natural gas fuel condensing boilers is projected. The current heating system is replaced with a condensing boiler, underfloor heating, and central floor heating systems at the second, third, and fourth levels. The photovoltaic system is added to the RB and four other improvement measures. The photovoltaic system type is monocrystalline (Mono-CSI) cells. Table 4 indicates individual renovation measures characteristic of the RBs. The RBs U-values are according to the Turkish Insulation standard, TS825-2013. Table 5 displays the possible individual and combination energy-efficient measures.

Tab. 4- Single energy efficiency improvement measures.

ID	Single Improvement Measures
O1	Brick- Wall= XPS 12 cm; Roof=Glass wool 15cm; Ground Floor=XPS 14cm
O2	Brick- Wall= XPS 17 cm; Roof=Glass wool 20cm; Ground Floor=XPS 18cm
O3	Autoclaved Aerated Concrete – Wall= XPS 17 cm; Roof=Glass wool 20cm; Ground Floor=XPS 18cm
GL1	Double Glazing- 4+16+4 (air) - 1.3 W/m^{2}K; 0.44 SHGC; 0.71 Tvis
GL2	Triple Glazing - 4+12+4+12+4 (Air) - 0.9 W/m^{2}K; 0.48 SHGC; 0.69 Tvis
LI1	LED Bulb
A1	Air filtration 0.3 ACH
H1	Central Systems- Gas fuel condensing boilers between 150.000-200.000 kcal / h
H2	Condensing Boiler - 20.000 kcal / h
H3	Individual Floor Heating-
H4	Central Floor Heating
PV	60 number of Monocrystalline silicon 13.9%

4.2 Life Cycle Inventory

LCA's foremost significant part is a life cycle inventory (LCI) or data collection. As there is insufficient inventory data in Turkey, the embodied energy and carbon emission of materials are based on the IPCC and the University of Bath's Inventory of Carbon and Energy (ICE) database. PV system's EE and EC were derived directly from the literature [17]. However, all calculations do not consider EE and EC of lighting and mechanical systems measurements.

RB's the most embodied energy percentages allocated to reinforcement concrete, brick, and concrete which are 52%, 24%, and 9%, respectively. The building lifespan is assumed to be 50 years. The primary energy consumption is considered for calculating the energy consumption of operational energy. Primary energy conversion factors are 1.00 for natural gas and 2.36 for electricity in Turkey [18]. Additionally, for calculating CO_2 emission during the operation stage, the emission factors for natural gas and electricity were taken as 0.234 and 0.626 kg.eq.CO_2/kWh, respectively [19].

Tab. 5- Energy efficiency improvement packages.

ID	Opaque System	Transparent System	Infiltration	Lighting System	Mechanical systems	Photovoltaic System
RB+PV	-	-	-	-	-	PV
P01	O1	-	-	-	-	-
P02	O2	-	-	-	-	-
P03	O3	-	-	-	-	-
P04	-	GL1	-	-	-	-
P05	-	GL2	-	-	-	-
P06	-	-	-	LI	-	-
P07	-	-	A1	-	-	-
P08	-	-	-	-	H1	-
P09	-	-	-	-	H2	-
P10	-	-	-	-	H3	-
P11	-	-	-	-	H4	-
P12	O1	GL2	A1	LI	H3	-
P13	O2	GL1	A1	LI	H3	-
P14	O2	GL2	A1		H3	-
P15	O2	GL2	A1	LI	H3	-
P16	O1	GL2	A1	LI	H2	-
P17	O2	GL1	A1	LI	H2	-
P18	O2	GL2	A1	-	H2	-
P19	O2	GL2	A1	LI	H2	-
P20	O1	GL2	A1	LI	H1	-
P21	O2	GL1	A1	LI	H1	-
P22	O2	GL2	A1	-	H1	-
P23	O2	GL2	A1	LI	H1	-
P24	O1	GL2	A1	LI	H1	PV
P25	O2	GL1	A1	LI	H1	PV
P26	O2	GL2	A1	-	H1	PV
P27	O2	GL2	A1	LI	H1	PV

5. Results

By overview of the primary energy consumption of the reference building, heating is more imperative than cooling. Ankara is located in a tempered-dry climate zone; hence, most of the reference building's primary energy consumption belongs to heating with 72.51 kWh/m².a. In contrast, the lowest primary energy consumption belongs to cooling with 5.03 kWh/m².a. After heating that is accounted for 57% of the whole primary energy, HVAC components (pumps and fans), lighting, and cooling are located with %4, %22, and %17, respectively. Figure 2 shows the distribution of the primary energy consumption by different systems in the reference building.

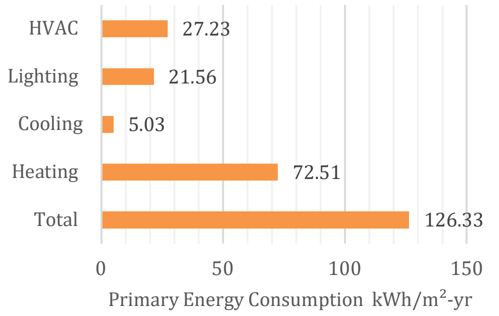

Fig. 2 - Distribution of RB's primary energy consumption.

Considering the PEC of all measures, the most reduction in single and combination steps is related to the P24 and P27 with 46% and 57.4% saving, respectively. The results show that adding thermal insulation to the envelope makes it possible to reduce PEC between 13.2% and 16.8%. P11 reveals that it can minimize operation energy by 19.3% with individual mechanical renovation. By modifying lighting systems to LED bulbs (P6), PEC saving is only 2.2%, the lowest saving among packages. P24, P26, and P27 support by renewable systems have the most PEC savings among all packages. Figure 3 demonstrates the annual PEC of RBs and improvement packages.

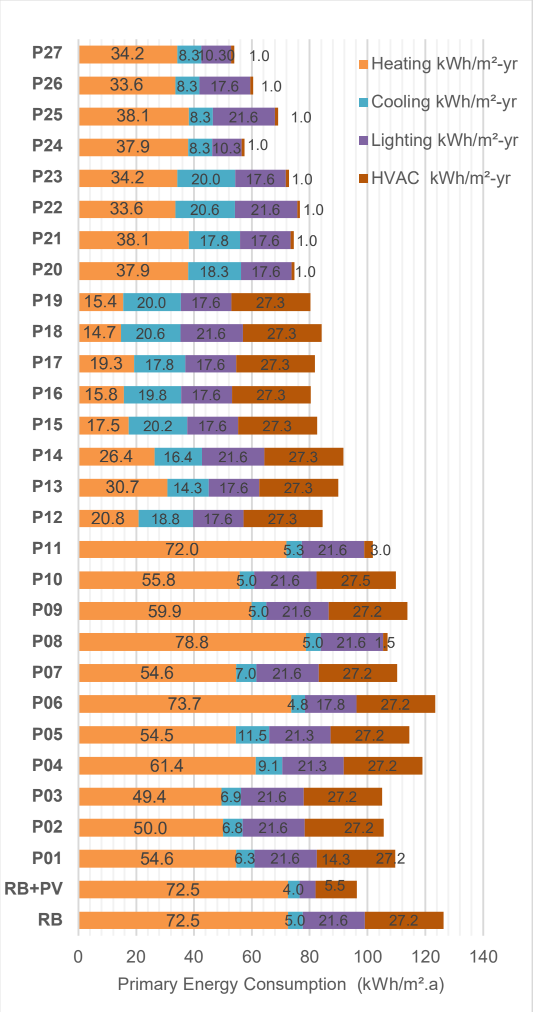

Fig. 3 - Annual Primary Energy Consumption of RBs and improvement packages.

Figure 4 illustrates the LCE and LCCO2E saving values of individual and combined improvement measures. P24, P25, P26, and P27 are the most LCE and LCCO2E savings scenarios among combination measures. Not surprisingly, all these alternatives contain PV system. RB+PV package and P11 have the most savings among single measures. Generally, single packages are not as efficient as combination measures. The lowest amount of LCE and LCCO2E savings are related to P6, P4, and P5.

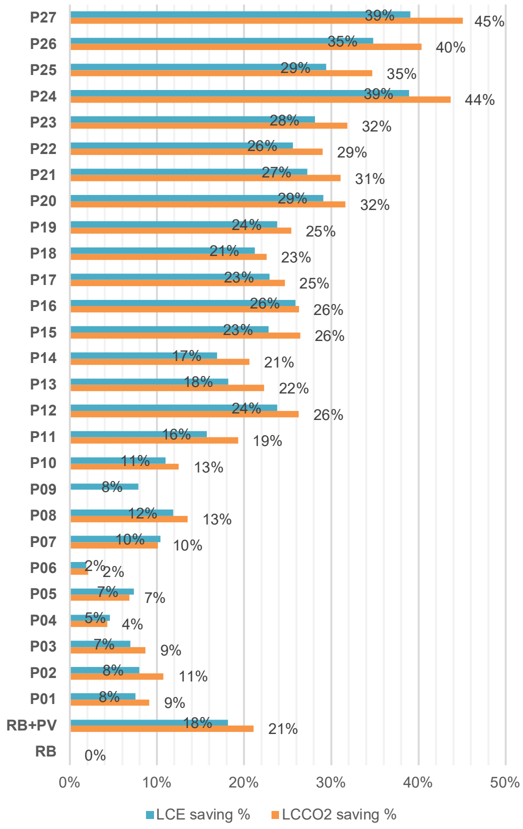

Fig. 4 - LCE and LCCO2E emission saving values.

RB has a low EE while it has the highest amount of LCEC. It is fundamental to note that the LCEC of renovation measures has been reduced by increasing the EE of measures. Not surprisingly, the highest EE options are related to the PV systems. Figure 5 displays the distribution of LCEC versus EE in different improvement scenarios.

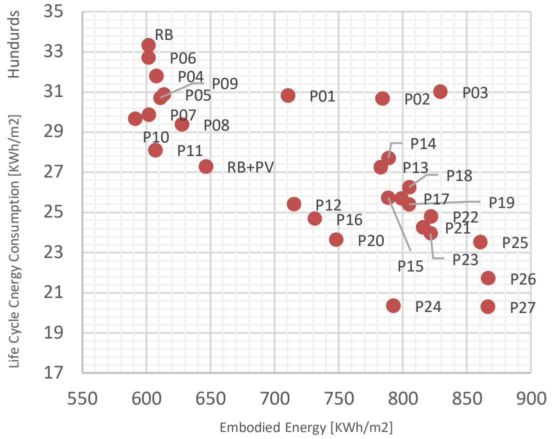

Fig. 5 - LCEC versus Embodied Energy of different improvement scenarios.

RB has the highest amount of LCEC and LCCO2E among all packages. In contrast, the least LCE and LCCO2E are P27, P24, and P26, respectively. Consequently, these packages are the most efficient LCE and LCCO2E measures. However, P6 and P4 have the most LCEC and LCCO2E among measures. Figure 6 demonstrates the LCE versus LCCO2E of renovation measures.

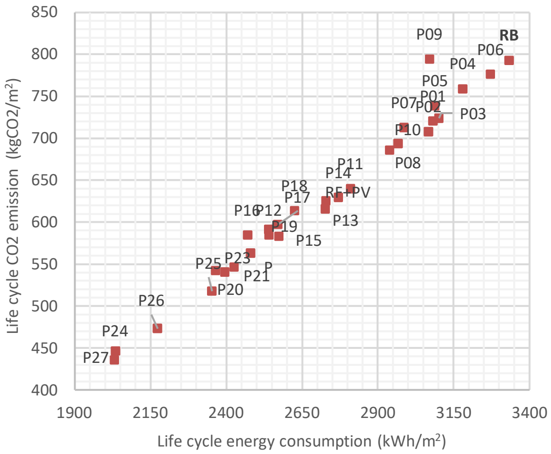

Fig. 6 - LCEC versus LCCO2E of renovation measures.

The results indicate that measures with almost the same LCEC and LCCO2E saving can have different EE. P24 and P27 have almost equal saving potentials. However, P24 has a comparable low EE. RB's embodied energy and operational energy share are approximately 18% and 82%, respectively. While, in nZEB scenarios, P27, P24, P26, and P25, the share is 40% to 60% for EE and operational energy. Consequently, by reaching nZEB, the embodied energy exceeds 18% to 40%. In comparison, the operational energy is decreased from 82% to 60%. Table 6 summarised the energy and CO_2 emissions for the RB and nZEB scenarios during the building life cycle.

Tab. 6 - Summary of the results for RB and measures located in the nearly zero-energy ranges.

Parameters		nZEB Scenarios		
	RB	**P.24**	**P.26**	**P.27**
PEC (kWh/m^2.a)	126.3	57.47	60.43	53.86
Primary Energy Saving (%)	n.a.	54.5	52.2	57.4
LCEC (kWh/m^2)	3333.7	2035.5	2173.4	2031.2
LCCO2E (kgCO$_2$/m^2)	792.6	446.3	472.9	435.4
LCCO2E Saving (kgCO$_2$/m^2)	n.a.	346.3	319.7	357.2
LCCO2E Saving (%)	n.a.	44%	40%	45%
Embodied Energy (MWh)	1391.4	1832.9	2003.7	2003.2
Embodied Carbon (TonCO$_2$)	334.1	383.8	401.2	401.4

6. Conclusion

In conventional buildings, the energy consumed in material production is almost a quarter of the operating energy consumption. A large amount of carbon is released in the material formation and transportation process. The operational energy is consumed during the building operation, which has a comparatively long span than the material formation and transportation. It means that the embodied energy is very intensive than operational energy. That's why Embodied Energy should play a pivotal role in building energy analysis.

Considering the life cycle of the building, it is obvious that zero energy buildings indeed are not actually zero energy. Due to the excess of components and materials used in these buildings, the materials' formation energy and carbon emissions are higher than in conventional buildings. Although this situation should not be considered an obstacle for buildings being developed with zero energy concepts, ignoring it may cause more significant challenges. Therefore, building materials with lower embedded energy and carbon emissions should be integrated into the zero energy building concept and all related initiatives. In addition, materials with these features should be disseminated with the necessary legal regulations.

The paper has focused on the life cycle impact of a case study building under different improvement measures. The results show that the measures with similar life cycle energy consumptions and CO2 emissions have different embodied energy consumption and CO_2 emissions. The study data is based on an international database. However, a national database is necessary to have more reliable outcomes from the studies on building life cycle. The embodied energy and CO_2 emission data for the HVAC system is not available in the literature. This deficiency also should be fulfilled to have an inclusive approach.

References

[1] Life Cycle Assessment for Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation (Annex 56), Energy in Buildings and Communities Programme, March 2017, International Energy Agency.

[2] T. Ramesh, Prakash R., Shukla K.K. Life-cycle energy analysis of buildings: an overview. Energy and Buildings. 2010; 10:1592–1600.

[3] Mangan S. D., Koçlar Oral G. Assessment of residential building performances for the different climate zones of Turkey in terms of life cycle energy and cost efficiency. Energy and Buildings. 2016 ;110: 362–376.

[4] Ferrari S., Beccali M. Energy-environmental and cost assessment of a set of strategies for retrofitting a public building toward nearly zero-energy building target. Sustainable Cities and Society. 2017; 32: 226–234.

[5] Pikas E., Thalfeldt M., Kurnitski J. Cost optimal and nearly zero energy building solutions for office buildings. Energy and Buildings. 2014; 74:30–42.

[6] Sicignano E., Di Ruocco G., Melella R., Mitigation Strategies for Reduction of Embodied Energy and Carbon, in the Construction Systems of Contemporary Quality Architecture, Sustainability, 2019, vol. 11, issue 14, 1-14

[7] Thormark C. The effect of material choice on the total energy need and recycling potential of a building. Building and Environment. 2006; 41:1019–1026.

[8] Chastas P., Theodosiou T., Bikas D. Embodied energy in residential buildings-towards the nearly zero energy building: A literature review. Building and Environment. 2016;105: 267-282.

[9] Shirazi A., Ashuri B. Embodied Life Cycle Assessment (LCA) comparison of residential building retrofit measures in Atlanta. Building and Environment. 2020;171: 106644.

[10] Ohta I. Embodied CO2 Evaluation of a Zero Life-Cycle CO2 Home: A Case Study of an Actual Industrialized Home. Journal of Asian Architecture and Building Engineering. 2017;16(1): 231-237.

[11] Cabeza L. F., Boquera L., M. Chàfer, D. Vérez. Embodied energy and embodied carbon of structural building materials: Worldwide progress and barriers through literature map analysis. Energy & Buildings. 2021; 231:110612.

[12] Lia X., Yanga F., Zhub Y., Gao Y. An assessment framework for analyzing the embodied carbon impacts of residential buildings in China. Energy and Buildings. 2014; 85:400–409.

[13] Augusto Morini A., Ribeiro M. J., Hotzac D., "Early-stage materials selection based on embodied energy and carbon footprint", Materials and Design. 2019 ;178:107861.

[14] Khadra A., Hugosson M., Akander J., Myhren J. A. Economic performance assessment of three renovated multi-family buildings with different HVAC systems. Energy & Buildings. 2020;224: 110275.

[15] Hammond G. P., Jones C. I. Embodied energy and carbon in construction materials. Proceedings of the Institution of Civil Engineers – Energy. 2008; 161 (2): 87-98.

[16] Turkish Standardization Institute, TS825-Thermal insulation requirements for buildings. 2013.

[17] Diaz Al. C., Energy Life Cycle Assessment (LCA) of silicon-based photovoltaic technologies and the influence of where it is manufactured and installed, Master thesis of renewable energy and energy sustainability, University of Barcelona, 2013- 2014.

[18] Turkish Ministry of Public Works and Settlement, Building's Energy Performance of Turkey (Bep-Tr), Official Gazette. 2008; 27075.

[19] Turkish Green Building Council (CEDBIK), Green Building Certification Guide for New Houses. 2019.