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Whole life carbon assessment of representative building typologies for nearly zero energy building definitions

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ABSTRACT

Evolution of nearly zero energy buildings (nZEB) has been one of the main drivers for mitigating operational energy consumption in the building industry. The progress was accelerated by the Energy Performance of Buildings Directive (EPBD) in 2010 and since 2018, member states in EU started the obligatory implementation of the nZEB definitions for public and then for all buildings. On the other hand, several studies displayed that the impact of embodied energy originates from the production, transportation and disposal of building materials has become as significant as that of operational energy. However, there is not a consensus of how the embodied energy should be regulated or how it may affect the nZEB definition in the future. In this context, the purpose of this study is to investigate the environmental impact of improved building envelope and technical systems that originates from the nZEB requirements. The study adopted a case study approach to analyze the representative residential and office buildings in Turkiye. By conducting a whole life cycle carbon assessment (wLCA), the embodied and operational carbon emissions were calculated for several building envelope and technical systems scenarios. The results displayed that current nZEB definition increases the embodied carbon by an average of 15 % and decreases operational carbon by 30 % in four different climates. An improved nZEB definition may increase embodied carbon 20 % and decrease operational carbon by 30–80 %. At the end of the study, recommendations were provided for optimal solutions for a low energy building definition for several climate zones and neighbouring regions.

1. Introduction

The construction sector is responsible for 40 % of all greenhouse gas emissions (GHG) and more efforts are required for decarbonization [1]. EU has been the main driver for energy transition with Energy Performance of Buildings Directive (EPBD) [2,3]. The last recast in 2021 was part of the "Fit for 55″ programme [4] that sets a minimum 55 % reduction target for GHG by 2030. The aim is to reach carbon neutrality by 2050. This requires a two-folded strategy: (i) ensuring high performance of new buildings and (ii) implementing deep energy renovations in the existing build stocks. With the renovation wave strategy [5], the member states (MS) aim to double the renovation rate by 2030.

In this context, each MS is required to develop specific definitions and roadmaps to integrate a nearly zero energy building (nZEB) strategy for their building sector. Even though the introduction of nZEBs was put forward in 2010, there has been a wide range of definitions due to the economic, geographical, and technical differences [6]. In a recent report, an overview of nZEB performance

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targets of residential buildings in EU displayed a range between 20 and 220 kWh/(m^2a) [7]. The difference is even greater when the definitions are considered in a larger geography such as Eastern Europe and the Middle East and North Africa (MENA) [8–10]. When carbon neutrality is considered, the energy consumption targets also have a deviation due to the carbon intensity of energy sectors. For better precision, some nZEB definitions include carbon emissions as a primary or secondary indicator.

Meanwhile, several studies [11–14] have previously reviewed the embodied emissions in buildings. Embodied emissions originate from the production of building materials, transportation, and construction activities. Such embodied assets have remained as hidden emission sources until the last decades. With each improvement in building energy performance regulations, the operational emissions decreased while embodied emissions increased due to the requirements for more insulation in the building envelope and increased active systems for HVAC [15,16]. As a result, several initiatives [4,17,18] incorporate whole life carbon assessments into building performance evaluation to yield more comprehensive results.

The relationship between operational and embodied assets requires a new approach to how nZEBs are defined. The definition can no longer rely on operational performance and an optimal solution between the two assets must be achieved. In the literature, there are focal points of integrating embodied emissions into an overall assessment.

- research focuses on the optimization of the building envelope [19,20] or
- use of bio-based materials [21,22] or
- recycle or reuse conventional materials [23] and
- evaluate embodied carbon of technical systems [24,25].

In recent years, Denmark [26] and UK [27] have set targets for embodied carbon. On the other hand, there is a lack of benchmarking studies for the embodied carbon of buildings in developing countries with large building stocks and/or urbanization rate. For such an example in the Turkish context, an nZEB definition is effective since 2023 but there is no regulation for embodied carbon emissions [28]. The aim of this study is to critically review the nZEB definitions with regard to the balance between operational and embodied carbon emissions.

To provide the scientific background of such an aim, a comprehensive literature review on progress in nZEB definitions and current studies on operational and embodied carbon emissions in buildings is given in the next chapter. Then, the methodology which adopts a representative building approach to analyze residential and office buildings at a national level is explained. For the results, an embodied assessment method was proposed as an addition to the existing building performance regulations. Several scenarios were recommended in comparison with nZEB definitions and embodied carbon benchmarks in EU and MENA. Finally, the limitations and outreach of the study such as comparability of the results in a larger geography in other regions and reflections on the global carbon neutrality targets are discussed.

2. Literature review

A literature review is presented in this section to provide background information about the nZEB definitions. The progress in nZEB concept in different geographies is explored together with a review of efforts to integrate embodied carbon emissions into nZEB definitions. The findings of this section formed the basis of the methodology of the study.

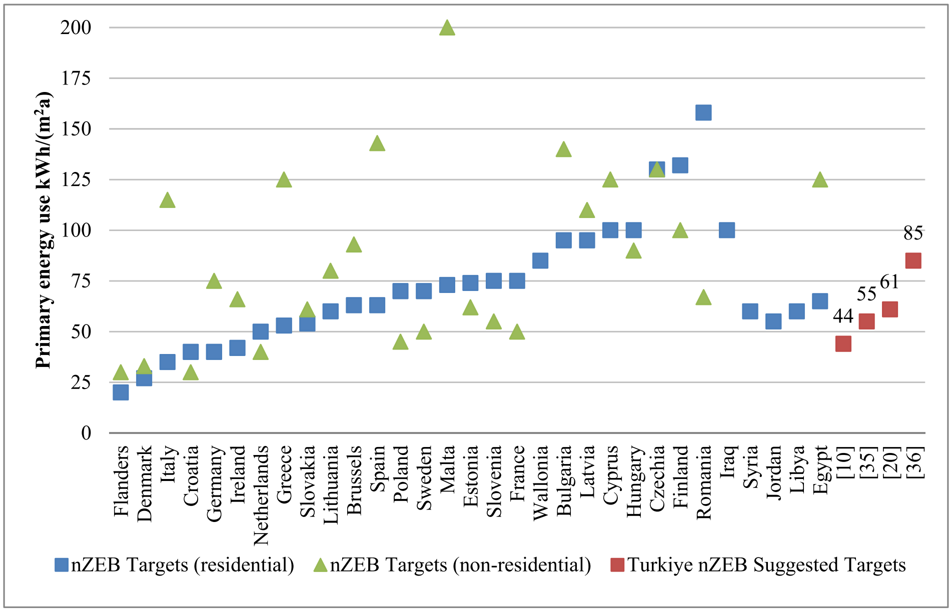

Fig. 1. Comparison of nZEB targets in buildings EU [7], suggested targets for MENA [33,34] and Turkiye [10,20,35,36].

2.1. Progress in nZEB definitions

There are certain events that paved the way for sustainability in the building sector towards energy efficiency (EE) and carbon neutrality [29,30] and circularity. This section specifically focuses on carbon neutrality in the building sector.

In the European Union (EU), the definition of an nZEB is both a technical and political decision that is expected by the European Council (EC) from each member state (MS). EC [31] recommended a range for primary energy consumption between 50 and 90 kWh/(m^2a) for residential and 80–100 kWh/(m^2a) for office buildings while considering four different climatic zones and varying contributions from renewable energy sources. While some countries have more ambitious targets, almost an equal number of countries provided less ambitious targets. It is necessary to tighten the regulations and phase out fossil fuels to meet the 2050 targets [7]. In Fig. 1, the collection of nZEB targets for residential and non-residential buildings in EU [32] and MENA are displayed and are compared with the targets suggested by different authors for Turkiye.

In the figure, the nZEB targets are ordered according to the values for residential buildings. It was seen that some countries provided significantly different targets for non-residential buildings. However, there was also a difference between the western and eastern EU countries originating from a couple of reasons: (i) climatic zone variation, (ii) low quality in construction, (iii) late integration of EE, (iv) large building stock, etc. [9]. There are few studies from other regions such as MENA, in which cooling energy consumption is dominant on the contrary to EU [33]. Al Saeed et al. [34] analyzed a hypothetical single-family house for several energy performance requirements such as ASHRAE and nZEB by locating the case building in different countries in MENA. The authors conclude that if an nZEB definition could be enforced, it could lead to net zero and positive energy buildings in the region.

In the case of Turkiye, the suggested targets imply a wide range for primary energy use between 44 and 85 kWh/(m^2a). To provide a refined comparison between the EU and a developing country such as Turkiye, the countries with similar climate zones and/or building stock are examined in greater detail in Table 1.

When nZEB targets are limited to similar climate zones and typologies, the range for primary energy demand in Turkiye and selected countries approximates to each other. In this comparison, it should be highlighted that there are slight differences in the energy uses included in the calculation of primary energy use. Nevertheless, there is a significant need for further studies to provide a precise value for nZEBs in developing countries.

The reason for not having a consensus on nZEB target in Turkiye is that the progress in EE in buildings has rather been slow with a late introduction of the concept by law in 2007 [38] and by regulation in 2008 [39] and development of a calculation method in 2010 [40]. This calculation method is a simple hourly dynamic simulation based on a reference-building methodology where a building is compared with its baseline version. The simulation considers the primary energy use for heating, cooling, ventilation and domestic hot water. Depending on the level of improvement in primary energy consumption when compared to the baseline, an EPC class from A to G is appointed to each building. All new buildings are obliged to have at least an EPC class of C, which refers to 80–99 improvement level (20 % to almost no mitigation). To receive an A class EPC, an improvement level of 0–40 (at least 60 % mitigation) is expected. Buildings with less performance than the baseline are not permitted (EPC Class D and below).

In 2020, an nZEB definition was introduced for all new buildings constructed after 2023 with a total area above 5.000 m^2 (to be decreased to 2.000 m^2 in 2025) [28]. Such new buildings must acquire minimum class B energy performance certificate (implies at least 20 % improvement for primary energy consumption) with a contribution of 5 % (to be increased to 10 % in 2025) renewable energy source. A supplementary guideline was also published to provide the scientific background [41]. Due to the reference building system, there are currently no reference values for nZEBs. On the other hand, there are several studies in the literature which may provide a rough range for possible nZEB options (see Fig. 1).

Both in the EU and other regions, energy performance benchmarking needs more ambitious targets with the inclusion of a whole life carbon assessment [7,18,27]. In the following sub-section, embodied and operational carbon assessment studies are reviewed and discussed.

2.2. Current studies on embodied and operational carbon in buildings

In literature, there are specific focal points of integrating embodied carbon emissions into comprehensive assessment frameworks. Some studies focus on the analysis of building stocks by reviewing existing studies on (i) regional or national level or (ii) specific building level.

Röck et al. [42] displayed a comprehensive overview which includes more than 100 case studies on the common approaches in

Table 1
Details of nZEB definitions of selected countries [7,37].

Country	Climate zone	Primary energy use kWh/(m^2a)		Renewable energy Share (%)	Energy use included[a]	Other Indicators[b]
		Residential	Non-residential			
Greece	1–2	53	125	60	h,c,v,dwh,l	ep,ts
Italy	1–2	35	115	50	h,c,v,dwh,l,s	ep,ts
Poland	3	70	45	None	h,c,v,dwh,s	–
Bulgaria	3	95	140	55	h,c,v,dwh,l	ep
France	4	75	50	75	h,c,dwh,l,s	ep,oh,ts
Germany	4	40	75	15–50	h,c,dwh,l	ep

[a] h: heating, c: cooling, dwh: domestic hot water, v: ventilation, l: lighting, s: services.

[b] ep: envelope performance, oh: overheating, ts: technical system performance.

environmental modelling of building stock at national levels. The authors emphasized two gaps in the literature (i) limited number of environmental indicators and (ii) lack of focus on impact of new buildings. Chastas et al. [43,44] conducted a review on embodied energy with 90 case studies and then applied a similar framework for embodied carbon [45] and conducted a case-specific study in Greece context [46]. The authors proposed to integrate embodied impact into EPBD recast and drew attention to the uncertainty originating from the methodological preferences in embodied impact assessment. The study confirmed the suggestions of a previous study [47] for dealing with standardized parameters. Norouzi et al. [48] explored decarbonization strategies in United Kingdom via a case-study. Horup et al. [49] distributed the country carbon budget down to buildings and materials in Denmark. Rucinska [50] conducted an LCA study to investigate GWP benchmarking for office buildings in Poland. Regardless of uncertainties, it is confirmed by several authors [15,16,51] that the importance of embodied impact in total emissions is on rise.

Other studies authors focus on (i) the optimization of the building envelope by (ii) use of low-carbon materials [21,22] or (iii) recycle or reuse conventional materials. Goggings et al. [52] explored the life cycle impact of residential nZEBs in Ireland and emphasized that building envelope is critical to achieve nZEB with lowest life cycle cost. Frischknecht et al. [53] considered whole life carbon of a high-rise resident based on different national methodologies. Maierhofer et al. [54] performed a critical assessment of an innovative passive house concept and suggested that further carbon mitigation is only possible through reducing the impact of production. The authors also suggested including embodied carbon assessment of appliances and technical systems. There are few studies which include and evaluate embodied carbon of HVAC and renewable energy systems [24,25,55,56].

In the Turkish context, there are several studies which consider embodied and operational emissions. Atmaca and Atmaca [57,58] conducted embodied impact assessment on a case study in southeast region of Turkiye and then expanded their work [59] on residential buildings. The studies heavily depend on a specific region and do not consider the impact of different climate zones on the embodied assessment. Sağlam et al. [35,36] applied a cost-optimal approach for optimizing the building envelope without considering embodied impacts. Acar et al. [20] conducted a similar study to explore zero energy buildings with life cycle costing (LCC) and then expanded to a whole building LCC [10] to achieve an optimal nZEB definition in Turkiye. Kayaçetin and Tanyer [60,61] performed embodied carbon assessment on residential and office buildings without considering operational assets.

Depending on the literature review, this study was designed with the parameters given in Table 2. The study was conducted at a national level including residential and office buildings to critically evaluate the current nZEB definition. The building stock in Turkiye can be classified as European and Middle Eastern. The case study buildings are considered as new buildings in four different climate zones and additional scenarios are necessary for baseline, nZEB and nZEB + buildings for future improvements. The scope of assessment should at least include structure, building envelope and technical systems. The embodied carbon assessment includes production, use and end-of-life phases for at least 50 years of building lifetime. Operational carbon assessment was reported via building energy simulation which is a dynamic hourly calculation on building archetypes and includes HVAC calculations. For such a study, the research questions and goals are provided in the next sub-section.

2.3. Research questions

The previous studies focused on specific cases and there is a need for a comprehensive assessment that analyzes the total life cycle emissions of the official nZEB definition on a national scale. Then the research questions for this study are as such.

- What are the envelope and technical system necessities to achieve nZEB definition?
- What is the amount of additional embodied carbon required to realize nZEB envelope and technical system scenarios?
- What could be the optimum level of embodied and operational carbon for improving buildings towards a carbon-neutral scenario that is in line with 2050 targets?

The goal of the study is to fill the gap of research on embodied carbon emissions of nZEBs. To achieve this, specific research goals

Table 2
Characterization of the study in literature

Spatial and temporal scope	**Region**	**Scale of stock**	**Temporal scope**	**Building types**
	Europe Middle East	National	50 years	Residential Non-residential
Building typology	**Object**	**Typology**	**Climate**	**Scenarios**
	New buildings	Single family Multi family Office	4	Baseline nZEB nZEB+
Building level scope	**Building parts**		**Material modelling**	
	Structure Envelope Technical systems		Building level Building elements Materials	
Modelling approach	**Life cycle scope**	**Modelling**	**Reference period**	**Modules**
	Embodied Operational	Product life cycle Energy simulation	50 years	Production End-of-life
Energy modelling	**Scope of energy uses**	**Modelling approach**	**Model resolution**	**Aggregation approach**
	HVAC	Dynamic	Hourly	Archetypes

are determined as follows.

- Identifying the building envelope and technical system combinations that meet the requirements of existing regulations,
- Determining the building envelope and technical system combinations that satisfy the new nZEB definition and evaluating the required additional embodied carbon,
- Comparing nZEB scenarios to investigate the balance between operational and embodied carbon and identifying the optimum level of whole-life carbon emissions.

This was achieved by performing an environmental life cycle assessment (LCA) study on a national scale. To reflect the national building stock, representative residential and office buildings in each climatic zone in Turkiye were considered. This approach enabled the research to provide valuable outputs for future recasts of nZEB definitions. In the following section, the methodology and case study are explained in detail.

3. Materials and methods

A whole life carbon assessment (wLCA) based on EN 15978 [62] and supplemented by a guideline prepared by RICS [27] was conducted on the selected representative residential and office building typologies. In Fig. 2, the flowchart of the study can be seen.

For the wLCA study, the goal was to assess the total carbon emissions of single-family house (SFH), apartment and office building for a reference study period of 50 years. The study progressed in two folds; embodied and operational carbon assessment to achieve optimal whole-life carbon emissions. A case study approach was adopted including 3 building typologies, 4 climate zones and 2 building regulations as baseline (TS825) and nZEB definition.

A life cycle inventory (LCI) was developed for both assessments. First, the building geometry and material quantities, technical and environmental data was collected. Available representative building descriptions that were identified in a previous study were utilized [41, 63]. These descriptions provided data such as geometry, total area, number of storey and window-to-facade ratio. Data collection included material characteristics and environmental product declarations (EPD) that were generated for local materials according to EN 15804 [64]. For the climatic data and available technical systems, the database of the national building energy performance tool (BEP-TR) was utilized [40]. Several scenarios were created for each building typology depending on (i) climate zones [65] (ii) thermal performance of the envelope and (iii) technical systems. When the LCI became sufficient, the life cycle assessment continued on two parallel fronts.

For the assessment of operational carbon, the national building energy performance certification tool was used. BEP-TR is a simple hourly dynamic-energy simulation tool that provides energy performance certificates (EPC) based on a reference building methodology. Building energy models were developed which includes the geometry, orientation, zoning and material and technical system

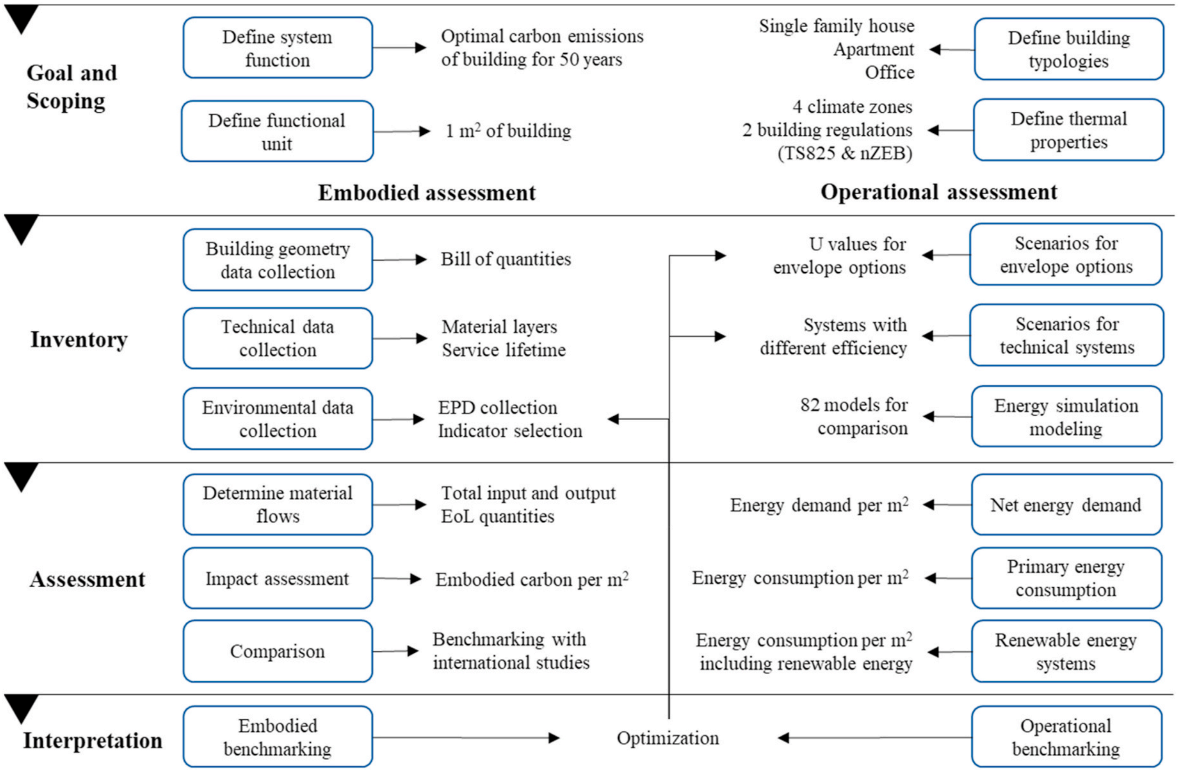

Fig. 2. Flowchart of the study.

selection. Then, primary energy demand was calculated for each building scenario. The calculation method is based on EN 13790 [66] and DIN 18599 standards [67]. In this study, heating and cooling energy demand were considered as the variables for the building scenarios focus on heating and cooling systems.

Meanwhile, for the assessment of embodied carbon, EN 15978 was adopted as a guidance since there is no national standard. The assessment was conducted by multiplying total building material quantities (including replacements during use and end-of-life scenarios) with environmental impact values per unit. The results were reported on a per gross floor area (GFA) basis that implies the enclosed area within the external walls [27].

This study may provide valuable input for future regulatory improvements. The proposed methodology overlaps with the data collection processes of the existing building energy performance system. In Fig. 3, the integration of embodied carbon assessment into the current building energy performance calculation is displayed. The common process that has significant impact on the embodied and operational carbon assessments is the identification of the building envelope. By introducing additional data collection on environmental data and life cycle of materials, the proposed method can be integrated into the current practice. In the following subsections, details of the building typology, climate zones and assessment methodology are provided.

3.1. Case study design

In this study, residential and office building typologies were selected to cover the highest percentage of new building stock in Turkiye. The descriptions of building typologies were derived from a previous study [63] that was based on statistical data from central government and municipalities and surveys in provincial directorates of Ministry of Environment, Urbanization and Climate Change (MoEUC). The study depended on several data sources; statistical data on building stock to determine construction area [68], a questionnaire study in each province with a response number of 1237 to identify typology characteristics. Several recommendations for building typologies in different climate zones were provided based on EPBD and EUROSTAT (see Table 3). Then these descriptions were updated to simply building typologies examples for EPC certification process and reported in a recent report on guidelines for nZEB [41].

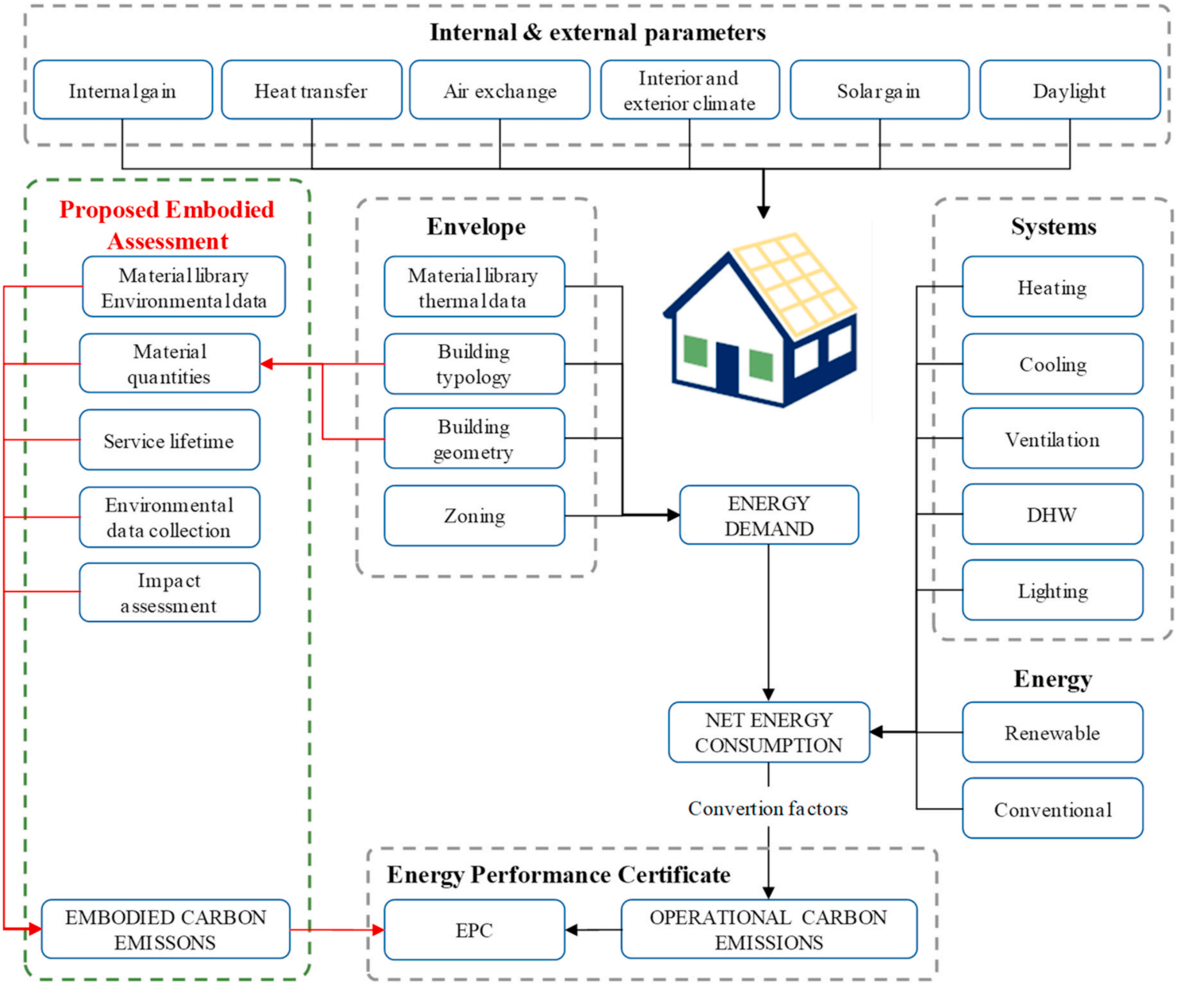

Fig. 3. Relationship of the proposed embodied assessment to the national EPC framework [41].

Table 3
Building typologies and climate zones in the Turkish context

	Building Typologies [63]	Update [41]
B1	Single family house (160 m^2)	160 m^2, 2 storeys
B2	Apartment buildings (1.680 m^2) up to 6 storeys	1.400 m^2, 6 storeys
B3	Residence (multipurpose) (5.400 m^2) 12 storeys	
B4	Offices w/Traditional Construction	2.500 m^2, 5 storeys
B4a	Offices w/Contemporary Construction	
B5	Educational building - School (Small: 2.400 m^2)	6.000 m^2, 5 storeys
B6	Educational building - School (Large: 5.700 m^2)	
B7	Health care facilities - Polyclinic (2.400 m^2)	12.600 m^2, 6 storeys
B8	Health care facilities - 30 beds Hospital (4.000 m^2)	
B8a	Health care facilities - 75 beds Hospital (12.600 m^2)	
Climate Zones		
Z1	Hot semi-arid	
Z2	Hot summer Mediterranean	
Z3	Cold semi-arid	
Z4	Cold dry/no-dry summer	

In the following sub-sections, building typology descriptions for residential and office buildings are given in detail including the envelope and technical system characteristics and climate zones.

3.1.1. Envelope

The Turkish building industry is dominated by (i) reinforced concrete, (ii) polystyrene thermal insulation and (iii) ceramic tiles and plaster & paint for exterior finish and (iv) single or double-glazed windows with plastic or aluminum frame. The selected building typologies reflect the same pattern and details are given in Table 4 and visuals in Fig. 4.

The building geometry does not display significant changes in different climate regions due to the globalization of construction materials and methods [63]. On the other hand, thermal insulation is dependent on the climatic data. For comparative purpose, two building envelope scenarios were generated by improving respectful U-values of the building components. The first scenario adopts the minimum U-value requirements provided by thermal performance regulation [65] and the second scenario meets the minimum U-value required by the new nZEB regulation. The differences between two scenarios can be seen in Table 5.

3.1.2. Technical systems

The technical system design is often based on heating as per existing regulation. On the other hand, the cooling demand is on the rise due to the changes in user behaviour and the climate crisis. The main energy source for heating and cooling is natural gas and electricity. Electricity production is heavily dependent on coal, natural gas and hydropower. For each climate zone, several technical system combinations were generated. These combinations were used for operational energy calculations. The technical systems and their respective efficiency values such as coefficient of performance (COP) and energy efficiency rating (EER) were calculated according to EN 14825 [69] within the BEP-TR tool and displayed in Table 6 for each climate zone. In order to meet the minimum nZEB requirements, an on-site solar PV system with the same output per GFA for each typology was proposed on the roof space.

3.1.3. Climate zones in Turkiye

The climate zones are regulated by TS825 [65] and four zones are recommended depending on heating and cooling degree days (HDD, CDD). The details of the zones can be seen in Table 7 and Fig. 5 shows the location of representative provinces for each climate zone.

The zones provide a wide variation in the Köppen-Geiger classification. Z1 is a dry, semi-arid and hot Mediterranean region (BSh), Z2 is a hot-summer Mediterranean climate (CSa), Z3 is a cold-semi arid climate in Central Anatolia (BSk) and Z4 is a continental region with no dry seasons and warm summer in Eastern Anatolia (Dfb). The geographical differences such as proximity to sea and altitude are the main reasons for such a variation.

3.2. Whole-life carbon assessment methodology

The assessments of the representative building scenarios are based on a cradle-to-cradle LCA approach. This approach considers the production (Module A), use (Module B) and end-of-life (Module C) stages of buildings. According to EN 15978 [62], benefits beyond system boundaries (Module D) are not mandatory, and even if included they should be reported separately. There are global data gaps for several modules especially for the use phase (Module B) due to high variety of different application during the maintenance and repair of building materials. Hence the current guidelines provide a minimal scope that is sufficient for reporting major activities in a

Table 4
Characteristics of representative buildings [41].

Typology	Storey #	Total area	Footprint	Window/Facade ratio
Single family house (SFH)	2	160	80	%15
Apartment	6	1.400	233	%15
Office	5	2.430	486	%25

Fig. 4. Representation of building typologies; (a) SFH (b) Apartment (c) Office.

life cycle. This study follows RICS guidelines [27] and the minimum scope for the life cycle phases are A1-A5, B4 and B6. Module C is also included as the data sources provide environmental data. B5 and B7 are not relevant for the study as the focus is on new buildings and not refurbishments. The operational water consumption is currently not a criterion for nZEBs. In Table 8, the scope and system boundaries are provided in brief.

In order to provide a comparison between different building typologies, the functional unit was defined as annual carbon emissions per GFA. The results are displayed in kgCO$_2$-eq/m^2. The reference study period is 50 years as per EN 15978. In this context, inventories were generated depending on building drawings and available building materials in the current market. The impact of technological advances during the reference study period was ignored for simplicity reasons. Environmental data for building materials are based on local EPDs [70] and displayed in Annex A. For the replacement of building materials, minimum service lifetime that is provided in the literature [27] was utilized. A brief life cycle inventory can be seen in Table 9.

For embodied carbon assessment, the amount of each material was multiplied with the GWP for different life cycle phases (Module A, B and C). There are significant changes on material thickness (i.e., insulation) or quality (i.e., window glass) due to the U-value requirements in climate zones. Recurring material during replacement (B4) was calculated by dividing the reference study period (rsp) to service lifetime (st) of the material. End-of-life scenarios as well as transportation data are based on EPD information as the study was conducted on representative buildings. For the embodied carbon originating from solar PV system, several studies [24,71] were reviewed and a 50 gCO$_2$-eq/kWh figure was adopted. The reference studies were conducted in EU, hence the maximum value was preferred due to higher transportation emissions. Then, the calculations for embodied carbon for each component (EC$_{\text{component}}$) were conducted according to Formula (1) utilizing parameters in Table 9. In Formula (2) the results for each component are summed up and divided by GFA to achieve EC$_{\text{building}}$ in kgCO$_2$-eq/m^2.

$$EC_{component} = \left(q_{component} * \left(1 + \frac{rsp_{building}}{st_{component}} \right) * w_{component} \right) * GWP_{component} \tag{1}$$

$$EC_{building} = \frac{\sum_{i=1}^{n} EC_{component}}{GFA_{building}} \tag{2}$$

The operational carbon assessment was conducted by modeling the building object and scenarios in BEP-TR. Scenario modeling includes the selection of materials, typology, schedule, climate zone, zoning, and technical systems. First, the operational primary energy demand for the building (OE$_{\text{building}}$) was calculated which includes demand for heating (OE$_{\text{heating}}$), cooling (OE$_{\text{cooling}}$)and renewable energy (OE$_{\text{renewable}}$) contribution as seen in Formula (3):

$$OE_{building} = \frac{\left(\left(OE_{heating} + OE_{cooling} \right) - OE_{renewable} \right) * efficiency_{system}}{GFA_{building}} \tag{3}$$

The amount of primary energy required to meet this demand includes losses and system efficiencies (efficiency$_{\text{system}}$). For the calculation of renewable energy contribution, solar panels with an efficiency rate of 25 % and a service lifetime of 35 years were used. It was assumed that the efficiency would diminish to 80 % at the end of the lifetime. Then, to convert the primary energy demand to operational carbon emissions (OC$_{\text{building}}$), each energy demand figure was multiplied by the conversion factor according to the utilized fuel type. After calculating operational carbon emissions, the total amount is divided by GFA, as shown in Formula (4).

$$OC_{building} = \frac{OE_{energy} * conversion\ factor_{fuel}}{GFA_{building}} \tag{4}$$

The results of embodied carbon calculations for Formula (1) and (2) are reported in Section 4.1 and those of operational carbon calculations for Formula (3) and (4) are provided in Section 4.2. Finally, in Section 4.3 the sum of Formula (2) and (4) which results in the whole life carbon of the representative buildings are given.

4. Results

This section presents the results for three building typologies in two-folds: embodied and operational carbon. For the embodied carbon assessment, there are two envelope scenarios (baseline TS825 and nZEB) for each building typologies in four climate zones. For the operational carbon, the same envelope scenarios were combined with several technical systems to explore the possible range of mitigating the consumption. Finally, both results were compared with each other to conclude the overall level of carbon emissions.

4.1. *Embodied carbon*

Embodied carbon of building envelope and renewable systems for the current standard TS825 and nZEB regulation were provided for different life cycle phases. Eight envelope scenarios were considered for each typology. The production phase (A1-A3) was the main contributor for more than 70 % of the overall embodied emissions. Scenarios with highest insulation (Z4 nZEB) had 25–30 % higher embodied emissions than those with the least insulation (Z1). When components were considered, structural concrete had a significant impact ratio between 32 and 54 %. Heat insulation followed with 11–36 % and window systems had an impact ratio between 6 and 13 %. The increase in embodied carbon due to the improved nZEB regulation was 16 % for SFH, 15 % for apartments and 18 % for offices. The range of embodied carbon per typology is.

Table 5
Scenarios for the building envelope for climatic zones [41,65].

	Climate zone #	External wall		Structure		Roof		Floor on soil		Window
		U value W/m^2K	Thickness m	U value W/m^2K	Thickness m	U value W/m^2K	Thickness m	U value W/m^2K	Thickness m	U value W/m^2K
TS825	Z1	0,53	0,04	0,69	0,04	0,44	0,08	0,69	0,04	2,40
	Z2	0,46	0,05	0,58	0,05	0,39	0,09	0,58	0,05	2,40
	Z3	0,41	0,06	0,50	0,06	0,30	0,12	0,45	0,07	2,40
	Z4	0,36	0,07	0,43	0,07	0,25	0,15	0,39	0,08	2,40
nZEB	Z1	0,41	0,06	0,49	0,06	0,30	0,12	0,50	0,06	1,00
	Z2	0,33	0,08	0,39	0,08	0,28	0,13	0,43	0,07	1,00
	Z3	0,30	0,09	0,35	0,09	0,22	0,17	0,35	0,09	1,00
	Z4	0,26	0,11	0,29	0,11	0,19	0,20	0,29	0,11	1,00

Table 6
Technical system combinations and efficiencies [28].

Heating	Efficiency (COP)				Cooling	Efficiency (EER)			
Climate zone	**Z1**	**Z2**	**Z3**	**Z4**	**Climate zone**	**Z1**	**Z2**	**Z3**	**Z4**
Heat pump (air)	3,46	3,24	3,24	2,95	Split air-conditioner	1,91	1,97	1,97	1,96
Heat pump (air)	3,46	3,24	3,24	2,95	Heat pump (air)	2,50	2,43	2,43	2,57
Heat pump (ground)	1,51	1,7	1,7	1,68	Split air-conditioner	1,91	1,97	1,97	1,96
Condensing boiler	0,82	0,85	0,85	0,85	Split air-conditioner	1,91	1,97	1,97	1,96
Condensing boiler	0,82	0,85	0,85	0,85	Heat pump (air)	2,50	2,43	2,43	2,57
Condensing boiler	0,82	0,85	0,85	0,85	VRV	3,36	3,57	3,57	3,5
Heat pump (air)	3,46	3,24	3,24	2,95	VRV	3,36	3,57	3,57	3,5
Heat pump (ground)	1,51	1,7	1,7	1,68	VRV	3,36	3,57	3,57	3,5

Table 7
Characteristics of climatic zones in Turkiye [65].

Climate zone		Representative province	Heating & Cooling		Relative Humidity	Altitude (m)	Solar Radiation (kWh/(m^2a))
TS825	Köppen-Geiger		HDD	CDD			
Z1	BSh	İzmir	948	693	66	9	1550
Z2	Csa	İstanbul	1675	208	70	25	1450
Z3	BSk	Ankara	2335	254	64	905	1500
Z4	Dfb	Erzurum	4444	13	64	1923	1600

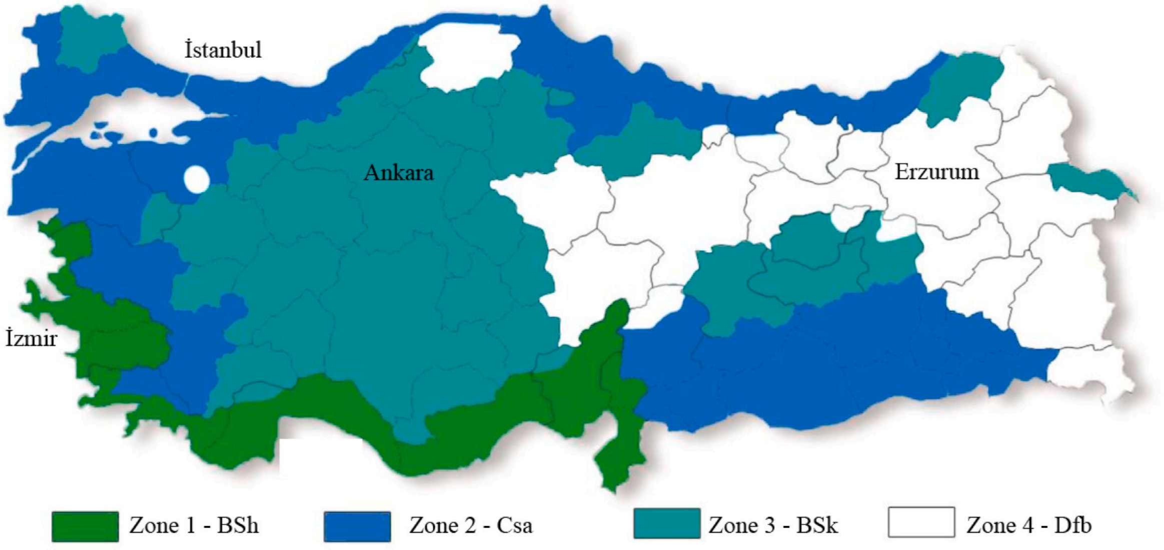

Fig. 5. Climatic zones and representative province locations.

Table 8
Scope of the LCA study

Production stage (A)			Construction stage (A)		Use (B)					End of Life (C)				Beyond Building Life (D)
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D1-D4
Raw material Extraction	Transport	Manufacturing	Transport	Construction &Installation	Use	Maintenance	Repair	Replacement	Refurbishment	Deconstruction Demolition	Transport	Waste processing	Disposal	Reuse Recovery Recycling Exported energy
X	X	X	X	X	–	–	–	X	–	X	X	X	X	–
					B6	Operational energy				X	Included in LCA study			X
					B7	Operational water				–	Module not declared			–

Table 9
Life cycle inventory (LCI) – component quantities, environmental data [70] and service lifetime [27].

Cluster	Building Component	Quantity (q) SFH	Quantity (q) Apartment	Quantity (q) Office	Unit	Weight (w) Kg/unit[a]	GWP[a] per unit	Service lifetime (st)
Roof	Cladding	81	233	486	m^2	3,16	1,36	10
	Heat Insulation 8–20 cm	81	233	486	m^2	2,45[b]	5,31	25
Exterior Walls	Brick Wall	150	633	900	m^2	112,5	0,40	50
	Heat Insulation 4–11 cm	175,4	873	1140	m^2	0,48[b]	6,44	25
	Exterior Paint	175,4	873	1140	m^2	0,13	1,91	10
	Exterior Plastering	175,4	873	1140	m^2	1	0,17	10
Windows	Window Profile	235,8	1386	3624,3	kg	1	2,33	25
	Window Glass	26,2	154	402,7	m^2	15[b]	1,3	25
Floors	Concrete	24,3	210	364,5	m^2	45	0,17	50
	Steel Rebar	2,43	21	36,45	m^2	50	0,69	50
Basement	Foundation Concrete	12,15	35	72,9	m^3	2350	0,17	50
	Foundation Steel Rebar	1215	3,5	7,29	kg	1000	0,69	50
	Heat Insulation 4–11 cm	81	233	486	m^2	0,89[b]	11,16	50
Structure	Concrete	6,3	33,6	54,7	m^3	2350	0,17	50
	Steel Rebar	0,63	3,36	5,47	kg	1000	0,69	50
Renewable Energy	Solar PV panels	4 in Z1, Z2, Z3 6 in Z4			kW	–	0,05 per kWh	35

[a] Data for weight and GWP per unit are derived from EPD files provided in Annex-A.
[b] For highlighted materials, weight and/or intensity varies depending on climate zones.

- For SFH, GWP per m^2 is between 240 and 335 with a total between 38,5 and 53,5 tCO_2-eq.
- For apartments, GWP per m^2 is between 145 and 191 with a total between 203 and 268 tCO_2-eq.
- For offices, GWP per m^2 is between 150 and 201 with a total between 364 and 488 tCO_2-eq.

The details for each typology are given in and explained under Figs. 6–8.

As displayed in Fig. 6, the ratio of production, construction, replacement, and end-of-life scenarios for SFH are respectively: 59–70 %, 12–16 %, 16–23 % and 2 %. SFH is characterized by the high amount of insulation material per m^2 due to the high ratio of building envelope area to total building area. The impact of insulation material was between 19% and 36 %. Hence the impact of both structural components and windows were lower than other typologies. As the impact of components with shorter service lifetime was higher, the replacement phase (B4) also had higher impact up to 23 %. SFH had the highest amount of embodied carbon per m^2.

As seen in Fig. 7, the ratio of production, construction, replacement, and end-of-life scenarios for apartments were respectively:

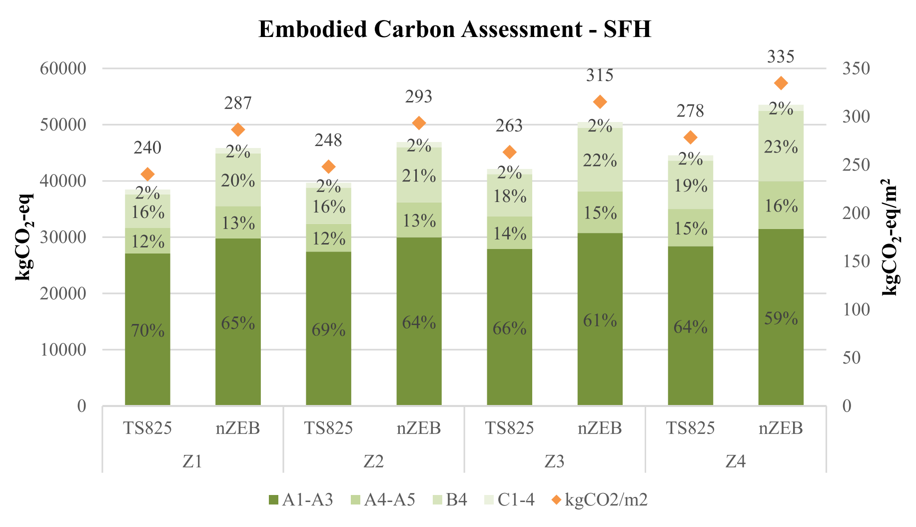

Fig. 6. Embodied Carbon Assessment for Single Family House typology.

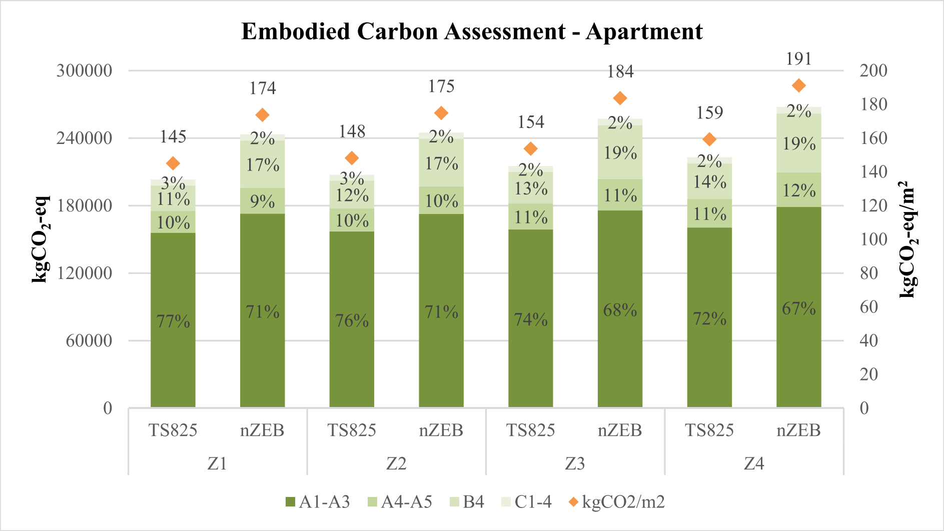

Fig. 7. Embodied Carbon Assessment for Apartment typology.

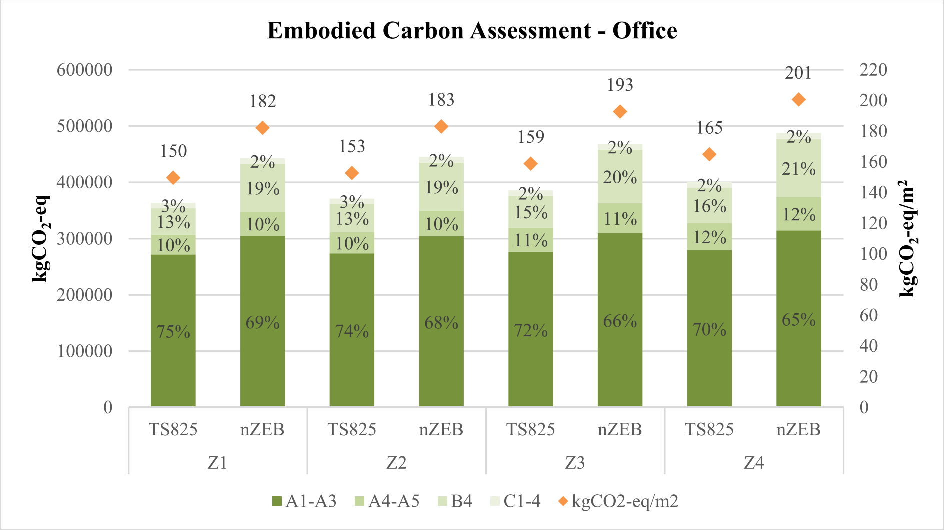

Fig. 8. Embodied Carbon Assessment for Office typology.

67–77 %, 9–12 %, 11–19 % and 2–3%. Apartments are medium-rise buildings with conventional construction techniques. The impact of insulation material was between 11% and 25 % and less than SFH. The impact of structural components was between 44 and 54 % and higher than other typologies. Apartments had the lowest embodied carbon per m^2.

As displayed in Fig. 8, the ratio of production, construction, replacement, and end-of-life scenarios for offices were respectively: 65–75 %, 10–12 %, 13–21 % and 2–3%. Offices had the largest GFA and window-to-façade ratio. The impact of windows was highest between 10% and 13 %. Offices had an average embodied carbon per m^2.

For validation, the interim results were comparisons with existing benchmarking studies in the literature (see Figs. 9 and 10). In the study of De Wolf et al. [72] 41 residential and 22 office buildings were evaluated and kgCO$_2$-eq ranges of 240–420 for residential and 100–340 for office buildings were displayed. In a larger database among 23 residential and 115 offices [73], kgCO$_2$-eq ranges of 150–397 for residential and 227–418 for office buildings were provided. Finally, Simonen et al. [74] put forward relatively higher ranges of 202–525 for residential and 266–515 for office buildings.

Lastly in a report from Röck et al. [75] presented 634 residential and 135 non-residential case studies from north European countries with slightly higher results: residential buildings between 400 and 800 kgCO$_2$-eq whereas non-residential buildings between 100 and 1200 kgCO$_2$-eq. The study also provided detailed information on the scope of their study, which is also relevant to preceding studies. Depending on their scope, the study can be considered as more comprehensive as additional life cycle phases were covered. Hence the results are consequentially higher for both typologies. The other parameters that may cause deviation are building parts

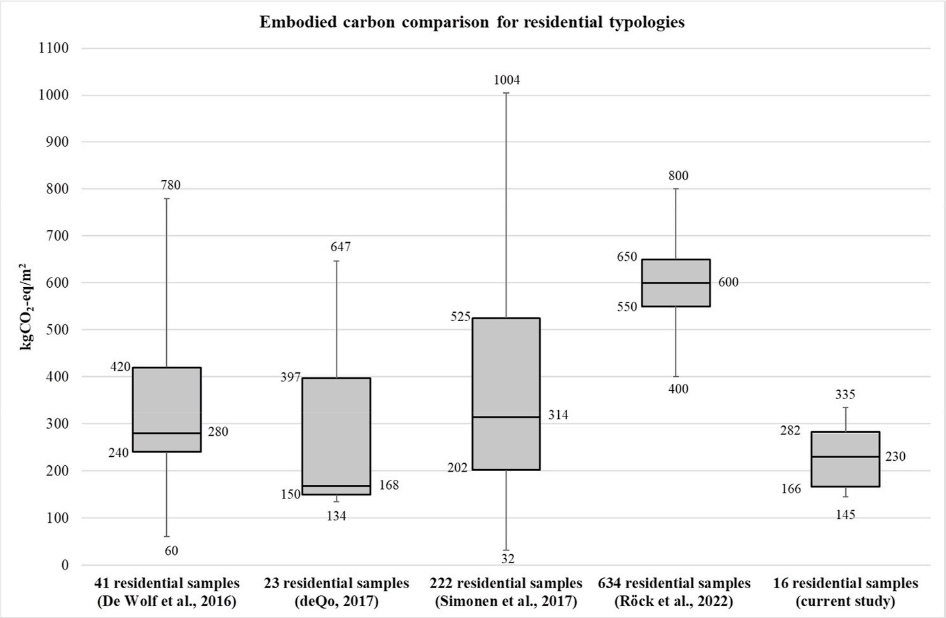

Fig. 9. Embodied Carbon Comparison for Residential typologies.

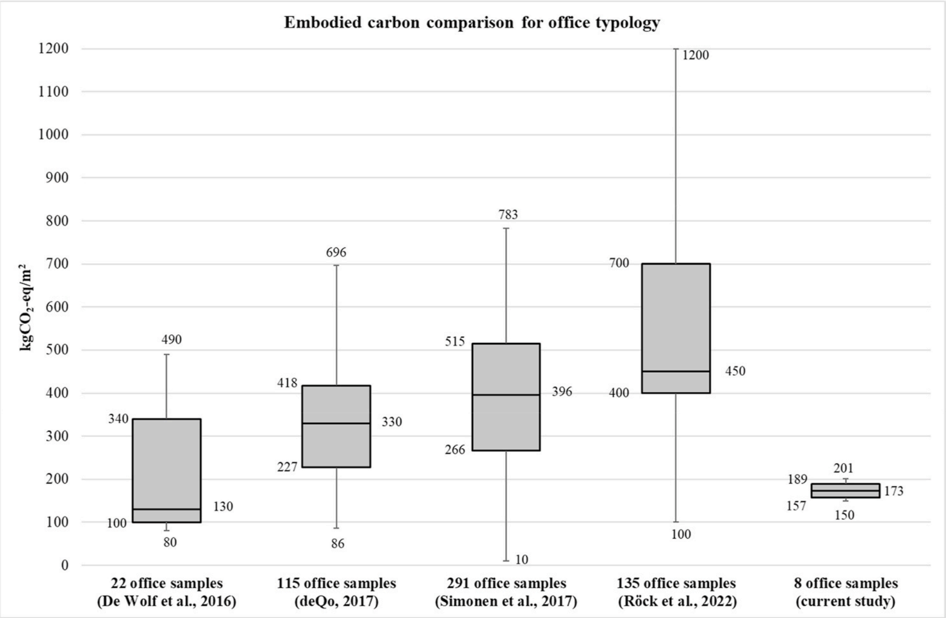

Fig. 10. Embodied Carbon Comparison for Office typology.

covered and slight differences in national methodologies.

In this study, the results for residential buildings and office buildings are in the lower range of the mentioned databases. The reason for such lower results originates from the fact that, the representative residential and office buildings in Turkiye are not high-rise buildings and neither do they possess high ratios of carbon intensive materials such as steel or glass. They contain less insulation than those in EU as well due to the climatic differences.

4.2. Operational carbon

For operational carbon assessment, the envelope scenarios were combined with the technical systems that were provided in Table 6. Only heating and cooling emissions were considered for the consistency with envelope scenario parameters. First, the primary energy demand for each typology in four climate zones were calculated annually. The results were converted to carbon emissions by using conversion factors based on the energy source (grid electricity 0,648 $kgCO_2$-eq/kWh and natural gas 0,234 $kgCO_2$-eq/kWh) and given in $kgCO_2$-eq/(m^2a). For demonstrative reasons, only office typology was used to display detailed operational carbon emissions in this sub-section. Operational carbon results for other typologies are provided in Annex-B.

The mitigation of operational carbon due to improved nZEB regulation was 28–32 % for SFH, 26–32 % for apartments and 38–51 % for offices. The range of operational carbon emissions for each typology is provided below in GWP per m^2 year and for a total of 50 years.

- For SFH, GWP per m^2 year is between 15 and 52 with a total between 120 and 416 tCO_2-eq.
- For apartments, GWP per m^2 year is between 13 and 46 with a total between 910 and 3200 tCO_2-eq.
- For offices, GWP per m^2 year is between 5 and 32 with a total between 607 and 3888 tCO_2-eq.

The contribution of solar PV system varies depending on the climatic regions. The GWP per m^2 year that are avoided due to the renewable energy contributions were 1,99 for Z1; 1,52 for Z2; 1,74 for Z3; and 2,53 for Z4. The results are compared in Fig. 11.

The operational carbon was mainly dominated by the emissions originate from the heating demand, except for Z1. The most promising technical system combination was observed as air-to-air heat pump and VRV due to high system efficiency rates coupled with renewable energy contribution for both healing and cooling demands. As the electricity mix in the country is dependent on fossil-fuel, the electricity-based systems yield more carbon emissions than expected. At this point, it must be noted that the current nZEB regulation requires a minimum 5–10 % contribution from renewable energy sources to the total primary energy use. When compared to nZEB requirements in EU, the level of contribution is quite low. Hence, the influence of renewable energy on embodied and operational carbon is further discussed in Section 5 by maximizing the solar PV system capacity within the available roof area.

4.3. *Life cycle impact interpretation*

Whole life cycle carbon emissions were compared per m^2 throughout 50 years of a lifetime for each typology per climate zone. The average of operational carbon emissions provided in Section 4.2 were adopted for this comparison. It should be noted that the upfront (A1-A5) embodied carbon emissions are realized in the first years of the lifetime, whereas operational carbon emissions happen over time. For simplicity reasons, this study did not apply a weighting factor according to the temporal impact of carbon emissions.

The range of whole life carbon per typology are as follows.

- For SFH, GWP is between 21 and 58 $kgCO_2$-eq/m^2 annually and 1056–2890 $kgCO_2$-eq/m^2 for 50 years with 73–90 % operational carbon.
- For apartments, GWP is between 16 and 33 $kgCO_2$-eq/m^2 annually and 809–1650 $kgCO_2$-eq/m^2 for 50 years with 79–90 % operational carbon.
- For offices, GWP is between 8 and 29 $kgCO_2$-eq/m^2 annually and 411–1143 $kgCO_2$-eq/m^2 for 50 years with 53–90 % operational carbon.

The contribution of renewable energy sources via solar PV systems are considered as avoided operational carbon emissions. The contribution ratio of solar PV systems to whole life cycle carbon emissions were observed as: for SFH is between 5 and 9%, for

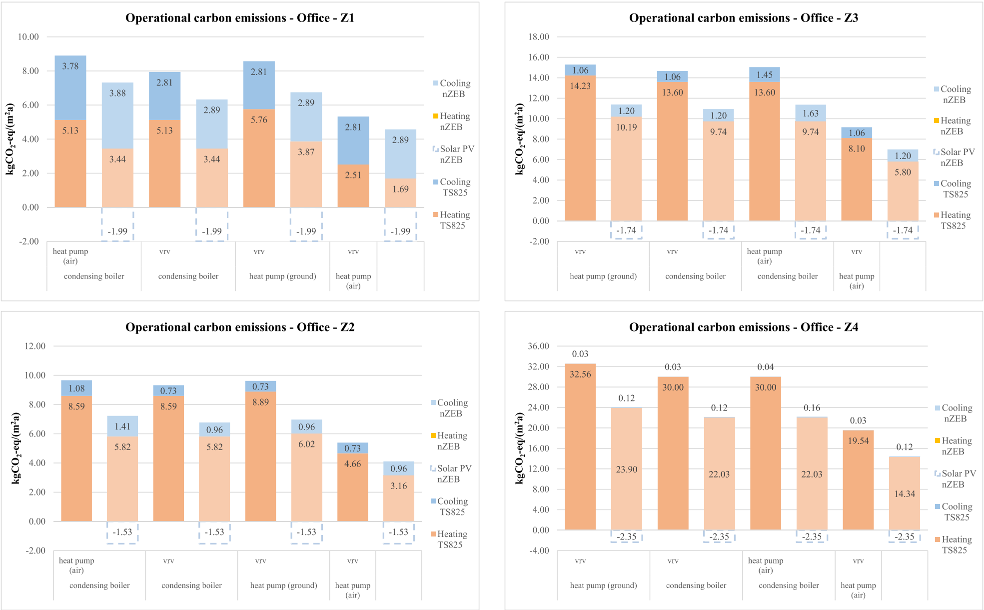

Fig. 11. Operational Carbon Assessment for Office typology.

apartments is between 7 and 12 % and for offices is between 13 and 24 %. This implies that ratio of operational carbon emissions would be lower after reduction of avoided carbon emissions. Even though the ratio of carbon mitigation in nZEBs were relatively high in Z3-Z4, the total amount of carbon emissions remained significant. This condition implies an additional potential for further mitigation in colder regions.

As displayed in Fig. 12, there was a carbon mitigation between 21 and 23 % due to nZEB regulation for SFH. The ratio of embodied carbon can increase up to 27 % of the total carbon emissions. 5–9% of total emissions will be discounted via renewable energy contribution. It was seen that nZEBs in Z1, Z2 and Z3 were levelling towards a normal between 1000 and 1400 kgCO2-eq/m2. On the other hand, nZEB Z4 requires specific attention for two reasons: the ratio of operational carbon emissions is as high as a conventional building and renewable energy contribution is at the minimum level.

As seen in Fig. 13, the total carbon mitigation for apartments was between 21 and 24 % due to nZEB regulation. The ratio of embodied carbon can increase up to 21 % of the total carbon emissions. 9–12 % of total emissions will be discounted via renewable energy contribution. nZEBs in Z1 and Z2 have 710 and 870 $kgCO_2$-eq/m^2 whereas Z3 and Z4 the figures are 1115 and 1250 $kgCO_2$-eq/m^2 after discounting avoided operational carbon emissions.

Finally, in Fig. 14 it is seen that 25–29 % decrease in total carbon emissions was achieved for office buildings. The ratio of embodied carbon can increase up to 47 % of the total carbon emissions. nZEB scenario in Z1 had a higher operational energy demand due to a rebound effect that creates additional cooling demand, but this was compensated by renewable energy contribution. nZEB Z1 and Z2 achieved a total carbon emission of 310 $kgCO_2$-eq/m^2. In Z3 and Z4, the whole life emissions of nZEBs were respectively 455 and 805 $kgCO_2$-eq/m^2 after reduction of avoided operational carbon emissions.

5. Discussion

According to the life cycle carbon results, it was interpreted that further improvement for the building envelope was required and essential for achieving net-zero carbon targets. When the ratio of the embodied and operational assets was concerned, there was still room for additional embodied carbon emissions to significantly decrease the operational emissions. Then, to demonstrate the mitigation potential on the typology that had the highest potential for renewable energy usage, a new scenario for office typology as nZEB+ was prepared. The residential building typologies were not utilized as the heating demand is generally supplied with natural gas. In Table 10, the improvements for the new office building envelope for each climate zone can be seen. The improvement rate of U values depends on the ratio between TS825 and nZEB and U values that are utilized in other countries.

Additionally, the on-site solar PV system was maximized for nZEB + cases. The maximum available space was calculated as one quarter of the roof and a system with 8 kW capacity was implemented. Additional embodied carbon of envelope improvements and solar PV were calculated separately as a significant increase was expected. The operational carbon emissions originating from heating and cooling were reported together. The contribution of solar PV system was categorized as the avoided operational carbon emissions and discounted from the operational carbon emissions. Then, the net operational carbon emissions were displayed. The results of life cycle carbon emissions of the nZEB + scenario with renewable energy contributions can be seen in Fig. 15.

Embodied carbon of building materials and solar PV system are displayed together with net operational carbon emissions when the avoided emissions by renewable energy contribution for 50 years are discounted. As the heating and cooling demand was supplied by electrical systems such as air-to-air heat pump and VRV, significant mitigation of operational carbon emissions between 24 and 88 % was achieved. For nZEB+ in Z1 and Z2, the ratio of operational carbon decreased to 11–20 %. This ratio was 45 % for Z3 and 70 % for

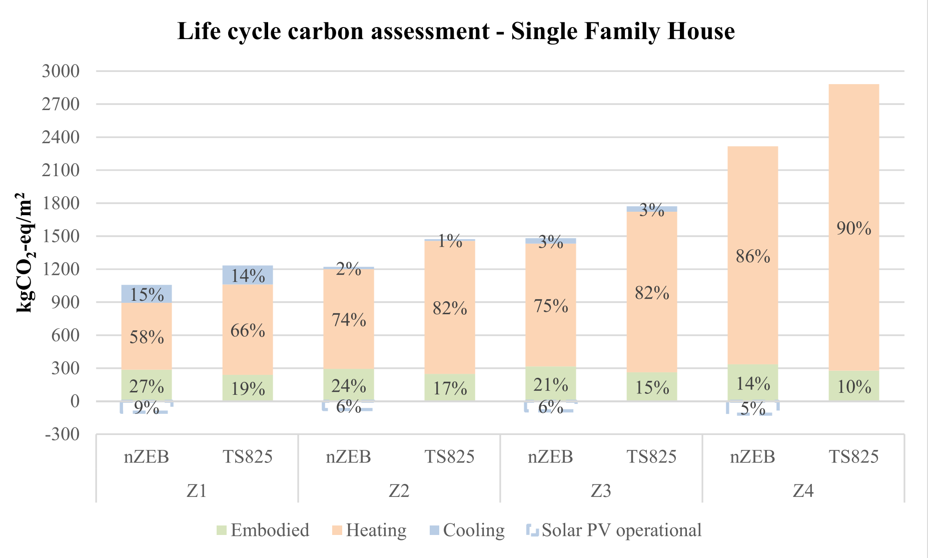

Fig. 12. Life-cycle Carbon Assessment for Single Family House typology.

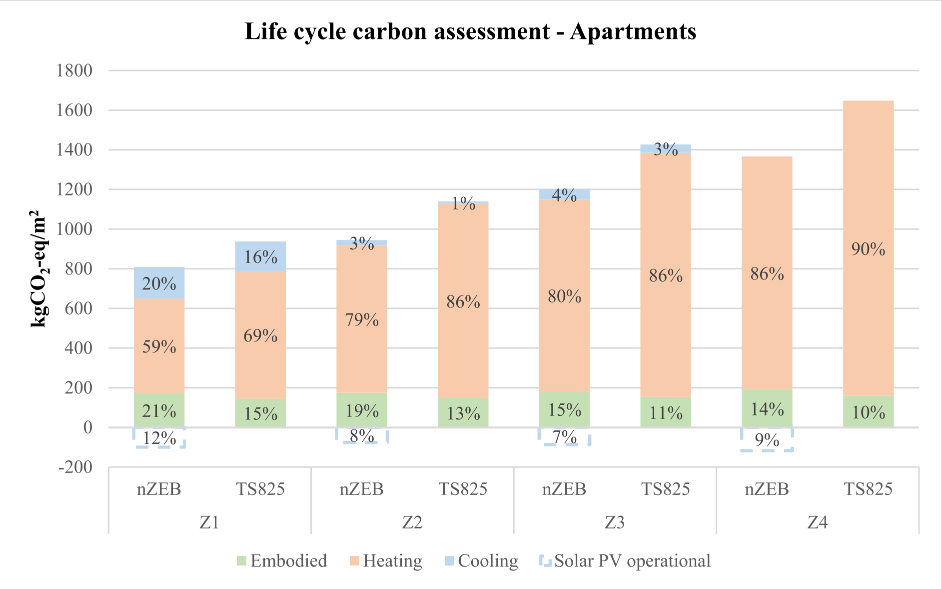

Fig. 13. Life-cycle Carbon Assessment for Apartment typology.

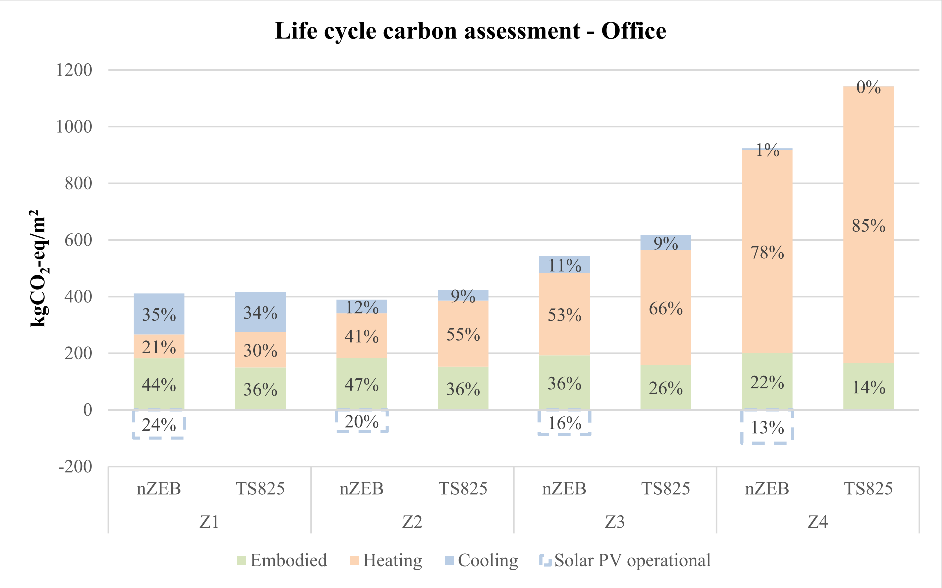

Fig. 14. Life-cycle Carbon Assessment for Office typology.

Table 10
Scenarios for the nZEB + office envelope scenario for climate zones

	Climate zone #	External wall		Structure		Roof		Floor on soil		Window
		U value W/m^{2}K	Thickness m	U value W/m^{2}K	Thickness m	U value W/m^{2}K	Thickness m	U value W/m^{2}K	Thickness m	U value W/m^{2}K
nZEB+	1	0,36	0,07	0,43	0,07	0,26	0,14	0,43	0,07	0,90
	2	0,28	0,10	0,36	0,10	0,24	0,15	0,36	0,08	0,90
	3	0,28	0,10	0,32	0,10	0,19	0,20	0,32	0,10	0,90
	4	0,22	0,13	0,25	0,13	0,16	0,24	0,25	0,13	0,90

Z4. The additional embodied carbon from solar PV system varied between 4 and 14 %. Finally, the range of whole life carbon emissions per climate zone are as follows.

- For Z1 and Z2 GWP per m^2 are around 235–260 $kgCO_2$-eq/m^2 with renewable energy contribution of respectively 45-37 %.
- For Z3, GWP per m^2 is 395 $kgCO_2$-eq/m^2 with renewable energy contribution of 30 %.
- For Z4, GWP per m^2 is 780 $kgCO_2$-eq/m^2 with renewable energy contribution of 18 %.

The calculations on nZEB + cases showed that when compared to nZEB scenarios, up to 25 % whole life carbon mitigation was possible by improving the building envelope and renewable energy contribution by increasing embodied carbon emission by an average of 12 %. At this point, it is important to reiterate the fact that around 80 % of the embodied emissions are realized at the beginning of lifetime (A1-A3 phases) in a shorter period than operational carbon emissions that take place over a period of 50 years. To provide a balance of these two assets, the carbon payback period (t) that represents the time when the avoided carbon emissions equal to the additional embodied carbon emissions by nZEB improvements was calculated according to Formula (5) given below:

$$EC_{nZEB+,nZEB} - EC_{TS825} = \left(OC_{TS825} - OC_{nZEB+,nZEB}\right) * t \tag{5}$$

In Fig. 16, the calculation was applied to nZEB and nZEB + scenarios in Z1. The carbon payback times were 9,5 and 10,5 years. After these break-even points, the additional embodied carbon emissions of nZEB and nZEB+ were compensated, and both scenarios emit less whole life carbon emissions when compared to TS825 baseline scenario. The difference between avoided operational carbon for nZEB and nZEB+ was significant when the whole lifetime is considered. The carbon payback times were shorter in other regions due to higher operational carbon savings: in Z2 8,5 and 10; in Z3 7 and 8,5 and in Z4 4 and 6 years.

It is important to highlight that this study adopted a static LCA method that utilizes fixed carbon conversion factors. This implies that operational carbon savings are constant. The results vary when a dynamic LCA is adopted as the conversion factors would decrease according to the climate-neutrality goals [76]. Van de Morteel et al. [77] conducted a comparison between the two approaches and concluded that the environmental impacts are generally lower in a dynamic LCA. To estimate the conversion factors, the existing energy balance tables for 2020–2023 [78] and energy consumption foresight for 2025, 2030, 2035 and 2050 retrieved from the National Energy Plan [79] are utilized. Then, the years in between are extrapolated (Table 11).

Table 11 displays the evolution of the energy sources used to generate electricity between 2020 and 2050. As a general trend, the contribution of renewable energy sources (solar, wind, geothermal and nuclear) increases from 11,7 % to 61,4 %. The carbon conversion factors are calculated depending on the real electricity generation data and come into effect in the BEP-TR system after two years. There was an increase in the carbon conversion factors in 2023 and 2024 due to a spike in coal consumption because of (i) the droughts that affected the electricity generation by hydro plants and (ii) unexpected energy demand due to the heat waves. Turkey's energy plan foresees that carbon emissions will peak in 2038. It was seen that the conversion factors tend to remain stagnant in the first 10 years until the nuclear power plants are activated. Then the conversion factors gradually decrease until 2050 and the study assumed the trend will continue until 2070.

When such conversion factors were applied to a building lifetime between 2020 and 2070, it was seen that the first 10 years when the majority of the carbon payback occurs are not significantly affected by the change in carbon conversion factors as seen in Fig. 17. There is a significant decrease in carbon emissions in the next 20 years. As a result, the carbon payback periods are delayed by 1 year for nZEB and nZEB + scenarios. Such an effect does not strongly influence decision-making on provided nZEB scenarios which is in line with the study of Van de Morteel [77]. On the other hand, the total amount of carbon savings was calculated as 35 % lower at 150 $kgCO_2$-eq/m^2 for nZEB+ and 85 $kgCO_2$-eq/m^2 for nZEB scenario.

The overall results are in line with several studies prepared in the Turkish context [59] which provided an average of 48 $kgCO_2$-eq/(m^2a) and with the average figures in EU around 30 $kgCO_2$-eq/(m^2a) [15,46,53]. On the other hand, it is shown that there is a significant difference in the results depending on climate zones in Turkiye. Hence, benchmarking for embodied emissions or

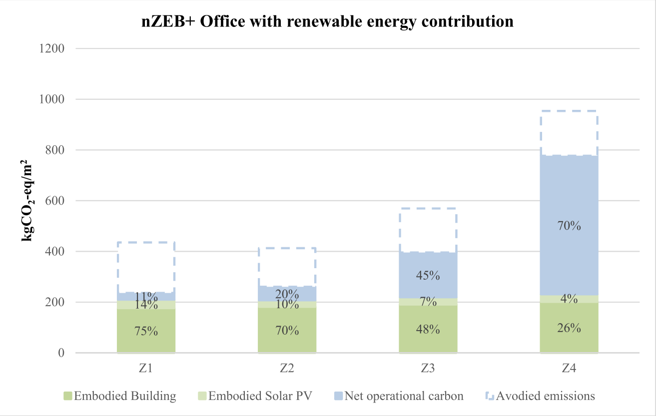

Fig. 15. Life-cycle Carbon Assessment for nZEB + Office with renewable energy contribution.

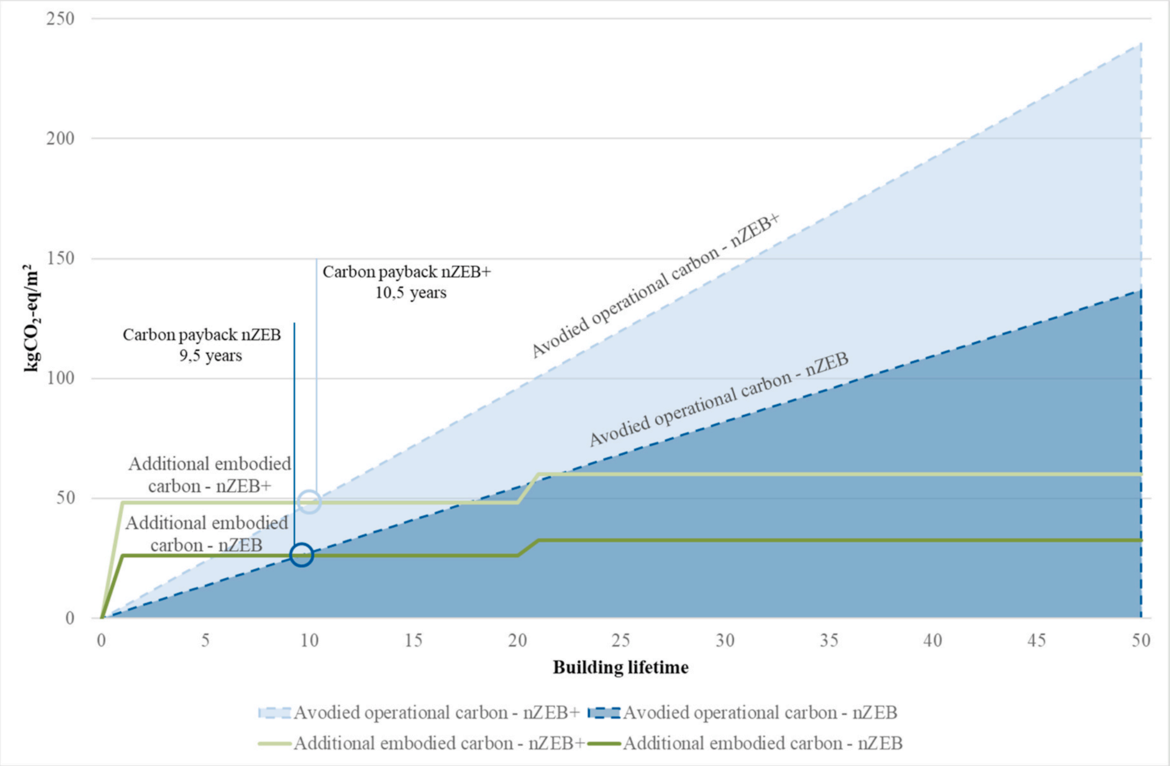

Fig. 16. Carbon payback period for nZEB and nZEB + scenarios for Z1.

Table 11
Resources for electricity generation and conversion factor foresight for Turkiye until 2050

Year	Electricity mix (%)						Conversion ($kgCO_2$-eq/kWh)	Factor in effect
	Solid	Gas	Hydro	Renewable	Other	Total		
2020	34,5	23,0	25,5	11,7	5,3	100,0	0,484	2022
2021	34,4	22,9	24,6	13,1	5,1	100,0	0,648	2023
2022	34,6	22,9	20,3	19,1	3,1	100,0	0,689	2024
2023	34,2	22,7	22,9	15,5	4,7	100,0	0,701	2025
2024	34,1	22,6	22,2	16,5	4,5	100,0	0,697	2026
2025	31,1	20,6	21,5	22,4	4,4	100,0	0,638	2027
2030	26,7	17,7	19,4	31,6	4,5	100,0	0,558	2032
2035	20,6	13,6	17,3	45,3	3,2	100,0	0,426	2037
2040	19,5	12,9	14,9	50,7	2,1	100,0	0,392	2042
2045	18,1	12,0	12,4	56,0	1,4	100,0	0,358	2047
2050	16,7	11,0	10,0	61,4	0,9	100,0	0,325	2052

operational carbon must include several reference values instead of a single target. This is also the reason why the results of this study may be useful for a variety of similar neighbouring regions. In Table 12, the results for nZEB+ in Z1 and in Z4 are compared with the results from MENA region and Eastern Europe, Poland [50].

It was seen that U-values were significantly similar, especially those of nZEB + Z4 and the reference study conducted by Rucinska et al. [50]. On the other hand, the number of degree days in Turkiye Z4 was higher than in Poland whereas the carbon intensity of the Polish electricity grid mix (0,936 $kgCO_2$-eq/kWh) was significantly higher than that of Turkiye (0,648 $kgCO_2$-eq/kWh). Hence, the difference between the operational carbon emissions originated from these factors together with the fact that renewable energy systems were not calculated in the Polish case study. It could be foreseen that the ratio of operational carbon emissions could be decreased to 70 %.

There are certain limitations to the study. The main obstacle was the lack of local environmental data. Specifically, the embodied carbon emission figures for solar PV panels were derived from studies in EU. Also, the end-of-life scenarios in Turkiye are not well developed, hence the emissions in Module C may be considered as low-quality data. The carbon emission factors were considered constant and then a possible scenario with lower carbon emission factors due to electricity mix decarbonization was provided. On the other hand, the decrease in emission factors depends on general forecasts. For developing countries, high fluctuations can be expected

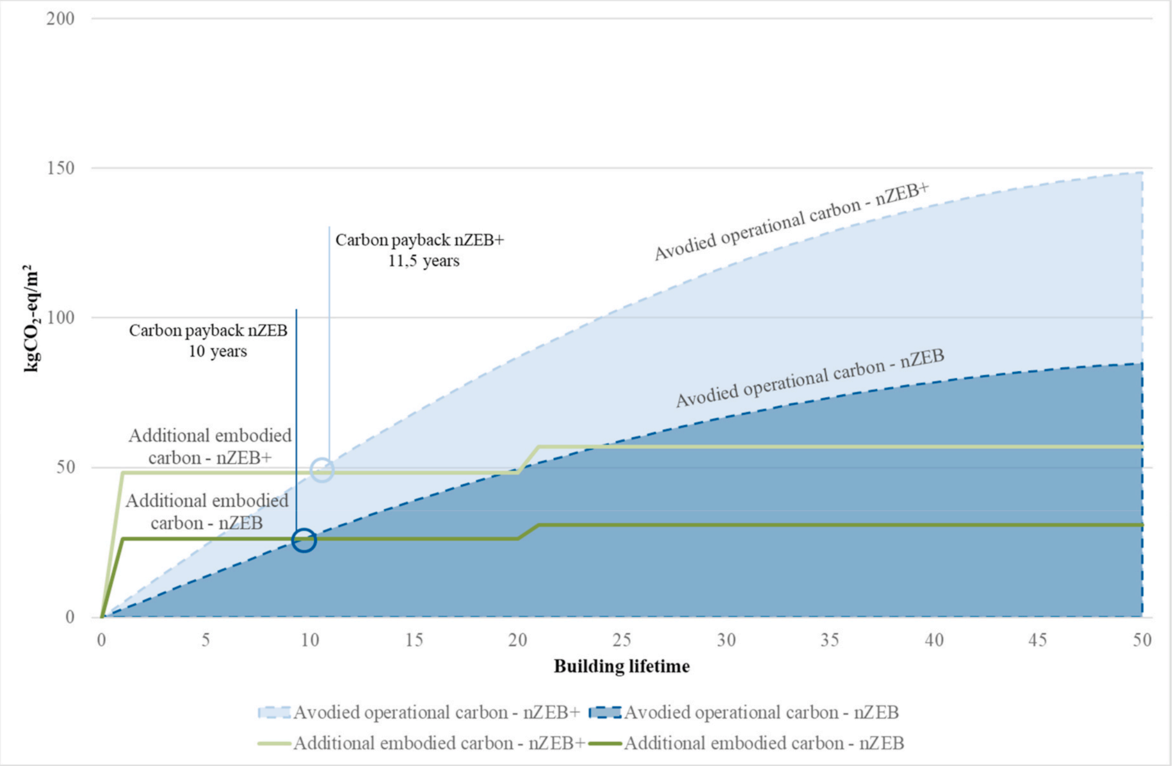

Fig. 17. Carbon payback period for nZEB and nZEB + scenarios for Z1 in dynamic LCA.

Table 12
Comparison of the nZEB + office scenarios with similar climate zones

	Wall	Structure	Roof	Floor	Window	HDD-CDD	Embodied Carbon	Operational Carbon
	U value W/m^{2}K	U value W/m^{2}K	U value W/m^{2}K	U value W/m^{2}K	U value W/m^{2}K	Degree days	kgCO$_2$-eq/m^2 (%)	kgCO$_2$-eq/m^2 (%)
nZEB + Z1	0,36	0,43	0,26	0,43	0,90	948–693	176 (75 %)	58 (25 %)
Egypt [34,80]	0,17	NA	0,11	NA	NA	400–1600	346 (15 %)	NA
nZEB + Z4	0,22	0,25	0,16	0,25	0,90	4444–13	231 (30 %)	546 (70 %)
Poland [50]	0,23	NA	0,18	0,25	1,1	3700–45	420 (20 %)	1670 (80 %)

due to infrastructural problems or external factors such as drought, climate change, etc. Dynamic LCA studies may be conducted with more precision and may result significantly differently in developed countries. Nevertheless, the study achieved to provide a local perspective for embodied carbon of building materials (Annex A) when compared to previous studies that depended on global databases.

Regarding the scope of the study, the embodied carbon assessment only considered significant building components (structure, envelope, technical systems) that have an impact on the thermal performance. The interior finishes and walls were not included. The method is based on optimization between embodied and operational carbon of representative buildings where the operational carbon emissions are based on simulation results without a possibility of comparing with actual consumption values. During operational carbon simulations, only heating and cooling demands were considered to provide consistency with U-value parameters of building envelope scenarios.

6. Conclusions

This study presents an evaluation of the current and future nZEB descriptions from a life-cycle perspective. The balance between embodied and operational carbon may guide the construction industry on how to further mitigate carbon emissions through the building lifetime. The method was conducted on residential and office buildings and is considered a complementary process for the existing building energy performance standards. While building envelope and technical system decisions are of paramount importance for ‘building energy performance’ in the current scope within EPCs, the same decisions also form the basis of the life cycle inventory for the embodied carbon assessment. The overlapping data collection processes for operational and embodied carbon assessment are significant and yet, up to 50 % of carbon emissions are omitted when the whole carbon assessment is not adopted by building energy performance standards.

Together with previous studies that are reviewed while conducting this study, the method and results may provide valuable data for benchmarking embodied and operational carbon emissions in Turkiye, EU and in MENA regions. Currently, the IPCC climate change goals [81] foresee a carbon emission peak between 2030 and 2035 and then recommend a dramatic decrease afterwards to reach carbon neutrality by 2050. This study provided supportive evidence for necessity to improve the nZEB regulations while considering additional embodied impacts. More ambitious nZEB targets can be achieved by improving building envelope in the following decade so that the avoided operational carbon emissions after 2035 would be maximized.

The results in mild climates were promising for achieving carbon neutrality as the embodied carbon emissions can be further decreased by using low-carbon materials such as bio-based or re-using demountable components. In case the initial whole life carbon emissions could be decreased, then the concept of carbon positive buildings would be an additional contribution to IPCC targets. For the colder climates, resilient buildings and components with longer lifetime could be feasible as higher amounts of insulation and increased renewable energy capacities are required. To extend the building lifetime, further studies on the use phase of building components and structures are necessary with a focus on low carbon maintenance and repair or reuse.

The conclusions of this study are briefly displayed below.

- Current nZEB regulations increase the embodied carbon by an average of 15 % and decrease operational carbon by 30 %.
- An improved nZEB regulations increase embodied carbon 20 % and decrease operational carbon by 30–80 % which results in 32–43 % decrease in the whole life carbon emissions.
- There is a significant variety for nZEBs in Turkiye between 5 and 46 $kgCO_2$-eq/(m^2a) when different typologies and climate zones are considered.
- Improving the required contribution of renewable energy is crucial for the transition to high performance technical systems in office and residential buildings.
- Future improvements in the carbon emission factors should be considered for long-term decision-making in carbon investments.

The results are also important in EU and MENA context to understand how neighbouring geographies are progressing towards the carbon neutral targets. The embodied carbon of building components is specifically linked to the influence of the EU Green Deal and the forthcoming carbon trading system. Further studies are required for other typologies such as educational and health-care buildings, hotels and mixed-used buildings to provide a complete benchmarking for the building stock at a national level. The lack of data on embodied carbon of technical systems implies a future research topic on this front. For all suggested research topics, real-life case studies will be crucial to increase the precision of the data and validate the results.

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CRediT authorship contribution statement

N. Cihan Kayaçetin: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Conceptualization. **Burak Hozatlı:** Writing – review & editing, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Environmental data

Table A1
EPD information for building materials

Building component	Material	Company	EPD id/Reference
Roof Cladding	Ceramic tile	Onduline	EPD-OND-20160087
Roof Heat Insulation	Rockwool	Ravaber	S–P-01673
Brick Wall 25 cm	Aerated concrete block	Ytong	S–P-01804
External Heat Insulation	EPS	ODE	S–P-04116
Exterior Paint	Silicone	Polisan	S–P-00741

(*continued on next page*)

Table A1 (*continued*)

Building component	Material	Company	EPD id/Reference
Exterior Plastering	Gypsum	Gips	S–P-03126
Window Profile	PVC	ASAŞ	S–P-04797
Window Glass	Laminated glass	Şişecam	S–P-04818
Concrete	Ready mixed concrete	İston	S–P-04806
Steel Reinforcement	Rebar mill	Tosyalı	S–P-04809
Foundation Heat Insulation	XPS	ODE	S–P-03943
Technical systems	Solar PV	Generic	[24,71]

Appendix B. Operational Carbon Assessment

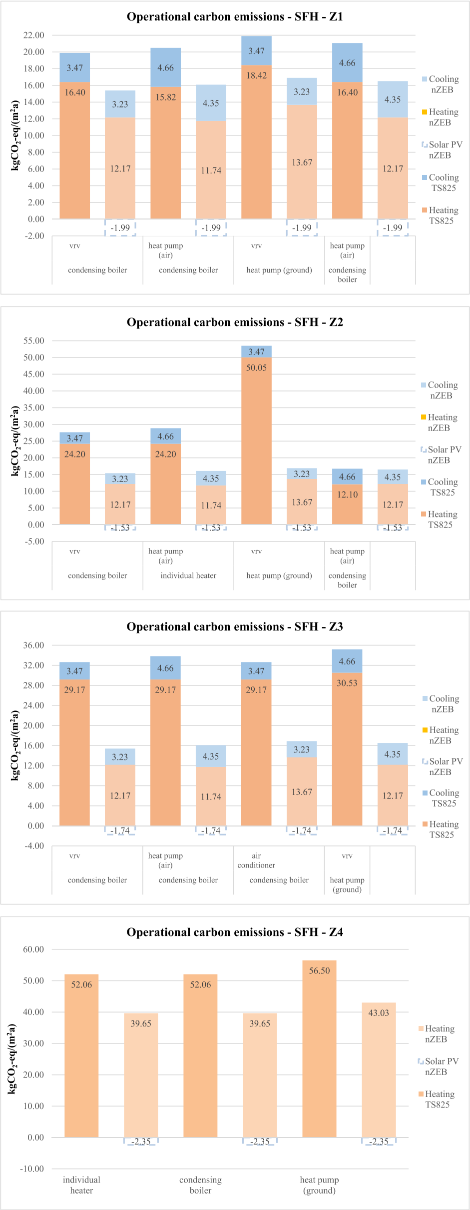

Fig. B1. Operational Carbon Assessment for Single Family house typology.

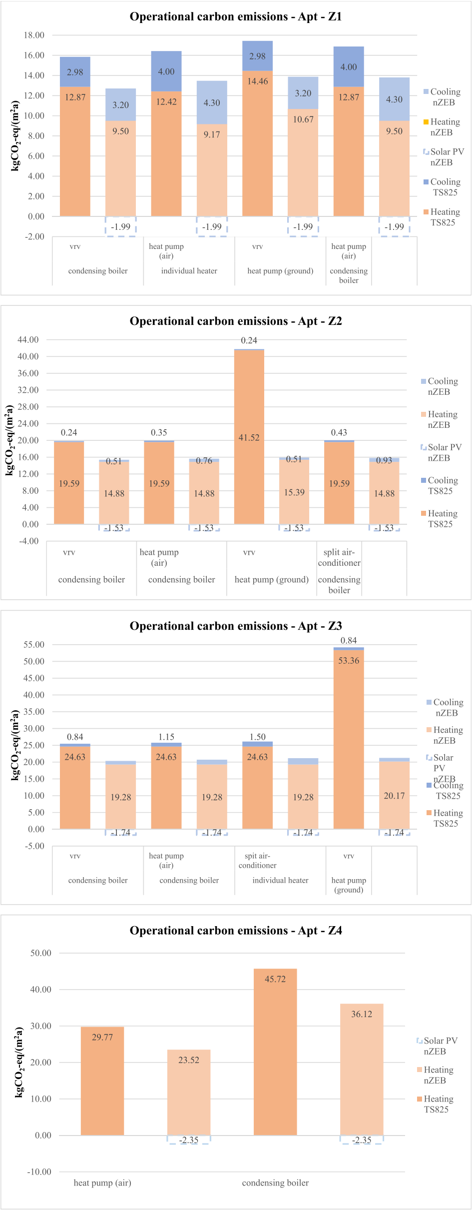

Fig. B2. Operational Carbon Assessment for Apartment typology.

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