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Research Article

Balancing seismic safety and sustainability: Comparative assessment of TEC and EC8 for RC frames

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Abstract

This study compares the minimum requirements of the Turkish Earthquake Codes (TEC 2007 and TEC 2018) and Eurocode 8 (EC8) for reinforced concrete (RC) frames, integrating seismic safety with material efficiency, cost, and environmental sustainability, specifically focusing on embodied energy (EE) and embodied carbon (EC). The analysis encompasses 4-, 7-, and 10-story RC frames with 6m bays and 3.5m story heights. The results indicate that both material usage and construction costs increase proportionally with an increase in building height for each seismic code. EC8 requires more concrete than TEC, while TEC requires more steel than EC8 for all buildings under consideration. Additionally, EC8 presents a more sustainable alternative compared to the Turkish codes. Notably, while EC8 requires up to 14% more concrete, it requires 27% less steel than TEC 2018, leading to a reduction in overall EE (by 9-11%) and EC (by 3-5%) per floor area. The findings highlight trade-offs between enhanced safety provisions and sustainability, providing recommendations for code harmonization that aim to optimize resource utilization in seismically active regions.

1. Introduction

Over the years, the devastating impacts of earthquake-induced disasters globally have highlighted the urgent need for robust RC seismic building codes. These codes ensure the safety and resilience of RC structures in high-risk regions. Located between the Eurasian and African tectonic plates, Turkey faces significant seismic vulnerability, as evidenced by a series of recent devastating earthquakes [1–4]. In response, advancements in technology and seismic research have led to the evolution of the TEC. The TEC 2018 [5] introduced performance-based design and updated seismic hazard maps after substantial revisions. It built upon TEC 2007 [6], which relied on zone-specific seismic forces with limited emphasis on deformation limits [7–9]. Eurocode 8 (EC8) [10], popularly used in Europe, employs a performance-based approach offering flexibility through ductility classes (Ductility Class Medium - DCM; Ductility Class High - DCH) to optimize material usage while ensuring safety.

Despite these advancements, variations in code provisions impact material quantities, construction costs, and environmental sustainability. This is evident in embodied energy (EE), the total energy consumed in the extraction, processing, manufacturing, and delivery of materials, and embodied carbon (EC), the associated greenhouse gas emissions [11–13]. Previous studies either focused only on comparisons of different building codes or assessed building EE and EC contributions. For instance, Doğangün and Livaoğlu [14] compared the EC8, International Building Code (IBC), Uniform Building Code (UBC), and TEC for spectral design. Kocer et al. [8] compared TEC 2018 and TEC 2007 by evaluating the Equivalent Earthquake Load analysis on two buildings having 3 and 9 floors. Aksoylu et al. [9] and Işık [15] compared the structural performance of ASCE 7, TEC-2007,

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and TEC-2018 across different RC buildings. Mergos [16] proposed designing RC frames with rocking footings that resulted in a 40% carbon footprint reduction compared to frames with conventional footings. Aljawhari et al. [17] investigated the influence of RC jacketing on a non-ductile RC frame and concluded that the retrofitting strategy could reduce about 40% of life-cycle EC compared to the as-built frame. Atmaca and Atmaca [11,18] assessed life-cycle energy in Turkish buildings, and Chen et al. [19] quantified EE/EC for Chinese materials. However, studies that systematically compare seismic code requirements by linking structural safety with embodied energy and carbon footprint are scarce. With the growing demand for housing and infrastructure, this gap is critical because of the expected rise in CO_2 emissions from concrete and steel production [20–23].

This study contributes to the existing body of knowledge by comparing the minimum requirements of TEC 2007, TEC 2018, and EC8 for low- to mid-rise RC frames (4-, 7-, and 10- stories). It quantifies material usage, construction costs based on local unit prices from the Turkish Republic of Northern Cyprus (TRNC), and EE/EC dependent on provisions from the Inventory of Carbon and Energy (ICE) database to illuminate trade-offs between seismic safety and sustainability. By integrating structural and environmental assessments, this research provides valuable insights for refining seismic building codes, incorporating recent advancements in sustainable seismic design [24–26].

2. Methodology

Based on the scope of the study, with a focus on the minimum code provisions, Figure 1 illustrates the adopted workflow. Three RC frame typologies (4-, 7-, and 10-story) with 6 m bays in both directions and 3.5 m story heights were selected (Figure 2). These configurations are representative of typical low- to mid-rise structures found in Turkey's seismic-prone urban areas [2]. This selection is justified by their widespread occurrence and compliance with relevant building codes for regular structures.

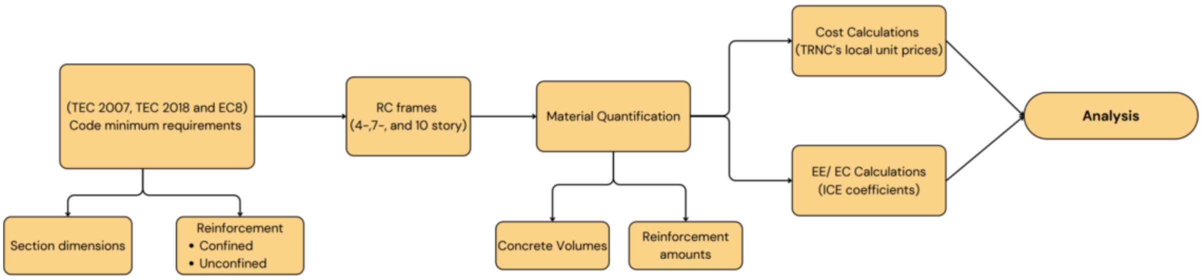


Fig. 1. Outline of the proposed methodology

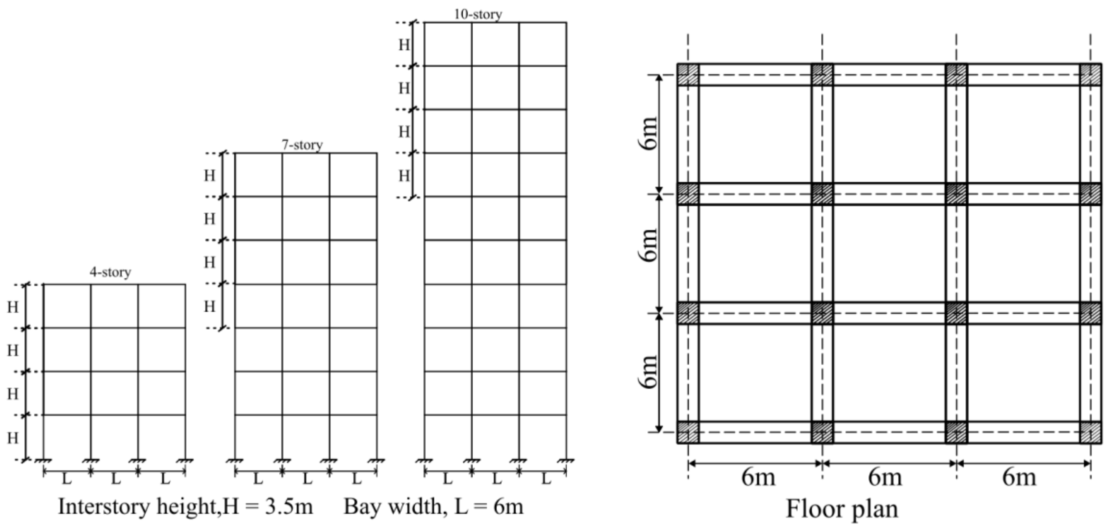


Fig. 2. RC frame and floor layout

Beams, columns, and slabs were assumed to be constant throughout the building height. Structural irregularities and soil-structure interactions were excluded to facilitate baseline comparisons. Material properties were standardized as C40 concrete (40 MPa compressive strength) and S420 steel (420 MPa yield strength) for all RC frames. Minimum provisions for dimensions (Table 1) and reinforcement (Tables 2- 3, and Figures 3-4) were extracted from TEC 2007, TEC 2018, and EC8.

Table 1. Dimension requirements

Element	Parameters	TEC 2007	TEC 2018	EC8
COLUMNS	Width (mm)	250	300	250
	Area (mm^2)	75,000	100,000	
BEAMS	Width (mm)	250	250	200
	Height (mm)	300	300	700

Table 2. TEC 2007 and TEC 2018 minimum reinforcement requirements

TEC 2007 & TEC 2018			
Parameters		COLUMNS	BEAMS
Reinforcement ratio (ρ)		0.01	$0.8\ f_{ctd}/f_{yd}$
Longitudinal bars, (mm)		4Ø16 or 6Ø14	4Ø12
Transverse bars, (mm)		Ø8	Ø8
Transverse reinforcement	Confinement Zone	≥ (bmax, ln/6, 500mm)	$2h_k$
Spacing of transverse reinforcement	Confinement Zone	(≥50mm, ≤100mm ≤bmin/3)	≤ ($h_k/4$, 8Ø, 150mm)
	Unconfined Zone	≤ (200mm, bmin/2)	≤ $h_k/2$

Table 3. EC8 minimum reinforcement requirements

EUROCODE, EC8					
Parameters		MEDIUM DUCTILITY (DCM)		HIGH DUCTILITY (DCH)	
		COLUMNS	BEAMS	COLUMNS	BEAMS
Reinforcement Ratio (ρ)		0.01	$0.5\ f_{ctm}/f_{yk}$	0.01	$0.5\ f_{ctm}/f_{yk}$
Longitudinal bars, (mm)		6Ø8	4Ø14	6Ø8	4Ø14
Stirrups, d_{bw} (mm)		Ø6			
Transverse reinforcement	Confinement Zone	max{h_c; $l_{cl}/6$; 450mm}	h_w	max{$1.5h_c$; $l_{cl}/6$; 600mm}	$1.5h_w$
Spacing of transverse reinforcement	Confinement Zone	<{$b_0/2$; $8d_{bl}$; 175mm}	< min{$h_w/4$; $24d_{bw}$; $8d_{bl}$; 225mm}	<{$b_0/3$; $6d_{bl}$; 125mm}	< min{$h_w/4$; $24d_{bw}$; $6d_{bl}$; 175mm}
	Unconfined Zone	<{h_c; $20d_{bl}$; 400mm}	0.75d	<{h_c; $20d_{bl}$; 400mm}	0.75d

Where; d_{bw} is the stirrup diameter, h_w is beam height, $d_{bl}=\min Ø_L$, d is effective depth of beam; l_{cl} is the clear span length; h_c is the maximum column dimension. Based on the minimum code provisions, the parameters for this study are summarized in Table 4. Structural modelling was conducted using SAP2000 software [27] to verify compliance with minimum code requirements.

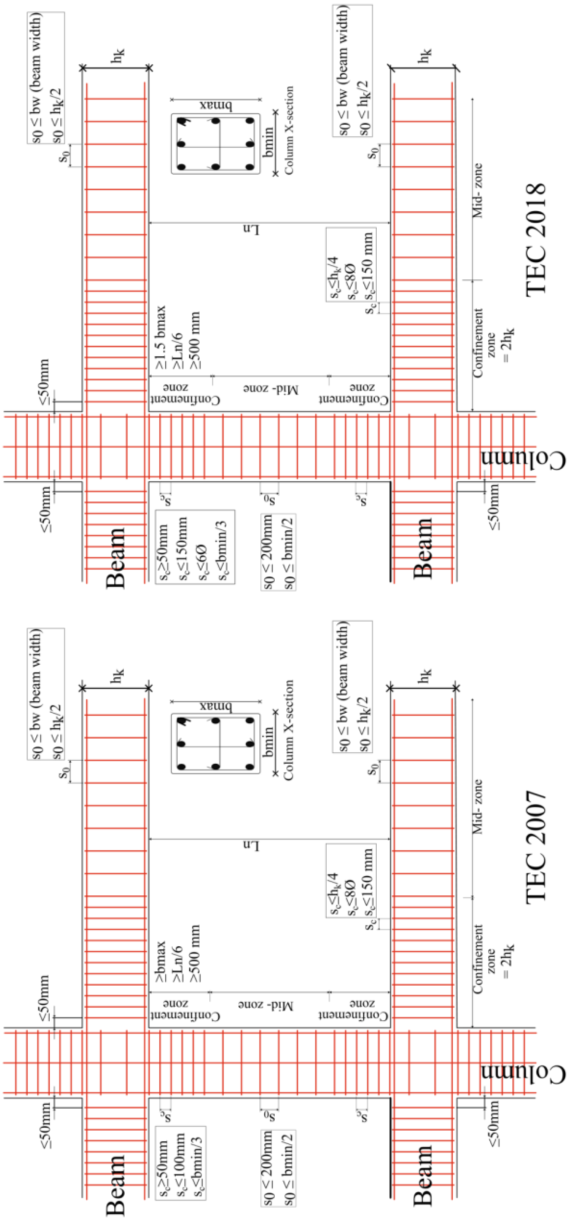


Fig. 3. Turkish building reinforcement considerations for TEC 2007 and TEC 2018

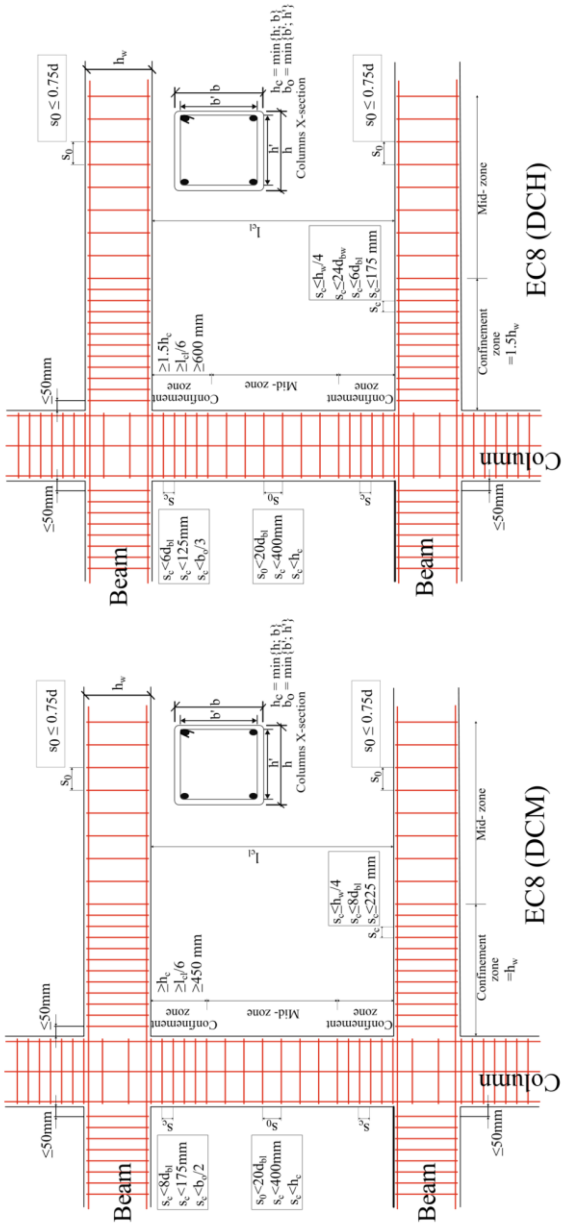


Fig. 4EC8 building reinforcement considerations EC8 (DCM) and EC8 (DCH)

Table 1. Design parameters based on code provisions

Parameters		TEC 2007	TEC 2018	EC8 (DCM)	EC8 (DCH)
Column dimensions (mm)		250 X 300	300 X 300	250 X 250	250 X 250
Beam dimensions (mm)		250 X 300	250 X 300	200 X 700	200 X 700
Slab thickness (mm)		120			
COLUMNS	Longitudinal Reinforcement	6Ø14	6Ø14	6Ø8	6Ø8
	Transverse Reinforcement	Ø8	Ø8	Ø6	Ø8
BEAMS	Longitudinal Reinforcement	4Ø12	4Ø12	4Ø14	4Ø14
	Transverse Reinforcement	Ø8	Ø8	Ø6	Ø6

The models shown in Fig. 5 were used to cross-check the manually calculated building weights, with discrepancies of less than 8%, 5%, and 6% for 4-, 7-, and 10-story buildings, respectively. Comprehensive dynamic analyses, such as response spectrum or time history, were not performed because the study focuses on comparing minimum concrete and steel requirements. Additionally, the unavailability of parameters, such as earthquake data and site location, makes performing these analyses cumbersome.

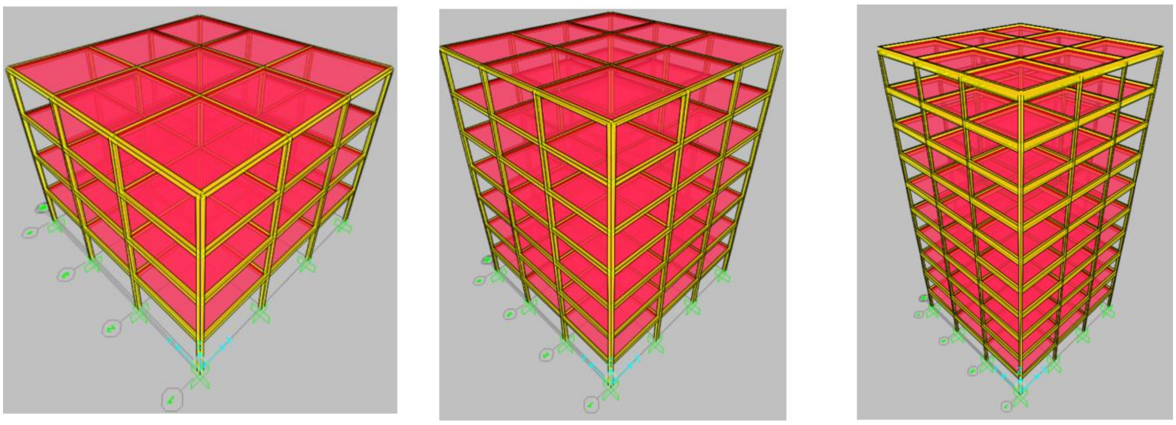


Fig. 5. SAP2000 RC frame models

2.1 Analysis Approach

To compare TEC 2007, TEC 2018, and EC8, this study considers material quantities (concrete and steel), cost estimates, and environmental impact assessments (EE and EC) as metrics to define the performance and impact of seismic design.

2.1.1 Material Quantities

Based on the design parameters taken for each code, concrete volumes are calculated for the structural elements (columns, beams, and slabs), based on each code's dimensional requirements. Concrete volumes for the RC structural elements per story were calculated as shown in Table 5, while Table 6 shows steel reinforcement based on confined and unconfined spacing.

Table 5. Concrete volume for each story and building roof

CODES	Column				Beam				Slab			Story Concrete (m³)	Roof Concrete (m³)
	A_c (mm²)	b_c (mm)	l_c (mm)	No.	b_w (mm)	h_k (mm)	l_b (mm)	No.	t (mm)	A (mm²)	No.		
TEC 2007	75000	250	3500	16	250	300	5750	24	120	3.31E+07	9	50.2575	39.968
TEC 2018	100000	300	3500	16	250	300	5750	24	120	3.31E+07	9	51.6575	39.968
EC8	62500	250	3500	16	200	700	5800	24	120	3.36E+07	9	59.3192	39.968

Table 6. Steel reinforcement for structural elements as per each code

CODE	Clear span (mm)		Column transverse reinforcement				Beam transverse reinforcement				No. of bars				Slab reinforcement	
			Confinement zone		Unconfined zone		Confinement zone		Unconfined zone		Transverse		longitudinal			
	Column	Beam	Dist.* (mm)	Spc.* (mm)	Dist. (mm)	Spc. (mm)	Dist. (mm)	Spc. (mm)	Dist. (mm)	Spc. (mm)	Column	Beam	Column	Beam	Spc. (mm)	No. of bars
TEC 2007	3200	5750	533	50	2133	125	600	75	4550	150	38	46	6	4	180	64
TEC 2018	3200	5700	533	50	2133	150	600	75	4500	150	36	46	6	4	180	64
EC8 (DCM)	3300	5750	550	64	2200	160	200	50	5350	150	31	44	6	4	360	32
EC8 (DCH)	3300	5750	600	48	2100	160	300	50	5150	150	38	46	6	4	360	32

*Distance: Dist., Spacing: Spc.

2.1.2 Cost Analysis

Using the material quantities determined, RC frames' costs were computed using the local unit prices for concrete and reinforcing steel from TRNC, shown in Table 7.

Table 7. Materials market cost prices as of December 2024

Unit	Material	Unit price ($/unit)
m^3	Concrete (C40/50)	120.00
tonnes	Steel Reinforcement	710.00

2.1.3 Environmental Impact

Over the years, RC frame construction has significantly contributed to the impact of global warming [28]. The environmental impact of building construction, driven by the substantial EE and EC associated with construction materials and practices, is a critical concern. According to [29], EE and EC related to building construction account for over 40% of the energy consumed and 30% of greenhouse gas emissions. This underscores the need to consider low carbon footprint materials and the integration of renewable energy for manufacturing to offset these values [19,30].

EE refers to the total energy consumed in the life cycle of building materials (extraction, processing, manufacturing, and delivery), while EC represents the associated greenhouse gas emissions throughout these processes [13,31,32]. For this study, the EE and EC coefficients for concrete and steel were taken from the Inventory of Carbon and Energy (ICE) database [33], as shown in Table 8.

Table 8. Embodied Energy (EE) and Carbon (EC) coefficients

Embodied Energy and Carbon coefficients					
Production	Materials	Unit	EE (MJ / unit)	EC ($kgCO_2$ / unit)	Reference
	Concrete (C40/50)	kg	1.00	0.15	ICE V 2.0
	Steel	kg	35.40	2.89	

Using these coefficients, the construction EE and EC estimates will be determined using simple multiplication formulas shown in equations (1) and (2), respectively.

$$EE = \sum(Material\ Quantities * EE_{Coeff}) \tag{1}$$

$$EC = \sum(Material\ Quantities * EC_{Coeff}) \tag{2}$$

3. Results

The performance of the different codes in terms of material efficiency, cost-effectiveness, and environmental impact was assessed.

3.1 Material Efficiency

The concrete volumes for each RC frame, as shown in Table 9, were determined based on the already determined concrete volume per story. The variation of concrete volumes for the different building stories indicates that EC8 requires the highest concrete volume, followed by TEC 2018, which slightly exceeds that of TEC 2007, as shown in Figure 6.

Concrete volumes increase proportionally with the number of stories, as illustrated in Figure 6. This trend is due to the minimum requirement approach, assuming uniform cross-sections across building heights, for ease of computation. However, in actual practice, nonlinear shear and moment demands may require larger lower-story elements. For 10-story frames, EC8 requires approximately 17% and 14% more concrete than TEC 2007 and TEC 2018, respectively. This is due to stricter dimensional requirements. It is important to note that the increase in concrete volume in turn reduces material efficiency by increasing the concrete carbon footprint.

Table 9. RC frame concrete volumes

CODES	Stories	Total storey concrete (m³)	Roof Concrete (m³)	Total Concrete (m³)
TEC 2007	4	150.773	39.968	190.74
	7	301.545	39.968	341.51
	10	452.318	39.968	492.29
TEC 2018	4	154.973	39.968	194.94
	7	309.945	39.968	349.91
	10	464.918	39.968	504.89
EC8	4	177.958	39.968	217.93
	7	355.915	39.968	395.88
	10	533.873	39.968	573.84

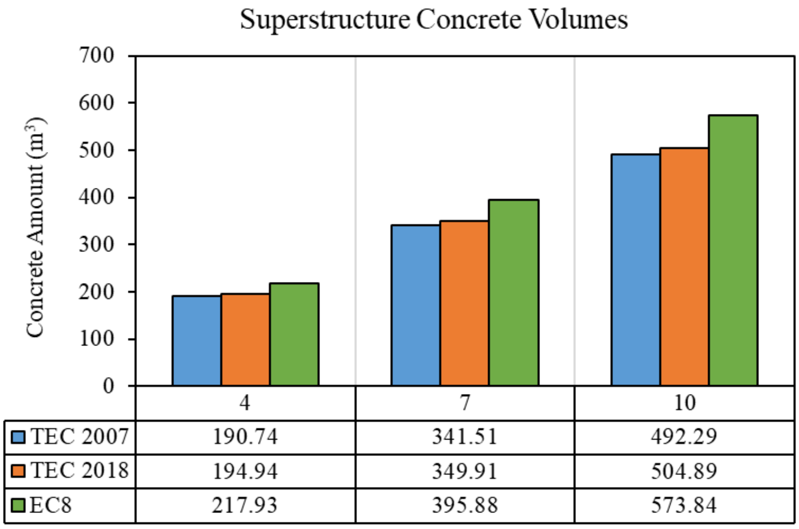


Fig. 6. Variation of concrete volumes per code for the different RC frames

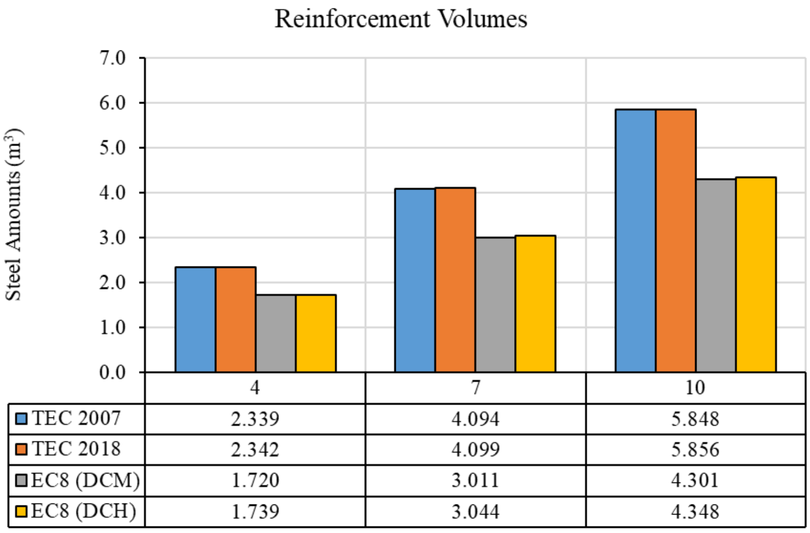


Fig. 7. Steel volumes for respective building stories

Table 10. RC frame reinforcement assignments

CODES	Stories	columns	Beams	Slabs	Longitudinal bars		Transverse bars		Slab bars
					Columns	Beams	Columns	Beams	
TEC 2007	4	64	96	36	384 Ø14	384 Ø12	2458 Ø8	4416 Ø8	2300 Ø12
	7	112	168	63	672 Ø14	672 Ø12	4301 Ø8	7728 Ø8	4025 Ø12
	10	160	240	90	960 Ø14	960 Ø12	6144 Ø8	11040 Ø8	5750 Ø12
TEC 2018	4	64	96	36	384 Ø14	384 Ø12	2276 Ø8	4416 Ø8	2300 Ø12
	7	112	168	63	672 Ø14	672 Ø12	3982 Ø8	7728 Ø8	4025 Ø12
	10	160	240	90	960 Ø14	960 Ø12	5689 Ø8	11040 Ø8	5750 Ø12
EC8 (DCM)	4	64	96	36	384 Ø8	384 Ø14	1980 Ø6	4224 Ø6	1150 Ø14
	7	112	168	63	672 Ø8	672 Ø14	3465 Ø6	7392 Ø6	2013 Ø14
	10	160	240	90	960 Ø8	960 Ø14	4950 Ø6	10560 Ø6	2875 Ø14
EC8 (DCH)	4	64	96	36	384 Ø8	384 Ø14	2440 Ø6	4416 Ø6	1150 Ø14
	7	112	168	63	672 Ø8	672 Ø14	4270 Ø6	7728 Ø6	2013 Ø14
	10	160	240	90	960 Ø8	960 Ø14	6100 Ø6	11040 Ø6	2875 Ø14

Table 11. RC frame reinforcement volumes

Steel Reinforcement Volume					
CODES	Stories	Columns (m^3)	Beams (m^3)	Slabs (m^3)	Total (m^3)
TEC 2007	4	0.318	0.460	1.561	2.339
	7	0.557	0.806	2.731	4.094
	10	0.795	1.151	3.902	5.848
TEC 2018	4	0.321	0.460	1.561	2.342
	7	0.562	0.806	2.731	4.099
	10	0.803	1.151	3.902	5.856
EC8 (DCM)	4	0.112	0.546	1.062	1.720
	7	0.197	0.955	1.859	3.011
	10	0.281	1.364	2.655	4.301
EC8 (DCH)	4	0.123	0.554	1.062	1.739
	7	0.215	0.970	1.859	3.044
	10	0.307	1.386	2.655	4.348

Table 12. RC frame steel and concrete quantities

Material Quantities					
CODES	Stories	Concrete		Steel Reinforcement	
		Volume (m^3)	Mass (tonnes)	Volume (m^3)	Mass (tonnes)
TEC 2007	4	190.74	457.78	2.3392	18.36
	7	341.513	819.63	4.0936	32.13
	10	492.285	1181.48	5.8479	45.91
TEC 2018	4	194.94	467.86	2.3424	18.39
	7	349.9125	839.79	4.0991	32.18
	10	504.885	1211.72	5.8559	45.97
	7	395.883	950.12	3.0109	23.64
	10	573.840	1377.22	4.3007	33.76
EC8 (DCH)	4	217.925	523.02	1.7394	13.65
	7	395.883	950.12	3.0444	23.90
	10	573.840	1377.22	4.3484	34.14

The reinforcement amounts for each building story were broken down as shown in Table 10, from which the reinforcement volumes based on the structural elements were determined in Table 11. Turkish seismic codes require higher reinforcement than their Eurocode counterpart, with TEC

2018 requiring slightly more than TEC 2007. Steel reinforcement (Tables 10-12) shows that TEC 2018 demands 27% more than EC8, while TEC 2007 demands 26%. These differences stem from TEC's conservative reinforcement standards aimed at enhancing ductility, as shown in Figure 7.

Material efficiency is a crucial factor in structural design, impacting both cost and environmental sustainability. The quantities of concrete and steel reinforcement required for buildings of different heights under each seismic code, as summarized in Table 12, are a key consideration in investigating both the cost and environmental impact.

3.2 Building Costs

Using the TRNC market prices, the variations in RC frame costs for the different seismic codes were determined as shown in Table 13. There are minimal variations in the building costs per square meter for the different seismic codes, as shown in Figure 8, despite TEC 2018 having slightly higher values than the other codes.

Table 13. Breakdown of RC frame costs based on material quantities

Cost calculation								
CODES	Stories	Total area (m^2)	Concrete		Steel		Total Cost ($)	Total Cost ($/m^2)
			Volume (m3)	Cost ($)	Amount (tonnes)	Cost ($)		
TEC 2007	4	1332.24	190.74	22888.80	18.363	13037.45	35,926.25	27.0
	7	2331.42	341.51	40981.50	32.134	22815.40	63,796.90	27.4
	10	3330.6	492.29	59074.20	45.906	32593.36	91,667.56	27.5
TEC 2018	4	1332.24	194.94	23392.80	18.388	13,055.32	36,448.12	27.4
	7	2331.42	349.91	41989.50	32.178	22,846.53	64,836.03	27.8
	10	3330.6	504.89	60586.20	45.969	32,638.02	93,224.22	28.0
EC8 (DCM)	4	1332.24	217.93	26151.01	13.504	9,587.97	35,738.98	26.8
	7	2331.42	395.88	47505.92	23.636	16,781.52	64,287.45	27.6
	10	3330.6	573.84	68860.84	33.760	23,969.93	92,830.76	27.9
EC8 (DCH)	4	1332.24	217.93	26151.01	13.654	9,694.37	35,845.39	26.9
	7	2331.42	395.88	47505.92	23.898	16,967.73	64,473.65	27.7
	10	3330.6	573.84	68860.84	34.135	24,235.94	93,096.77	28.0

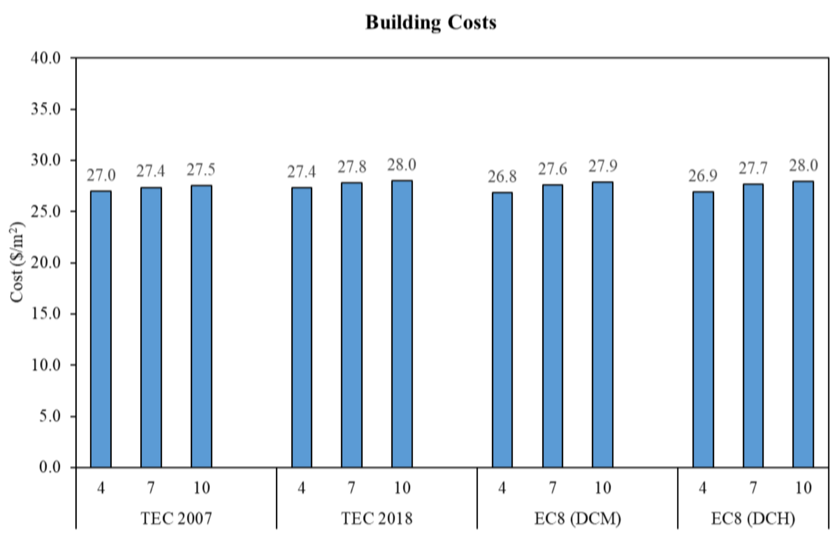


Fig. 8. Variation in building costs

Structural modelling was conducted using SAP2000 software [27] to verify compliance with minimum code requirements. The models shown in Figure 5 were used to cross-check the manually calculated building weights, with discrepancies of less than 8%, 5%, and 6% for 4-, 7-, and 10-story buildings, respectively. Comprehensive dynamic analyses, such as response spectrum or time history, were not performed because the study focuses on comparing minimum concrete and steel requirements. Additionally, the unavailability of parameters, such as earthquake data and site location, makes performing these analyses cumbersome.

3.3 Environmental Impact

Due to the constraints of this study, the sustainability aspect was investigated based on the EE and EC contributions of the RC frames under consideration. Utilizing the EE and EC coefficients proposed by the ICE database, the total energy consumed to produce concrete and steel, as shown in Table 14, along with the CO_2 emissions released during construction, shown in Table 15, were determined with respect to the different building codes.

Table 14. Building embodied energy (EE)

Production Embodied Energy (EE) Calculations								
CODES	Stories	Total area (m^2)	Concrete		Steel		Total EE (GJ)	Total EE (GJ/m^2)
			Amount (kg)	EE (GJ)	Amount (kg)	EE (GJ)		
TEC 2007	4	1332.24	457,776.00	457.78	18,362.60	650.04	1,107.81	0.832
	7	2331.42	819,630.00	819.63	32,134.37	1137.56	1,957.19	0.839
	10	3330.6	1,181,484.00	1181.48	45,906.14	1625.08	2,806.56	0.843
TEC 2018	4	1332.24	467,856.00	467.86	18,387.77	650.93	1,118.78	0.840
	7	2331.42	839,790.00	839.79	32,178.21	1139.11	1,978.90	0.849
	10	3330.6	1,211,724.00	1211.72	45,969.04	1627.30	2,839.03	0.852
EC8 (DCM)	4	1332.24	523,020.24	523.02	13,504.18	478.05	1,001.07	0.751
	7	2331.42	950,118.48	950.12	23,635.95	836.71	1,786.83	0.766
	10	3330.6	1,377,216.72	1377.22	33,760.46	1195.12	2,572.34	0.772
EC8 (DCH)	4	1332.24	523,020.24	523.02	13,654.05	483.35	1,006.37	0.755
	7	2331.42	950,118.48	950.12	23,898.21	846.00	1,796.12	0.770
	10	3330.6	1,377,216.72	1377.22	34,135.12	1208.38	2,585.60	0.776

Table 15. CO_2 emission quantities for the RC frames

Production Carbon dioxide emissions Calculations								
CODES	Stories	Total area (m^2)	Concrete		Steel		Total CO_2 (tCO_2)	Total CO_2 ($kgCO_2/m^2$)
			Amount (kg)	CO_2 (tonnes)	Amount (kg)	CO_2 (tonnes)		
TEC 2007	4	1332.24	457,776.00	69.12	18,362.60	53.07	122.19	91.72
	7	2331.42	819,630.00	123.76	32,134.37	92.87	216.63	92.92
	10	3330.6	1,181,484.00	178.40	45,906.14	132.67	311.07	93.40
TEC 2018	4	1332.24	467,856.00	70.65	18,387.77	53.14	123.79	92.92
	7	2331.42	839,790.00	126.81	32,178.21	93.00	219.80	94.28
	10	3330.6	1,211,724.00	182.97	45,969.04	132.85	315.82	94.82
EC8 (DCM)	4	1332.24	523,020.24	78.98	13,504.18	39.03	118.00	88.57
	7	2331.42	950,118.48	143.47	23,635.95	68.31	211.78	90.84
	10	3330.6	1,377,216.72	207.96	33,760.46	97.57	305.53	91.73
EC8 (DCH)	4	1332.24	523,020.24	78.98	13,654.05	39.46	118.44	88.90
	7	2331.42	950,118.48	143.47	23,898.21	69.07	212.53	91.16
	10	3330.6	1,377,216.72	207.96	34,135.12	98.65	306.61	92.06

EE and EC calculations position EC8 as the most sustainable option, with 9-11% lower EE and 3-5% lower EC per m^2 compared to TEC 2018, as shown in Figure 9. Since steel has higher EE/EC coefficients, EC8's higher concrete volumes are offset by reduced steel use, while TEC's EE and EC are magnified due to their high steel requirement despite having low concrete demands. These findings can optimize designs by adopting EC8's reinforcement strategies within TEC frameworks, thereby reducing environmental impacts without compromising structural safety.

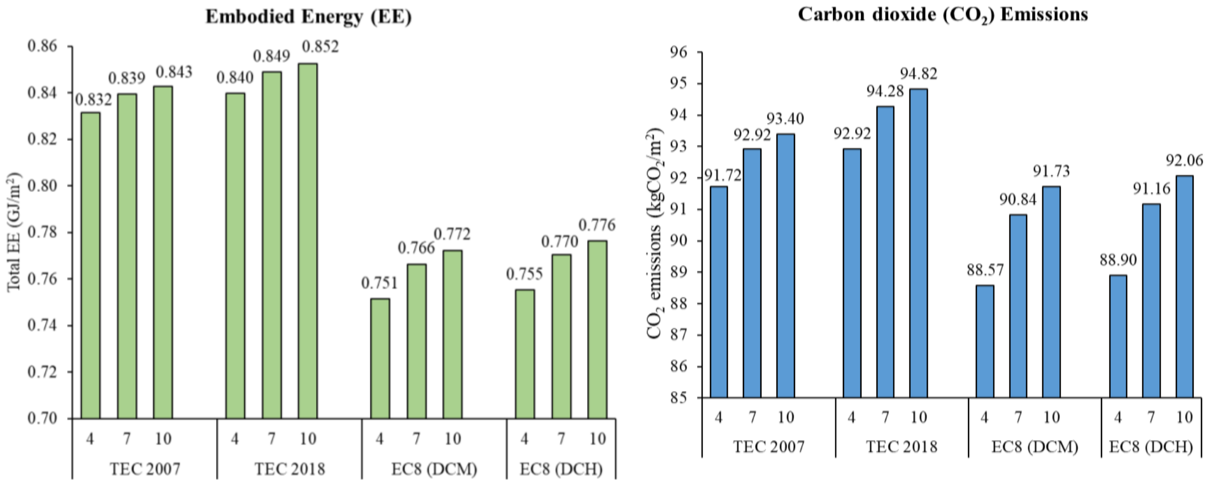


Fig. 9. Variations in EE and EC per floor area for RC buildings

Table 16. GHG emissions for different electricity generation sources in Türkiye

Energy Source	2021 Elec. Gen share	GHG emissions ($tonCO_2/GWh$)
Natural Gas	33.2	499
Coal	30.9	888
Hydro	16.7	26
Liquid fuels	0.1	733
Other renewables & Waste	19.1	97

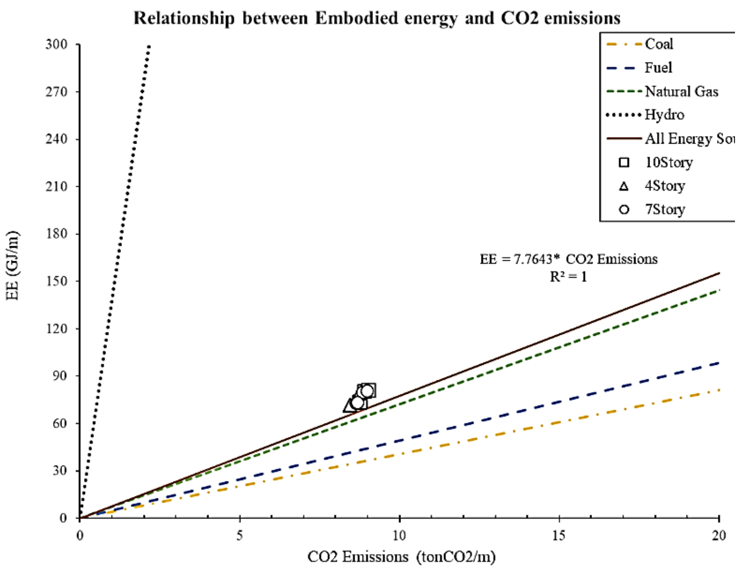


Fig. 10. EE and CO_2 relation for the different RC frame stories compared with Türkiye's energy sources

Given that the majority of the construction materials used in the TRNC are sourced from Türkiye, the CO2 released from the different electricity generation sources was analyzed together with that from the RC frames under investigation. The distribution of Türkiye' s electricity generation by source in 2021 (Natural gas 33.2%, Coal 30.9%, Hydro 16.7%, Liquid fuels 0.1%, and other renewables & Waste 19.1%) [34] is summarized in Table 16, along with corresponding GHG emissions [35].

Figure 10 shows the EE and EC relationship for the RC frames compared to that of the different energy sources in Türkiye. The RC frame stories have lower CO_2 emissions as compared to coal, liquid fuel, and natural gas for each GJ of EE. The lower the CO_2 emissions of an energy source, the more sustainable it is, thus making hydro a more sustainable alternative compared to other energy sources due to its lowest emissions. The relationship between EE and EC for the RC frames considered within the scope of this study lies along the line combining all the energy sources, thus implying that the materials used in the construction of these building stories are produced using energy varying from less sustainable sources to more sustainable sources, including renewables.

3.4 Sensitivity Analysis

To address uncertainties in input parameters, a univariate sensitivity analysis (SA) was conducted on key variables (material unit costs, as well as EE and EC coefficients) [36,37]. This analysis evaluates how ±10% variations in these inputs affect the total costs, EE, and EC for the RC frames. The ±10% range was selected as a benchmark to represent potential uncertainties arising from moderate real-world fluctuations due to market volatility, regional production differences, or database assumptions applied to ICE coefficients. The impacts of these variations on the results are shown in Figures 11-13.

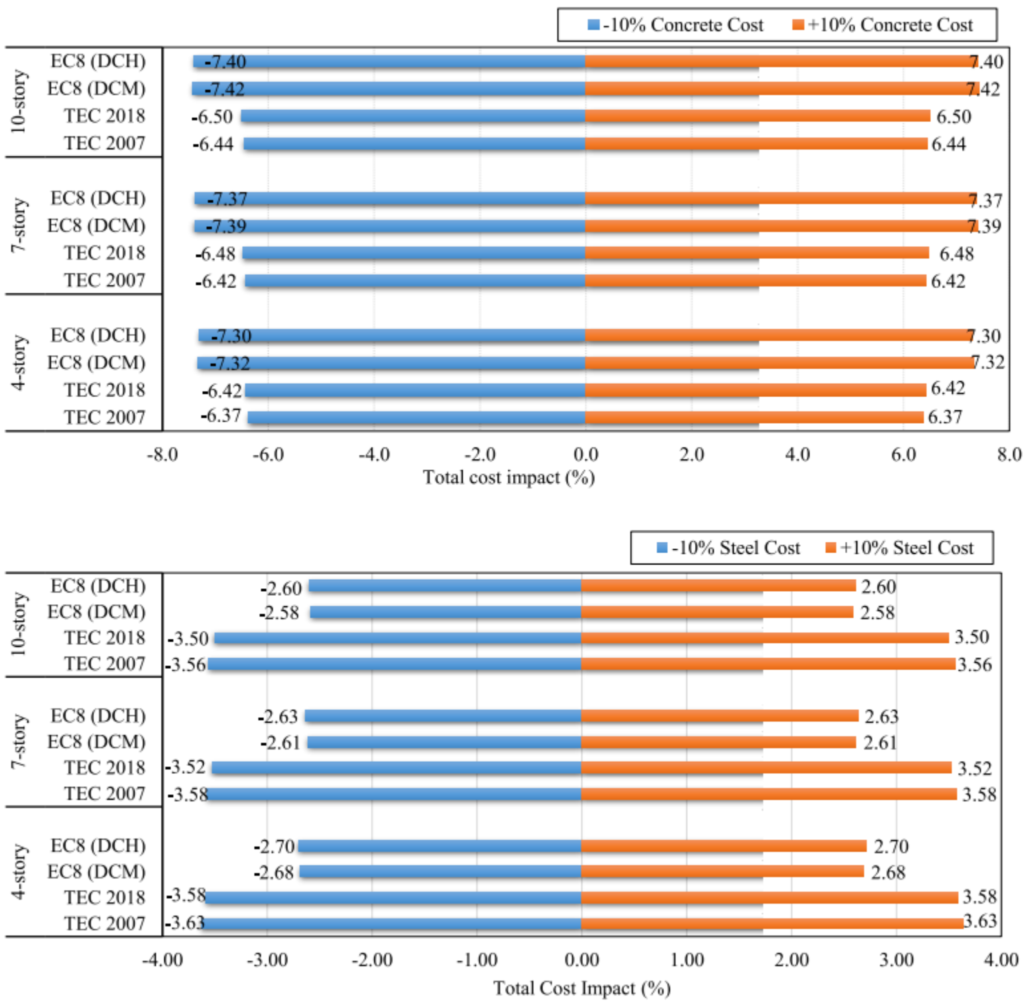


Fig. 11. Impact on total costs due to variation in concrete and steel costs

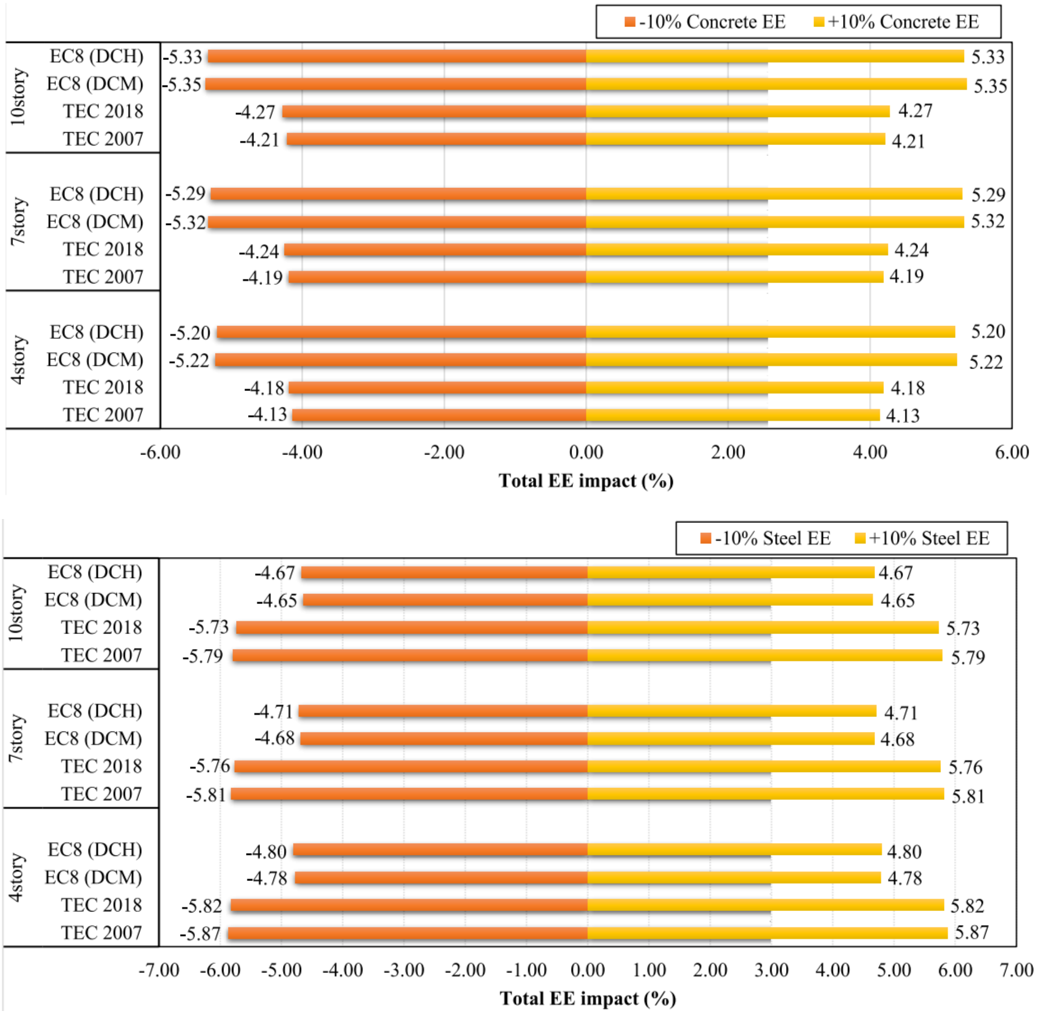
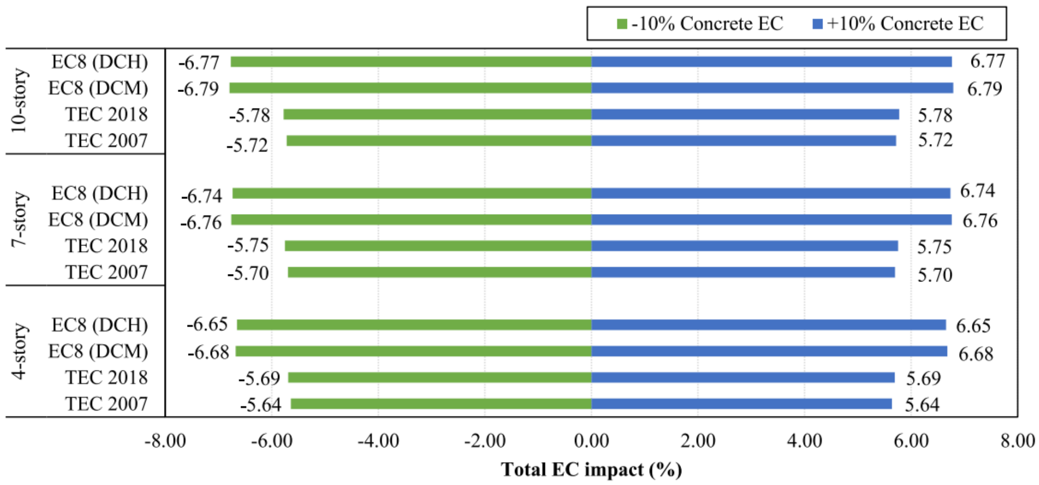


Fig. 12. Impact on overall EE due to variation in concrete and steel EE coefficients

A +10% increase in concrete costs raises overall costs by approximately 7.3-7.42% for EC8 across story heights, compared to a 6.37-6.5% increase for TEC codes, reflecting EC8's higher concrete volumes. Conversely, a +10% increase in steel costs has a more pronounced effect on TEC codes than on EC8, due to TEC's greater reinforcement requirements (Figure 11). In alignment with material breakdowns, a +10% increase in concrete EE coefficients increases EE totals by 5.2-5.35% for EC8, compared to 4.13-4.27% for TEC codes. Similarly, a +10% increase in concrete EC coefficients raises EC8's EC values more than those for TEC.



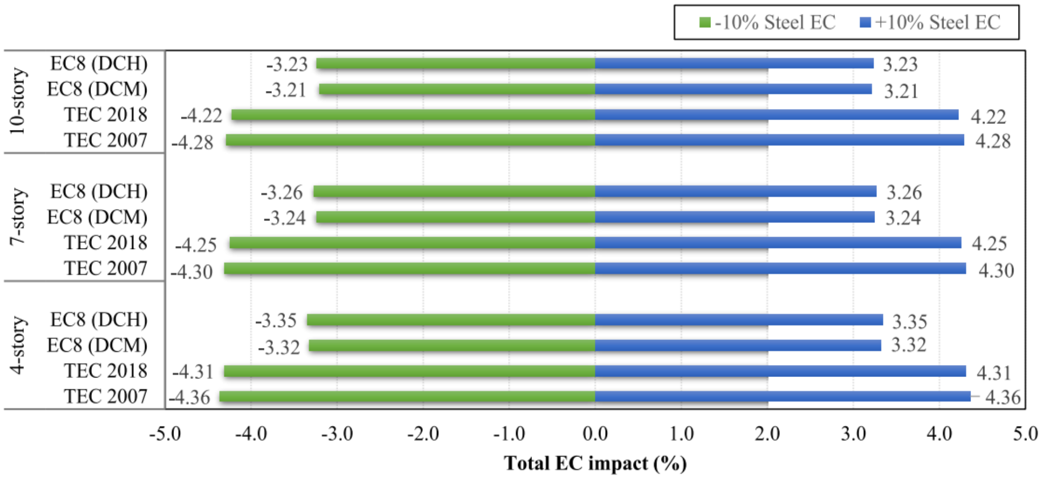


Fig. 13. Impact on overall EC due to variation in concrete and steel EC coefficients

Conversely, variations in steel EE and EC coefficients impact TEC more than EC8, Figure 11-12. This SA highlights the need for code harmonization to mitigate economic and environmental risks. EC8's concrete sensitivity makes it vulnerable to cement price surges or carbon-intensive production. This underscores the need for the adoption of low-EC materials in seismic regulations, emphasizing resilient, low-carbon rebuilding.

3. Conclusion

This study systematically compares the minimum requirements of TEC 2007, TEC 2018, and EC8 for RC frames. The analysis demonstrates that while newer codes improve seismic safety, they often lead to increased material consumption. For 10-story frames, EC8 requires approximately 14% more concrete and 25-27% less steel compared to TEC 2018. This results in 5-10% lower EE and 8-12% lower EC per floor area, with minimal cost differences ranging from 5-8%. Encouraging low- to mid-rise (4 to 7 story) developments that optimize material use, cost, and environmental impact is recommended. On the other hand, high-rise buildings (10 or more stories) should be limited to densely populated areas where land-use efficiency justifies increased material usage. The sensitivity of EC8 and TEC to concrete- and steel-related variations, respectively, presents opportunities for code harmonization to improve safety, efficiency, and sustainability.

The reliance on minimum code provisions introduces several limitations that restrict the scope and applicability of this analysis. These limitations include:

- Exclusion of dynamic seismic simulations, such as response spectrum or time-history analyses, which could reveal nonlinear effects on material quantities in actual designs.
- Cost estimates are based solely on 2024 TRNC market prices, limiting relevance to other regions.
- EE and EC calculations employ simplified ICE coefficients without a comprehensive life cycle assessment (LCA).

Future research should address these gaps by utilizing comprehensive LCA frameworks that encompass the entire building lifecycle, including operational and end-of-life impacts, to more accurately evaluate sustainability trade-offs [38]. Incorporating real-world case studies and post-earthquake data, such as that from the 2023 Kahramanmaraş earthquake [39], will enhance code compliance based on recent assessments. Furthermore, broader comparisons with established codes such as ASCE 7 or the IBC under various scenarios may contribute to the improvement of international standards. Additionally, the adoption of environmentally friendly building practices, including the use of renewable materials with low-carbon footprints and energy-efficient designs, can significantly reduce EE and EC emissions [40].

The implications of this study are extensive, guiding policymakers toward code improvements that incorporate sustainability indicators. This includes post-earthquake reforms that emphasize resilient rebuilding and stricter enforcement measures to reduce risks in high-density areas. In engineering practice, it underscores practical trade-offs, promoting material-efficient designs that minimize environmental impacts while ensuring safety, potentially lowering global construction emissions through retrofitting instead of new construction.

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