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LIFE CYCLE ASSESSMENT AND LIFE CYCLE COSTING APPROACH FOR BUILDING DECARBONIZATION BY DESIGN CHOICES: A CASE STUDY

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Abstract: Decarbonizing the urban environment has two significant challenges: Increasing electricity demand due to the electrification of space heating and increased renewables share in the electricity supply. The European Commission defines a new grid support mechanism for peak-shaving products in renewed Electricity Market Design. This aims to enable a new market tool to stabilize electric supply and demand. This study examines a grid-integrated thermal storage device's technical feasibility and economic performance to meet net zero building (nZEB) definitions. Alternative scenarios considering current national nZEB targets, present energy market options, and regulations are compared using the life cycle cost and the global warming potentials over the building lifetime. The results show that better building performance is possible even with a low investment increase of 6.7% compared to minimum

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building standards based on regulations. This enables older building cases to perform similarly with new building targets for Turkish National nZEB. Building electrification using heat pumps and thermal storage systems gives similar economic performances in the long term when a dynamic electricity tariff is available. Adapting the life cycle approach to decision-making in construction contracts can lead to a 50% decrease in building emissions while staying within the same construction budget.

Keywords: Building energy efficiency, Life cycle cost, Life cycle emissions, Global warming potential, Energy performance of buildings

1. Introduction

Although the use of energy and the understanding of the built environment have changed with the needs of society throughout the ages [1, 2], they are both required for urban development and the continuation of civil life. These interlinked aspects become agenda-directing powers for economic growth and environmental impact [3]. The European Union defines its targets to minimize this impact and reach climate neutrality in 2050. Among other sectors, construction has a high share of energy-related emissions. Buildings in the European Union are responsible for consuming around 40% of total energy [4] and producing 35% of the total greenhouse gas (GHG) emissions [5].

Developing building performance is one of the most effective options for reducing energy demand and related GHG emissions through building lifespan [6]. Therefore, building systems' Life Cycle Assessment (LCA) has become critical and crucial for multi-criteria decision tools

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to reach economic and environmental goals [7]. Many political, economic, and social authorities, such as the EU, have applied this approach to improve their decisions, practices, and strategies regarding environmental goals [8].

In the case of Europe, these issued directives, strategic sector plans, climate action plans, and regulations [8, 9] have a broader impact, covering associated countries such as Turkey. The European Green Deal and the Climate Law [9, 10], adopted in 2019 and 2020, respectively, have more challenging goals regarding the sustainable built environment, of which construction is essential. The targets that aim to decrease the GHG (greenhouse emissions) of the European Union by 55% in 2030 [11] and 85-90% in 2050 [12] require national and local changes in the legal framework. However, looking at current measurements, it is thought that the current situation will reach a 45% reduction in 2030, and the 55% target will fall back [13]. That's why many changes have occurred to the EU's nZEB target after 2020.

A transition has been made from the nZEB target to the Zero Energy Building (ZEB) target. In this regulation, the Energy Performance of Buildings Directive and the Energy Efficiency Directive were revised in 2023, gaining a new framework and introducing new rules. Revisions in old buildings will be supported, and ZEB is mandatory for all new public buildings after January 1, 2027, and for all new buildings after January 1, 2030. [14, 15]. The 85%-90% carbon neutrality determined for 2050 in the first version of the Directive has been changed to decarbonization and fully decarbonized building stock. Additionally, Energy efficiency will also be considered an energy source in 2050 [13]. These points to the aim of zero-emission and reducing GWP in buildings.

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The construction sector, which is both Europe's and Turkey's 3rd largest sector [16, 17], is expected to comply with these targets. The nearly zero-energy building (nZEB) has become one of the main implements to achieve these goals and has an essential role in the new building approach and renovation plans [18]. The construction sector in Turkey has an impressive growth rate of approximately 4.4%, and its buildings are responsible for 33% of all energy consumption in the country [19].

According to the specifications in the European Commission 2010/31/EU building energy performance (EPBD, 2010/31/EU), nZEB is defined as a building with very high energy performance [18]. There are two paths to achieve nearly zero targets defined by member states. The first is decreasing building energy demand. The second path is to cover this demand significantly with energy from renewable resources. Associate countries, such as Turkey, also adapt these approaches to their national regulations and strategies as a part of their membership process.

The central government policies regarding energy efficiency in Turkey are regulated by:

- The Energy Efficiency Law, adopted in 2007 [20];
- The TSE 825 standard, established in 2008 (revised version in 2013) [21];
- Energy Efficiency Regulation, adopted in 2011 [19];
- EU Energy Efficiency and Amending Regulation, established in 2023 [22];
- National Energy Efficiency Action Plan, created in 2017 [19];
- Buildings Energy Performance Regulation and the Green Buildings Regulation, established in 2017 for the energy and construction sectors [19];

- The nZEB Turkish national guideline was published in 2020 [19].

EPBD adaptation studies resulted in the guideline for the national nZEB report, which was prepared to introduce the concept of nZEB to the country sector [23] in 2020. However, there are many gaps in all these policies [19]. Turkey has no detailed nZEB definition, unlike most European Countries. However, current legislations define national plans, definitions, and regulations according to their economic, regional, and climatic conditions [24-25].

Current building integrated technologies lower temperature units which include latent heat systems with phase transfer materials, and sensible heat systems with water as heat storage medium. These applications cover hot water (day to month) and PCM (hour to month) operations [26]. However, there is little work done for rapid charge discharge thermal energy storage systems for intraday energy storage as an alternative to conventional heating systems such as natural gas boilers, resistive heaters and heat pumps which are straining electrical grid supply capacities. This study aims to reveal the extent of optimizations to nZEB that can be made within the current market options and legislation and offer intraday thermal storage as an alternative technology for building heating. An existing office building in İzmir, Turkey, is used as a case to evaluate the calculation methodology stated in the TS825 to find the decline in energy needed for heating and cooling purposes. Beyond standard methodology, life cycle cost (LCC) and emissions (LCE) are analyzed to find benefits for the building user and society. Consequently, a cost-effective method that can be easily used by the construction industry and shows low-emission alternatives can be created.

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2. Materials and Methods

The building used as a case is an office building of Yaşar University Faculty of Engineering in İzmir. The ground floor of this 3-story building is designed as laboratories, and the other two floors are faculty members' offices. The building's plan is demonstrated in Figure 1. Building energy measurements are done with the technique stated in EN TSE 825 Thermal Insulation Rules in Buildings Standard, which is the primary methodology behind the national building energy measurement software BEP-BUY and BEP-IS [12]. This methodology calculates 225 cases of building envelope scenarios in MS Excel macros.

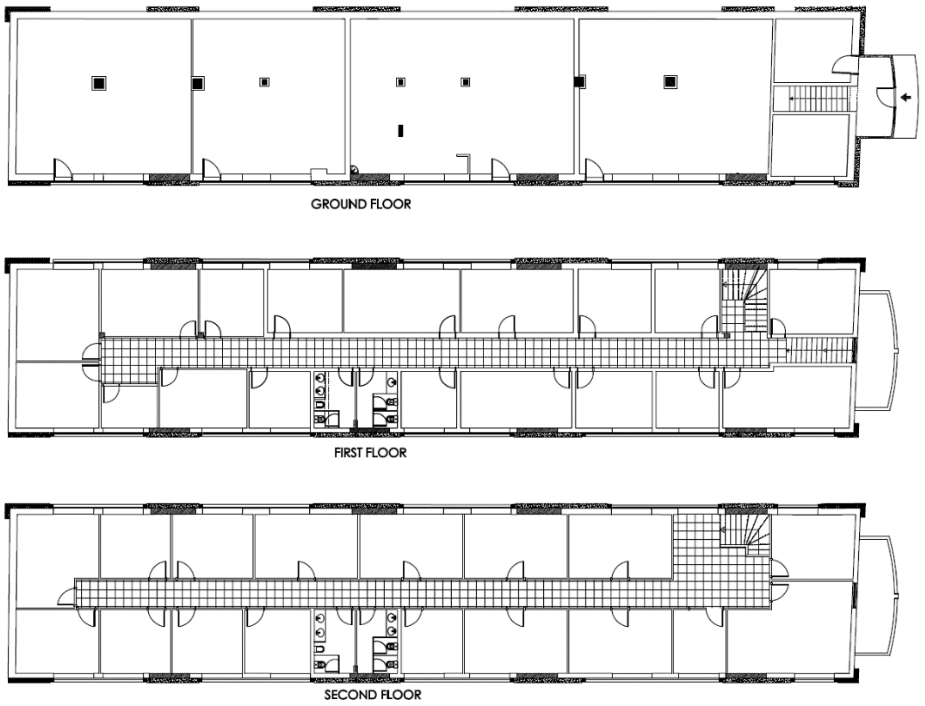


Figure 1. Floor plans of the case building

The building is located along the southwest and northeast planes. Figure 2 shows the location of the building and the sun and wind situation.

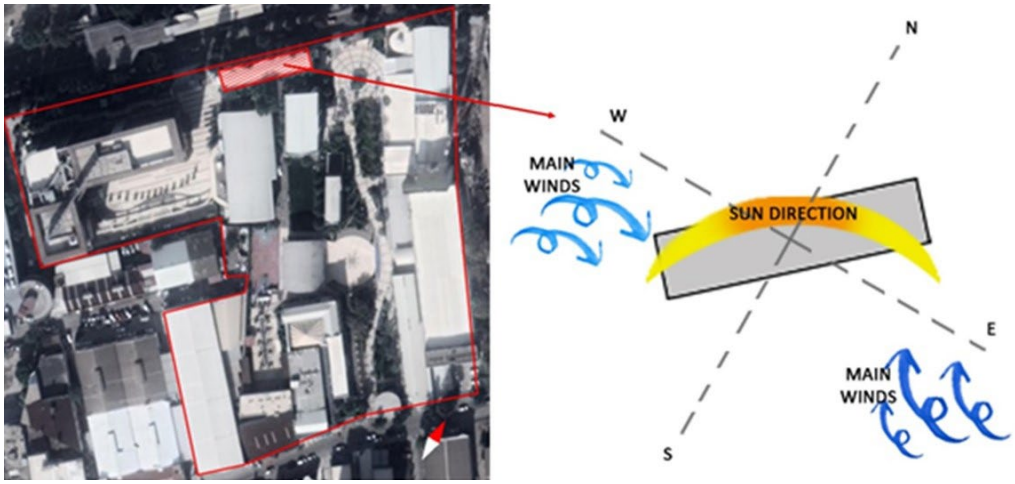


Figure 2. Case building location and sun-wind directions

Local heating degree days (HDD) and cooling degree days (CDD) of the city are 1385 and 700, respectively, for comparison with other cases [27]. Physical building properties are summarized in Table 1.

Table 1. Properties of the case building.

Floor number	3
Floor height (m)	3.5
Width (m)	46
Length (m)	9.6
Useful building area (A_n) (m^2)	1324.8
Gross volume of the building (V_{gross}) (m^3)	4636.8
Total heat loss area of the building (A_{total}) (m^2)	2050.8
A_{total} / V_{gross}	0.44
Total window area (A_i) (m^2)	103.8
North-facing windows total area (A_{north}) (m^2)	38.7
South-facing windows total area (A_{south}) (m^2)	62.1
West and east facing windows total area ($A_{west/east}$) (m^2)	3.0
External door area (m^2)	11.1

The total annual energy is calculated by the sum of the annual heating energy, $Q_{h,year,}$ and cooling energy, $Q_{c,year}$. Base cases use the electric radiator and air conditioner to provide heating and cooling, respectively. These systems are selected based on the national statistics of the most common systems registered in the region based on Turkey Statistical Institute (Türkiye İstatistik Kurumu, TUIK) data [23].

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$$Q_{year} = Q_{h,year} + Q_{c,year} \quad (1)$$

Comfort temperatures stated in the TS825 standard [21] in the indoor environment are used in the calculations. The monthly heating need ($Q_{h,mth}$) required to maintain standard temperature was calculated by subtracting the sum of monthly internal and solar energy gains from the monthly total heat losses as below:

$$Q_{h,mth} = \left[H\,(\theta_i - \theta_e) - \eta_{h,mth}\left(\phi_{h,mth} + \phi_{h,mth}\right)\right]t \quad (2)$$

Where $Q_{h,mth}$ is the monthly heating energy; θ_i is the monthly average internal temperature, θ_e is the monthly average external temperature; $\eta_{h,mth}$ is the monthly average gain utilization factor; $\varphi_{i,mth}$ is the monthly average internal gain of the building; $\varphi_{s,mth}$ is the monthly average solar energy gain, and t is the time in a month as seconds. H is the specific heat loss of the building and is found by the addition of transmission and convection of the building, HT, and heat loss through ventilation, HV.

$$H = H_T + H_V \quad H = H_T + H_V \quad (3)$$

$$H_T = \sum A\,U + I\,U_I = U_w\,A_w + U_{win}\,A_{win} + 0.8\,U_c\,A_c + 0.5\,U_f\,A_f + I\,U_I \quad (4)$$

In this equation, IU_I represents heat losses from the heat bridges, U is the heat transmission coefficient, and A is the surface area. AU represents envelope components aspects: Heat loss from the walls, U_wA_w, heat loss from the windows, $U_{win}A_{win}$, heat loss from the ceiling, $0.8U_cA_c$, heat loss from the floor, $0.5U_fA_f$. Heat loss through ventilation is calculated from the relationship:

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$$H_V = 0.33\,\eta_{air}\,(0.8V_{gross}) \quad (5)$$

While η_{air} is the air change rate, V_{gross} is the gross building volume. The equation calculates the monthly gain utilization factor, $\eta_{h,mth}$:

$$\eta_{h,mth} = 1 - e^{\left(\frac{-1}{KKO_{mth}}\right)} \quad (6)$$

The gain/loss ratio, KKO_{mth} is calculated as:

$$KKO_{mth} = \frac{(\phi_{i,mth}+\phi_{s,mth})}{H\,(\theta_i-\theta_e)} \quad (7)$$

Where average monthly solar energy gain $\varphi_{s,mth}$ is calculated as:

$$\Phi_{s,mth} = \sum r_{i,mth}\, g_{i,mth}\, I_{i,mth}\, A_i \quad (8)$$

Where monthly average shadowing factor of transparent surfaces in i direction, $r_{i,mth}$; transparent elements solar energy conversion factor in i direction, $g_{i,mth}$; monthly average solar radiation intensity from vertical surfaces in i direction, $I_{i,mth}$; and total window area in i direction is A_i. Transparent elements' solar energy conversion factor in i direction is calculated as follows:

$$g_{i,mth} = F_w\, g_\perp \quad (9)$$

In this formula, F_w is the correction factor for glasses, and $g\perp$ is the solar energy transfer factor for the vertical beam. In equation 2, negative energy requirements are considered cooling ones and summed monthly to find the required energy to cool the building, $Q_{c,year}$. In addition, the comfort temperature is defined as 19°C in TS 825. The basic calculations are evaluated as specified in the standard. Besides, the effects of different interior comfort calculations are

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explored. The total energy requirement is found by adding each month's heating and cooling needs.

The parameter groups changed in the building envelope design used in the study are building insulation, glass, and wall materials. The material features are gathered from Turkish companies' Environmental product declarations (EPDs) [28]. These EPDs were based on EN 15978:2011 module A1 [29], and the cost data used is based on approximate unit building costs in 2021 published by Turkey's Ministry of Environment, Urbanization, and Climate Change [30]. Both these sources are combined and presented in Table 2.

Table 2. Properties of building materials used in calculations based on EPDs

			U (W/m^2K)	Initial investment (₺ /m^2)	Lifetime (years)	Emissions (kg CO_2 eq./m^2)
Window Glazing	Wood (Oak, ash/hardwood)	single panel	5.10	210.00	20	0.50
		double panel, space between panels 6mm	3.30	240.00	20	0.50
		double Low-E panel, space between panels 6mm	2.80	250.00	20	0.50
	Wood (coniferous softwoods)	single panel	4.90	180.00	20	1.00
		double panel, space between panels 6mm	3.10	180.00	20	1.00
		double Low-E panel, space between panels 6mm	2.60	180.00	20	1.00
	Plastic (2 chambers)	single panel	5.20	120.00	30	3.20
		double panel, space between panels 6mm	3.40	150.00	30	3.20
		double Low-E panel, space between panels 6mm	2.90	160.00	30	3.20
	Aluminum	single panel	5.90	300.00	30	3.70
		double panel, space between panels 6mm	4.00	330.00	30	3.70

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		double Low-E panel, space between panels 6mm	3.60	340.00	30	3.70
	Aluminum with insulation foam	single panel	5.20	310.00	30	4.40
		double panel, space between panels 6mm	3.40	340.00	30	4.40
		double Low-E panel, space between panels 6mm	2.90	350.00	30	4.40
Walls (Including mortar gaps-joints)	Hollow clay brick		0.88	170	30	19.15
	Clay brick		0.81	367.46	30	19.15
	Aerated air concrete		0.24	275.00	30	13.80

		U (W/m^2K)	Capital cost C = ax + b (₺ /m^2.cm)		Lifetime (years)	Emissions (kg CO_2 eq./m^2)
			(a)	(b)		
Isolation materials	XPS	0.04	5.2891	71.14	20	5.21
	Glass wool	0.04	5.4366	81.289	30	3.23
	Glass Foam	0.04	86.2	0	30	1.45
	Ceramic fiber	0.02	31.48	0	30	3.85

Annual energy cost equals the sum of annual heating and cooling costs, where energy demand for both needs is divided by the heating system's efficiency, $\eta_{s,i}$, that are considered in relevant calculations. LCC is calculated by summation of annual costs:

$$\mathrm{LCC} = \sum C_{cs} + \sum \mathrm{C}_{EC,h} = \sum \frac{\mathrm{Q_c}}{\eta_{\mathrm{s,i}}} C_{cs} + \sum \frac{\mathrm{Q_h}}{\eta_{\mathrm{s,i}}} \mathrm{C_e} \quad (10)$$

C_{cs} is the capital cost of the building envelope and is calculated based on construction costs published annually by the Ministry of Environment, Urbanization, and Climate Change [30]. Moreover, hourly energy costs for heating and cooling, $C_{EC,h}$ is calculated by multiplying the unit price of electricity declared by the Turkish Republic Energy Market Regulation Authority [32], Ce, with building energy loss over the heating system's efficiency, $\eta_{s,i}$. Energy gain from

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the building envelope is used for cooling. The thermal comfort range temperature is used as 20 ± 1 °C mandated by the related national standard [24]. Initial investment and replacement of building envelope material are added to the LCC of the building when their lifetime ends. Furthermore, the cost data used is based on approximate unit building costs in 2021 published by the Turkish Ministry of Environment and Urbanization. The present value (PV) formula was used for discounting future cash flows to present values in the LCC calculation.

$$PV = F_t \frac{1}{(1+d)^t} \tag{11}$$

Where present value, PV; time in unit of the year, which is 40 years in this case, t; future cash amount that occurs in year t, Ft and discount rate used for discounting future cash amounts to the present value, which is 15.75 % as reported by Turkey Central Bank for the same period, d. Similarly, annual Global Warming Potential (GWP) based on CO_2 emissions is calculated using energy demand for heating and cooling and individual system CO_2 emission rates, $E_{s,i,}$ and embodied CO_2 emissions.

$$GWP = \sum E_a = \sum \frac{Q_h}{\eta_{es,h}} E_{s,i} + \frac{Q_h}{\eta_{es,h}} E_{s,i} \tag{12}$$

There are 4 different heating and cooling system configurations considered in the study based on their adaptability to the current building infrastructure. Heating systems are considered to cover electrical radiators, natural gas (NG) boilers with reflux, air-source heat pumps, ground-source heat pumps, and thermal storage units. Thermal storage units charge with electricity by converting electrical energy to thermal energy during low-cost times based on data electricity tariff [31]. Thermal storage material is steel and sensible heat energy is later discharged, heating

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the building. Air conditioners are considered for all systems that are not capable of cooling. These systems are electrical radiators, natural gas (NG) boilers with reflux, and thermal storage units. COP values of these systems are given in Table 3.

The case building is steel-reinforced concrete and has been used as an office building for 20 years. Its remaining life span is considered to be 40 years. [32].

3. Results and Discussion

The national TS 825 standard, which is the basis for nZEB definitions in Turkey, is used to evaluate the extent of economic and environmental gains by selecting building envelope materials, heating and cooling systems, and annual energy. National cost information stated by the government is used in energy demand-related cost and emission calculations. Environmental product declarations EPD from local companies are used in embedded emissions. Both LCC and GWP are calculated for envelopes only to simplify decision-making.

LCC and GWP determine optimum envelope parameters based on aggregated results evaluated over 40 years. LCC, GWP, and LCA are terms that are all classified as cradle-to-grave. Life cycle cost (LCC) is the total cost of owning, operating, maintaining, and disposing of a structure, a product, or a system over a specified period. It is the total cost of creating and operating a product over time [33]. Global warming potential (GWP) calculates the greenhouse gas emissions associated with a product or building at different stages throughout its entire life cycle. Therefore, it estimates the building's overall contribution to emissions that lead to climate change [13]. Life Cycle Assessment (LCA) is an analytical tool that measures and demonstrates the overall environmental impacts of a product, process, or human activity (in this case, a

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building) from raw material acquisition to production, use, and waste management. It is the product's carbon footprint throughout its life [34, 35]. It basically covers LCC and GWP as well.

In scenarios with insulation replacement, the entire insulation is considered at the end of the life of the material, and costs are added as a new installation. There are five scenarios for insulation with four different insulation materials: XPS, glass wool, glass foam, and ceramic fiber, and without insulation since the resulting U values for the case are satisfactory for the national standard. Also, three different wall materials are considered for the envelope: Hollow clay brick, clay brick, and aerated air concrete, which are locally available. Furthermore, 12 different glazing alternatives are considered for the scenarios.

A total of 225 calculations are evaluated to find the optimum envelope conditions, and later, the lowest LCC and GWP option is further investigated for four different heating and cooling system scenarios and five different insulation thickness alternatives.

Basement and roof designs are considered the same in all scenarios and by the TS 825 standards. Also, the isolation material thickness is taken as 4 cm for all materials to determine the optimum configuration.

It is found that improvements in only one parameter, either glazing, wall material, or isolation, do not result in a decline in the total energy requirements, even if they are developed to the extremes. In addition, increasing just the initial investment of the building envelope from a

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baseline of 432,998₺ to 628,014₺ is enough to reach minimum heating and cooling energy requirements to a minimum total, as shown in Figure 3.

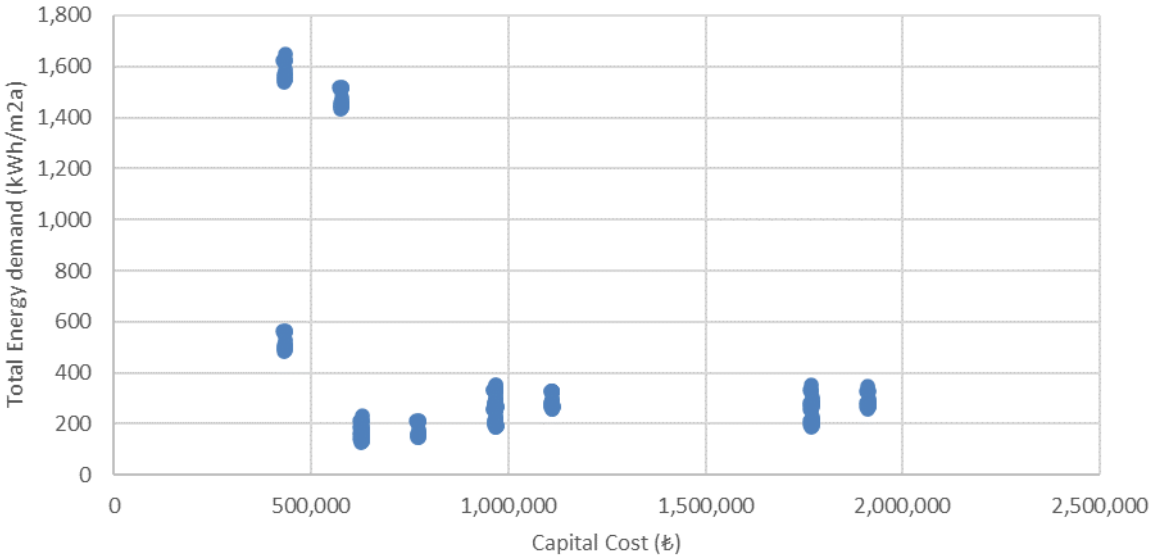


Figure 3. Total Energy Demand (kWh/m^{2}a) versus capital cost for building envelope scenarios

Although an almost 50% increase might seem high, the overall effect of this budget increase is minimal, considering it is only 154 ₺ /m^2, and it is just a 6.7% increase from the costs stated by the Ministry of Environment and Urbanization [30]. This decreases energy requirements for heating and cooling by nearly 10% of the base case, reflecting a 28-time decrease in LCC calculated. Unfortunately, decision-making tools supplied and mandated by the ministry do not cover the LCA approach applied by some European counterparts [36] but solely describe construction expanses. Adapting the LCA approach in building systems other than building envelopes can lead to further improvement in the potential of GWP by up to 22% [6]. The calculations in this study show that compared to the energy costs of case building, the investment for the envelope is minor; thus, the lifecycle costs shown in Figure 4 have near-linear behavior with lower energy requirements based on the different building envelope.

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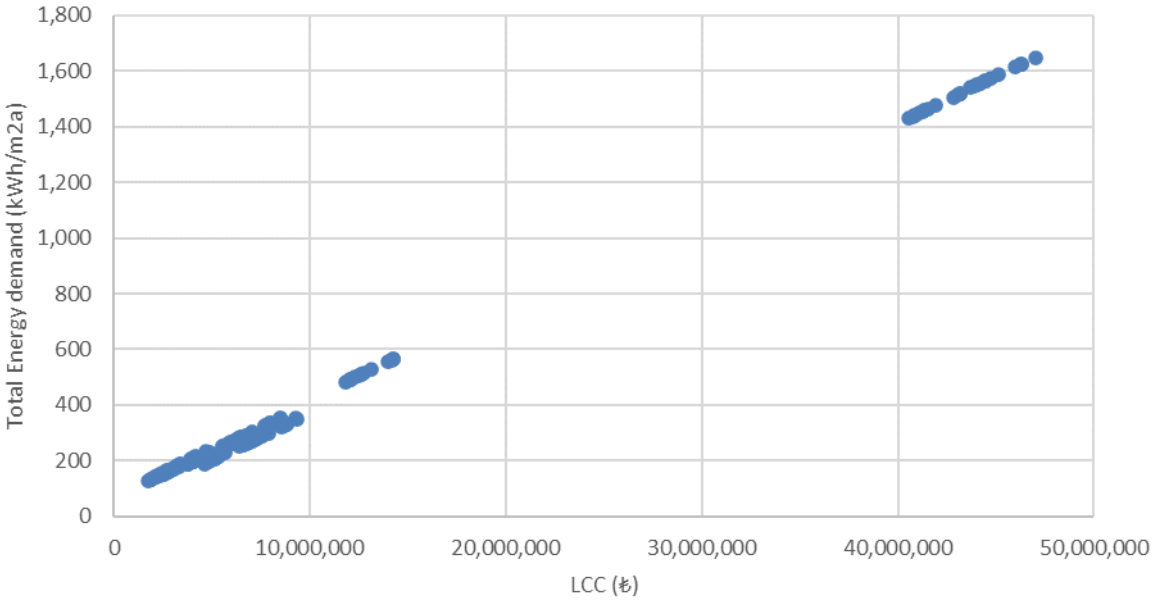


Figure 4. Total Energy requirements (kWh/m^{2}a) versus LCC for building envelope scenarios

Although the GWP is important, it is not included in the building energy directives of Turkey or other countries [37]. Although the annual greenhouse gas amount per usage area produced from the final energy consumption is specified in the energy performance certificates, the GWP is omitted. This approach has its drawbacks. Because embodied emissions of building materials, which contribute almost 10% of the total emissions of buildings, are neglected [38]. A directive to include the GWP reduces the 10% emission burden of structures built per that Directive. Considering 335 to 560 kg CO_2eq/m^2 embodied emissions measured on average for similar buildings [39], the calculated embodied emission of the building envelope, 20.54 kgCO_2eq/m^2 with the best performance, has an even lower share in GWP.

Nevertheless, this share increases as the envelope decreases energy requirements for heating and cooling. In the studied case, the share of embodied emissions increased 16 times and reached 0.9% of lifetime cumulative operational emissions compared to the minimum base case, which the TS 825 standard can apply. One of the study's important findings is that low

emissions, 33% of baseline, are possible within the lowest cost regions with no additional capital investment but just changing building practices and tailoring building design parameters of the envelope. The lowest two capital cost groups shown in Figure 5 have nearly three times different GWP results.

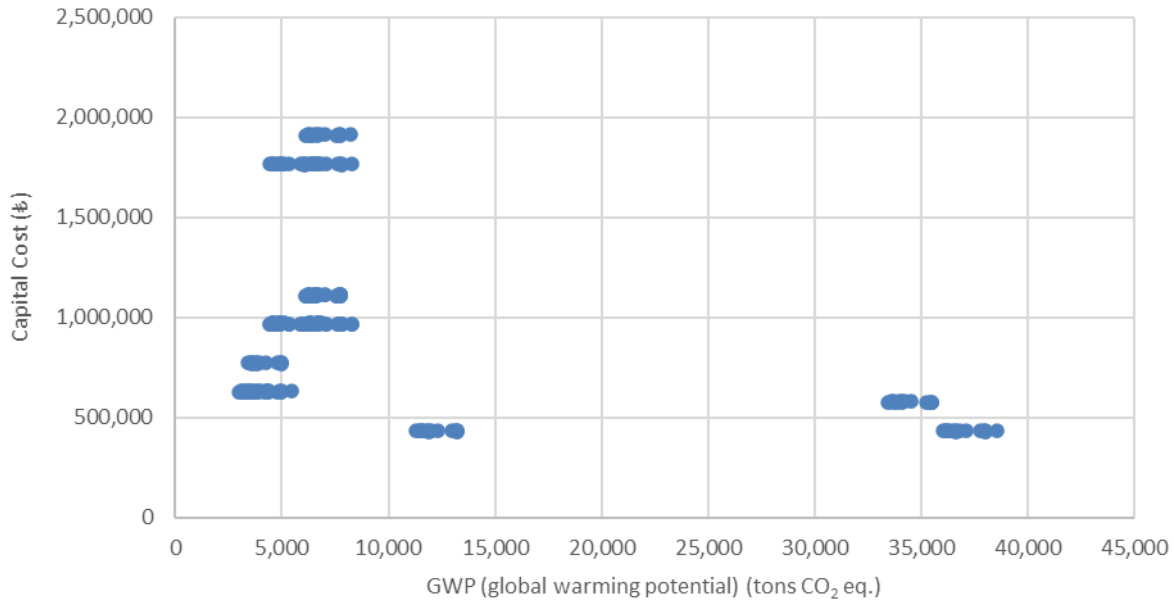


Figure 5. Total Energy requirements (kWh/m^{2}a) versus LCC for building envelope scenarios

This can be improved for building user's benefit when the LCA is applied, as shown in Figure 6. No insulation cases result in extremes for both the LCA and GWP results for the 40-year lifetime of the building.

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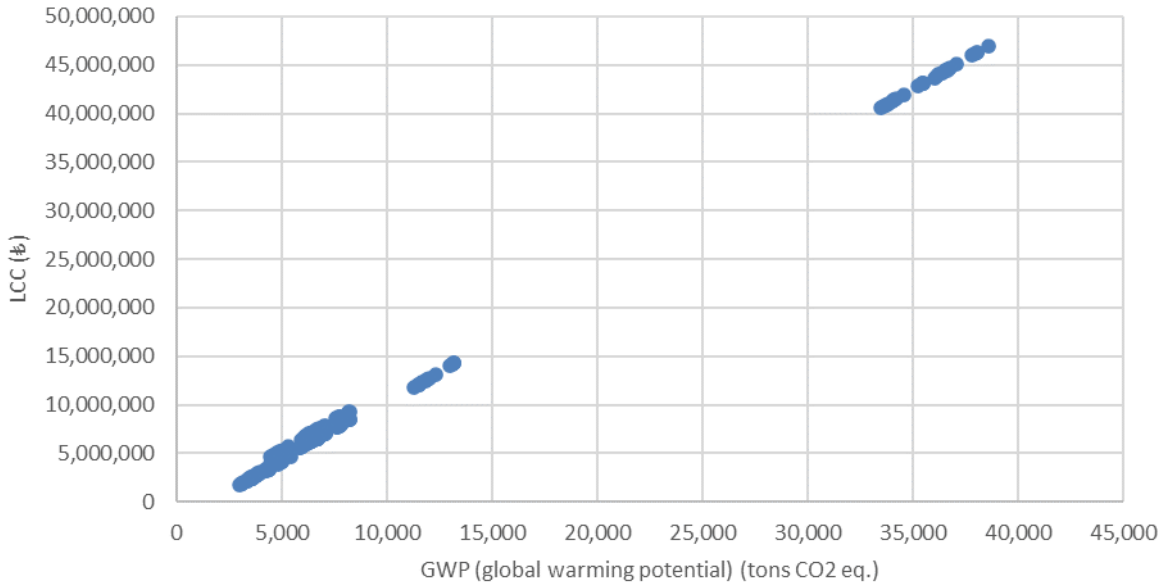


Figure 6. GWP versus LCC for all building envelope scenarios

The building performance can be further improved by increasing insulation thickness of ceramic fiber insulation. The building energy requirements for heating and cooling are 127.04 to 92.03 kWh/m^{2}a by increasing thickness from 4 cm to 10 cm. This also reflects a 40% drop in GWP and a 46.5% drop in the LCC, as shown in Figure 7.

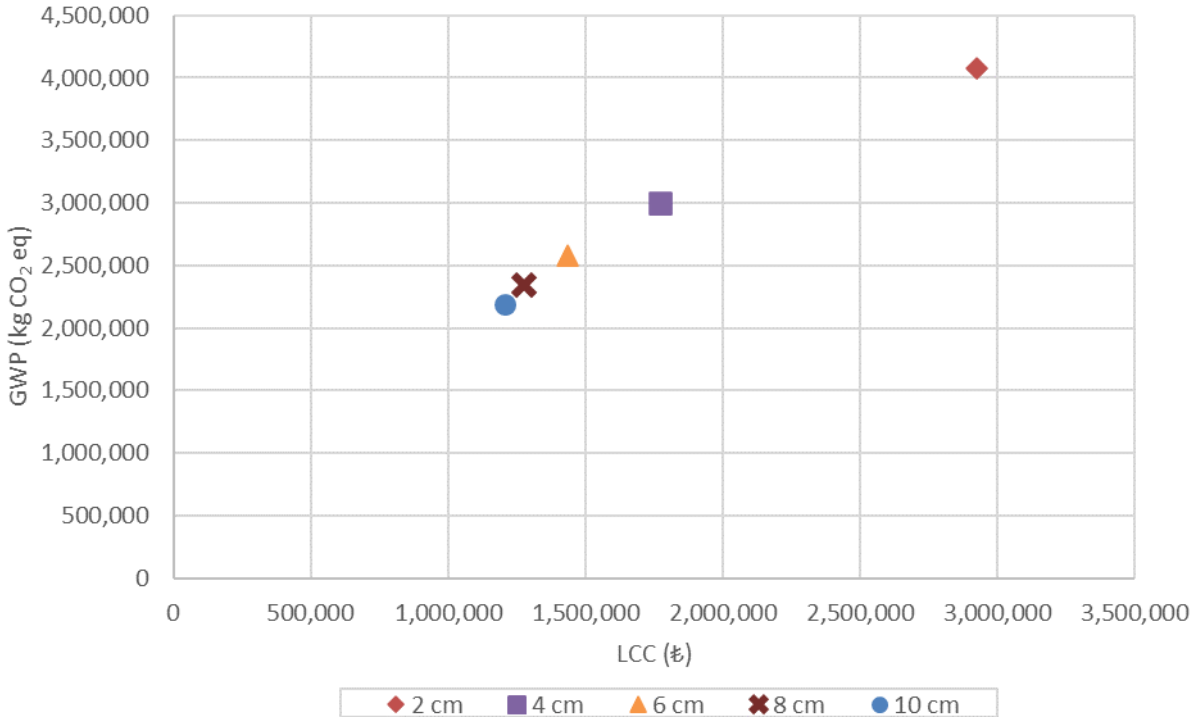


Figure 7. GWP versus LCC for selected building envelope scenarios where only insulation thickness altered

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Another way to improve building performance further is by changing heating and cooling equipment with higher efficiency. Details on four different heating and cooling equipment scenarios show that it can decrease building energy requirements to 34.3 kW/m^{2}a from 59.6 34.3 kW/m^{2}a as in replacement of NG boiler and air conditioner systems replaced by ground source heat pump for best building envelope scenario. This leads to the best economic and environmental performance, as shown in Figure 8. The thermal storage unit matched the best economic performance if day-ahead market prices were enabled and the ground source heat pump scenario where each has 1,842,369.78 ₺ and 1,848,501 ₺, respectively. The higher emission observed for thermal storage is associated with grid-based electricity emissions for Turkey. Both systems can be used for zero-emission if building integrated renewable energy systems are integrated.

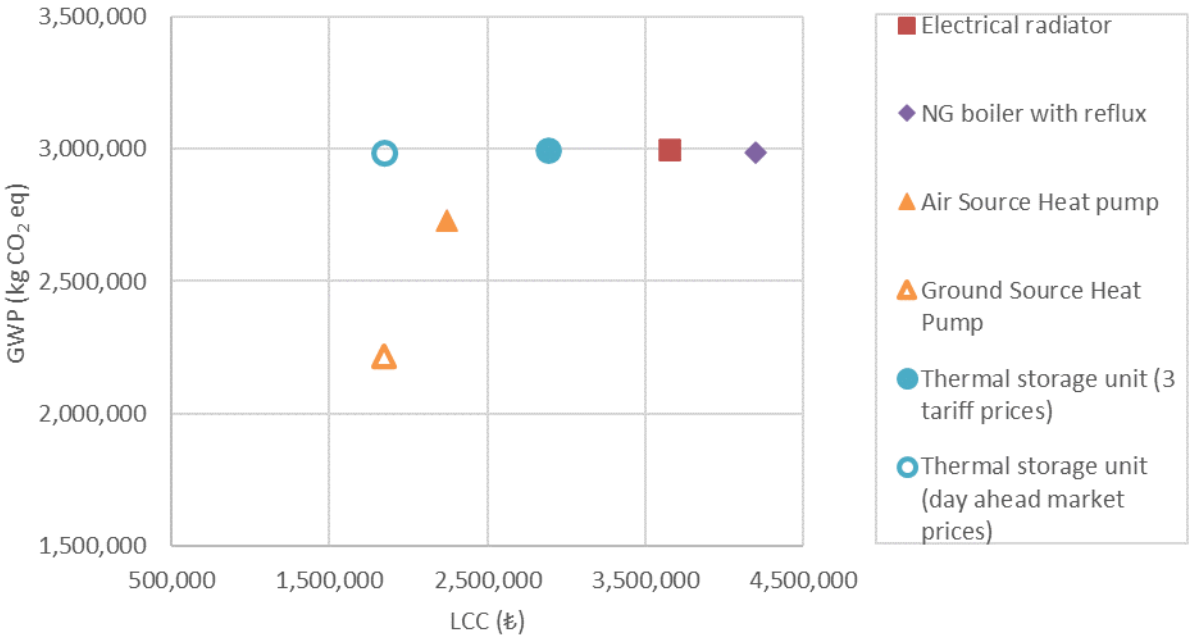


Figure 8. GWP versus LCC for selected building envelope scenarios where only heating technology changes, all heating systems are supported by only air conditioners for cooling operations.

When both heating and cooling systems change, and insulation thickness increases from 4 to 10 cm, the final energy requirements decline to 77.24 kWh/m^2. It is 125.6 kWh/m^2 based on TUIK data to achieve higher efficiency for building operation, which is 61% of the annual energy requirement of office buildings in Turkey. This data also aligns with observed cases reported to be a bit higher for 170 kWh/m^2 for a similar building [27]. Moreover, examples of the effects of different isolation material thicknesses and heating and cooling systems for the selected case with glazing double Low-E panel and Wood (coniferous softwoods) double panel and space between panels 6mm, Wall Material AAC and isolation material ceramic fiber is shown in Table 3.

Table 3. Examples of the effects of different isolation material thicknesses and heating and cooling systems

Isolation material thickness (cm)	4	4	4	4	2	4	6	8	10	10	10	10
Heating system	ER	NgB	ASHP	GSHP	ER	ER	ER	ER	ER	GSHP	TS*	TS**
COP	1	1.015	3	3.7	1	1	1	1	1	3.7	1	1
Heating energy demand (kWh/m^{2}a)	41,613	40,998	13,871	11,247	87,049	41,613	25,715	16,420	10,322	2,790	10,322	10,322
Heating CAPEX (₺)	628,013	628,013	628,013	628,013	530,505	628,013	725,520	823,028	920,535	920,535	2,880,000	2,880,000
Heating OPEX (₺/year)	78,307	22,266	26,102	21,164	163,808	78,307	48,390	30,899	19,424	5,250	12,043	4,645
Cooling system	AC	AC	ASHP	GSHP	AC	AC	AC	AC	AC	GSHP	AC	AC
COP	3.3	3.3	3	3.7	3.3	3.3	3.3	3.3	3.3	3.7	3.3	3.3
Cooling energy demand (kWh/m^{2}a)	127	127	139	113	143	127	119	115	112	100	127	127
Total energy demand (kWh/m^{2}a)	168	168	153	124	230	168	145	131	122	102	137	137
Cooling CAPEX (1000 ₺)	628	628	628	628	531	628	726	823	921	921	628	628

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Cooling OPEX (1000 ₺/year)	33	13	11	9	69	33	20	13	8	2	33	33
Total expenditure (TOTEX) (1000 ₺)	7,597	3,304	3,998	3,717	11,977	6,969	6,382	5,874	5,708	3,981	5,943	5,647
Material embedded emissions (kg CO_2 eq)	27,212	27,212	27,212	27,212	24,332	27,212	30,093	32,974	35,854	35,854	90,279	90,279
Annual operational emissions (kg CO_2 eq)	73,377	73,109	66,805	54,167	100,211	73,377	63,104	57,097	53,156	44,612	0	0
GWP (ton CO_2 eq)	3,017	2,952	2,727	2,221	4,081	2,990	2,614	2,383	2,234	1,856	90	90

Electrical radiator (ER), Ng boiler with reflux (NgB), Air source heat pump (ASHP), Ground source heat pump (GSHP), Thermal storage unit (TS), Air Conditioner (AC)

**3-part tariff*

***day-ahead market*

4. Conclusions

The authors aim to show that national and regional authorities can significantly improve building environmental performance even under the current framework. This can be gained by raising awareness of selecting building systems defined within the current legal framework and decision-making mechanisms. Thus, national, and European climate targets can be approximated within the same construction cost limits dictated by local laws and without waiting for legal framework changes, which take more than a decade. In this context, national standard TS825 and other related regulations are used to define limits on the alternative scenarios for building envelope and heating and cooling systems of public buildings in a case located in İzmir, Turkey. The major goal is achieving low life cycle GWP within the same cost range currently approved for public buildings.

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The calculations show improvements in only one building envelope parameter; glazing, wall material, or isolation do not significantly decrease the total energy requirements. They are improved to the extremes. Multiple parameters should be considered in a synergistic approach, leading to a 33% lower life cycle GWP.

Changing standard building practices and tailoring building envelope design parameters for individual cases can lead to better energy and related GWP performances even within the lowest capital cost alternatives.

An investment increase of 6.7% of all building costs is enough to reach the building's heating and cooling energy requirements to reach 127.04 kWh/m^2. This leads to a lower life cycle cost of the building down to 10% due to high energy costs associated with heating and cooling. The ground-source heat pump scenario gives the best economic and environmental performance for replacing a more common NG boiler. Moreover, it has been concluded that the lifetime performance of thermal storage systems is similarly economical if dynamic electricity prices are provided. Both systems can be used for zero-emission if building integrated renewable energy systems are integrated. Public decision-makers can decrease building emissions by half by changes in the structure within the same construction budget by just adapting the life cycle approach into decision-making in construction contracts.

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There is no conflict of interest

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

[1] Erdemir, D., & Dincer, I. (2020). Potential use of thermal energy storage for shifting cooling and heating load to off-peak load: A case study for residential building in Canada. Energy Storage, 2(2), e125. https://doi.org/10.1002/est2.125

[2] Davis, H. (2006). The Culture of Building. Oxford University Press.

[3] EC [European Commission]. (2019a). European Construction Sector Observatory - Analytical Report. https://ec.europa.eu/docsroom/documents/33883/attachments/1/translations/en/renditions/native (Accessed on 25.07.2023)

[4] EC [European Commission]. (2010) Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings OJ L 153, 18.6.2010, p. 13–35 (BG, ES, CS, DA, DE, ET, EL, EN, FR, IT, LV, LT, HU, MT, NL, PL, PT, RO, SK, SL, FI, SV) Special edition in Croatian, 12(3). 124 – 146.

[5] EU [European Commission]. (n.d.). Construction. Internal Market, Industry, Entrepreneurship and SMEs. https://commission.europa.eu/about-european-commission/departments-and-executive-agencies/internal-market-industry-entrepreneurship-and-smes_en (Accessed on 20.08.2023)

Author Manuscript

Author Manuscript

[6] Röck, M., Saade, M. R. M., Balouktsi, M., Rasmussen, F. N., Birgisdottir, H., Frischknecht, R., ... & Passer, A. (2020). Embodied GHG emissions of buildings–The hidden challenge for effective climate change mitigation. Applied Energy, 258, 114107. https://doi.org/10.1016/j.apenergy.2019.114107

[7] Delavar, H., & Sahebi, H. (2020). A sustainable mathematical model for design of net zero energy buildings. Heliyon, 6(1), e03190. https://doi.org/10.1016/j.heliyon.2020.e03190

[8] Umdu, D. Ç., & Alakavuk E. (2020) Avrupa Birliği'nin sürdürülebilirlik, enerji verimliliği ve akıllı şehirlere bakış açısı (in Turkish), Mühendislik ve Mimarlik Arastırmaları Teori, Uygulama ve Yeni Yaklaşımlar, Ed. Dr. Öğr. Üyesi Serhan Haner, IKSAD, 3-30.

[9] Moazzen, N., Ashrafian, T., Yilmaz, Z., & Karagüler, M. E. (2020) A multi-criteria approach to affordable energy-efficient retrofit of primary school buildings. Applied Energy, 268, 115046.

[10] EC [European Commission]. (2019b). Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal. COM/2019/640 final.

[11] EC [European Commission]. (2020). Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999 (European Climate Law) COM/2020/80 final.

Author Manuscript

[12] EC [European Commission] (2012). COMMUNICATION FROM COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL Strategy for the sustainable competitiveness of the construction sector and its enterprises. COM/2012/0433 final. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52012DC0433 (Accessed on 25. 06.2022)

[13] Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast) (Text with EEA relevance)

[14] EC [European Comission]. (2023). Energy Performance of Buildings Directive. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en (Accessed on 10/02/2024).

[15] EC [European Commission]. (2023, December 7). Commission welcomes political agreement on new rules to boost energy performance of buildings across the EU. https://ec.europa.eu/commission/presscorner/detail/en/ip_23_6423 (Accessed on 10/02/2024).

[16] Rao, P. (2023). The $16 trillion European Union economy. Visual Capitalist. https://www.visualcapitalist.com/16-trillion-european-union-economy/ (Accessed on 25.07.2023)

[17] TUIK [Türkiye İstatistik Kurumu]. (2022). Sektör bilançoları, 2021 [Sector balance sheets, 2021].

Author Manuscript

[18] Magrini, A., Lentini, G., Cuman, S., Bodrato, A., & Marenco, L. (2020) From nearly zero energy buildings (NZEB) to positive energy buildings (PEB): The next challenge-the most recent European trends with some notes on the energy analysis of a forerunner PEB example. Developments in the Built Environment, 3, 100019. https://doi.org/10.1016/j.dibe.2020.100019

[19] Saygin, D., Ercumen, Y., De Groote, M., & Bean, F. (2019). Enhancing Turkey's Policy Framework for Energy Efficiency of Buildings, and Recommendations for the Way Forward Based on International Experiences. SHURA Energy Transition Center and the Buildings Performance Institute Europe https://shura.org.tr/wp-content/uploads/2019/06/SHURA-2019-06-Enhancing-Turkeys-Policy-Framework-for-Energy-Efficiency-of-Buildings.pdf (Accessed on 25. 06.2022)

[20] Republic of Turkey Official Newspaper. (2007). 5627 Enerji Verimliliği Kanunu [5627 Energy Efficiency Law]. T.C. Resmi Gazete. https://www.mevzuat.gov.tr/mevzuat?MevzuatNo=5627&MevzuatTur=1&MevzuatTertip=5 (Accessed on 25.07.2023)

[21] TSE [Türk Standartları Enstitüsü] (2013). TSE 825, Thermal insulation requirements for buildings. The Turkish Standards Institute, Ankara

[22] Directive (EU) 2023/1791 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast)

Author Manuscript

[23] Umdu, E. S. (2018). Turkiye Bina Stoğu Durum Analizi [Turkey Building Stock Situation Analysis]. Paper presented at Workshop on Near Zero Buildings, DKTI Programme for Energy Efficiency in Public Buildings in Turkey: 28 June, Ankara, Turkey.

[24] Erhorn, H., & Erhorn-Kluttig, H. (2018). Overview of national applications of the nearly zero-energy building (NZEB) definition Detailed report. Concerted Action. Energy Performance of Buildings. https://epbd-ca.eu/wp-content/uploads/2019/06/CT1-Factsheet-National_applications_of_NZEB_definition.pdf (Accessed 25.06.2021)

[25] Republic of Turkey Ministry of Environment and Urbanization. (2020). Neredeyse Sıfır Enerjili Binalar (NSEB) için Rehber Kitap. Ankara: Republic of Turkey Ministry of Environment and Urbanization.

[26] Ali, H. M., Rehman, T. U., Arıcı, M., Said, Z., Duraković, B., Mohammed, H. I., ... & Teggar, M. (2024). Advances in thermal energy storage: Fundamentals and applications. Progress in Energy and Combustion Science, 100, 101109.

[27] Büyükalaca, O., Bulut, H., & Yılmaz, T. (2001) Analysis of variable-base heating and cooling degree-days for Turkey. Applied Energy, 69(4), 269-283. https://doi.org/10.1016/S0306-2619(01)00017-4

[28] Aydin, N., & Biyikoğlu, A. (2021). Determination of optimum insulation thickness by life cycle cost analysis for residential buildings in Turkey. Science and Technology for the Built Environment, 27(1), 2-13. https://doi.org/10.1080/23744731.2020.1776066

[29] ISO, EN. "15978, Sustainability of Construction Works. Assessment of Environmental Performance of Buildings." (2011).

Author Manuscript

[30] Ministry of Environment and Urbanization "Notice on Approximate Unit Costs of Construction in 2021 to Be Used in The Account of Architecture and Engineering Service Fees", Official Gazette, 24 Mart 2021, No: 31433. https://www.resmigazete.gov.tr/fihrist?tarih=2021-03-24, (Accessed on 12/02/2024)

[31] EPDK [Enerji Piyasası Düzenleme Kurumu - Energy Market Regulatory Authority]. Elektrik Faturalarına Esas Tarife Tabloları (in Turkish) https://www.epdk.gov.tr/Detay/Icerik/3-1327/elektrik-faturalarina-esas-tarife-tablolari, (Accessed 22.07.2023)

[32] Bahramian, M., & Yetilmezsoy, K. (2020). Life cycle assessment of the building industry: An overview of two decades of research (1995–2018). Energy and Buildings, 219, 109917.

[33] Mearing, & Moris. (2018). Life Cycle Cost Analysis Handbook (2nd ed.). State of Alaska - Department of Education & Early Development. https://education.alaska.gov/facilities/publications/LCCAHandbook.pdf (Accessed on 20/01/2024).

[34] Curran, M. A. (2013). Life cycle assessment: a review of the methodology and its application to sustainability. Current Opinion in Chemical Engineering, 2(3), 273-277. https://doi.org/10.1016/j.coche.2013.02.002

[35] Athena Sustainable Materials Institute. (n.d.). LCA, LCI, LCIA, LCC: What's the Difference? Athena Sustainable Materials Institute. https://www.athenasmi.org/resources/about-lca/whats-the-difference/ (Accessed on 12/02/2024).

Author Manuscript

[36] Grieder, A., Hubler, P., Pöll, M. (2016) Ökobilanz Betonfertigteile. Schlussbericht. Stadt Zürich, Amt für Hochbauten. Zürich. https://www.stadt-zuerich.ch/hbd/de/index/hochbau/bauen-fuer-2000-watt/grundlagen-studienergebnisse/archiv-studien/2016/2016-07-nb-oekobilanz-betonfertigteile.html, (Accessed on 20/08/2023)

[37] Hamida, A., Alsudairi, A., Alshaibani, K., & Alshamrani, O. (2022). Parametric study of the impact of building envelope systems on embodied and operational carbon of residential buildings. International Journal of Building Pathology and Adaptation, 40(5), 753-774. https://doi.org/10.1108/IJBPA-08-2020-0064

[38] Mannheim, V., Fehér, Z. S., & Siménfalvi, Z. (2019). Innovative solutions for the building industry to improve sustainability performance with Life Cycle Assessment modelling. Solutions for Sustainable Development, 1st ed.; CRC Press: Boca Raton, FL, USA, 245-253. https://doi.org/10.1201/9780367824037-31

[39] Kaya, D., Çanka Kılıç, F., Öztürk, H.H. (2021). Energy Performance Certificate. In: Energy Management and Energy Efficiency in Industry. Green Energy and Technology. Springer, Cham. https://doi.org/10.1007/978-3-030-25995-2_5