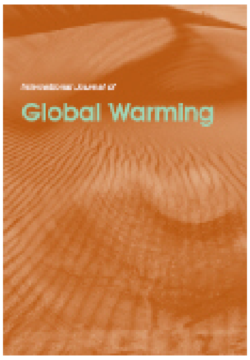

International Journal of Global Warming

ISSN online: 1758-2091 - ISSN print: 1758-2083
https://www.inderscience.com/ijgw

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Kübra Sumer Haydaraslan, Yalçın Yaşar

DOI: 10.1504/IJGW.2023.10055641

Article History:

Received:	26 March 2022
Last revised:	25 August 2022
Accepted:	06 September 2022
Published online:	24 April 2023

Evaluation of building design strategies according to the effects of climate change by simulation-based optimisation: a case study for housing in different climate regions

Kübra Sumer Haydaraslan*

Department of Architecture,
Süleyman Demirel University,
Isparta, Turkey
Email: kubrahaydaraslan@sdu.edu.tr
*Corresponding author

Yalçın Yaşar

Department of Architecture,
Karadeniz Technical University,
Trabzon, Turkey
Email: yyasar@ktu.edu.tr

Abstract: The lifespan of buildings has been extended due to technological developments. It is predicted that 75%–90% of the existing buildings will continue to be used in 2050. Buildings have an important place in total energy consumption and carbon emissions. With the measures taken in buildings, it is possible to reduce energy consumption by 25%–40%. In this study, we analysed ways to reduce the energy consumption of existing buildings by taking into account the effects of climate change. In the study, a numerical study was conducted on reducing PEC and CO_2 emissions in existing buildings. The suggestions for the buildings were created based on the optimum building envelope, mechanical system, and building form group. These optimum suggestions were optimised with the NSGA II algorithm, taking into account the climate change scenarios from 2020 to 2080. As a result, the province with the lowest decrease in PEC and CO_2 emissions was Kirikkale (PEC 36%, CO_2 33%) and the province with the highest number was Isparta (PEC 69%, CO_2 75%). Regionally, the region with the lowest decrease in PEC and CO_2 emissions was the Aegean Region (PEC 41%, CO_2 42%) and the region with the highest number was the Mediterranean Region (PEC 68%, CO_2 72%).

Keywords: building energy consumption; CO_2 emission; simulation-based optimisation; NSGA II; climate change.

Reference to this paper should be made as follows: Sumer Haydaraslan, K. and Yaşar, Y. (2023) 'Evaluation of building design strategies according to the effects of climate change by simulation-based optimisation: a case study for housing in different climate regions', *Int. J. Global Warming*, Vol. 30, No. 1, pp.33–59.

Biographical notes: Kübra Sumer Haydaraslan is a Research Assistant at Süleyman Demirel University, Faculty of Architecture, Department of Architecture. She has received her PhD in Building Science from Karadeniz Technical University in 2021. She conducts research on climate change and building energy consumption.

Yalçın Yaşar was a Professor Doctor at Karadeniz Technical University, Faculty of Architecture, Department of Architecture. He has received her PhD in Building Science from Karadeniz Technical University in 1989. He conducted research on building material and building energy consumption.

1 Introduction

The amount of greenhouse gas emissions are increasing due to the use of mostly fossil fuels as an energy source. Energy consumption-based CO_2 emissions increased by 1.7% from 2010 to 2018. This rate means 33.1 Gt of CO_2 emissions and it reached a historical record level (Tracking Clean Energy Progress, 2019; Report of the Intergovernmental Panel on Climate Change, 2014). The increase in the amount of CO_2 emissions all over the world causes climate change. Climate change has become an important problem for the world in recent years. The international climate change panel predicts that temperatures will increase in the range of 1.1°C–6.4°C till the end of the 21st century. In addition, it has been stated that one of the main reasons for this temperature increase is the use of fossil fuels (Report of the Intergovernmental Panel on Climate Change, 2014). About one-fifth of the increase in energy consumption in 2018 was witnessed because of the rise of temperature based to climate change and the necessity for cooling (Tracking Clean Energy Progress, 2019. Therefore, efficient energy use has become significant to reduce damage given to the environment. Because buildings are the most energy consumed areas there have been future strategies and plans to reduce energy demand and consumption in buildings (Climate Change Strategy (2010–2023), 2020; National Energy Efficiency Action Plan, 2020).

The energy consumption rate of buildings in Europe is 60%. 50% of this consumption is for heating and cooling of buildings. 65% of this consumed energy is provided from fossil sources (Energy Technology Perspectives, 2016). It is necessary to decrease the energy consumption of buildings to reduce the amount of CO_2 emissions. In addition, reducing the amount of CO_2 emissions is necessary to decrease the effects of climate change. On the other hand, although studies are carried out to reduce the effects of climate change, buildings need to adapt to climate change according to the best scenarios. In this regard, there are studies examining building envelope elements (Huang and Hwang, 2016; Domínguez-Amarillo et al., 2019), effects on building electricity consumption (Nik et al., 2015), mechanical system performances (Vong, 2016; Kurnitski et al., 2014), and energy consumption costs according to projected future climate scenarios (Chan, 2011; Wan et al., 2012). Furthermore, energy plans and directives are published to minimise energy consumption and CO_2 emissions in buildings (Energy Technology Perspectives, 2016). According to those published directives, parameters affecting the energy consumption of buildings are building design, building location and orientation, thermal properties of the building (heat insulation, heat capacity, passive heating and cooling elements, thermal bridges), heating and cooling systems, building lighting, passive solar systems, and interior space conditions (Directive 2002/91/EC of the European Parliament and of the Council, 2003; EPBD Recast Directive 2010/31/EU of the European Parliament and of Council, 2010; Directive 2010/31/EU of the European Parliament and of Council, 2018).

The energy consumption of buildings with the same physical characteristics varies according to their location on land. This is caused by shading, the amount of solar radiation reaching the surface and wind speed. Therefore, to reduce energy consumption and CO_2 emissions in buildings, the relationship of the building with the environment should be considered (Sanaieian et al., 2014). One of the most important factors in the relationship between the building and the environment is the shape factor (SF) of the building. There have been studies on the effect of SF on energy consumption (Hachem et al., 2011; Berkovic et al., 2012). One of the most important elements in the thermal properties of the building is the building envelope. The building envelope is in direct interaction with the external environment. The material types, thermal properties, and layer thicknesses of the elements in the building envelope (roof, flooring, exterior wall, window, door, etc.) affect energy consumption. Building energy consumption can be greatly reduced by applying thermal insulation to external walls (Cheung, 2011; de Oliveira Neves and Marques, 2017). Within EU climate and energy goals it has been suggested to renovate existing buildings with advanced construction techniques and increase the use of thermal insulation materials which have higher energy performance (European Union Energy Topics, 2019).

The International Energy Agency (IEA) has divided the areas where innovation is required in the building envelope into different topics. These topics are airflow, airtightness, ventilation controls, enhanced windows, building integrated storage systems, and renewable energy technologies (Energy Information Administration, 2019). Phase changing materials (PCM) are used in building-integrated storage systems. PCM can hold in the heat via absorption when the temperature rises, and they are also able to release it when the temperature falls (Auzebya et al., 2017). The use of PCMs as a storage medium in both cooling and heating applications can dramatically reduce the energy need of the building thanks to its high hidden heat under low temperatures. (Thambidurai et al., 2015). The EU proposed to increase the intensity of the use of PCMs in its energy plan in 2015 (The Strategic Energy Technology (SET) Plan, 2019). PCMs s can be applied to different parts of buildings such as ceilings (Karaoulis, 2017; Wang et al., 2018), exterior walls, roofs (Tokuç et al., 2015), etc.

Another of the building envelope elements is windows. With the changes made in the window systems, the energy consumption of the buildings can decrease. The glass used in windows has an important role in heat transfer. In this regard, the IEA has made some recommendations for countries depending on whether the building is existing or newly built, the climate where the building is located, and the development level of the country (Technology Roadmap, 2019). In the studies conducted by the IEA, it has been emphasised that investment in advanced glass technologies will be positive in terms of energy consumption costs in the long run. It has been stated that the single glazing that is still used in many countries should be avoided to ensure energy conservation of the buildings. It has been suggested to use double glazing, low-e and advanced glazing instead of single glazing (Technology Roadmap, 2019). In addition, the IEA has suggested that instead of replacing the windows in existing and new buildings, window film can be applied (Single-Pane Highly Insulating Efficient Lucid Designs, 2020). Considering the cost and technical features, it has been found that the replacement of existing windows to improve the energy performance of buildings is not optimal in terms of cost and time (Kaklauskas et al., 2006). On the other hand, in buildings in hot climate too much heat transfer from outside causes an overheated inner environment. Shading elements are used in buildings for overheating problems (Kirimtata et al., 2019; Leal and Maldonado, 2008). Shading elements are widely preferred in hot climates due to their ease of application and low cost (Mandalaki et al., 2014; Valladares-Rendón and Lo, 2014).

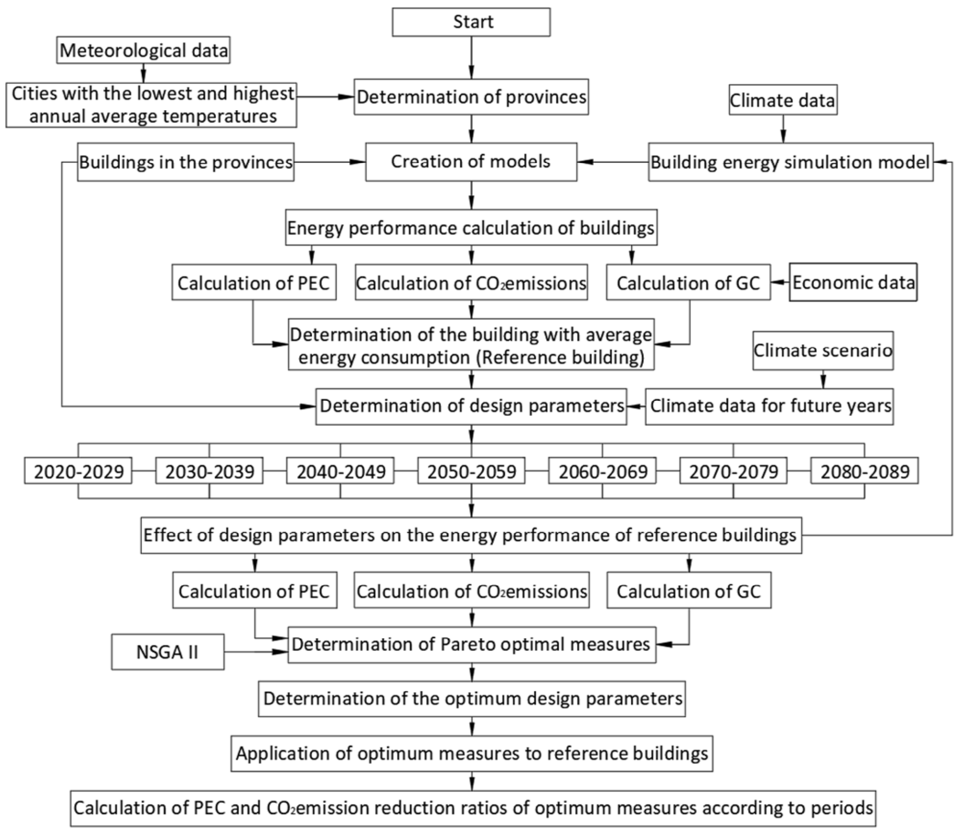
In the energy efficiency directives, it is stated that the mechanical systems in existing buildings should be improved and the use of renewable energy sources in new buildings should be increased to achieve energy saving targets (Directive 2012/27/EU of The European Parliament and of The Council, 2012). In studies for the improvement of mechanical systems some suggestions were offered, replacing individual systems with central/regional systems (Delmastro et al., 2016; Oliveira Panao et al., 2013), changing current system types with more efficient ones, providing electricity from the solar based photovoltaic (PV) panels (Becchio et al., 2016; Hailu et al., 2015), and using renewable energy as a source of energy for heating/cooling needs of buildings (Delmastro et al., 2017; Xia et al., 2017). In studies examining the energy performance of buildings, it has been observed that many parameters affect the energy consumption and CO_2 emission of buildings. The initial investment cost may be high in some of the suggestions for reducing building energy consumption. For this reason, in addition to reducing energy consumption in buildings, results such as cost, and life cycle should also be examined. Optimisation studies are carried out to find the minimum value of each of the parameters such as energy consumption, CO_2 emission, and cost. In optimisation studies on energy consumption in buildings, simulation-based optimisation (simultaneous operation of building simulation tools and optimisation tools) is mostly applied (Zhao and Du, 2020; Zhai et al., 2019).

In the coming years, it is predicted that 75%–90% of the existing buildings in the northern hemisphere will continue to be used in 2050. In addition, the effects of climate change will continue to increase. Therefore, this study, it was aimed to reduce the energy consumption of existing and new buildings by taking into account the effects of climate change. It is known that the energy consumed in buildings can be reduced by 25%–40% with the taken measures (Chowdhury et al., 2008). Within this framework in directives issued by the EU in 2012, it is advised that renovations should be done to reduce the energy consumption of existing buildings with optimal solutions (Sumer Haydaraslan, 2021). In comprehensive studies of the literature on the reduction of building energy consumption, a certain scenario has been created generally with design parameters. Afterwards, the effects of scenario suggestions on primary energy consumption (PEC) have been examined. However, in this study, optimisations have been made by combining many design parameters. As a result of the optimisation, many scenarios have been obtained. Suggestions in these scenarios have been categorised as nearly zero-energy building (nZEB), utopia, and cost optimum. A suggestion has been chosen among others in accordance with the aim of the study.

2 Methods

In this study, existing and new buildings were studied to achieve the goals specified in the long-term energy plans and strategies. The building envelope, mechanical system and building form design parameters were investigated in terms of optimum PEC, CO_2 emission and global cost (GC). Future climate data were used considering future climate scenarios. The study was conducted over ten-year periods from 2020 to 2089, using future climate data. Future climate data was generated using the IPCC AR4 A1B scenario. In addition, it was aimed to reduce PEC and CO_2 emissions gradually over the years. The method flow diagram of the study is given in Figure 1 (Sumer Haydaraslan, 2021).

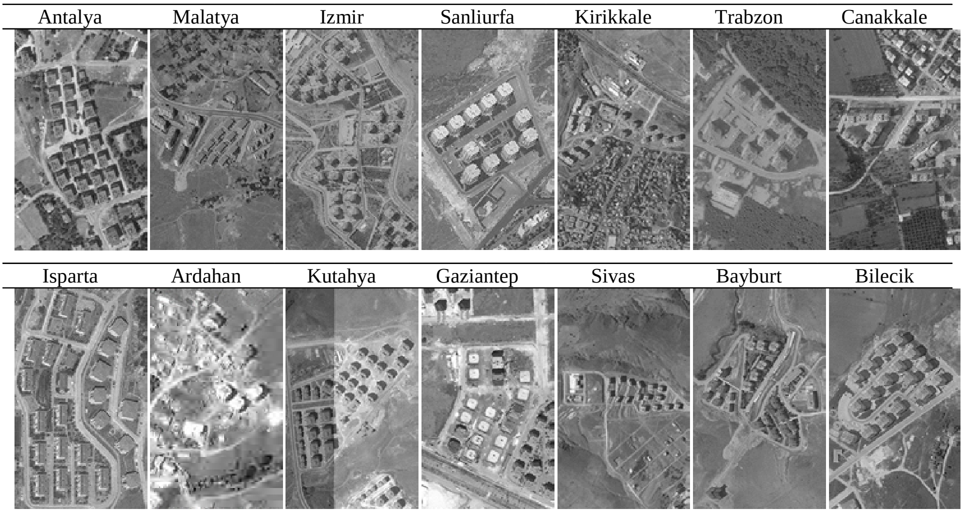
Figure 1 Flow chart of the method



2.1 Analysed buildings

The study was conducted in seven different geographical regions of Turkey. Two provinces (fourteen in total) with the lowest and highest annual average outdoor temperatures were selected as study provinces from these regions. Thanks to the different climatic and geographical characteristics of these provinces, all geographical regions and climate types were represented. In the study, the buildings in these provinces investigated, which were built by the Republic of Turkey Prime Ministry Housing Development Administration (TOKI). The provinces selected for the study and the site plans of the selected buildings in these provinces are given in Figure 2.

Figure 2 The provinces selected for the study and the site plans of the selected settlements in these provinces



The buildings in the settlements have nine different architectural plans in total. These plans are given in Figure 3. The total number of buildings in each settlement is different. For this reason, a building representing all the buildings in the settlement was determined for each settlement. A preliminary study was carried out for these buildings. In the preliminary study, the building closest to the average PEC of each settlement was determined as the study building.

The technical specifications of the building construction components were determined according to the TS 825 Thermal Insulation Rules in Buildings (Turkish Standardization Institute, 2013). The heating system of the buildings is usually a solid fuel or natural gas sourced central system. There is no cooling and ventilation system except in hot climates. The domestic hot water system is individual. These features of the buildings were taken as references for the study. Architectural plan type, construction year, the total heat transmission coefficient of the wall (Uwall) of the exterior walls, and mechanical system information of the buildings were given in Table 1.

Figure 3 Architectural plan type

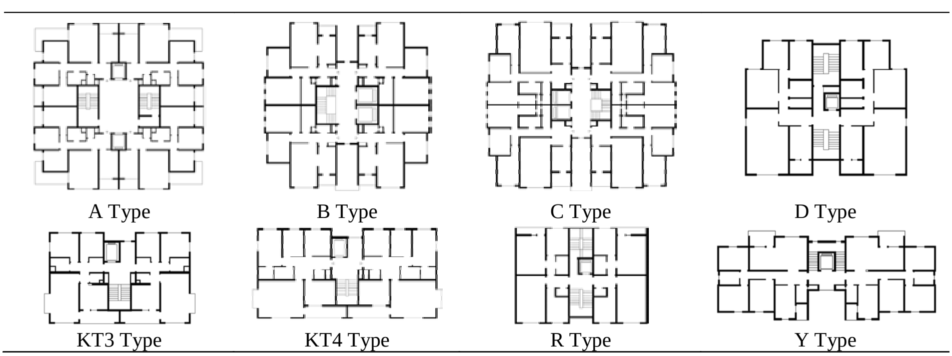


Table 1 Information on reference buildings

Province	*Year*	*Plan type*	U_{wall} (W/m^2K)	*Insulation thickness (m)*	*Mechanical system*		
					Heating system	*Cooling system*	*Domestic hot water*
Antalya	2018	B, C	0.356	0.04	Centre (coal)	Elec.	Individual (elec.)
Isparta	2016	B, C	0.396	0.06	Centre (coal)	-	Individual (elec.)
Malatya	2004	C, D, R	0.327	0.09	Centre (coal)	-	Individual (elec.)
Ardahan	2017	B	0.327	0.09	Centre (coal)	-	Individual (elec.)
İzmir	2006	B, C	0.396	0.04	Centre (coal)	Elec.	Individual (elec.)
Kutahya	2018	B, C, Y	0.390	0.07	Centre (nat. gas)	-	Individual (nat. gas)
Sanliurfa	2018	B	0.433	0.06	Centre (coal)	-	Individual (elec.)
Gaziantep	2019	B, C	0.433	0.06	Centre (nat. gas)	-	Individual (nat. gas)
Kirikkale	2019	B, C	0.390	0.07	Centre (nat. gas)	-	Individual (nat. gas)
Sivas	2018	B, C	0.302	0.10	Centre (nat. gas)	-	Individual (nat. gas)
Trabzon	2019	A, B	0.390	0.07	Centre (coal)	-	Individual (elec.)
Bayburt	2012	C	0.390	0.08	Centre (nat. gas)	-	Individual (nat. gas)
Canakkale	2019	KT3, 4	0.433	0.06	Centre (nat. gas)	-	Individual (nat. gas)
Bilecik	2013	B, C	0.390	0.07	Centre (coal)	-	Individual (elec.)

2.2 *Mathematical model*

In the study, PEC, CO_2 emission and GC were calculated for the energy performance calculation of the buildings.

- PEC:

$$\dot{Q}_{PEC} = \sum \left(\dot{Q}_{cons} \times K_{PE} \right) \tag{1}$$

- CO_2 emission:

$$E_{CO_2} = \sum \left(\dot{Q}_{cons} \times K_{CO_2} \right) \tag{2}$$

- GC:

$$C_G(T) = C_I + \sum_{i=1}^{T} \left(C_a(i) \times f_{pv}(i) \right) - \sum_{j} V_{T-f}(j) \tag{3}$$

K_{PE} and K_{CO_2} in equations (1)–(2) are the conversion coefficients depending on the energy source. The primary energy conversion coefficient in Turkey is 2.36 for electricity and 1 for natural gas and other fuels. The CO_2 emission conversion coefficient is 0.626 for electricity, 0.234 for natural gas and 0.467 for solid fuel (CEDBIK, 2019). $\dot{Q}_{cons}$ is the annual energy consumption for each energy source. In the study, this value for heating and cooling was determined according to the energy loads of the building. Energy loads were calculated according to the ASHRAE thermal balance method. Details of this method were given in our previous study (Sumer Haydaraslan, 2021). The GC in Equation (3) is the sum of the present value of the investment (C_I) and operating ($C_a(i)$) costs (including only energy cost in this study) over the lifetime. The GC is determined by subtracting the scrap value of the equipment at the end of its life (V_{T-f} (j)) from this total. In the study, the GC calculation was calculated by considering the time value of the money factor ($f_{pv}(i)$). The market interest rate is 0.1942 and the inflation rate is 0.0966 in the time value of money factor calculation (The Central Bank of the Republic of Turkey (TCMB), 2020). While reducing the energy consumption of the buildings, suggestions were made for certain periods so that the occupants would not suddenly have high costs. Therefore, the calculation period was taken as 10 years. The equations were solved using the DesignBuilder software that co-operated with the EnergyPlus software.

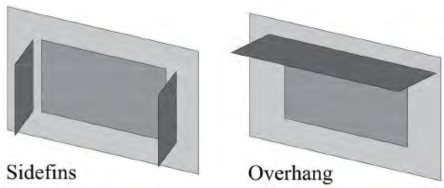
2.3 Numerical simulation

Building performance is the behaviour of the components of the building system under different conditions. The performance of buildings is examined as environmental performance, cost performance, comfort performance, and energy performance (Szigeti and Gerald, 2005). Building energy performance is expressed as buildings' final energy consumption, PEC, energy costs, CO_2 emissions etc. (Schüler et al., 2015; Monsalvete et al., 2015). To reduce the energy consumption of buildings, design support systems have been developed that can assist in the design phase of buildings. One of these design support systems is the use of simulation tools in building energy performance evaluation. Through these simulation tools, the size and shape of the building, the properties of the building elements used, heating, cooling, ventilation, lighting, etc. usage can be analysed. The analyses in this study were made with the DesignBuilder simulation tool. The buildings in the study were modelled with this simulation tool. The functions of the buildings, the properties of the building elements, the user profile and mechanical system information were defined. Equations (1), (2) and (3) were calculated using the simulation tool for the buildings in ten-year periods. Chan (2011) and Alam et al. (2014) validated the algorithm used in this study with an experimental study by Kuznik and Virgone (2009).

2.3.1 Design parameters

The design parameters in the study were in three groups building envelope, mechanical systems and building form. These design parameters and their contents, along with the codes representing the design parameters, are given in Table 2.

Figure 4 The view of the shading elements



An expanded polystyrene sheet (EPS) has been applied in existing buildings for thermal insulation. For this reason, eps was applied in the study. The case of thermal insulation thickness between 0.03 m and 0.14 m was examined. The heat transfer coefficient of the material at these thicknesses was 0.032 W/m K. Another design parameter from the building envelope was the use of PCM. Preliminary work was required for PCM to perform optimally in the study because PCMs performed differently according to boundary conditions. Therefore, the PCMs used in this study were determined according to our previous study (Sumer Haydaraslan, 2021). PCMs were applied to the inner surface of the wall in the provinces where cooling is carried out, at a melting temperature of 23 °C (BioPCM M27/Q23) and a layer thickness of 0.02 m; In provinces where cooling was not done, it was applied to the surface of the wall close to the interior, at a melting temperature of 21 °C (BioPCM M27/Q21) and a layer thickness of 0.02 m. In the study, three different models were selected from the market (Monsalvete et al., 2015) for the window films. Among these, according to the catalogue recommendations, the Ecolux model was used in cities where there was no need for cooling, and the Silver 50 and Silver AG 50 Low-e models were used in cities that needed cooling. The properties of the window films were given in Table 3 (Architectural Window Film, Products, Solar Gard, 2020). The last design parameter from the building envelope group was the use of the shading element. In the study, a total of four shading elements were used, two vertical (side fins) (0.5 and 1 m) and two horizontal (overhang) (0.5 and 1 m). The view of the shading elements used were given in Figure 4.

In the mechanical systems group, the energy source change became the design parameter in the existing systems. Solid fuel, natural gas, and ground source heat pumps were used in heating and hot water systems. In addition, solar energy support was added to these systems. An electric and ground source heat pump was used for the cooling system. In addition, PV collectors were used to generating electricity for the building. Solar thermal and PV collectors were placed on the roof slope and in numbers to fit on the roof surface. The SF was used as the design parameter in the building form group. Since the reference buildings were existing buildings, it was thought that the buildings would be demolished when their life span was completed. SFs were determined for the buildings to be rebuilt in the coming years. Since the total square meter of the buildings and the total number of flats were to be preserved, new SFs were determined with the aspect ratio of 1.8 and 4.5 by keeping the floor area and volume of the building constant Figure 5.

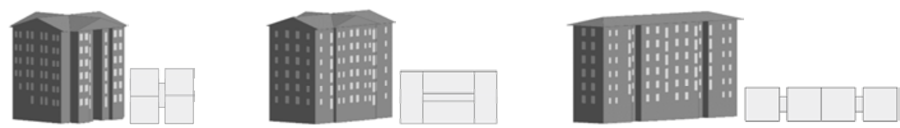
Table 2 Design parameters and codes

	Building envelope				*Mechanical systems*													*Building form*	
					Heating system						*Cooling system*		*DHW system*						
	Thermal insulation thickness	*Phase change material*	*Window film*	*Exterior shading*	*Solid fuel*	*Solar energy supported solid fuel*	*Natural gas*	*Solar energy supported natural gas*	*Heat pump*	*Solar energy supported heat pump*	*Electricity*	*Heat pump*	*Electricity*	*Natural Gas*	*Solar energy supported natural gas*	*Heat pump*	*Solar energy supported heat pump*	*PV collector*	*Building shape factor*
Code	*D*		*S*	*G*							*H*							*Y*	

Table 3 The window film properties

	Ecolux	*Silver 50*	*Silver AG 50*
Solar transmittance (%)	43	38	36
Outside solar reflectance (%)	28	23	27
Inside solar reflectance (%)	28	23	27
Visible transmittance (%)	68	53	51
Outside visible reflectance (%)	13	23	23
Inside visible reflectance (%)	4	22	27
Emissivity	0.09	0.77	0.37

Figure 5 Building forms in different SF



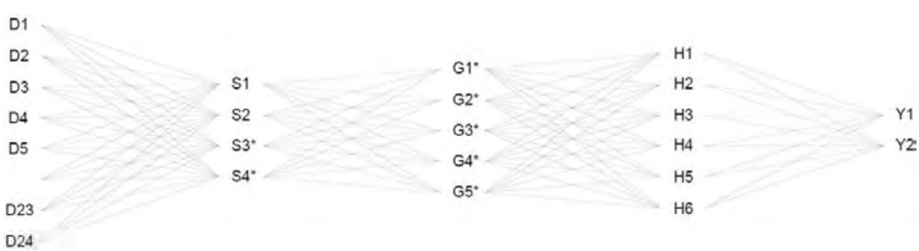
SF1 SF1.8 SF4.5

All the design parameters in Table 2 were not used in each province and period. The lifetime of the equipment used in these parameters was considered (EN 15459, 2007). When the life of the heating and cooling system was not completed, these systems were not used as design parameters for a decade. In cold climates, the shading element was not used as a design parameter. According to these constraints, the maximum number of suggestions that can be created with the design parameters was 5,760.

2.3.2 Optimisation and evaluation

NSGA II, which is widely used in the solution of multi-objective optimisation problems, was used in the study (Echenagucia et al., 2015). Optimisation objective function, constraints, design parameters, and optimisation parameter settings are given in Table 4. The combinations that may occur with all suggestions are given in Figure 6. Objective function of optimisation was to find the minimum values of PEC, CO_2 emissions, and GC values. The design variables were thermal insulation thickness change, PCM addition, film addition to windows, use of shading elements, mechanical system change, and use of renewable energy technology. Since the design parameter that was not expired was not included in the optimisation, no constraints were defined in the optimisation.

Figure 6 Combination of design parameters



Note: *Design parameters not used in hot climate.

Figure 7 NZEB, utopia and cost optimum points (see online version for colours)

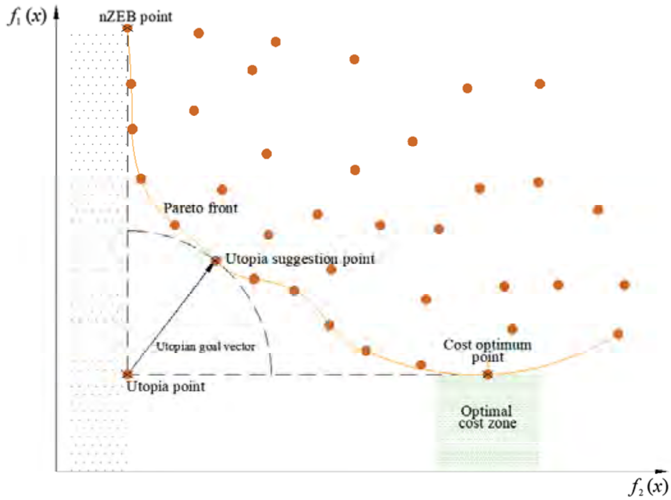


Table 4 Objective functions and design variables of the study

Objective functions	$f(x) = [f_1(x), f_2(x), f_3(x)]$ the minimum value of the function		
	$f_1(x) = \dot{Q}_{PEC} = \sum(\dot{Q}_{cons} \times K_{PE})$		
	$f_2(x) = E_{CO_2} = \sum(\dot{Q}_{cons} \times K_{CO_2})$		
	$f_3(x) = C_G(T) = C_I + \sum_{i=1}^{T}(C_a(i) \times f_{pv}(i)) - \sum_{j} V_{T-f}(j)$		
	$f_1(x)$: Primary energy consumption (kWh/year)		
	$f_2(x)$: CO_2 emission (kg/year)		
	$f3(x)$: Global cost (€/calculation period)		
Constraint	*No*		
Design variables	$f_1(x) = (x_1, x_2, x_3 \ldots x_n)^T$		
	$f_2(x) = (x_1, x_2, x_3 \ldots x_n)^T$		
	$f_3(x) = (x_1, x_2, x_3 \ldots x_n)^T$		
	Here the variables $x_1, x_2, x_3 \ldots x_n$;		
	D1, D2, D3 … D12	Thermal insulation thickness change	
	D13, D14, D15… D24	Change of thermal insulation thickness and addition of PCM	
	S1, S2, S3, S4	Adding film to windows	
	G1, G2, G3, G4, G5	Use of shading element	
	H1, H2, H3, H4, H5, H6	Mechanical system replacement	
	Y1, Y2	Use of renewable energy technologies	
Population size	*Maximum population*	*Mutation rate*	*Cross*
20	100	0.4	0.99

Pareto optimal solutions are preferred more than other solutions in multi-objective optimisation studies (Asadi et al., 2014; Delgarm et al., 2016). In the Pareto optimal solution, the choice should be made by following per under the purpose of the problem. In this study, this selection was made over three points. One of these points was the nZEB point. nZEB buildings have very low energy requirements and high energy performance (EPBD recast. Directive 2010/31/EU of the European parliament and of Council, 2010). The other point was the utopia point. The utopia point is the extreme value desired to be obtained in both objective functions. This point cannot be obtained in multi-objective optimisation problems but can be used as a reference between candidate points (Deb et al., 2002). A vector (utopian objective vector) is drawn concerning the utopia point. With this vector, a point on the pareto front line is determined. This point provides the ideal solution for each of the objective function components. In the study, this point was called the utopia objective point. The last of the selection points was the cost optimum point. This point in the study is the suggestion that the sum of the present value of the initial investment and operating costs over the lifetime is the lowest. nZEB, utopia and cost optimum points on the Pareto front line are given in Figure 7 (Nguyen et al., 2014). In the study, nZEB, utopia, and cost-optimal suggestions were determined for each ten-year period. For each period, one of these suggestions or a proposal suitable for the purpose of the study on the Pareto front was selected.

3 Results and discussion

In this sub-chapter, the optimisation model results are given for 14 cities in seven regions of Turkey to investigate the PEC, CO_2 emission rates and GC from the climate change indicators viewpoints.

3.1 The findings of the provinces by years

The design parameters given in Table 2 on the reference buildings in all provinces were applied in ten-year periods from 2020 to 2089. In Antalya, from 2020 to 2029, a total of 5760 combinations with all design parameters were optimised. The period’s nZEB, utopia, and cost optimum suggestions were D23.S4.G5.H6.Y2, D6.S3.G5.H6.Y1 * and D5*.S1*.G1*.H1*.Y1* respectively. The study, it was aimed to reduce the PEC and CO_2 emissions in buildings gradually over the years. In this period, the cost-optimal suggestion was the existing design parameters. Had the existing design parameters been continued, PEC and CO_2 emissions could have increased due to climate change. Therefore, the second cost-optimal suggestion (D5*.S1*.G5.H1*.Y1*) was chosen for this period. The shading element was used as the design parameter in this suggestion and so it was not used next period again design parameters. In the next periods, the number of suggestions increased or decreased depending on the design parameters selected in the previous period. The lifetime of the mechanical systems was accepted as twenty years. For this reason, if the design parameters in the mechanical system group were selected in the previous period, they were not used as redesign parameters in the next period. Since the buildings in Antalya were built in 2018, their lifetimes will be complete in the

2070–2079 period, and they will be rebuilt. Because of this, in this period, the effect of the SF from the building form group on PEC and CO_2 emission was examined first. The buildings were remodelled in SF 1, SF 1.7 and SF 4.5 SFs, preserving the existing floor area, volume, and flats number. According to the results, the settlement's average PEC and CO_2 emissions were at least SF 1.7 SF. Thus, SF 1.7 was used for the buildings to be reconstructed during this period. These results for all provinces, including Antalya, were given in Table 5. Considering these restrictions, the GC-PEC and GC-CO_2 emission optimisation results made in ten-year periods from 2020 to 2089 were given in Figure 8. All suggestions on the pareto front line or not for Antalya's optimisation result graphs are given separately for ten-year periods. However, for other provinces, these graphs were collected in a single graph only for the proposals on the pareto front line. A method like the Antalya solution was followed to generate these graphs. Suggestions on the pareto front line of all provinces (including Antalya) are given in Figure 9 for GC-PEC. It is also given in Figure 10 for GC-CO_2 emission.

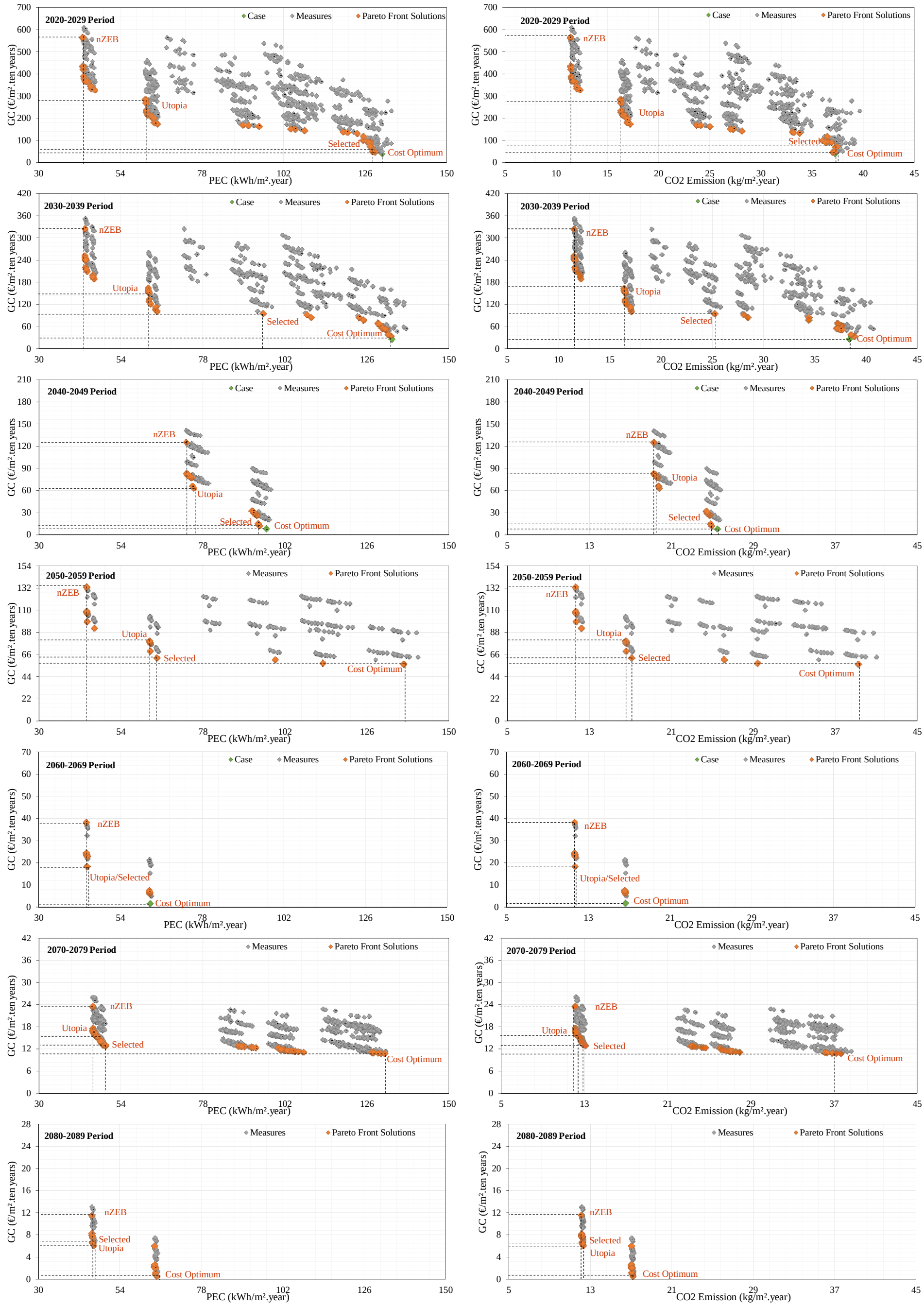
Table 5 SFs selected for all provinces

Province	*Period*	*Selected SF*	*Province*	*Period*	*Selected SF*
Antalya	2070–2079	SF 1.7	Isparta	2070–2079	SF 1.7
Malatya	2060–2069	SF 1	Ardahan	2070–2079	SF 1.7
İzmir	2060–2069	SF 4.5	Kütahya	2070–2079	SF 1.7
Şanlıurfa	2070–2079	SF 1	Gaziantep	2070–2079	SF 1
Kırıkkale	2070–2079	SF 1.7	Sivas	2070–2079	SF 1.7
Trabzon	2070–2079	SF 1.7	Bayburt	2070–2079	SF 1.7
Çanakkale	2070–2079	SF 1.7	Bilecik	2070–2079	SF 1.7

The design parameters, which constitute nZEB, utopia and cost optimum suggestions, affected the PEC and CO_2 emissions of the buildings at different rates depending on the climates of the provinces. So, the number of these design parameters in the suggestion groups also differed. The numbers (sum of study periods) for nZEB, utopia, cost optimum, and the number of times they were selected was determined for these parameters Figure 11.

From 2020 to 2089 in Antalya which is in the hot climate category, D22 and D23 were included once as design parameters in nZEB measures, while D24 was included five times. In Isparta which has a cold climate, between the same years, D24 was included for nZEB seven times. The initial investment costs of these design parameters, which include phase-change material, are high. Therefore, this parameter has been the utopia proposal and the cost optimum proposal. Design parameters with less thermal insulation thickness such as D1, D2 and D3 were not included in the selected recommendations. However, this parameter was included in the cost-optimal recommendations in most provinces. The reason was the low initial investment cost. However, since these design parameters did not reduce PEC and CO_2 emissions, they were not included in the selected recommendations. The design parameters from D4 to D12, where the thermal insulation thickness is higher, were selected in different numbers for most provinces.

Figure 8 Optimisation results for Antalya by periods (a) GC-PEC (b) GC-CO_2 Anatolia (see online version for colours)



(a) (b)

Figure 9 GC-PEC optimisation results by provinces and periods (see online version for colours)

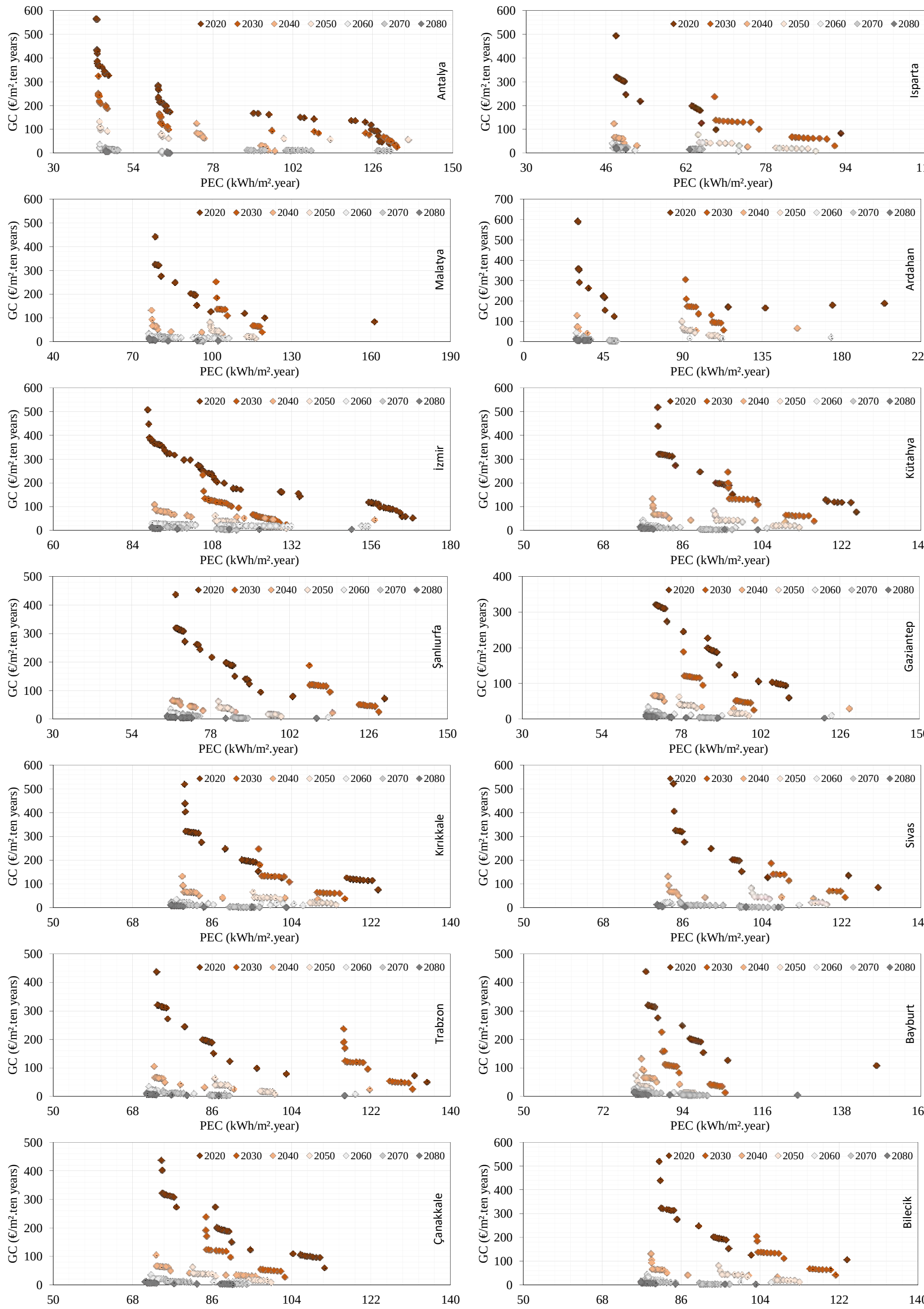


Figure 10 GC-CO_2 emission optimisation results by provinces and periods (see online version for colours)

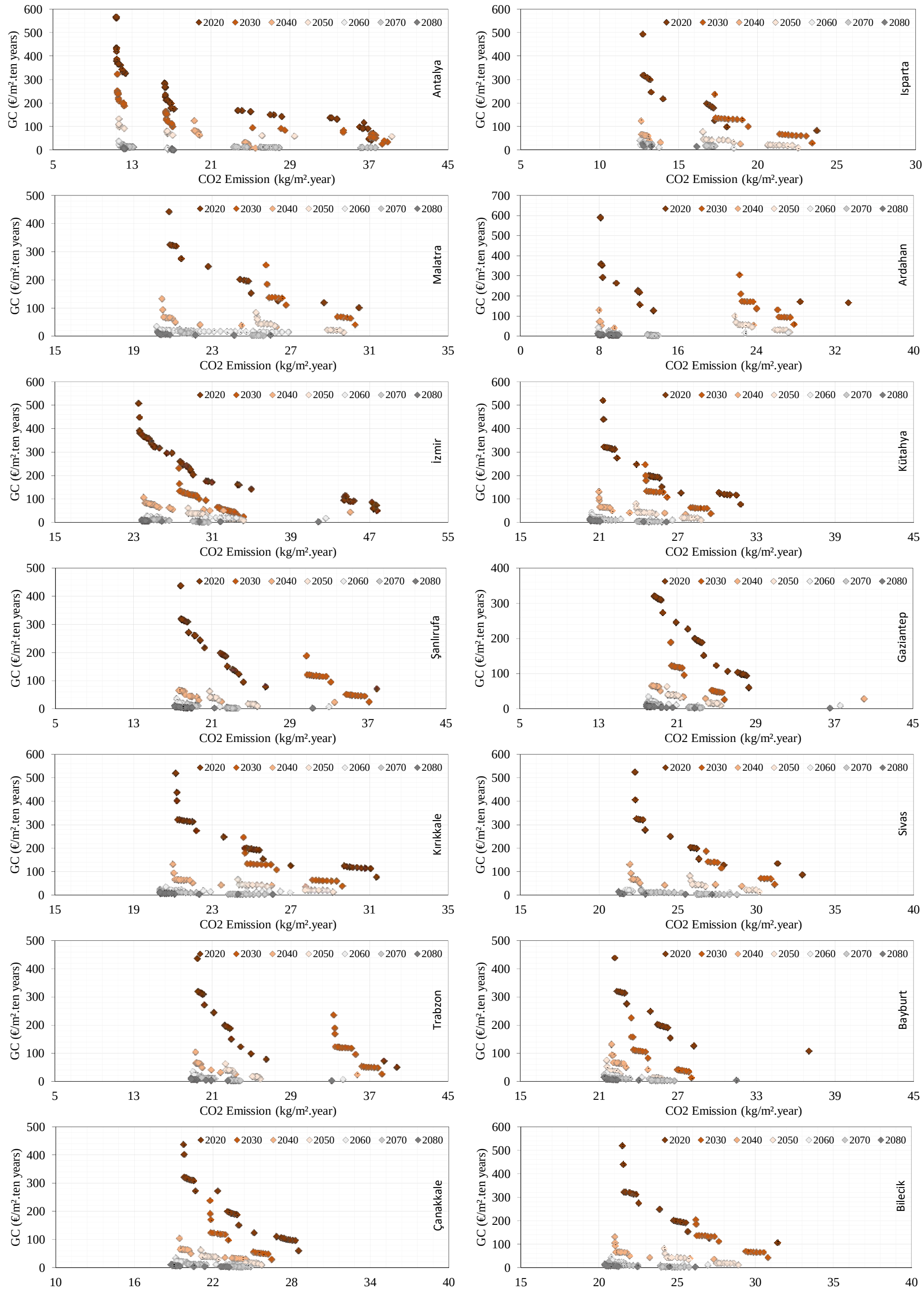


Figure 11 Number of selections of design parameters as measures by province (see online version for colours)

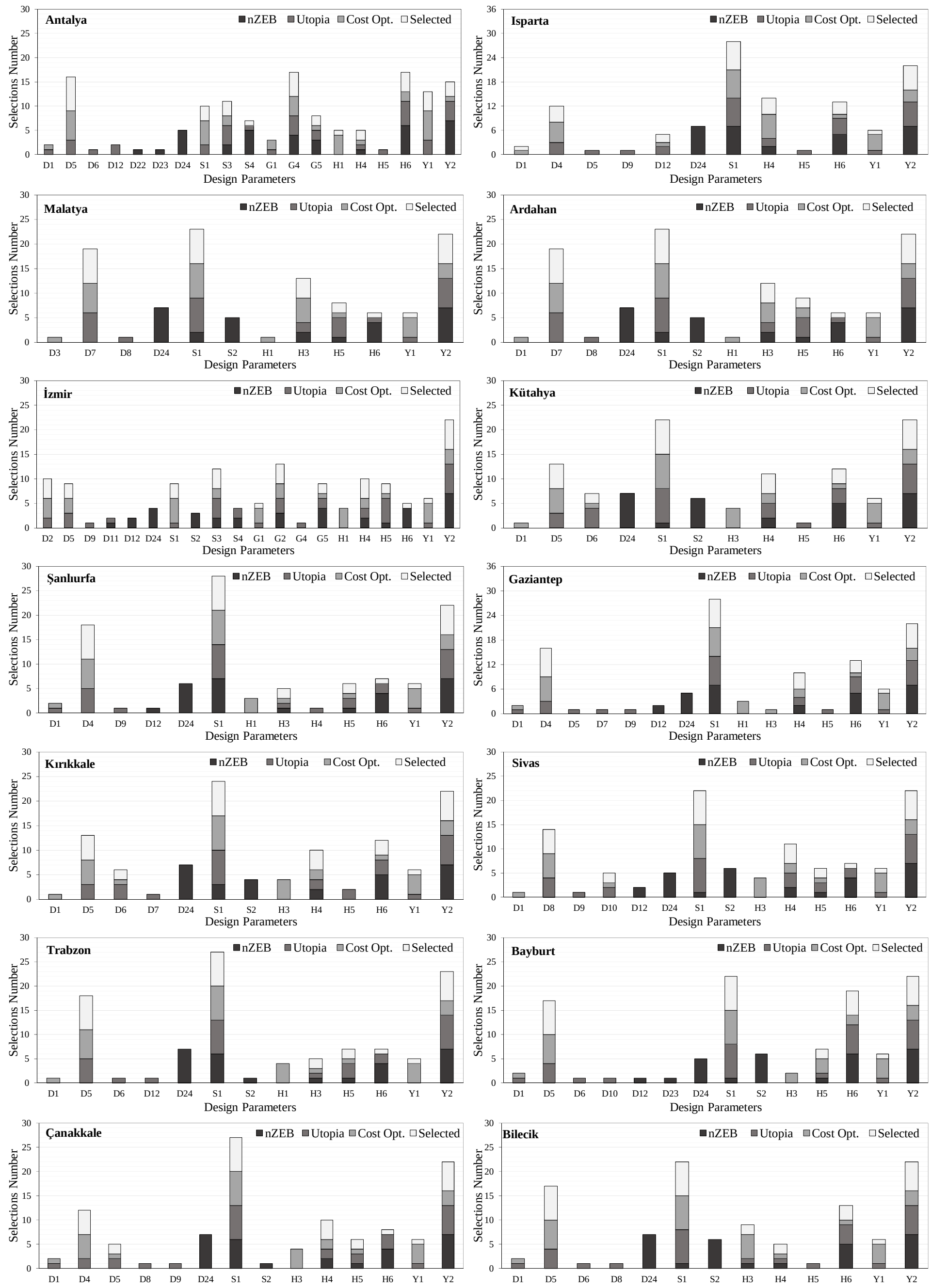
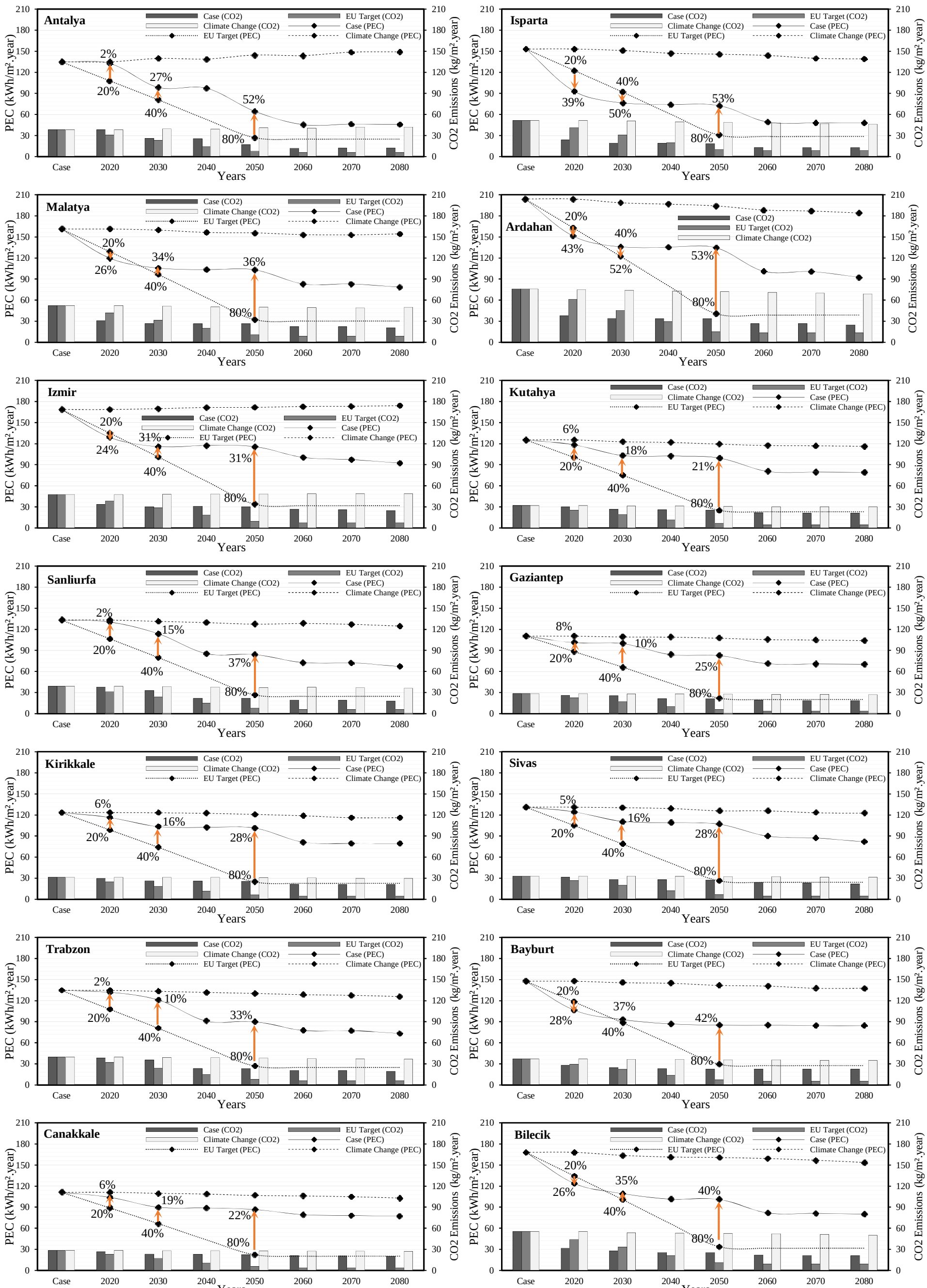


Figure 12 Changes in PEC and CO_2 emissions by years (see online version for colours)



From the building envelope group, S1 and S3 were chosen three times, S4 once, G4 five, and G5 twice in Antalya, while S1 nine, S2 three, S3 twelve and S4 four times in İzmir were chosen as design parameters. The high number of selections for these parameters showed that the use of window films and shading elements in cities with hot climates such as Antalya and Izmir are important in reducing energy consumption. In provinces such as Kutahya, Ardahan and Bayburt, S1 was chosen as the design parameter seven times. The high number of selections for this parameter showed that the use of window film in cities with cold climates had a low effect on reducing energy consumption, as well as high window film costs. In the mechanical systems group, the initial investment cost of the H1 design parameter is low. Therefore, this parameter was included in the cost-optimal recommendations. However, this parameter was not among the selected recommendations because it did not reduce PEC and CO_2 emissions. While H5 was included in the utopia and nZEB measure in the provinces where the sunshine duration was less, H6 was included in the utopia and nZEB measure in the provinces where the sunshine duration was high.

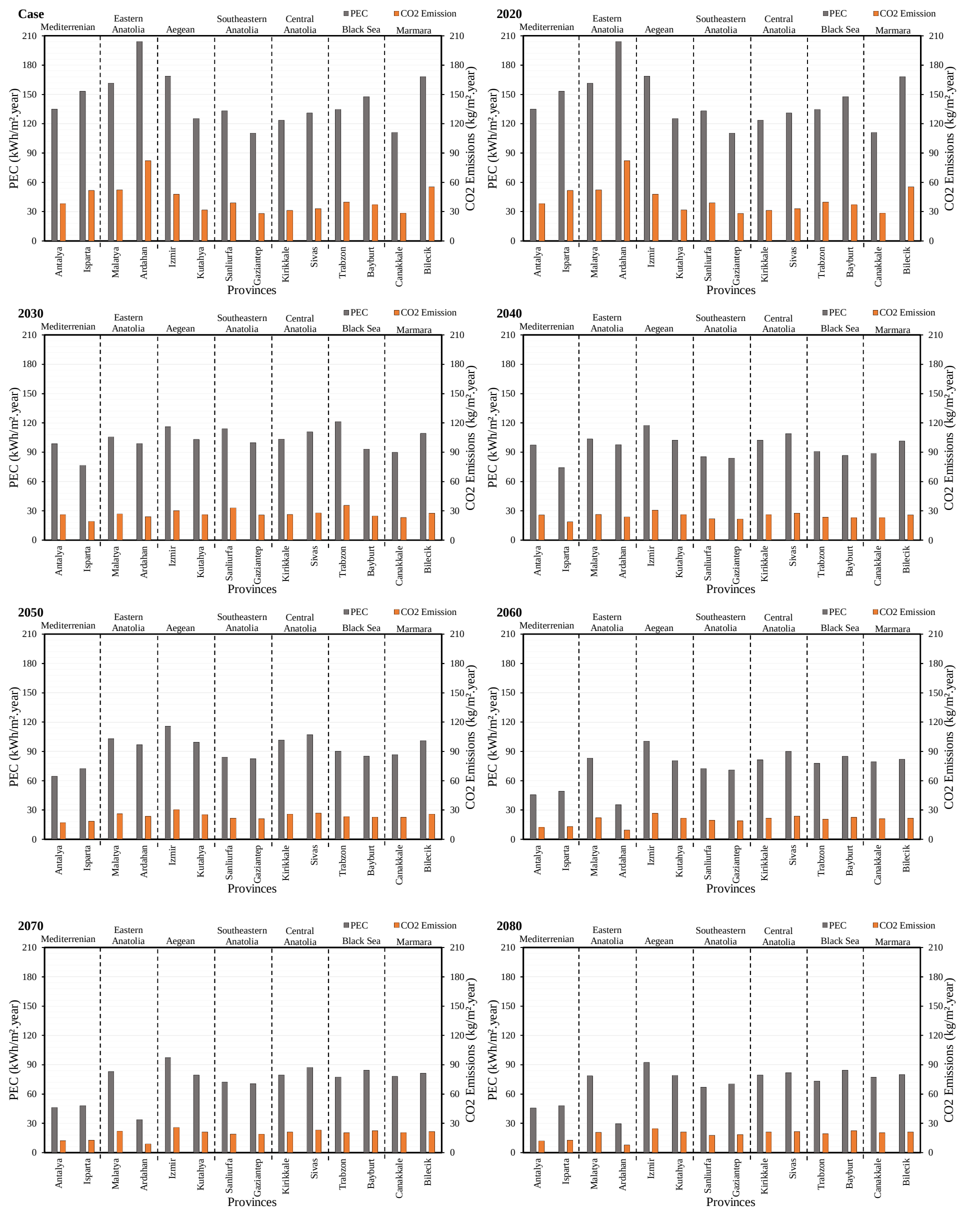
3.2 Energy consumption variation of provinces by years

In the study, PEC and CO_2 emissions of buildings were reduced gradually over ten-year periods. This decrease differed according to each selected province. The change of PEC and CO_2 emissions of all provinces used in the study by years is given in Figure 12. In addition, the EU has targets to reduce energy consumption and CO2 emissions by 20% in 2020, 40% in 2030 and 80-95% in 2080 compared to 1990 (National Long-Term Strategies, 2020). In this study, the existing PEC and CO_2 emissions of the buildings were taken as reference, instead of the EU reference year of 1990. The approach to these goals was given on the same figures. In addition, the effects of climate change on PEC and CO_2 emissions are given in the same figure if the current state of buildings is maintained until 2080.

According to the current situation in Antalya, which has a hot climate, PEC decreased by 2%, 27%, 28%, 52%, 66%, 66% and 67%, respectively, in the ten-year periods from 2020 to 2089. In addition, CO_2 emissions decreased by 1%, 32%, 33%, 55%, 68% and 69%. According to the current situation in Isparta, which is the coldest province of the Mediterranean Region, PEC decreased by %39, %50, %51, %53, %68, %69 and %69, respectively, in the ten-year periods from 2020 to 2089. In addition, CO_2 emissions decreased by %54, %62, %63, %64, %75, %75 and %75. In Malatya, which is the warmest province in the Eastern Anatolia Region, PEC decreased by 51% and CO_2 emission savings by 60% until 2089. In Ardahan, the coldest province of the region, PEC decreased by 56% and CO_2 emission savings by 68% thanks to the measures. In Izmir, one of the warmest provinces in Turkey, 45% savings were achieved in PEC and 48% in CO_2 emissions. In buildings in Kutahya, which has a cold climate feature, a savings rate of 37% in PEC and 34% in CO_2 emissions was achieved from 2020 to 2089. In the study, PEC and CO_2 emission savings rates for other provinces until 2089 compared to the current year 2020 are 50% and 54% in Sanliurfa, 36% and 34% in Gaziantep, 36% and 33% in Kirikkale, 38% in Sivas. and 35%, 46% and 51% in Trabzon, 43% and 40% in Bayburt, 30% and 28% in Canakkale, 52% and 61% in Bilecik. The aim of the study was achieved by reducing PEC and CO_2 emissions gradually over the years by using future climate data in the provinces. The EU's target of increasing the use of renewable energy by 20% in 2020 and 27% in 2030 was achieved. In addition, Turkey's target of a14% reduction in PEC between 2017 and 2023 was achieved (National Energy Efficiency Action Plan, 2020; National Long-Term Strategies, 2020). The current situation, PEC and

CO_2 emissions of provinces and regions from 2020 to 2089 in ten-year periods are given in Figure 13.

Figure 13 Changes in PEC and CO_2 emissions in ten-year periods according to regions and provinces (see online version for colours)



At the end of the ten-year periods, the province with the lowest decrease in PEC and CO_2 emissions was Kirikkale with a decrease of 36% for PEC and 33% for CO_2 emissions, while the province with the highest decrease was Isparta with a decrease of 69% for PEC and 75% for CO_2 emissions. It has been observed that in the provinces with high PEC and CO_2 emission reductions, a solid fuel-based heating system is currently used. Then, it was seen that this system gradually switched to the first natural gas source and then the heat pump source heating system. At the end of ten-year periods, the reduction in PEC and CO_2 emissions remained below 40% in provinces where natural gas-based heating systems were existing situation used. In addition, increasing the thermal insulation thickness compared to the current situation also affected these rates. Regionally, the region with the lowest decrease in PEC and CO_2 emissions at the end of ten-year periods was the Aegean Region, while the region with the highest rate was the Mediterranean Region.

4 Conclusions

In this paper, a numerical study was conducted to reduce PEC and CO_2 emissions in existing buildings in Turkey until 2089. The main conclusions were gained as follows:

Design parameters with phase-change material had high initial investment costs, even if they lowered the PEC. For this reason, nZEB was often among the suggestions. However, since these design parameters did not reduce PEC and CO_2 emissions, they were not included in the selected suggestions. The design parameters from D4 to D12, where the thermal insulation thickness was higher, were selected in different numbers according to the existing thermal insulation thickness in each province.

It was founded that the use of window films and shading elements is important in reducing energy consumption in provinces with hot climates such as Antalya and Izmir. On the other hand, it was seen that window film should not be preferred in cities with cold climates, since it reduces energy consumption to a small extent and has high costs.

In the mechanical systems group, the design parameters mostly included in the utopia and nZEB proposal, thanks to the high reduction of PEC and CO_2 emissions, were H5 in provinces with less sunshine duration than other provinces and H6 in provinces with more sunshine duration. These findings revealed that the use of solar-assisted heat pumps should become widespread in the future.

At the end of the decade, the province with the lowest decrease in PEC and CO_2 emissions was Kirikkale with a decrease of 36% for PEC and 33% for CO_2 emissions, while the province with the highest decrease was Isparta with a decrease of 69% for PEC and 75% for CO_2 emissions.

It was observed that in provinces with high PEC and CO_2 emission reductions, the solid fuel-based heating system is the existing situation used, and these systems gradually switched to first natural gas sourced, and then heat pump sourced heating systems. At the end of the decade, the decrease in PEC and CO_2 emissions remained below 40% on average in provinces where natural gas-based heating systems were used.

Regionally, the region with the lowest decrease in PEC and CO_2 emissions at the end of ten-year periods was the Aegean Region with a decrease of 41% for PEC and 42% for CO_2 emissions, while the region with the highest decrease was 68% for PEC and 72% for CO_2 emissions.

According to these findings, it has been seen that the PEC and CO_2 emission reduction targets set by Turkey and the EU can be achieved with the suggestion implemented progressively in existing buildings. In addition, the study revealed that to reduce the energy consumption of buildings, it is necessary to design by considering climate change in the long term. The approach proposed in the study can also be applied to existing and newly constructed buildings with functions other than housing. In this way, the targets set in the field of energy can be reached faster. In addition to adapting to buildings with different functions, the scope of work will also expand with technological suggestions that will develop over time.

Acknowledgements

This work was supported by Scientific Research Project Coordination Unit of Karadeniz Technical University (Project number: FDK-2019-8564).

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Nomenclature

Q	Energy consumption per unit area ($kWh.m^{-2}$)
K	Conversion coefficient
E	CO_2 emission ($kg/m^2.year$)
C_G	Global cost (€/calculation period)
C_I	Initial investment cost (€)
C_a	Operating costs (€)
f_{pv}	Present value factor
V_{T-f}	scrap value of the component (€)
U	total heat transmission coefficient (W/m^2K)
Abbreviations	
PEC	Primary energy consumption
GC	Global cost
SF	Shape factor
EU	European union
PCM	Phase changing materials
IEA	International energy agency
NSGA-II	Non-dominated sorting genetic algorithm
nZEB	Nearly zero-energy building
PV	Photovoltaic