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Techno-economical analysis of building envelope and renewable energy technology retrofits to single family homes

Gul Nihal Gugul [a], Merih Aydinalp Koksal [b,*], V. Ismet Ugursal [c]

[a] Department of Computer Engineering, Faculty of Technology, Selcuk University, Konya 42075, Turkey
[b] Department of Environmental Engineering, Hacettepe University, Beytepe Campus, Ankara 06800, Turkey
[c] Department of Mechanical Engineering, Dalhousie University, Halifax, Nova Scotia B3H4R2, Canada

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ABSTRACT

In recent years, the popularity of single family homes, which have higher energy intensity than multi-family homes, has increased steadily in Turkey. This trend can be contributed to the interest of middle and high-income families towards living in larger homes, which also offer more privacy. Since multi-family homes are prevalent in Turkey, various studies are conducted to investigate the application of energy efficiency measures to these type of homes. Due to the increase in the number of single family homes and lack of research conducted to reduce the energy consumption for these type of dwellings, determining the feasibility of energy efficiency measures for the Turkish single family housing stock is an important concern. In this study, the techno-economic feasibility of applying a wide range of energy efficiency measures and renewable energy technologies to existing single family homes is investigated using monitored energy consumption data and building energy simulation program. The findings are extrapolated to the existing single family housing stock in three major cities of Turkey, namely Ankara, Istanbul, and Izmir, to estimate the potential for energy and emission reductions in Turkey. The results indicate that applying window glazing, roof, and a combination of window, wall, and roof improvements reduce heating energy demand by 21%, 34%, and 50%, respectively, with favorable payback periods. Among the renewable energy technologies analyzed, solar domestic hot water system results in the highest energy savings with the shortest payback period. Applying the combination of wall, window, and roof improvements and the retrofit of solar domestic water heating systems to existing single family homes in Ankara, Istanbul, and Izmir result in reductions of about 14 million, 8 million, and 15 million m^3/year natural gas consumption in Ankara, Istanbul, and Izmir, respectively. These results can be used to develop policies for building insulation and equipment standards towards achieving low energy and emission national housing stock.

Introduction

Turkey is a member of OECD and thus it can be considered as a developed country, however its gross domestic product *per capita* is 10,787 USD (The World Bank, 2016) as of 2016 and has a human development index of 0.767 (UNDP, United Nations Development Program, 2015) which are both lower than those of the majority of the fellow OECD countries. The total sectoral energy consumption in Turkey reached 104.3 Mtoe as of 2016 and has been increasing at an average rate of 4% per year since 2000. The residential sector constitutes about 20% of the total energy consumption and has been increasing at an average of 3.5% annually (MENR, The Ministry for Energy and Natural Resources, 2017). Due to current low building envelope insulation and lack of efficiency standards for equipment (heating, cooling, ventilation, and water heating), there is energy conservation potential in the residential sector of Turkey (MENR, The Ministry for Energy and Natural Resources, 2018). Especially improving the building envelope insulation would increase the energy savings in this sector, since the insulation use in Turkey is about to 0.06 m^3/capita, whereas the value is about 0.6 m^3/capita for European countries (MEUP, Ministry of Environment and Urban Planning, 2017). Thus, regulation regarding the increase of insulation level of the building envelope (National Standard of Thermal Insulation Requirements for Buildings, TS 825) has been put into effect for the new and also existing housing stock (MEUP, 2008).

The residential building stock of Turkey is mostly composed of multi-family dwellings, whereas the single family homes constitutes about 20% of the building stock (TurkStat, 2018a). In recent years, the interest of the middle and high-income families preferring to live in large homes with more privacy has increased, which eventually increased the demand for single family homes in Turkey (Erengezgin, 2010). Between 2004 and 2014, the number of newly built single family homes increased by about 4.5% annually (TurkStat, 2018b). However, many of the newly built homes in Turkey are energy inefficient compared to the newly built homes in European countries with similar degree-days (UNDP, 2010). In order to increase the energy efficiency

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* Corresponding author.
E-mail address: aydinalp@hacettepe.edu.tr (M. Aydinalp Koksal).

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standards of the buildings in Turkey to those of European countries "Building Energy Performance (BEP) Regulation" (EPR, 2008) is put into effect. This regulation is adapted from the European Union's Energy Performance for Building Directive (European Commission, 2018). Based on this regulation, all new and existing buildings in Turkey should obtain BEP certificates that identifies the energy and emission classes of the buildings by 2020.

The interest in Turkish single family dwellings regarding energy consumption is due to the fact that they are substantially bigger both in terms of floor and envelope areas, and have more appliances compared to their multi-family counterparts, resulting in higher space and domestic hot water (DHW), space cooling, lighting, and appliance energy consumption. Since almost all of the residential space and water heating energy and majority of electricity generation in Turkey is fossil fuel based, there is also a parallel potential in reducing the carbon dioxide (CO_2) emissions associated with the energy consumption in the single family housing stock.

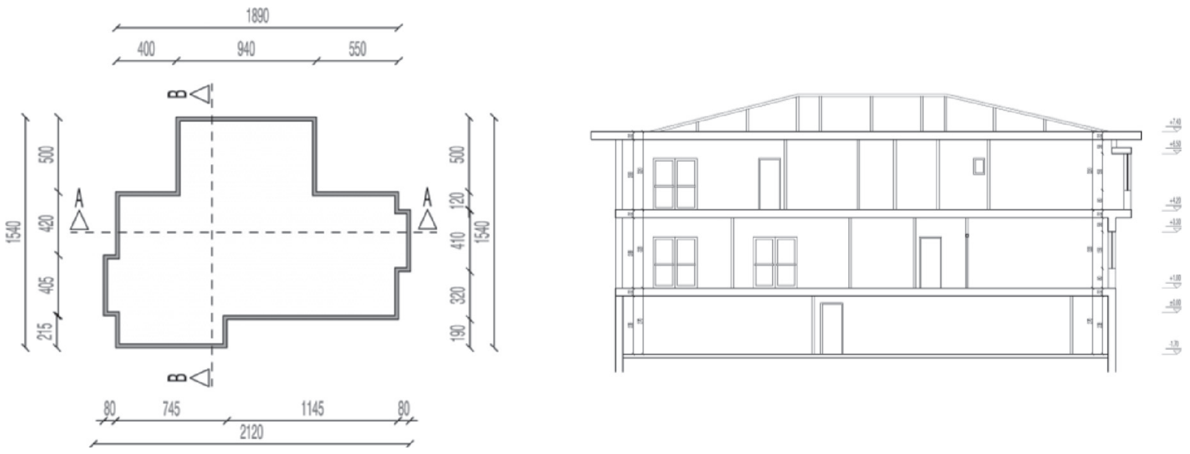
Energy savings in buildings can be achieved by improvements made to the building envelope and by introducing renewable energy technologies. Building envelope improvements can be achieved by increasing external wall, roof, and floor insulation, reducing infiltration, and installing better windows. The use of renewable energy technologies results in reducing the fossil fuel usage and associated emissions. In addition to the savings in energy expenditures, such improvements also have the potential to increase the value of the dwelling itself.

There are many studies in the open literature on reducing the energy consumption and emissions of residential buildings as well as the residential sector as a whole. Many of these studies are conducted by modeling the energy demand of residential buildings and determining the amount of energy savings obtained from the application of various improvement scenarios using building energy simulation programs such as DOE-2 (DOE2, 2015), EnergyPlus (USDOE, 2015), eQUEST (DOE2, 2015), TRNSYS (TRNSYS, 2015), ESP-r (ESRU, 2015), BSim (DBRI, Danish Building Research Institute, 2015), Ener-Win (Ener-Win, 2015), HAP (Carrier, 2015), HEED (HEED, 2015). These improvement scenarios can be in the form of applying renewable energy technologies for space and DHW heating, space cooling, or on-site power generation (Yoon, Song, & Lee, 2011; Huang, Shi, Wang, Lu, & Cui, 2015; Syed, Fung, Ugursal, & Taherian, 2009; Nikoofard, Ugursal, & Beausoleil-Morrison, 2014) and/or retrofitting the building envelope or design (Florides, Kalogirou, Tassou, & Wrobel, 2000; Friess, Rakhshan, Hendawi, & Tajerzadeh, 2012; Sozer, 2010).

The studies conducted for Turkish housing sector are mostly limited to high rise buildings where the effectiveness of existing building retrofits are evaluated (Cetiner & Edis, 2014; Cetiner & Metin, 2017; Ashrafian, Yilmaz, Corgnati, & Moazzena, 2016; Ganic Saglam, Yılmaz, Becchio, & Corgnati, 2017). Cetiner and Edis developed a method to assess the environmental and economic sustainability of retrofits to existing Turkish apartment buildings (Cetiner & Edis, 2014). The authors applied this method to six apartment buildings in Istanbul and assessed various retrofit options (Cetiner & Metin, 2017). In a study, cost of retrofit measures for existing apartment buildings in three climate regions of Turkey are analyzed and the results showed that even most energy savings ones are not cost effective except for cold climates (Ashrafian et al., 2016). Saglam et al. developed a comprehensive cost-optimal approach for existing building retrofits. The results of the study show that the cost-effective energy saving potential of high rise apartments is higher than 70% at very cold regions of Turkey (*e.g.* Erzurum province) (Ganic Saglam et al., 2017). In one of the studies on single family homes, various envelope retrofits to an existing home in Istanbul is studied, reductions of 72% in heating and 24% in cooling demand, and 62% in CO_2 emissions are estimated by Öztürk-Kerestecioğlu et al., (2015). In another study, 37% in heating demand is estimated to be reduced by applying various energy efficiency measures to a single family home in Eskisehir, Turkey (Yildiz, Ozbalta, & Eltez, 2014).

As it can be seen from the review of the previous studies and to the authors' best knowledge, studies on the techno-economically feasibility of building envelope and renewable energy technology retrofits to single family housing stock of Turkey is very limited. These few studies on individual single family homes are on determining the cost effectiveness of various energy efficiency measures; however the models developed in these studies are not calibrated with the monitored data and the results of these studies have not been extrapolated to the housing stock. Thus, in this study, the economically beneficial building envelope improvement and renewable energy technology retrofits to existing single family houses are examined and the effects of applying these energy saving measures and associated emissions of single family housing stock in three major cities of Turkey, namely Ankara, Istanbul, and Izmir are determined.

In summary, this study analyses the potential in energy and associated emissions reductions in single family housing stock due to the application of optimal thermal envelope and renewable energy technologies in three major cities of Turkey by using a calibrated hourly energy model. As stated before, to the authors' knowledge, there is no study that covers developing an hourly energy consumption model for an existing dwelling, calibrating this model using actual annual energy consumption data, applying building envelope improvement and renewable energy technology scenarios to the developed model, determining the reductions in energy consumption and associated greenhouse gas (GHG) emissions, and the payback period (PBP) of these scenarios, and extrapolating the results of the optimal scenarios to the housing stock.



(a) Floor Plan

(b) Cross-Section

Fig. 1. The floor plan (a) and cross-section (b) of the test house.

Table 1
Thermal characteristics of the envelope components of the test house.

	Material	Thermal resistance, m^2 K/W	Heat transfer coefficient, W/m^2 K
External wall	Cement mortar	0.021	
	Perforated brick	0.193	
	Polystyrene foam	2.000	
	Perforated brick	0.193	
	Stucco	0.025	
	Total	**2.432**	**0.41**
External wall column	Mortar (inorganic aggregate)	0.085	
	Concrete	0.119	
	Buffed and channel plate	1.666	
	Stucco	0.025	
	Total	**1.895**	**0.53**
Unheated attic floor	Concrete	0.152	
	Stucco	0.025	
	Total	**0.177**	**5.65**
Unheated attic ceiling	Concrete	0.195	
	Stucco	0.025	
	Total	**0.220**	**4.55**
Window	Double glazed	**0.510**	**1.96**
Door	Wood	**0.130**	**7.69**
Slab on grade floor	Concrete	0.071	
	Rock fill	0.034	
	Membrane	0.010	
	Polystyrene foam	2.500	
	Waterproofing membrane	0.010	
	Cement plaster	0.107	
	Total	**2.732**	**0.37**

In the first step of the study, a detailed energy consumption data are collected for an entire year of 2013 from a newly built owner-occupied single family house in Ankara. The data collected from the test house is then used to verify the accuracy of the hourly energy consumption model of the house developed in the ESP-r building energy simulation software (ESRU, 2015). A sensitivity analysis is applied by examining the variation of space heating demand with respect to room set temperature and window opening area of the test house. Various scenarios on building envelope improvements and renewable energy technologies are applied to the developed model. Then, the scenarios with low investment costs, high energy savings, and low PBP are determined and applied to the entire single family dwelling stock in Ankara, Istanbul, and Izmir and have the same energy class with the test house.

The description of the test house is presented in Description of the test house section. The methodology section starts with information on the data collected for this study, followed by the development of the hourly model. The building envelope improvement and renewable energy technology scenarios evaluated are presented in Scenarios evaluated section, and the parameters used in the economic analysis are given in Economic analysis. In Extrapolation of results to the stock of similar houses in Ankara, Istanbul, and Izmir section, the methodology used to extrapolate the results to the single family housing stock in Ankara, Istanbul, and Izmir is described. The results and discussion are presented in Results and discussion section followed by general conclusions and recommendations in Conclusions section.

Description of the test house

A single family three-storey owner-occupied house in Ankara, Turkey, is selected as the test house due to the availability of the dwelling in applying building envelope improvements and renewable energy technologies, and the owners agreed to provide full cooperation for data collection over an entire year. The total area of the house is 700 m^2, however only 500 m^2 is heated regularly during the heating season. The floor plan and cross-section of the house are given in Fig. 1, and the thermal characteristics of envelope components are given in Table 1. The house is occupied by four adults and three children and built in 2007. The energy demand of the dwelling for space and DHW heating is met by a natural gas (NG) fired boiler chosen to satisfy the design load of 32 kW at the design outdoor temperature of −10 °C. The thermal efficiency of the boiler is taken as 92% (Buderus, 2013). In addition, NG is also used for cooking at the home.

Methodology

This section provides information on the methodology followed during data collection, model development, building envelope improvement and renewable energy technology scenarios development, economic analysis of the scenario results, and extrapolation of the scenario results to the housing stock.

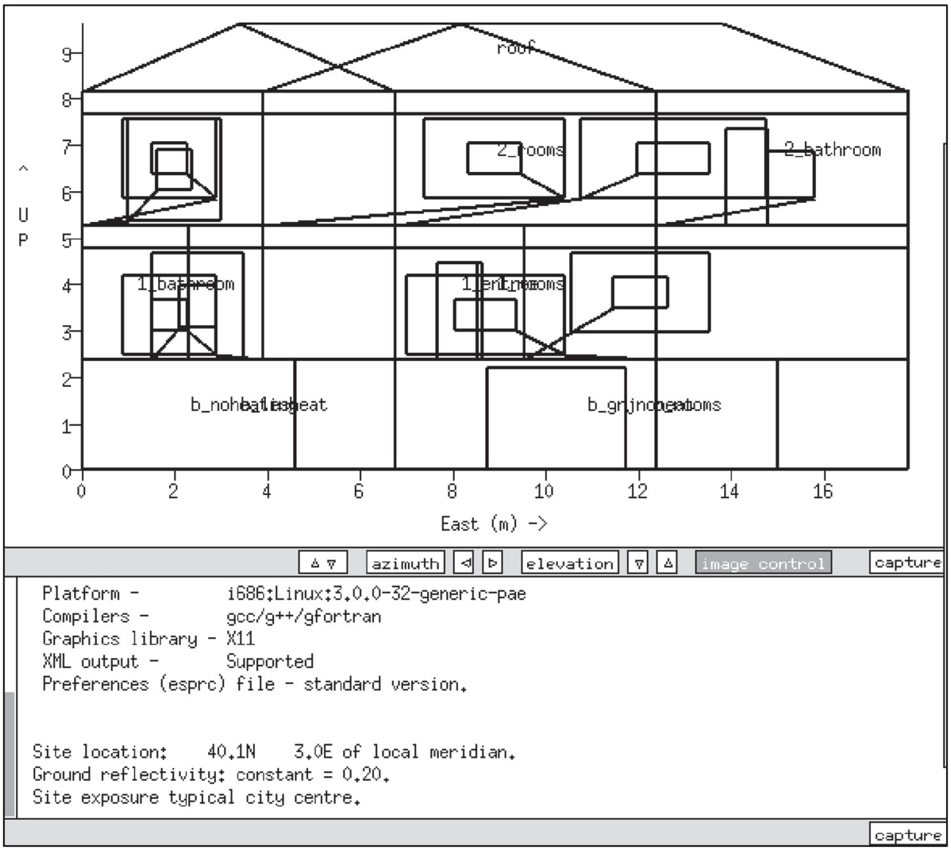
Data collection

Data on socio-economic characteristics and energy consumption behavior of the occupants, construction details of the dwelling, space and DHW heating equipment, lighting and appliances, and heat gain sources are obtained by conducting a detailed survey to the homeowners of the test home. The daily NG consumption of the house is recorded manually throughout 2013, whereas the hourly electricity consumption is monitored using a remote meter reading system (Mikrodizayn, 2014). The hourly meteorological data are obtained from a nearby weather station for 2013 (TSMS, 2014). The normal climate data of Ankara, Istanbul, and Izmir used for scenario analyses are downloaded from the EnergyPlus' weather data web site for Turkey (EnergyPlus, 2015).

The technical and cost data of the selected scenarios are obtained from local companies. GHG emissions associated with energy consumption are calculated using the emission factors of 2.15 kg CO_2/m^3 for NG (IPCC, 2006) and 0.446 kg CO_2/kWh for electricity (Ari & Koksal, 2011). The sources and frequency of data collection are presented in Table 2. The heating value of natural gas is taken as 9155 kcal/m^3 (Ari & Koksal, 2011).

Table 2
Detailed information on the data collected.

	Data type	Collection frequency	Data source
Modeling data	Dwelling architecture and construction materials	Once	House owner
	Internal heat gain sources	Once	House owner
	NG consumption	Daily	Manual recording
	Electricity consumption	Hourly	Remote metering modem
	Climate data	Hourly	Weather Station
	Underground soil temperature data	Hourly	Weather Station
Scenario data	NG and electricity emission factors	Once	(IPCC, 2006; (Ari & Koksal, 2011)
	Thermal performance and cost data for envelope improvements and renewable energy technologies	Once	Related local companies
	Electric and NG tariffs	Once	(TEDC, 2013a; BaskentGaz, 2015)
	Nominal interest rates	Once	(TurkStat, 2014)
Energy performance certificate data		Once	(EPR, 2008)



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Platform -         i686:Linux:3.0.0-32-generic-pae
Compilers -        gcc/g++/gfortran
Graphics library - X11
XML output -       Supported
Preferences (esprc) file - standard version.


Site location:    40.1N    3.0E of local meridian.
Ground reflectivity: constant = 0.20.
Site exposure typical city centre.
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Fig. 2. South elevation of the house in the ESP-r model.

Hourly modeling of the test home

The hourly heating demand model of the dwelling is developed using the ESP-r building energy simulation software (ESRU, 2015). The geometric model of the dwelling developed in ESP-r is presented in Fig. 2.

Heat gains from the occupants, lighting, and appliances are determined based on actual owners' schedules and appliance loads are input into the model. Three distinct and fixed (no thermostat setback) temperature settings are used in the house, and the ESP-r thermal model reflects this mode of operation: all rooms are kept at 22 °C, bathrooms are kept at 24 °C, and the basement is kept at 15 °C. An airflow network and specific window opening area defined within the ESP-r model is used to estimate the amount of air entering through the windows by natural ventilation.

The ESP-r model is executed using 2013 weather data since the energy consumption data for that year is collected. Space heating demand predictions of the model are compared with the actual space heating consumption data, and validation of the model is performed by determining regression coefficient (R^2) and mean absolute percentage error (MAPE) between the estimated and actual daily heating energy consumption for 2013. Detailed information on model development is presented elsewhere (Gugul, 2016; Gugul & Aydinalp Koksal, 2016).

Table 3
Envelope improvement scenarios evaluated.

	Current state	Scenario code	Improvements evaluated	Cost of scenarios, USD
Window glazing	12 mm, air filled, double glazed R = 0.510 m^2 K/W	S.1-a	16 mm Argon filled, double glazed R = 0.918 m^2 K/W	2110
		S.1-b	16 mm Argon filled, triple glazed R = 1.828 m^2 K/W	2374
Insulation	Wall ➔ 80 mm polystyrene foam insulation (k = 0.040 W/mK) R = 2.432 m^2 K/W	S.2-a	Wall ➔ 90 mm polystyrene foam (k = 0.040 W/mK) R = 2.683 m^2 K/W	974
		S.2-b	Wall ➔ 80 mm XPS[a] (k = 0.035 W/mK) R = 2.719 m^2 K/W	1057
		S.2-c	Wall ➔ 90 mm XPS (k = 0.035 W/mK) R = 3.004 m^2 K/W	1178
	Roof ➔ no insulation	S.2-d	Roof ➔ 100 mm XPS (k = 0.035 W/mK) R = 3.035 m^2 K/W	3743
Window glazing & insulation	Window ➔ 12 mm, air filled, double glazed R = 0.510 m^2 K/W Wall ➔ 80 mm polystyrene foam insulation (k = 0.04 W/mK); R = 2.432 m^2 K/W Roof ➔ no insulation	S.3	Window ➔ 16 mm, Argon filled, triple glazed R = 1.828 m^2 K/W Wall ➔ 90 mm XPS (k = 0.035 W/mK) R = 3.004 m^2 K/W Roof ➔ 100 mm XPS (k = 0.035 W/mK) R = 3.035 m^2 K/W	5563

[a] XPS: extruded polystyrene.

Table 4
Technical data of the materials used for envelope improvement scenarios.

	Total area, m^2	Material	Thermal conductivity, W/mK	Density, kg/m^3	Heat capacity, J/kg K	Water vapor diffusion resistance factor	Thickness (mm)
Window glazing space	73	Argon	0.01774 (Bich, Millat, & Vogel, 1990)	1.78 (Leland Gas, 2015)	520.33 (Leland Gas, 2015)		16
Existing wall insulation	367	Polystyrene foam	0.040 (TSI-TS 825, 2009)	15 (TSI-TS 825, 2009)	1500 (Edis & Kuş, 2014)	20–250 (TSI-TS 825, 2009)	80
Wall insulation	367	Foam board 2500 P (XPS)	0.035 (Izocam, 2018)	28–32 (Izocam, 2018)	1500 (Edis & Kuş, 2014)	100 (Izocam, 2018)	80–90
Roof insulation	228	Foam board 1500 D (XPS)	0.035 (Izocam, 2018)	20 (TSI-TS 825, 2009)	1500 (OrcanGroup, 2018)	100 (Izocam, 2018)	100

Table 5
Detailed information on the renewable energy technology scenarios.

	Scenario code	Current state	Improvements evaluated	Cost of scenarios, USD
PVP	S.4	Electricity is supplied from the grid	BP 380 80-Watt poly crystal PVP with an area of 45 m^2	3785
SDHW	S.5	Hot water is supplied by the boiler system	10 panel collectors with 18 m^2 total area and an efficiency of 66%	2378
GSHP	S.6	Space heating is supplied by the boiler system	30 kW capacity GSHP with COP of 4.3	7717

Scenarios evaluated

The hourly heating demand model is developed using the climate data of 2013. However, the building envelope improvement and renewable energy technology scenarios are evaluated running the developed hourly ESP-r model with normal climate data of Ankara, Izmir, and Istanbul (EnergyPlus, 2015). The envelope improvement scenarios and technical data of the materials used for these scenarios are summarized in Tables 3 and 4, respectively. The scenarios are determined taking into account that they are regularly applied to existing homes in Turkey.

Three renewable energy technology scenarios are selected for evaluation considering the types of renewable energy technologies available in the domestic market of Turkey: photovoltaic panels (PVP) (S.4), solar domestic hot water heater (SDHW) (S.5), and ground source heat pump for space heating (GSHP) (S.6). The details of the PVP, SDHW, and GSHP systems evaluated are given in Table 5.

The installation of BP 380, 80-Watt poly crystal PVP to 45 m^2 of the southeast and southwest-facing roof of the dwelling is considered for scenario S.4. For SDHW scenario (S.5), the cost of the system is obtained from a local company for a SDHW system that consists of 10 panel collectors with 18 m^2 total area. For the GSHP scenario (S.6), GSHP with 30 kW capacity and Coefficient of Performance (COP) of 4.3 is applied to the model as the heating system of the dwelling. Total costs of installation of PVP and GSHP are also obtained from local companies.

The ESP-r model of the test house is incrementally modified to reflect envelope and renewable energy technology retrofits to be evaluated, and simulations were conducted. The reductions in fuel and/or electricity consumption are determined for each scenario by comparing the energy consumption values of the original house (base case) with the energy consumption obtained with the retrofit scenario. The corresponding reductions in CO_2 emissions were calculated using NG and electricity emission factors.

Economic analysis

The cost of each building envelope improvement and renewable energy technology scenario is determined by taking into account the cost of installing the retrofits only. These costs do not include the costs for removing and disposing the already present structures in the dwelling, such as seen for the window structures. This is due to the lack of reliable removal and disposal costs for windows from local companies. Since the home does not have any roof insulation, PV, GSHP (based on using already present radiators), and SDHW structures, the total costs of these scenarios include only the cost for installation.

Using the estimated fuel savings and capital cost of each scenario, the net cash flow (NCF) and net present value (NPV) of each scenario for the future years is calculated annually, and the PBP for each scenario is determined as the year in which NPV becomes positive. Thus, these analyses require the estimation of future electricity and NG prices, which are estimated by using the historical tariff data of electricity (between 2008 and 2015) (TEDC, 2013b) and NG (between 2004 and 2015) (BaskentGaz, 2015).

The future electricity and NG prices are estimated based on three scenarios; namely low, medium, and high price scenarios. Using the historical trends of the electricity tariffs, the equations for high (E1), medium (E2), and low (E3) electricity price estimate scenarios are developed as shown in Table 6. In these equations, the "*PRICE*" parameter is the monthly electricity price in USD/kWh and "*DATE*" parameter is the first day of the month converted to a sequential serial number taking 1/1/1900 as 1. The historical electricity tariff trends between 2011 and 2015 is used for E1, between 2008 and 2015 is used for E2, and between 2012 and 2015 is used for E3. These trends are chosen based on the increasing characteristics of historical electricity tariffs.

Similarly, future NG prices are also estimated based on three scenarios [NG1 (High), NG2 (Medium) and NG3 (Low)] as shown in Table 7. In these equations, the "*PRICE*" parameter is the monthly NG price in USD/m^3 and "*DATE*" parameter is the first day of the month converted to a sequential serial number taking 1/1/1900 as 1. The historical NG tariff trends between 2009 and 2015 is used for NG1, between 2004 and 2015 is used for NG2, and between 2008 and 2015 is used for NG3.

Annual nominal interest rate of 2013 is taken as 6.5% to calculate PBPs for each suggested scenario. Due to the significant changes in the

Table 6
Future electricity price estimation equations for three scenarios.

Scenario code	Equation
E1 – High scenario	$\text{PRICE} = 1.57828 \cdot 10^{-5} * \text{DATE} - 0.585667$
E2 – Medium scenario	$\text{PRICE} = 1.38610 \cdot 10^{-5} * \text{DATE} - 0.505991$
E3 – Low scenario	$\text{PRICE} = 1.18441 \cdot 10^{-5} * \text{DATE} - 0.422064$

Table 7
Future NG price estimation equations for three scenarios.

Scenario code	Equation
NG1 – High scenario	$\text{PRICE} = 6.55171 \cdot 10^{-5} * \text{DATE} - 2.45956$
NG2 – Medium scenario	$\text{PRICE} = 4.77845 \cdot 10^{-5} * \text{DATE} - 1.72558$
NG3 – Low scenario	$\text{PRICE} = 4.07379 \cdot 10^{-5} * \text{DATE} - 1.43783$

Table 8
Distribution of number and floor area of single family houses built after 2007 and with energy performance certificate in Ankara, Istanbul, and Izmir.

	Ankara			Istanbul			Izmir		
Energy class	Number of homes	% of homes	Floor area, m^2	Number of homes	% of homes	Floor area, m^2	Number of homes	% of homes	Floor area, m^2
A	26	0.12	5784	7	0.15	5593	35	0.32	12,495
B	8166	38.76	1,816,662	2237	46.89	1,787,260	1561	14.30	557,290
C	12,704	60.31	2,826,216	2507	52.55	2,002,978	9163	83.94	3,271,268
D	83	0.39	18,465	16	0.34	12,783	139	1.27	49,624
E	21	0.10	4672	1	0.02	799	5	0.05	1785
F	52	0.25	11,568	1	0.02	799	8	0.07	2856
G	14	0.07	3115	2	0.04	1598	5	0.05	1785
Total	21,066	100.00	4,686,482	4771	100.00	3,811,810	10,916	100.00	3,897,104

nominal interest rates observed in the past few years in Turkey, PBPs are also calculated for the cases in which the nominal interest rate is assumed as 4% and 8%.

Economic analysis of building envelope improvements

The NCF values of the building envelope improvement scenarios are determined using Eq. (1) as given below.

$$NCF_j^{BE} = AEC_{EC\,j} - AEC_{R\,j} \tag{1}$$

where;

NCF_j^{BE}: net cash flow for building envelope improvement scenarios in year j, USD/year

j: year

BE: building envelope improvement scenario

AEC_{EC}: cost of annual energy consumption based on existing construction, USD/year

AEC_R: cost of annual energy consumption based on retrofit, USD/year

Economic analysis of renewable energy technologies scenarios

The economic analysis of the renewable energy technology scenarios are conducted by taking into account the cost of scenario, and income due to the surplus of power generation (PVP systems) or expenses due to energy consumption (GSHP and SDHW systems).

The NCF of the PVP systems is determined using Eq. (2).

$$NCF_j^{PVP} = CI_j^{PVP} - CO_j^{PVP} = \left(t_{e,j}\left(E_{PVP} - E_{PVP,c}\right)\right) \tag{2}$$

where;

NCF_j^{PVP}: net cash flow of PVP system in year j, USD/year

CI_j^{PVP}: cash inflow of PVP system in year j, USD/year

CO_j^{PVP}: cash outflow of PVP system in year j, USD/year

$t_{e,j}$: average electricity price estimate in year j, USD/kWh

E_{PVP}: electricity generated by PVP system, kWh/year

E_{pv_c}: electricity consumed by PVP system, kWh/year

The NCF of the GSHP systems is determined using Eq. (3).

$$NCF_j^{GSHP} = CI_j^{GSHP} - CO_j^{GSHP} = \left(NG_{Ht} \times t_{NG,j}\right) - \left(E_{GSHP\_c} \times t_{e,j}\right) \tag{3}$$

where;

NCF_j^{GSHP}: net cash flow of GSHP system in year j, USD/year.

CI_j^{GSHP}: cash inflow of GSHP system in year j, USD/year

CO_j^{GSHP}: cash outflow of GSHP system in year j, USD/year

NG_{Ht}: annual NG consumption of the NG fired boiler for heating demand, m^3/year

$t_{NG,j}$: average NG price estimate in year j, USD/m^3

E_{GSHP_c}: electricity consumed by GSHP system, kWh/year

$t_{e,j}$: average electricity price estimate in year j, USD/kWh

The NCF of the SDHW systems is determined using Eq. (4).

$$\begin{aligned} NCF_j^{SDHW} &= CI_j^{SDHW} - CO_j^{SDHW} \\ &= \left(NG_{DHW} \times t_{NG,j}\right) - \left(SOC_j + \left(HW\_B_{SDHW} \times t_{NG,j}\right)\right) \end{aligned} \tag{4}$$

where;

NCF_j^{SDHW}: net cash flow of SDHW system in year j, USD/year.

CI_j^{SDHW}: cash inflow of SDHW system in year j, USD/year

CO_j^{SDHW}: cash outflow of SDHW system in year j, USD/year

NG_{DHW}: annual NG consumption of the NG fired boiler for DHW demand, m^3/year

SOC_j: system operating cost in year j, USD/year

NG_{DHW_CI}: annual NG consumption of the NG fired boiler for DHW demand when SDHW system does not provide sufficient DHW, m^3/year

After determining the NCF for each scenario using Eqs. (1)–(4), NPV for each scenario is determined as given in Eq. (5).

$$NPV = \sum_{j=1}^{N} \frac{NCF_j}{(1+ni)^j} \tag{5}$$

where;

NPV: net present value, USD

NCF_j: net cash flow of each scenario in year j, *i.e.* NCF_j^{BE}, NCF_j^{PVP}, NCF_j^{GSHP}, and NCF_j^{SDHW}

ni: nominal interest rate

N: operating time of the system, years

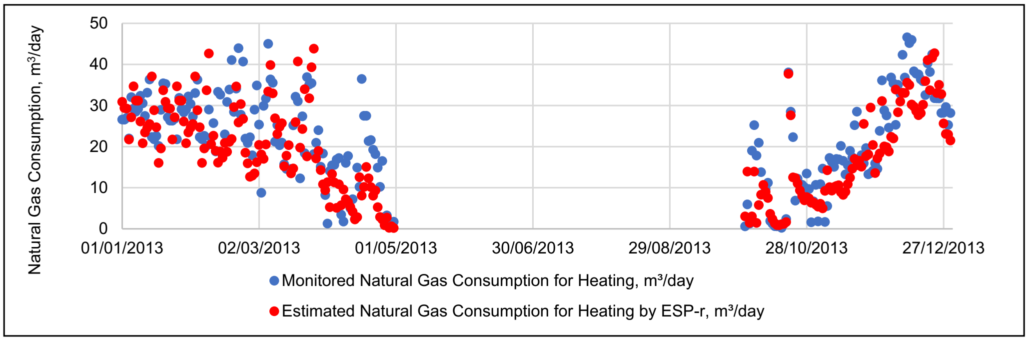

Fig. 3. NG equivalent of daily heating demand estimate and monitored daily NG consumption for heating, m^3/day.

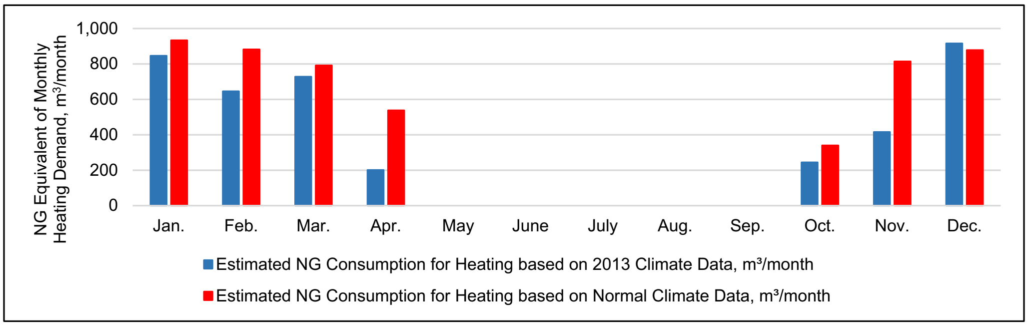

Fig. 4. NG equivalent of monthly heating demand estimate with 2013 climate data and normal climate data, m^3/month.

The lowest j value that allows the NPV to take a positive value is defined as the PBP of the evaluated building envelope improvement scenario (Bernal-Agustín & Dufo-López, 2006).

Extrapolation of results to the stock of similar houses in Ankara, Istanbul, and Izmir

The developed hourly model is run with normal climate data of Ankara, Istanbul and Izmir to determine the annual energy consumption and associated emissions of single family homes at these locations, which are then used to determine the energy (kWh/m^2) and emission (kgCO_2/m^2) indices. Using these indices, the energy and emission classes of the homes are determined based on the criteria given Tables A.2 and A.3 given in the Appendix.

The building envelope improvement and renewable energy technology scenarios are applied to determine the potential in energy savings (in kWh/m^2-year) at the homes located in these cities. These savings are then extrapolated to the housing stock of relevant energy classes located at these major cities by using the total floor area of homes in each energy consumption and emission classes.

The number of single family houses with energy performance certificate and built after 2007 in these cities are obtained from the Ministry of Environment and Urban Planning (MEUP, 2017). In addition, the total floor area of single family homes constructed after 2007 is 4,686,482 m^2 for Ankara, 3,811,810 m^2 for Istanbul, and 3,897,104 m^2 for Izmir are obtained from Turkish Statistical Institute (TurkStat, 2015). After determining the percent distribution of number of single family homes for each energy class, the floor area for each energy class is determined by multiplying percentage of dwellings in each energy class by total single family home floor area in the relevant city. These calculated floor areas are then used to determine the total savings at each location due to the application of energy saving scenarios. The distribution of the number of single family homes with energy performance certificate built after 2007 for each energy class and corresponding floor area are presented in Table 8. Since, it was not possible to obtain the individual floor area of the homes with energy performance certificate from the Ministry of Environment and Urban Planning due to privacy issues, the calculations are carried out using the overall floor area and number of the single family homes with energy performance certificate.

As it can be seen from Table 8, out of all the homes with energy performance certificate and built after 2007, 60% in Ankara, 53% in Istanbul, and 84% in Izmir are in energy class C. This distribution also shows that majority of the homes located in three cities are not energy efficient and there is a potential in energy savings in single family homes stock in Turkey. In addition, it is important to mention that the single family homes constitute only 8%, 22%, and 35% of the whole housing stock in Istanbul, Ankara, and Izmir, respectively (TurkStat, 2015). Since Istanbul has a very high population density, majority of the dwellings are high rises and thus the single family home share is only 8%.

Results and discussion

Using the ESP-r model, the annual space heating energy demand of the test house is estimated as 141 GJ based on 2013 Ankara climate. The NG consumption of the 92% efficient NG fired boiler corresponding to this energy demand is calculated as 3998 m^3 at a cost of 2242 USD based on the 2013 NG price in Ankara (BaskentGaz, 2015). The associated CO_2 emissions of this annual NG consumption is determined as 8584 kg CO_2.

The monitored NG data showed that 6753 m^3 NG is consumed by the homeowners for space and DHW heating, and for cooking in 2013. Based on monitored usage patterns of the homeowners, it is estimated that 135 m^3 is used for cooking and 2036 m^3 is used for DHW heating, leaving 4582 m^3 for space heating, which is 584 m^3 higher than the ESP-r estimate. The NG equivalent of the estimated daily heating demand and monitored daily NG consumption for space heating during 2013 are plotted in Fig. 3. While there is general agreement between the observed and estimated NG consumption values, the simulation

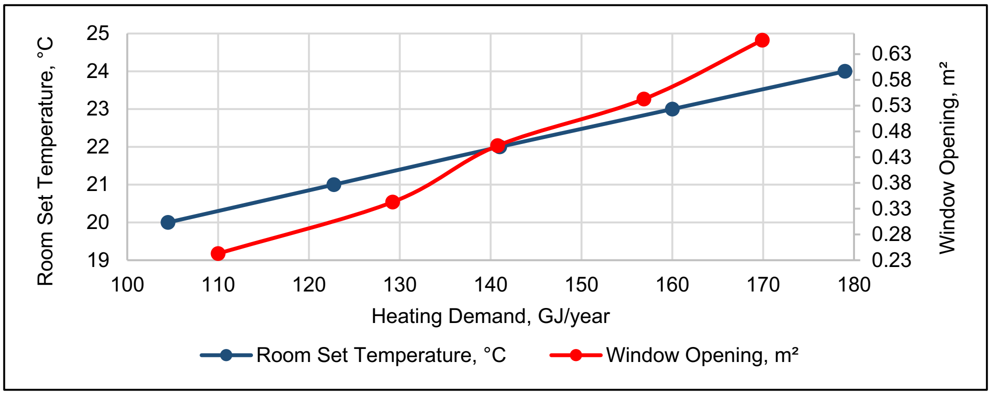

Fig. 5. Variation of heating demand with room temperature and window opening area.

Table 9
Overall results of the scenarios for the test home.

Scenario code	Scenario description	Energy savings, GJ/year	Cost of scenarios, USD	PBP, year	CO_2 reduction, kg/year
S.1-a	Window glazing	35	2938	0	2110
S.1-b		39	4521	3	2374
S.2-a	Insulation	16	1926	23	974
S.2-b		17	4777	>40	1057
S.2-c		19	5807	>40	1178
S.2-d		61	3111	3	3743
S.3	Window + insulation	91	13,439	7	5563
S.4	PVP	31	25,687	27	3785
S.5	SDHW	39	5248	8	2378
S.6	GSHP	127	23,092	>40	7717

cannot keep up with the large fluctuations in the actual NG consumption, especially, during the shoulder months (*i.e.* March, April, and October). These deviations are likely due to the large fluctuations in the outdoor temperature observed in 2013. It appears that the occupants consume more NG than necessary following cold spells. These observations are supported by the results of the error analysis. The R^2 between the estimated and monitored NG consumption is 0.97 while the MAPE is 21%. The high MAPE is largely due to the large differences between the estimated and monitored values during the shoulder months in which the consumption is lower than winter months.

The winter of 2013 was warmer than the normal year, with a total heating degree days (HDD) of 2563 °C-day compared to the normal HDD of 3307 °C-day, with a difference of 744 °C-day (23% lower HDD). Therefore, after the hourly model is validated using 2013 actual NG consumption data, the model is run using the normal climate data of Ankara to evaluate the techno-economic potential of the energy saving scenarios. The estimated annual space heating demand of the dwelling based on normal climate data is 182 GJ, with the monthly values plotted in Fig. 4. The associated CO_2 emissions based on normal weather heating demand is determined as 11,133 kg CO_2. Except for the month of December, the heating demands estimated based on normal weather data result in higher values than the ones estimated based on 2013 weather data.

The variation of heating energy requirement of the dwelling with respect to the thermostat set point and the area of window opening area is shown in Fig. 5. As to be expected, the estimated demand increases with increasing thermostat set point and window opening area as shown in this sensitivity analysis.

Techno-economic impact of energy saving scenarios

Savings in the space or DHW heating energy consumption and associated CO_2 emissions are calculated and the corresponding PBP are determined for each scenario based on three price scenarios and nominal interest rate between 4% and 8%. The results of the scenarios based on medium electricity (E2) and medium NG (NG2) price estimates and nominal interest rate of 6.5% are presented in Table 9.

As it is shown in Table 9, economically the most favorable scenarios for the test house are the window glazing (S.1-a and b) and roof insulation (S.2-d) upgrades, combined window glazing, wall, and roof insulation upgrades (S.3), and the installation of SDHW retrofit (S.5), all resulting in PBPs of <10 years with substantial energy savings and GHG reductions. Thus, it can be concluded that these scenarios can be suggested for the retrofit of existing buildings as well as new constructions. Wall insulation upgrades (S.2-a, b, and c) are not feasible for existing buildings due to long PBPs; however, using additional wall insulation in new construction will require a small incremental cost, and will result in much shorter PBPs. Savings of 72% and 37% in heating demand of singled family homes in Istanbul (Öztürk-Kerestecioğlu et al., 2015) and Eskisehir (Yildiz et al., 2014), respectively, are obtained after applying various building envelope retrofits. The combination scenario (S.3) results in 50% reduction in heating demand for this test home. The PBP of the retrofits applied to the test home in Eskisehir is 10 years (Yildiz et al., 2014), which is close to the PBP determined for combination scenario (S.3) in this study.

In PVP scenario (S.4), 45 m^2 PVP is considered to be mounted on the roof; half of which is on the south-east section of the roof and the other half is on the south-west section. The analyses show that the panels facing southwest generate 12% more electricity than those facing southeast. The estimated electricity generation is 7375 kWh/year with normal climate data and 8484 kWh/year with 2013 climate data. The monitored electricity consumption during 2013 is 15,702 kWh/year. Since surplus electricity can be stored for only one day in the batteries of the PVP system and cannot be sent to the grid due to regulations, 7354 kWh of electricity is required from the grid for 2013. Thus, 53% of electricity consumption of the dwelling can be met by PVP in 2013. The daily monitored electricity consumption of the dwelling in 2013 and the estimated electricity generation by the PVP system along with the electricity obtained from the grid and the daily surplus electricity based on 2013 climate data are plotted in Fig. 6.

As shown in Fig. 6, PVP electricity generation is higher than the consumption for 51 days between 12/04/2013 and 06/09/2013 (shown as "electricity surplus" in the graph). As expected, electricity consumption and PVP generation are very close in summer days while consumption is much higher than the generation in most winter days.

Using various nominal interest rates and electricity price forecasts, the PBP of PVP scenario is estimated to vary from 19 to 40 years due to the high investment cost of the PVP systems in Turkey. Thus, it is concluded that the use of PVP is not suitable under the current electricity and PV panel prices. If panel prices come down, or electricity

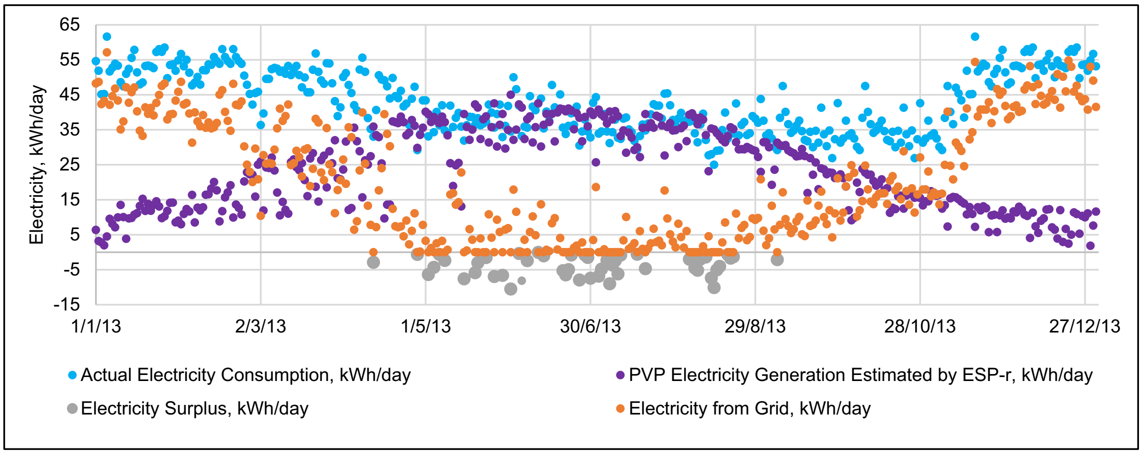

Fig. 6. Actual and estimated electricity data of the test house for 2013, kWh/day.

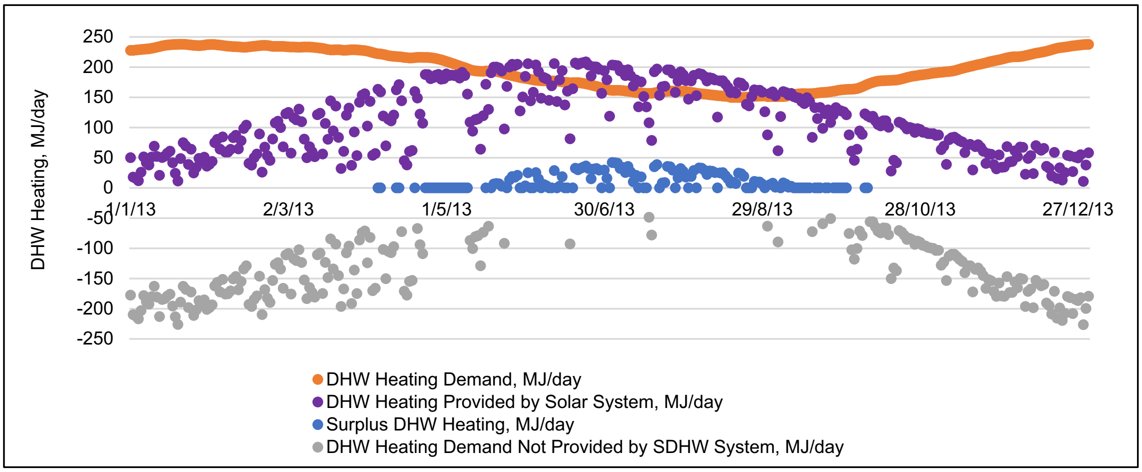

Fig. 7. Energy demand for DHW and energy generated by the SDHW system, MJ/day.

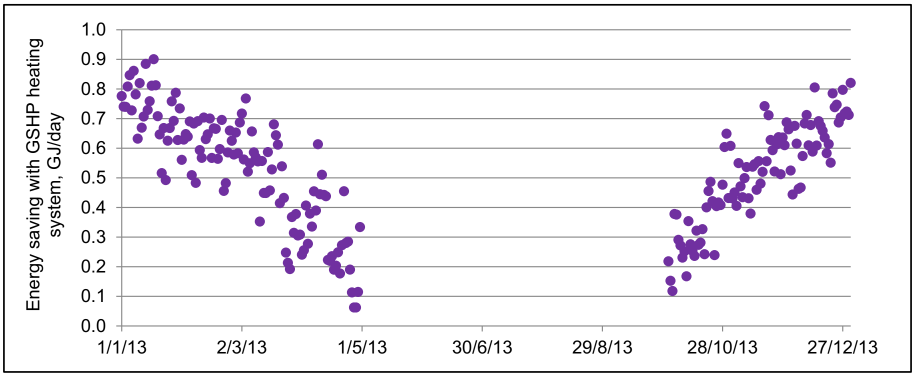

Fig. 8. Daily energy savings with the GSHP heating system.

prices go up, PV systems will become more economical in Ankara region.

Using a DHW demand of 172 L/day-person and 1203 L/day for the dwelling, the annual DHW energy demand of the dwelling is calculated as 72 GJ/year (NG equivalent of 2036 m^3/year). It is estimated that 39 GJ/year (55%) of this demand can be provided by the SDHW system (Scenario S.5), lowering the NG consumption of the boiler by 1108 m^3/year. Due to the short PBP of SDHW system (8–9 years) and 55% energy saving, the use of SDHW system for a dwelling in Ankara climate is a feasible option. The DHW energy demand of the dwelling and the DHW energy generated by the SDHW system are plotted in Fig. 7.

For the GSHP (S.6) scenario, the heating system of the dwelling is changed to a GSHP in the ESP-r model. The electricity consumption of the GSHP system is estimated to be 55 GJ/year (15,485 kWh/year) corresponding to an annual energy savings of 127GJ (69% savings based on normal data). Daily energy savings due to the use of GSHP system are plotted in Fig. 8. Although the GSHP system produces substantial energy savings, it is economically not feasible due to its high capital cost as shown in Table 9.

The overall results of the scenarios based on PBP, investment cost, and energy savings are presented in Figs. 9 and 10.

The scenarios that resulted in PBPs >40 years (S.2-b, S.2-c, and S.6) are not shown in Fig. 9. Investment cost and PBP of window glazing

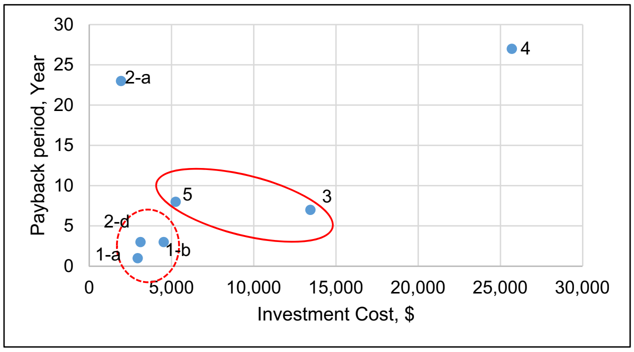

Fig. 9. The PBP and investment costs of the scenarios.

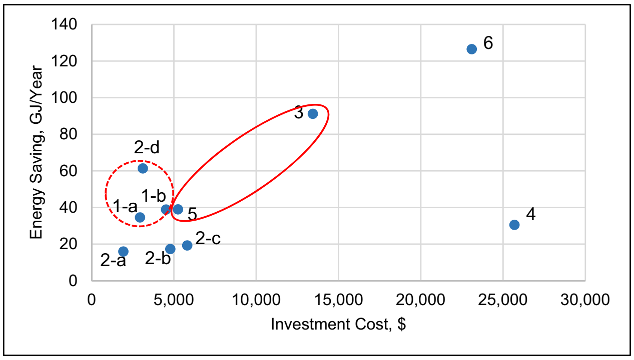

Fig. 10. The energy savings and investment costs of the scenarios.

Table 10
Energy consumption and emission indices and classes after scenario applications for the test home.

Scenario	Scenario code	Energy class index, kWh/m^2-yr	Energy class	Emission class index, kg CO$_2$/m^2-yr	Emission class
Window glazing	S.1-a	156	B	39	C
	S.1-b	154	B	39	C
Insulation	S.2-a	166	B	41	C
	S.2-b	166	B	41	C
	S.2-c	164	B	41	C
	S.2-d	141	B	36	B
Window + insulation	S.3	124	B	33	B
PVP	S.4	161	B	35	B
SDHW	S.5	154	B	39	C
GSHP	S.6	105	A	36	B

scenarios (S.1-a, S.1-b) and roof insulation scenario (S.2-d) are very low which make them reasonable improvement options. The investment cost and PBP of the combination scenario (S.3) and SDHW scenario (S.5) are similarly reasonable. Although investment cost of the wall insulation scenario (S.2-a) is low, its PBP is 23 years, which makes it not reasonable for retrofit. However, this scenario can be preferred in newly constructed buildings due to its low investment cost. The PVP scenario (S.4) has high investment cost and a PBP of 27 years, which makes it infeasible as well.

As shown in Fig. 10, window glazing scenarios (S.1-a, S.1-b) have low energy savings and low investment costs as well as low PBP. Thus, these scenarios are justifiable for existing buildings as well as for new construction. The wall insulation scenarios (S.2-a, S.2-b, S.2c) have low energy savings, which makes them not preferable as an energy saving option, especially for current homes. The roof insulation scenario (S.2.d) and combination scenario (S.3) have low PBPs (4 years and 7 years, respectively) in addition to their high-energy savings and low investment costs. Among the renewable energy based scenarios, the SDHW scenario (S.5) results in low PBP and moderately high-energy savings.

Energy consumption and emission classes of the test home

In 2013, the monitored electricity and NG consumptions of the test house are 15,702 kWh and 6753 m^3 (66,041 kWh), respectively, which sums up to 81,743 kWh as the total energy consumption of the dwelling based on 2013 climate data. The annual energy consumption then corresponds to 163 kWh/m^2-year, placing the test house in Ankara in energy class B for energy consumption index. The CO$_2$ emissions of the test house associated with energy consumption is calculated as 21,504 kg CO$_2$/year corresponding to 43 kg CO$_2$/m^2-year and C emission class index for Ankara.

The energy and emission class indices are also calculated based on normal Ankara climate as 175 kWh/m^2-year placing the test house in energy class B and 46 kgCO$_2$/m^2-year placing the test house in energy class C. The corresponding energy and emission classes of the dwelling after the application of each scenario are presented in Table 10.

As seen in Table 10, only the application of the GSHP scenario (S.6) moves the energy class of the dwelling from B to A since this scenario results in the highest reduction in heating demand among all scenarios applied. The application of the roof insulation (S.2-d), combination insulation (S.3), PVP (S.4), and GSHP (S.6) scenarios move the emission class of the dwelling from C to B, since these scenarios result in high energy savings and directly reduces the associated emissions of the dwelling.

In order to determine the energy and emission classes of similar dwellings located at Istanbul and Izmir, the hourly energy model developed in ESP-r is run with normal Istanbul and Izmir weather data. Energy consumption for appliance and lighting, DHW heating, and cooking are assumed to be the same as the monitored values of the test house for the single family homes located at Istanbul and Izmir. The total energy consumption and emissions, their indices, and classes of the single family homes located at Ankara, Istanbul, and Izmir are presented in Table 11.

Extrapolation of results to the single family dwelling stock in Ankara, Istanbul and Izmir

As stated in Techno-economic impact of energy saving scenarios section, the combination scenario (S.3) and SDHW scenario (S.5) have low investment costs and PBPs, and result in high-energy savings. Hence, these scenarios can be suggested as feasible options for the new constructions, as well as, for the existing homes. Thus, in this study, these scenarios are applied to the entire B energy class single family dwelling stock in Ankara, Istanbul, and Izmir. The application of S.3 and S.5 scenarios to all single family houses with B energy class is shown in Table 12.

As shown in Table 12, the application of these savings to the single family B energy class dwelling stock in Ankara results a NG savings of about 14 million m^3/year. The single family homes represent 22% of the total housing stock in Ankara, and these scenarios are applied for about 40% of the single family homes built after 2007 which are in energy class B, thus the NG savings corresponds to a reduction of only 0.85% in the total residential NG consumption of Ankara in 2013 (RTEMR, 2014).Due to very small share of single family homes in Istanbul, the NG savings correspond to only 0.22% of the residential NG consumption in 2013 (RTEMR, 2014). However, the NG savings due to the application

Table 11
Energy consumption and CO$_2$ emissions classes of the model single family homes located at Ankara, Istanbul, and Izmir.

	Total energy consumption, kWh/year	Energy consumption index, kWh/m^2-year	Energy consumption class	Total CO$_2$ emission, kg CO$_2$/year	CO$_2$ emission index, kg CO$_2$/m^2-year	Emission class
Ankara	87,586	175	B	21,524	43	C
Istanbul	79,716	159	B	19,934	40	C
Izmir	75,053	150	B	18,993	38	C

Table 12
Application of S.3 and S.5 scenarios to all single family houses with B Energy class.

	Savings per home, GJ/m^2-yr	Total area of all homes at each class, m^2	Total savings of all homes, GJ/yr	Total NG savings, million m^3/yr	Total reduction in CO$_2$ emissions, ton CO$_2$/yr
Ankara	0.261	1,816,662	474,333	14	28,924
Istanbul	0.154	1,787,260	274,658	8	16,748
Izmir	0.161	3,271,268	528,240	15	32,211

of these scenarios to the single family homes in Izmir correspond to almost 6% of the residential consumption in 2013 (RTEMR, 2014). This high saving percentage is due the high share of single family homes eligible for scenario application in Izmir. The emission savings are also high in Izmir due to estimated high savings in energy demand.

Conclusions

The effects of various energy efficiency measures on single family housing stock are investigated in this study. The heating demand of a single family dwelling located at Ankara, Turkey, was monitored for a year, and the findings were used to validate the energy model developed using the building energy simulation software ESP-r. The validated ESP-r model was used to assess the techno-economic feasibility and the CO_2 emission reduction potential of various energy saving scenarios. These scenarios are then used to estimate the potential in energy and emission savings in single family housing stock in three major cities of Turkey, namely Ankara, Istanbul, and Izmir.

The simulation results show that energy savings up to 21% with a PBP of 1 to 3 years is possible by window glazing improvements. Due to lack of insulation in the dwelling's roof, which is a common practice for majority of the existing homes in Turkey, adding roof insulation provided high-energy savings and low PBP (3 years). Application of the wall, window and roof insulation improvements together results in 50% energy savings and a PBP of 7 years, demonstrating the importance of building envelope improvements to reduce space heating energy consumption. Although high-energy savings can be obtained by incorporating PVP (53% of electricity demand of the dwelling can be met by PVP system), due to its high installation cost, PBP of this scenario is prohibitively high (27 years). Similarly, the GSHP system retrofit is not feasible with a PBP of >40 years. However, the SDHW system has a reasonable PBP of 8 years, and provides high-energy savings (55%) making this option a preferable renewable energy application. These results show that a combination of wall, window and roof insulation improvements (S.3) and the use of SDHW (S.5) can be accepted as optimal energy savings measures for Turkish single family homes.

The application of the combination (S.3) and SDHW (S.5) scenarios to the single family homes in the same energy classes of the test home located at Ankara, Istanbul, and Izmir and constructed after 2007 result in reductions of about 14 million, 8 million, and 15 million m^3/year NG consumption in Ankara, Istanbul, and Izmir, respectively. These savings correspond to <1% of 2013 residential NG consumption in Ankara and Istanbul, and about 6% in Izmir. These results show favorable effects of the building envelope improvements and use of renewable energy technologies to reduce the household energy consumption, expenditure, and associated emissions in cities where the single family housing stock share is high, as seen in Izmir. Since Turkish government is in the process of determining the economic effects of climate change mitigation measures in the building sector to comply with EU registration and other agreements, the results of this study can further be used by policy and decision makers to develop new building insulation and equipment standards towards achieving low energy and emission national housing stock in the future.

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Appendix A

The energy and emission classes of dwellings are determined using the reference energy consumption and emissions indices as given in Table A.1 for climate zones 1, 2, and 3, which include Izmir, Istanbul, and Ankara, respectively.

Table A.1
Reference energy consumption and emission indices of four climate zones of Turkey (YEGM, 2015).

	Climate zone 1	Climate zone 2	Climate zone 3	Climate zone 4
Reference energy consumption index, kWh/m^2-year	165	240	285	420
Reference GHG emission index, kg CO_2/m^2-year	28	40	47	70

The energy consumption and emission intervals for each energy and emission classes are determined by using the reference indices given in Table A.1 and energy performance (EP) and GHG emission performance (GEP) factors given in Energy Performance Regulations (EPR, 2008) as presented in Tables A.2 and A.3, respectively.

Table A.2
Energy class indices for single family houses in Ankara, Istanbul, and Izmir.

Energy class	Houses located in Ankara kWh/m^2-year			Houses located in Istanbul kWh/m^2-year			Houses located in İzmir kWh/m^2-year		
A		EP<	114		EP<	96		EP<	66
B	114	≤EP<	228	96	≤EP<	192	66	≤EP<	132
C	228	≤EP<	285	192	≤EP<	240	132	≤EP<	165
D	285	≤EP<	342	240	≤EP<	288	165	≤EP<	198
E	342	≤EP<	399	288	≤EP<	336	198	≤EP<	231
F	399	≤EP<	499	336	≤EP<	420	231	≤EP<	289
G	499	≤EP		420	≤EP		289	≤EP	

Table A.3
Emission class indices for single family houses in Ankara, Istanbul, and Izmir.

Emission Class	Houses located in Ankara kg CO_2/m^2-year			Houses located in Istanbul kg CO_2/m^2-year			Houses located in Izmir kg CO_2/m^2-year		
A		GEP<	19		GEP<	16		GEP<	11
B	19	≤GEP<	38	16	≤GEP<	32	11	≤GEP<	22
C	38	≤GEP<	47	32	≤GEP<	40	22	≤GEP<	28
D	47	≤GEP<	56	40	≤GEP<	48	28	≤GEP<	34
E	56	≤GEP<	66	48	≤GEP<	56	34	≤GEP<	39
F	66	≤GEP<	82	56	≤GEP<	70	39	≤GEP<	49
G	82	≤GEP		70	≤GEP		49	≤GEP	

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