Energy for Sustainable Development 45 (2018) 159–170

Contents lists available at ScienceDirect

Energy for Sustainable Development

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

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ARTICLE INFO

Article history:
Received 24 January 2018
Revised 7 June 2018
Accepted 8 June 2018
Available online xxxx

Keywords:
Building energy simulation
Residential energy consumption
Energy saving technologies
Economic analysis
Emission reductions

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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https://doi.org/10.1016/j.esd.2018.06.006
0973-0826/

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.

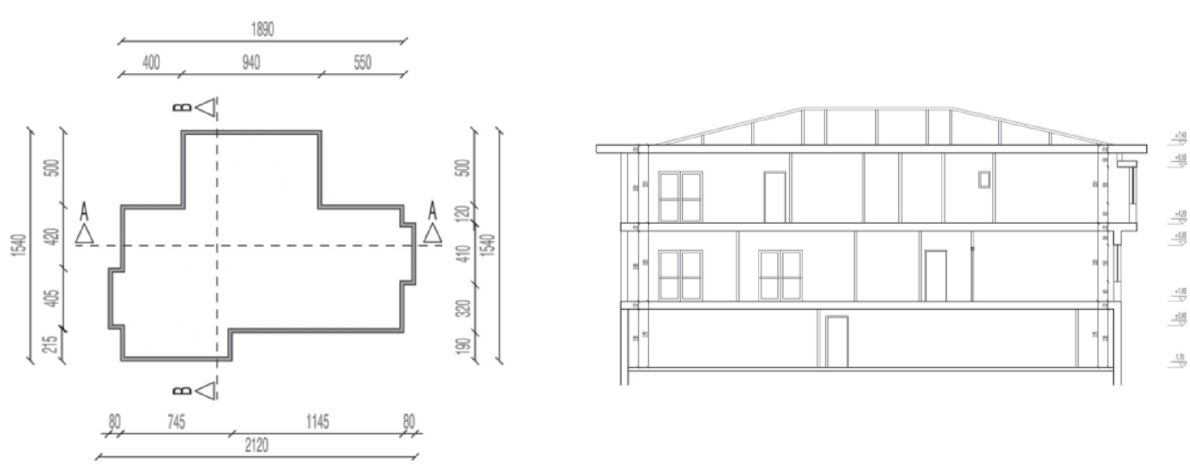
Energy savings in buildings can be achieved by improvements made to the building envelope and by introducing renewable energy technologies. Building envelope improvements can be achieved by increasing external wall, roof, and floor insulation, reducing infiltration, and installing better windows. The 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.