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Research Article

Building Thermal, Lighting, and Acoustics Modeling

# The impact of hourly solar radiation model on building energy analysis in different climatic regions of Turkey

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## Abstract

The purpose of this study is to investigate the effect of solar radiation models on the determination of energy performance of a single-family house assisted with renewable energy system including photovoltaic panels and solar water heater. An Angström-Prescott type solar radiation model was compared with Zhang and Huang model derived based on hourly meteorological data of 12 locations in Turkey. Since regression coefficients of the Zhang and Huang model are valid for China, new regression coefficients were derived by using local meteorological data. A clear distinction could not be observed in simulated annual heating load intensity for each model since the average relative deviation of the models' results was 2.5%. However, the average deviation was 12.5% for space cooling load intensity. Primary energy ratings (PER) and the renewable energy ratio (RER) were determined for each location. For total PER, the highest deviation was 4.6% and 3.3% for Mersin and Muğla, respectively. For the other locations, this parameter deviates between 0.02%–2.11%. The highest RER was 18.6% for Mersin.

## Keywords

building energy simulation,
solar radiation models,
renewable energy ratio,
primary energy rating,
heating load intensity,
cooling load intensity

## Article History

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## 1 Introduction

In the period of 2010–2014, buildings are averagely responsible for 35% of the total energy consumption in Turkey according to the statistical report published by MENR (2016). In the same period, Turkish Statistical Institute (2016) reported averagely 303.6 Mton greenhouse gas emissions ($CO_2$ equivalent) due to the energy consumption of buildings (fuel combustion). Since 75% of the total buildings are for residential usage, investigation of advanced technologies and renewable energy usage in residential buildings will have a significant influence on energy consumption and greenhouse gas emissions. The main difficulty of the scientific studies in determining the energy consumption characteristics of buildings is the large costs of building construction and experiments. For this reason, reliable building energy simulation programs have gained importance. For building energy simulation, a weather file of the relevant region is essential on an hour-by-hour basis for an entire year. Solar radiation is the most important parameter of a weather data since it plays an important role in the calculation of heating/cooling loads, solar water heater, and renewable energy system designs. The most glaring deficiency in the hourly weather data file is the absence of the solar radiation measurement (Huang et al. 2014). Recently, Kambezidis et al. (2017) discussed techniques and models for solar radiation simulations. The need for high accuracy solar radiation model was featured due to the low density and the limited number of solar radiation measuring stations. For that reason, reliable solar radiation models to estimate global, diffuse, and direct normal irradiations must often be demanded.

## 2 Literature review

Harish and Kumar (2015) reviewed all the significant modeling methodologies to model the energy systems of buildings. Modeling procedure of building energy simulation programs and software was discussed. Among the other simulation programs BLAST, BSim, DeST, DOE-2, ECOTECT, eQuest, ESP-r and TRNSYS, EnergyPlus program is defined as completely implemented for modelling characteristics such as simulation solution, time step approach, simultaneous

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## List of symbols

| | |
|---|---|
| AM | absolute air mass |
| $c_0$, $c_1$, $c_2$, $c_3$, $c_4$, $c_5$, $d$, $k$ | coefficients of ZHM solar radiation model |
| CC | cloud cover |
| DNI | direct normal solar irradiation (Wh/m$^2$) |
| $e$ | latitude (°) |
| $E_e$ | effective irradiance |
| $f$ | energy conversion factor |
| $h$, $H$ | hour angle and hour angle at sunrise (°) |
| $I$, $I_b$, $I_d$, $I_o$ | hourly global, direct, diffuse and extraterrestrial solar radiation on horizontal surface (Wh/m$^2$) |
| $I_{mp}$ | current at the maximum power point (A) |
| $I_{sc}$ | solar constant (1355 W/m$^2$) |
| $I_t$ | global radiation on tilted surface (Wh/m$^2$) |
| $K_T$ | hourly clearness index |
| $K_\theta$ | incidence angle modifier (°) |
| $P$ | power at maximum-power point (W) |
| $Q$, $Q_o$ | daily global and extraterrestrial solar radiation on horizontal surface (Wh/m$^2$) |
| RH | relative humidity (%) |
| $t$, $t_o$ | sunshine duration and day length (hr) |
| $T$ | dry-bulb temperature (°C) |
| $T_{cell}$ | temperature of cells inside PV module (°C) |
| $T_{in}$ | inlet water temperature of the flat plate solar collector (°C) |
| $U$ | overall heat transfer coefficient (W/(m$^2$·K)) |
| $V_{mp}$ | voltage at maximum-power point (V) |
| $V_r$ | wind speed (m/s) |
| $Z$ | elevation (m) |
| $\delta$ | declination angle (°) |
| $\varepsilon$ | relative deviation (%) |
| $\eta$ | thermal efficiency |
| $\theta$ | solar incidence angle (°) |
| $\theta_z$ | zenith angle (°) |

*Subscripts and superscripts*

| | |
|---|---|
| del, exp | delivered and exported |
| $i$, $i$–3 | dry-bulb temperature at hours $i$ and $i$–3 |
| nren, ren | renewable and nonrenewable |
| * | standard test conditions |

*Abbreviations*

| | |
|---|---|
| APM | Angström-Prescott type solar radiation model |
| CDD | cooling degree-days |
| CTF | conduction transfer function |
| DHW | domestic hot water |
| FPC | flat-plate collector |
| HDD | heating degree-days |
| MABE | mean absolute bias error (Wh/m$^2$) |
| MAPE | mean absolute percentage error (%) |
| MBE | mean bias error (Wh/m$^2$) |
| MPE | mean percentage error (%) |
| PER | primary energy ratings (kWh/(m$^2$·yr)) |
| PVs | photovoltaic system |
| RER | renewable energy ratio (%) |
| RMSE | root mean square error (Wh/m$^2$) |
| SNL | Sandia National Laboratories |
| STC | standard test conditions |
| SWH | solar water heating systems |
| TARP | Thermal Analysis Research Program |
| TMY | typical meteorological year |
| ZHM | Zhang-Huang solar radiation model |

radiation and convection, combined envelope heat and mass transfer, internal mass considerations, occupant comfort, solar gains, shading, and sky considerations. Al-Anzi et al. (2008) discussed the impact of the selection of solar radiation model for the weather file on energy consumption predictions of whole-building simulation program EnergyPlus. Weather files suitable for building energy simulation were developed by using the measured data as well as predictions from the four solar models (Kasten and Czeplak 1980; Zhang and Huang 2002; Muneer et al. 1996, 1997; Krarti 2003). It was concluded that predicting hourly solar radiation by using the Zhang and Huang (2002) model was appropriate for energy analysis of buildings in Kuwait. Similar to that study, Wang et al. (2009) investigated possible solutions for zero energy building design in Cardiff, UK by using EnergyPlus and TRNSYS simulation programs. The aim of the study was reported as minimizing the energy consumption of the building with passive design methods and balancing the energy requirements by using active techniques and renewable technologies. To achieve this, various parameters including $U$ values (overall heat transfer coefficient) of external walls, window to wall ratios, and building orientations were investigated. Weather data analysis was given as the primary step for the zero energy building design. Representative Cardiff weather data were analyzed in the aspect of wind, solar radiation, and ambient temperature. Ramesh et al. (2012) investigated the quantity of life cycle energy of the residential buildings in Indian context by using DesignBuilder, e-Quest, and EnergyPlus simulation programs. Effects of energy saving properties such as thermal insulation of wall and roof, double pane glass for windows on building energy consumption characteristics were discussed. Hourly weather data file of ISHRAE (Indian Society of Heating, Refrigerating, and Air-Conditioning Engineers) from DesignBuilder database were used for the simulation. Hachem et al. (2014) examined energy performance enhancement methods in multi-story residential buildings for Montreal, Canada by using EnergyPlus. CWEC (Canadian Weather for Energy Calculations) hourly weather data file is used in simulations. Becchio et al. (2015) investigated cost optimal and nZEB solutions for Italy. Energy assessment was performed by means of the dynamic energy simulation software EnergyPlus. A detailed sub-hourly simulation was conducted using the reference IWEC (International Weather for Energy Calculations) weather file for Turin. Kwak and Huh (2016) remarked the importance of weather data in building simulation as much as input data in modeling and developed a real-time building energy simulation method for efficient predictive control of the building. For this purpose, an EnergyPlus-specific real-time weather data file was generated for every day by using local forecast data. Global solar radiation was estimated by using the Zhang and Huang (2002) model by changing the regression coefficients. Direct and diffuse solar radiations were calculated by using the Watanabe et al. (1983) model. Seo and Krarti (2007) investigated the impact of solar radiation models used to estimate hourly global, diffuse, and direct solar radiation on annual building energy use. The four solar radiation models include the Kasten (Thevenard and Brunger 2002) model, Muneer et al. (1996, 1997) model, Zhang and Huang (2002) model, and neural network-based (Krarti 2003) model. Zhang and Huang (2002) model with site-fitted coefficients predicted annual building energy use more accurately rather than the other models. Wan et al. (2008) derived two-parameter regression models to predict global solar radiation for different regions of China and examined the impact of those models on building energy simulation. Solar heat through the windows, building heating and cooling loads were analyzed by using measured global solar radiation and the modeled solar radiation, separately. Simulated annual heating/cooling loads differed by 0.1%–6.2%. Kim et al. (2016) stated that only 22 out of 92 weather stations are equipped with solar radiation sensors in South Korea. Thus, solar radiation must often be calculated by reliable solar models. In order to identify the impact of solar radiation model on building energy performance, the three solar radiation models including cloud cover radiation model (Kasten and Czeplak 1980), Zhang and Huang (2002) model and meteorological radiation model (Kambezidis and Psiloglou 2008) were used. From an analysis of annual solar radiation, Zhang and Huang (2002) model was selected as the most appropriate one. However, it was stated that monthly-calculated solar radiation was found to have seasonal variations in summer and winter. It was concluded that a new solar radiation model was needed including seasonal characteristics such as absorption and scattering of solar radiation by the atmosphere, cloud amount, sunshine duration, etc.

Literature survey reveals the importance of the solar radiation model in studies on building energy simulation. Numerous empirical models have been developed in literature for predicting solar radiation on the horizontal surface. Chukwujindu (2017) classified the models for estimating global solar radiation into six different categories based on the employed meteorological parameters such as sunshine-based models, cloud-based models, temperature-based models, relative humidity-based models, precipitation-based models and hybrid parameter-based models. One of the simplest models was developed by Hargreaves and Samani (1982). Global solar radiation was evaluated from the difference between daily maximum and daily minimum dry bulb temperature. Hunt et al. (1998) used precipitation with daily maximum and daily minimum dry bulb temperatures in their model. Almorox et al. (2011) derived a new formula as a function of extraterrestrial solar radiation, saturation vapor pressures at maximum and minimum temperatures, transformed rainfall data, and daily minimum relative humidity. As it is seen, the solar radiation models are of different types and accuracy. Besides that, more complicated solar radiation models are available in the literature. Kambezidis et al. (2017) modified the Meteorological Radiation Model (MRM) which is a solar radiation code for the estimation of the broadband components of solar radiation (global, diffuse and direct) on horizontal surface using inputs of some basic meteorological parameters, i.e., air temperature, relative humidity, barometric pressure, and sunshine duration. New expressions for calculations of the cloud transmittance, which allow the use of cloud fraction and cloud optical depth for simulations under cloudy skies, were developed. By the way, diffuse fraction of the solar radiation estimated accurately.

### 2.1 Objective of the study

The aim of this study is to perform the hourly energy simulation of a single-family house assisted with solar energy system located in 12 locations of Turkey. Determination of solar radiation data plays an important role in the energy simulation results and this data is not available for all regions of Turkey. Proper use of global solar radiation model depends principally on the availability of periodically measured meteorological/atmospheric parameters. Generally, solar radiation models are used to predict solar radiation by using other meteorological variables such as temperature, sunshine duration, cloud cover, and precipitation, etc. (Hargreaves and Samani 1982; Zhang and Huang 2002; Muneer et al. 1996, 1997). Accordingly, this study focused on benchmarking of simple and complex models in dynamic building simulation. In the first model, the Angström-Prescott type solar radiation model for brevity APM, which was only a function of sunshine duration, is used to predict the global horizontal solar radiation. Sunshine duration data are more available and more accurate rather than the other meteorological parameters for Turkey (Kilic and Ozturk 1983; MENR 2017). Due to its availability and accuracy for Turkey, in most of the solar engineering application, this model has been used. To determine the diffuse fraction of this model, Erbs et al. (1982) correlation is used for its simplicity. The second model was prepared by adopting regression coefficient of Zhang and Huang (2002) model for brevity ZHM for different locations of Turkey. ZHM was developed for TMY files, which are preferred in building energy simulations and predicting solar radiation was accurately on an hourly basis for energy analysis of building (NREL 2008; Al-Anzi et al. 2008). This model estimates global horizontal radiation by using meteorological data. However, local regression coefficients are not available for Turkey. New regression coefficients were developed and the direct normal radiation is calculated by using Perez et al. (1992) model. In this way, a complex model (ZHM) of building energy simulation is compared with a simple one (APM).

## 3 Methodology

Two different weather files were prepared by including APM and ZHM. In order to address the effect of two solar radiation models on the energy performance of the building, a single-family house assisted with solar energy system was designed by using EnergyPlus® (V8.4) building energy simulation tool. The designed building system consisted of HVAC systems and renewable energy system composed of photovoltaic panels and solar hot water system. Flow chart of this study was presented in Fig. 1. Space heating and cooling loads, electric energy produced from PVs and service water heating (SWH) useful heat gain calculated by using two different hourly weather files derived for APM and ZHM. Effect of solar radiation models on energy performance ratings of designed building system discussed in detail.

### 3.1 Meteorological weather files and database

For building energy simulation, hourly weather file including information on the ambient conditions for an entire year is required. A typical weather file includes dry bulb and dew point temperatures, relative humidity, global horizontal irradiation, direct normal solar irradiation (DNI), wind speed and direction, cloudiness, liquid precipitation, etc. In this study, a five-year period database (2005–2010) was prepared for 12 locations of Turkey shown in Fig. 2. Locations were determined according to the climatic regions of Turkey defined in TS825 (Turkish Standards Institution 2013) heat insulation regulation. Measured weather data was taken from Turkish State Meteorological Service. Deficient and incorrect data corrected by comparing the hourly database utilized from Meteonorm (2014). DNI is not measured in 12 locations. Two different models were used to estimate global, diffuse horizontal radiations and DNI. The hourly weather file was modified according to the models and thus hourly database included two different solar radiation models was obtained for Turkey's 12 locations. The database was generated as Typical Meteorological Year (TMY) using Finkelstein and Schafer (1971) statistical method that proposed by Hall et al. (1978). Moreover, degree-days for both heating (HDD) and cooling (CDD) were calculated by generated TMY. Annualized HDD and CDD, each degree-days that the daily mean outdoor temperature and balance temperature 18 °C for HDD and 22 °C for CDD, for 12 locations of Turkey are 2890, 142 for Ankara; 1816, 295 for Bursa; 1672, 318 for Çanakkale; 3157, 139 for Erzincan; 1893, 684 for Gaziantep; 1714, 276 for İstanbul; 1407, 556 for İzmir; 3009, 93 for Kayseri; 2752, 204 for Konya; 2497, 471 for Malatya; 789, 874 for Mersin and 1834, 452 for Muğla, respectively.

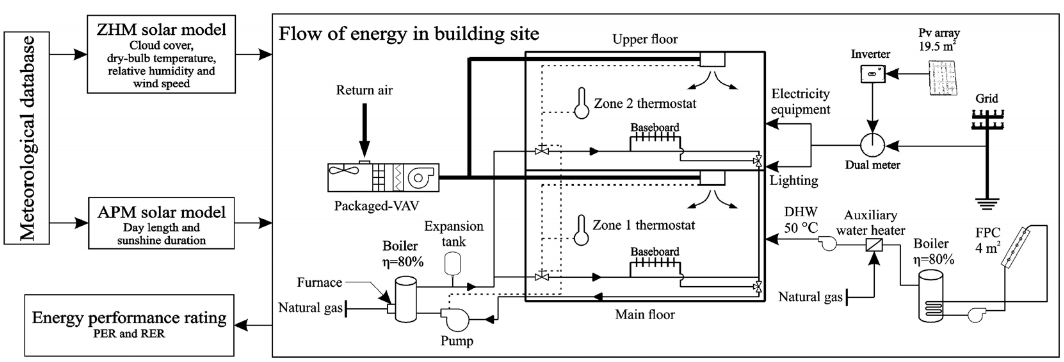


**Fig. 1** Energy flow chart of the building system

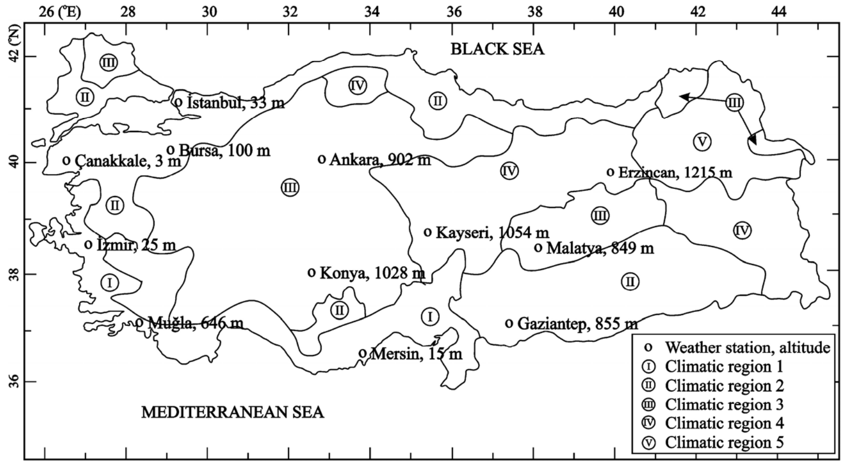


**Fig. 2** Weather stations' information

## 3.2 Solar radiation models

Building energy consumption rate is directly related to meteorological data in terms of temperature, relative humidity, wind speed and direction, and solar radiation values. In order to eliminate the effect of parameters except for solar radiation, two different weather files were prepared by including APM and ZHM for each location. The only difference of the weather files is the method used to estimate global, diffuse, and direct normal radiation data. By the way, the effect of solar radiation models on simulation results was compared.

### 3.2.1 *ZHM solar radiation model*

Zhang and Huang (ZHM) solar radiation model included almost all meteorological parameters. Zhang and Huang (2002) developed a solar radiation model that is valid for China to predict hourly solar radiation on the horizontal surface. This model was correlated according to the typical meteorological year data. Cloudiness (cloud cover, CC), dry-bulb temperature ($T$), relative humidity (RH), and wind speed ($V_r$) were used to estimate the solar radiation.

$$I = \begin{cases} \{I_{SC}\sin(h)[c_0 + c_1\mathrm{CC} + c_2\mathrm{CC}^2 + c_3(T_i - T_{i-3}) \\ \quad + c_4\mathrm{RH} + c_5V_r] + d\}/k & I > 0 \\ 0 & I = 0 \end{cases} \tag{1}$$

The constants in Eq. (1) were given as $c_0$=37.6865, $c_1$=13.9263, $c_2$=−20.2354, $c_3$=0.9695, $c_4$=−0.2046, $c_5$=−0.098, $d$=−10.8568, $k$=49.3112. Al-Anzi et al. (2008) modified this model according to the meteorological data of Kuwait and indicated that weather files similarly derived from correlation-based models were suitable for energy analysis of the buildings in Kuwait. Since the climate of Turkey is different from China and Kuwait, the predicted solar radiation data using these regression coefficients shows a very high deviation. For this reason, regression coefficients of the ZHM were modified. Table 1 shows new regression coefficients developed for each 12 locations of Turkey and generalized coefficients

**Table 1** Modified regression coefficients of the Zhang-Huang (2002) model for 12 locations of Turkey

| Coefficients | $c_0$ | $c_1$ | $c_2$ | $c_3$ | $c_4$ | $c_5$ | $d$ | $k$ |
|---|---|---|---|---|---|---|---|---|
| General | 0.6049 | 0.00238 | −0.00329 | 0.0142 | −0.00131 | −0.00073 | 2.045 | 0.843 |
| Ankara | 0.5831 | 0.0018 | −0.0029 | 0.0186 | −0.0019 | −0.0023 | 1.71 | 0.843 |
| Bursa | 0.6099 | 0.0070 | −0.0035 | 0.0161 | −0.0020 | −0.0007 | −0.81 | 0.843 |
| Çanakkale | 0.6565 | 0.0057 | −0.0034 | 0.0134 | −0.0019 | −0.0026 | −2.97 | 0.843 |
| Erzincan | 0.5803 | 0.0019 | −0.0030 | 0.0188 | −0.0018 | −0.0002 | 1.83 | 0.843 |
| Gaziantep | 0.5074 | −0.0199 | 0.0000 | 0.0403 | −0.0020 | −0.0015 | 25.49 | 0.843 |
| İstanbul | 0.6864 | 0.0109 | −0.0038 | 0.0152 | −0.0029 | −0.0019 | −1.52 | 0.843 |
| İzmir | 0.6813 | 0.0014 | −0.0028 | −0.0050 | −0.0021 | 0.0005 | −0.64 | 0.843 |
| Kayseri | 0.5708 | −0.0034 | −0.0026 | 0.0211 | −0.0011 | −0.0008 | 2.70 | 0.843 |
| Konya | 0.5810 | −0.0024 | −0.0027 | 0.0191 | −0.0010 | −0.0013 | 1.48 | 0.843 |
| Malatya | 0.4758 | −0.0066 | −0.0015 | 0.0353 | −0.0019 | −0.0010 | 19.47 | 0.843 |
| Mersin | 0.6848 | 0.0042 | −0.0032 | 0.0097 | −0.0021 | −0.0016 | −1.65 | 0.843 |
| Muğla | 0.6546 | 0.0028 | −0.0033 | 0.0064 | −0.0020 | −0.0001 | −3.60 | 0.843 |

valid for all locations. Also in this model, DNI is calculated by using Perez et al. (1992) model with the algorithm developed at Sandia National Laboratories (SNL 2016).

*3.2.2 APM solar radiation model*

Angström-Prescott type (APM) solar radiation model estimates daily global solar radiation on a horizontal surface by using the day length ($t_o$) and sunshine duration ($t$) as given in Eq. (2).

$$\frac{Q}{Q_o} = a + b\frac{t}{t_o} \tag{2}$$

where $Q$ and $Q_o$ are the daily global and extraterrestrial solar radiation on horizontal surface, respectively. The constants $a$ and $b$ may differ according to the location of the region where solar radiation is going to be estimated. Kilic and Ozturk (1983) correlated those constants given in Eqs. (3) and (4) by using latitude ($e$), elevation ($Z$), and declination angle ($\delta$) of different regions in Turkey.

$$a = 0.103 + 0.000017Z + 0.198\cos(e-\delta) \tag{3}$$

$$b = 0.533 - 0.165\cos(e-\delta) \tag{4}$$

For practical applications, hourly solar radiation data will be derived from daily solar radiation data by using day length, hour angle and the solar azimuth angle at sunrise and sunset times. Hourly solar radiation ($I$) is calculated by using Eqs. (5) and (6).

$$\psi = \exp\left[-4\left(1-\frac{|h|}{H}\right)^2\right] \tag{5}$$

$$I = Q\frac{\pi}{4t_o}\left[\cos\left(90\frac{h}{H} + \frac{2}{\sqrt{\pi}}(i-\psi)\right)\right] \tag{6}$$

In this model, the necessary diffuse component of solar radiation ($I_d$) is determined by using Erbs et al. (1982) correlation for its simplicity. Direct normal radiation is calculated by using diffuse component and zenith angle ($\theta_z$).

$$\frac{I_d}{I} = \begin{cases} 1-0.09K_T & \text{for} \quad K_T \le 0.22 \\ 0.9511-0.1604K_T+4.388K_T^2 & \text{for} \quad 0.22 < K_T \le 0.8 \\ 0.165 & \text{for} \quad K_T > 0.8 \end{cases} \tag{7}$$

The hourly clearness index ($K_T$) is defined as the ratio of horizontal global solar radiation to the extraterrestrial solar radiation as given in Eq. (8). Perez et al. (1990) defined the clearness index ($K_T$) as a parameter to characterize the status of the atmosphere, especially in the absence of complementary data (cloud cover, percent sunshine, humidity, etc.). By the way, both the level of availability of solar radiation and changes in the atmospheric condition in a given environment could be determined with the only piece of information available, in addition to the solar position.

$$K_T = I/I_o \tag{8}$$

The hourly direct solar radiation on horizontal surface ($I_b$) is calculated as,

$$I_b = \frac{I - I_d}{\cos(\theta_Z)} \tag{9}$$

Application of this model is straightforward. However, the effect of change of weather conditions on solar radiation in a day is not included.

## 3.3 Building simulation analysis

Building energy analysis was carried out for single-family house assisted with solar energy system (photovoltaic and solar water heating systems). The EnergyPlus building energy simulation tool was used. The conduction transfer function (CTF) algorithm is selected as the heat balance algorithm that utilizes one dimension transient heat conduction through multilayers such as walls and floors. Comprehensive convection algorithm was used as Thermal Analysis Research Program (TARP) developed by Walton (1983). Time step of 15 min was selected during the simulations.

The building dimensions and construction components were selected from conventional buildings in Turkey. In Figs. 3 and 4, the isometric view of the building model and the floor plan were given. Each floor was modeled as a single conditioned zone. There were three bedrooms and WC, two baths, one great room, and kitchen. The building has a net floor area of 128.6 m$^2$ and a net floor height of 2.8 m. The rates of window surface area to wall surface area for the south side, north side, east side and west side are 0.103 m$^2$/m$^2$, 0.038 m$^2$/m$^2$, 0.151 m$^2$/m$^2$ and 0.38 m$^2$/m$^2$, respectively. $U$-value of building envelope was set in accordance with the limit values required by national mandatory heat insulation standard TS825 (Turkish Standards Institution 2013). The weighted mean $U$-value of all components of building envelope was obtained by changing in insulation levels. Mean $U$-values were 0.71 for climatic region 1 (İzmir, Mersin and Muğla), 0.62 for climatic region 2 (Bursa, Çanakkale, Gaziantep and İstanbul), 0.51 for climatic region 3 (Ankara, Konya, and Malatya) and 0.44 for climatic region 4 (Erzincan and Kayseri). Table 2 shows $U$-values and other parameters in detail. For space cooling, the packaged variable air volume system was used. This system was a zone air conditioning system that provided conditioned air without heating. The

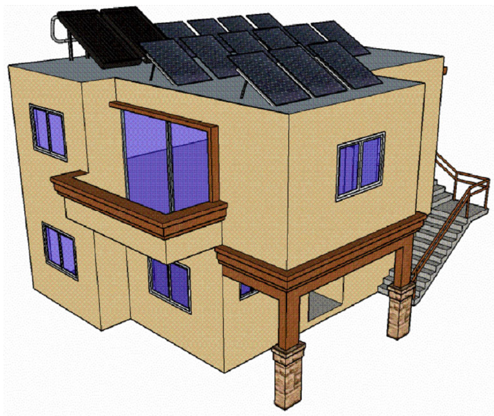

**Fig. 3** Isometric view of the building

packaged unit consisted of a DX cooling coils to condition the air. Cooling performance rated COP was 3 (a typical value for residential building in Turkey) and net cooling capacity ranged between 35 and 50 kW. For space heating, baseboard heating system with natural gas fired hot water boiler was preferred. Temperature set points were 23 °C from 8 a.m. to 5 p.m. (18 °C for the remaining hours) for heating and 23 °C from 8 a.m. to 5 p.m. (26 °C for the remaining hours) for cooling, respectively.

The renewable energy generator consists of the energy load (both electricity and heat), photovoltaic system (PVs) and solar water heating (SWH) systems. The PVs generates DC output current whose inverter converts to AC to meet the electric load of the residential house. The inverter with an efficiency range from 0.84 to 0.93 was used to convert electricity generated by solar modules to consumable alternating current. Total PVs surface area was 19.5 m$^2$. PVs consisted of a single row of three, six and four photovoltaic panels (1 m by 1.2 m) connected in series and parallel. The inclination angle of the panels was set to owner latitude coordinate of each location and also the orientation of the panels are 0° from the south. Generated PVs power was determined by using the Sandia model developed by SNL (2017). PVs power generation for Sandia model is calculated

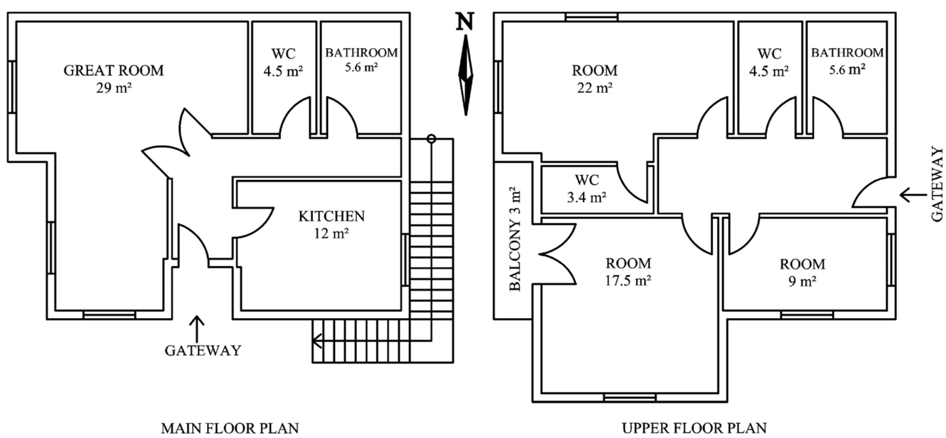


**Fig. 4** Floor plan of the building

**Table 2** Characteristics of the building system

| Parameters | | | | | | Unit |
|---|---|---|---|---|---|---|
| | | Walls *U*-value | Roof *U*-value | Floor *U*-value | Window *U*-value | |
| Building of envelope | Climatic region 1 | 0.66 | 0.43 | 0.65 | 1.80 | W/(m$^2$·K) |
| | Climatic region 2 | 0.57 | 0.35 | 0.51 | 1.80 | W/(m$^2$·K) |
| | Climatic region 3 | 0.44 | 0.28 | 0.37 | 1.80 | W/(m$^2$·K) |
| | Climatic region 4 | 0.33 | 0.25 | 0.34 | 1.80 | W/(m$^2$·K) |
| HVAC | Heating supply | Baseboard—hot water boiler | | Efficiency= 0.8 | | |
| | Cooling supply | Packaged—VAV | | COP= 3 | | |
| Schedule | Weekdays | 5 p.m. – 8 a.m. | | | | |
| | Weekend | 8 a.m. – 5 p.m. | | | | |
| Ventilation | 0.8 | Natural | | | | hr$^{-1}$ |
| People density | 0.05 | | | | | person/m$^2$ |
| Lighting density | 10 | | | | | W/m$^2$ |
| Other equip. | 2.5 | | | | | W/m$^2$ |

by using Eqs. (10) and (11).

$$P = I_{mp}(E_e, T_{cell})V_{mp}(E_e, T_{cell}) \quad (10)$$

$$E_e = I_t(T_{cell} = T^*)/I^* \quad (11)$$

where, $P$ is the power, at maximum power point current ($I_{mp}$) and also voltage ($V_{mp}$) are functions that depend on effective solar radiation ($E_e$) and cell temperature ($T_{cell}$).

PVs consists of cr-Si panels that includes number of cells in series per module (36 units), short circuit current (4.75 A), open circuit voltage (21.4 V), temperature coefficient of short circuit current (0.00065 A/K), temperature coefficient of open circuit voltage (−0.08 V/K) and NOCT (Nominal Operating Cell Temperature) cell temperature (47 °C) at standard test conditions (STC): $I^*$=1000 W/m$^2$, AM*=1.5 and $T^*$=25 °C. These empirical coefficients are available from the database provided by National Renewable Energy Laboratory (NREL 2017).

For domestic hot water (DHW) demand, the solar heating system with tempering valve included single tank (0.5 m$^3$) was used. DHW is set to 50 °C. Hot water demand was satisfied with natural gas-fired auxiliary water heater when solar energy was not enough to heat the water in the storage tank. DHW demand of the building is assumed 200 L per day. Two flat plate solar collectors whose gross surface areas are 4 m$^2$ in total were used in the system. The inclination angle of the flat plate solar collector was set to owner latitude coordinate of each location and the orientation of the collectors is 0° from the south. The solar thermal energy collected by the system can be determined by using Eq. (12):

$$\eta = a_0 K_\theta + a_1 \frac{(T_{in} - T)}{I_t} + a_2 \frac{(T_{in} - T)^2}{I_t} \quad (12)$$

The constants in the thermal efficiency equation, $a_0$=0.735, $a_1$=−3.6809, and $a_2$=−0.0281 are given by Alternate Energy Technologies which are evaluated by the Solar Rating & Certification Corporation™ (SRCC 2017). $I_t$ is the total incident solar radiation. $T_i$ is the inlet water temperature of the flat plate solar collector. The incidence angle modifier $K_\theta$, defined by using Eq. (13) was used to determine thermal efficiency.

$$K_\theta = 1 - b_0\left(\frac{1}{\cos\theta}\right) - b_1\left(\frac{1}{\cos\theta}\right)^2 \quad (13)$$

$\theta$ is solar incidence angle and $b_0$, $b_1$ coefficients are 0.025, −0.086, respectively.

### 3.4 Energy performance rating

Energy consumption and production in a building are affected by solar radiation models. These consisted of space heating intensity, space-cooling intensity, lighting, other equipment, and SWH that were provided by two different types of fuels (electricity and natural gas). In this way, annual primary energy rating (PER) is calculated in Eq. (14) which is defined by Kurnitski (2013).

$$\mathrm{PER} = \sum E_{del} f_{del,nren} - \sum E_{exp} f_{exp,nren} \quad (14)$$

where $E_{del}$, $E_{exp}$ are defined as delivered and exported energy and, $f_{del,nren}$, $f_{exp,nren}$ are delivered and exported nonrenewable energy conversion factor, respectively. Equation (15) is employed in order to calculate the renewable energy potential of the building.

$$\mathrm{RER} = \frac{\sum E_{ren} + \sum((f_{del,total} - f_{del,nren})E_{del})}{\sum E_{ren} + \sum E_{del} f_{del,total} - \sum E_{exp} f_{exp,total}} \quad (15)$$

where $E_{ren}$ is the renewable energy produced on building system. According to different types of fuels factors provided in EnergyPlus, energy conversion factor for electricity is 3.167 and is 1.084 for natural gas (DOE 2005).

According to ZHM and APM, relative deviation ($\varepsilon_{ZHM}$) is defined as Eq. (16).

$$\varepsilon = \frac{|y_{ZHM} - y_{APM}|}{y_{ZHM}} \times 100\% \quad (16)$$

$y_{ZHM}$ and $y_{APM}$ represent simulated value according to ZHM and APM, respectively.

## 4 Results and discussion

In this study, the effect of two solar radiation models on the energy performance of a single-family house assisted with solar energy system was examined for 12 locations of Turkey, in total 24 cases. Results were presented in terms of "Estimation of solar radiation", "Effect of solar radiation models on building energy performance" and "Energy performance rating of building system".

### 4.1 Estimation of hourly global solar radiation based on meteorological data

The estimated global horizontal solar radiation for 12 locations selected in Turkey was calculated by using Zhang and Huang (2002) model with derived new coefficients. Statistical indices such as coefficient of determination ($R^2$), mean bias error (MBE), mean absolute bias error (MABE), root mean square error (RMSE), mean percentage error (MPE), and mean absolute percentage error (MAPE) were used to evaluate adequacy of the model between the measured solar radiation on horizontal surface and the estimated solar radiation on horizontal surface. Table 3 shows the obtained

**Table 3** Statistical results of the modified Zhang and Huang (2002) solar radiation model for different regions of Turkey

| | Coefficient | $R^2$ (hourly) | $R^2$ (daily) | $R^2$ (monthly) | MAPE (daily, %) | MAPE (monthly, %) | MBE (Wh/m$^2$) | MABE (Wh/m$^2$) | RMSE (Wh/m$^2$) |
|---|---|---|---|---|---|---|---|---|---|
| All regions | General | 0.957 | N/A | N/A | N/A | N/A | −2.35 | 31.9 | 55.0 |
| Ankara | General | 0.967 | 0.958 | 0.995 | 18.26 | 6.23 | −10.7 | 27.1 | 45.8 |
| | Local | 0.969 | 0.961 | 0.992 | 14.6 | 4.5 | −1.6 | 24.7 | 42.9 |
| Bursa | General | 0.967 | 0.969 | 0.997 | 17.4 | 6.04 | −8.2 | 25.8 | 43.8 |
| | Local | 0.967 | 0.970 | 0.997 | 13.9 | 2.6 | −2.1 | 23.9 | 42.7 |
| Çanakkale | General | 0.966 | 0.972 | 0.993 | 15.71 | 4.58 | 1.83 | 28.4 | 46.74 |
| | Local | 0.968 | 0.975 | 0.995 | 15.6 | 4.6 | −3.4 | 25.4 | 43.9 |
| Erzincan | General | 0.971 | 0.973 | 0.997 | 15.8 | 5.9 | −7.9 | 26.2 | 44.2 |
| | Local | 0.972 | 0.975 | 0.996 | 12.9 | 3.9 | −1.2 | 24.3 | 42.0 |
| Gaziantep | General | 0.916 | 0.974 | 0.995 | 9.3 | 4.3 | 5.9 | 55.1 | 87.1 |
| | Local | 0.959 | 0.973 | 0.990 | 11.0 | 5.7 | −7.8 | 47.9 | 62.5 |
| İstanbul | General | 0.963 | 0.966 | 0.996 | 22.5 | 5.0 | −1.3 | 28.2 | 46.4 |
| | Local | 0.965 | 0.971 | 0.995 | 18.3 | 3.7 | −2.9 | 25.2 | 43.7 |
| İzmir | General | 0.962 | 0.984 | 0.997 | 8.9 | 4.8 | 8.9 | 35.2 | 59.9 |
| | Local | 0.990 | 0.987 | 0.998 | 7.4 | 2.3 | −1.2 | 14.8 | 27.7 |
| Kayseri | General | 0.976 | 0.974 | 0.998 | 9.96 | 4.66 | 0.73 | 26.3 | 44.1 |
| | Local | 0.979 | 0.974 | 0.998 | 9.9 | 4.1 | −1.5 | 24.1 | 41.5 |
| Konya | General | 0.976 | 0.975 | 0.999 | 8.7 | 2.4 | −1.1 | 26.5 | 44.5 |
| | Local | 0.978 | 0.975 | 0.999 | 8.7 | 1.9 | −2.2 | 24.2 | 42.6 |
| Malatya | General | 0.918 | 0.966 | 0.995 | 15.1 | 5.7 | −8.7 | 47.7 | 77.6 |
| | Local | 0.955 | 0.964 | 0.989 | 15.2 | 6.4 | −5.8 | 41.6 | 57.4 |
| Mersin | General | 0.965 | 0.975 | 0.998 | 9.3 | 5.7 | 5.5 | 31.7 | 52.2 |
| | Local | 0.970 | 0.974 | 0.997 | 8.8 | 5.5 | −2.6 | 26.8 | 46.6 |
| Muğla | General | 0.972 | 0.972 | 0.994 | 21.3 | 9.4 | −13.1 | 25.1 | 46.7 |
| | Local | 0.978 | 0.972 | 0.992 | 15.8 | 3.7 | −2.5 | 20.9 | 38.9 |

results in hourly, daily, and monthly basis. For each location, statistical analysis was represented for general coefficients derived by using the whole data and local coefficients derived by using only the location meteorological data, separately. It was obtained that the estimation of solar radiation on the horizontal surface could be performed with an acceptable accuracy. The highest and lowest MABE values were 55.1 Wh/m$^2$ and 25.1 Wh/m$^2$ obtained for Gaziantep and Muğla, respectively.

In Fig. 5, ZHM and APM solar radiation model versus measured global solar radiation data are given for 12 locations in hourly basis. ZHM was more successful than APM to

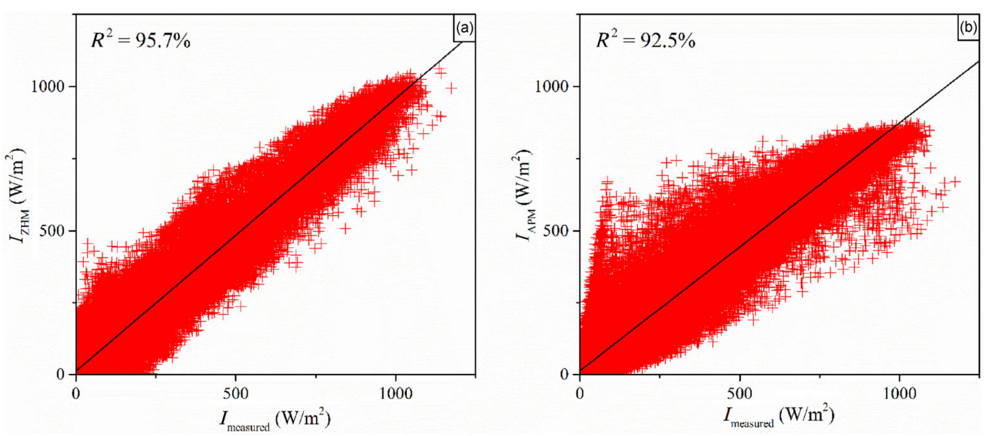


**Fig. 5** Solar radiation model against measured global solar radiation for 12 locations of Turkey in hourly basis for (a) ZHM model and (b) APM model

estimate solar radiation. As Kambezidis et al. (2017) stated, solar radiation depends on several astronomical and geographic factors, such as Earth–Sun distance, solar altitude, season, latitude and altitude as well as on atmospheric transparency defined by the amount of clouds, aerosols, trace and mixed gases, water vapor, and ozone. Especially, solar radiation models deviation increases under cloudy conditions. The main reason why ZHM is more successful is to consider the cloudiness.

In Fig. 6, total monthly global solar radiation obtained from ZHM and APM solar radiation models, measured global solar radiation and monthly average cloud cover data are given for Mersin. APM model estimated measured solar radiation successfully between May and September. In this period, a decrease in average cloud cover was observed and clear sky condition was valid. Reversely, increasing average cloud cover leads to an increase in the deviation of APM model from measured data. Similar results were obtained for other locations. Moreover, in the daily analysis, this relation was shown for representative day February 01. APM model is derived by integrating global daily solar radiation between sunrise and sunset. The only parameter is the sunshine duration. Differently, ZHM is derived based on hourly data and for that reason, it is more sensitive to the sudden change in weather conditions. This phenomenon may not be distinguished for hourly heating and cooling loads due to the transient effects. However, instantaneous PVs electricity generation and SWH useful heat gain directly affected.

## 4.2 The effect of solar radiation models on building energy performance

Parameters directly affected by solar radiation such as space heating and cooling intensities, photovoltaic electricity production, and useful heat gain of the SWH were analyzed for each simulation. Table 4 shows the obtained results on the annual basis. For space heating intensity, the highest deviation was 8% and obtained for Gaziantep. Average relative deviation of all locations was 2.5% so the effect of solar radiation models on this parameter was negligible. Other meteorological parameters such as outdoor dry bulb

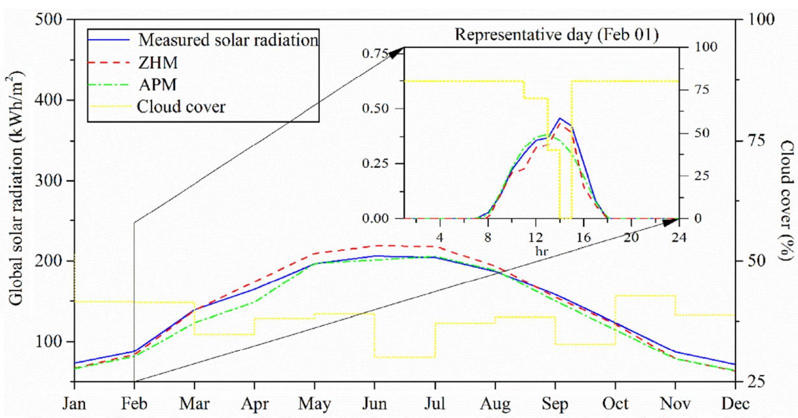


**Fig. 6** Total monthly global solar radiation on horizontal surface and cloud cover ratio for Mersin and representative day of February 01

**Table 4** Simulation results and percentage relative deviation (values are shown in bracket) for each model and location (kWh/(m²·yr))

| Location | Space heating | | | Space cooling | | | PVs production | | | SWH useful heat gain | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ZHM | APM | | ZHM | APM | | ZHM | APM | | ZHM | APM | |
| Ankara | 261.6 | 267.0 | (2) | 59.3 | 51.8 | (13) | 64.0 | 66.6 | (4) | 472.2 | 491.7 | (4) |
| Bursa | 164.0 | 168.5 | (3) | 72.8 | 64.4 | (12) | 59.6 | 61.4 | (3) | 443.3 | 459.8 | (4) |
| Çanakkale | 159.5 | 160.7 | (1) | 90.8 | 80.2 | (12) | 60.2 | 63.3 | (5) | 415.6 | 458.3 | (10) |
| Erzincan | 288.2 | 290.0 | (1) | 72.9 | 65.3 | (10) | 65.5 | 69.9 | (7) | 460.6 | 495.2 | (8) |
| Gaziantep | 145.1 | 157.3 | (8) | 154.7 | 125.7 | (19) | 80.3 | 74.4 | (7) | 536.6 | 513.9 | (4) |
| İstanbul | 163.4 | 169.3 | (4) | 77.6 | 70.8 | (9) | 57.5 | 60.1 | (5) | 420.8 | 439.9 | (5) |
| İzmir | 123.6 | 125.3 | (1) | 124.0 | 113.3 | (9) | 72.5 | 69.9 | (4) | 482.8 | 493.9 | (2) |
| Kayseri | 267.3 | 270.4 | (1) | 75.1 | 63.5 | (15) | 76.8 | 76.1 | (4) | 542.0 | 552.6 | (2) |
| Konya | 246.1 | 253.1 | (3) | 79.7 | 66.4 | (17) | 78.5 | 74.4 | (1) | 547.7 | 537.8 | (2) |
| Malatya | 215.2 | 224.2 | (4) | 117.0 | 100.7 | (14) | 71.2 | 74.2 | (5) | 492.4 | 517.7 | (5) |
| Mersin | 57.8 | 57.1 | (1) | 171.3 | 156.5 | (9) | 69.3 | 72.7 | (4) | 453.5 | 487.9 | (8) |
| Muğla | 149.9 | 148.6 | (1) | 109.6 | 96.2 | (12) | 67.6 | 70.0 | (4) | 462.3 | 513.0 | (11) |

temperature and wind speed were more dominant in space heating intensity. For space cooling intensity, the highest deviation and the lowest deviation of the models were 19% and 9%, respectively. Deviation in space cooling intensity was obviously higher than the deviation in space heating intensity. Solar radiation is much more effective in cooling load calculation rather than heating load. Heating and cooling loads calculation procedure includes terms such as heat transfer through the building envelope, internal heat gain, heat loss due to ventilation and infiltration, heat gain due to equipment and lights, etc. In heating load, the term heat transfer through building envelope due to temperature difference and heat gain due to equipment and lights are dominant factors when compared with the effect of solar radiation. However, in cooling load calculation, solar radiation is a dominant factor and the deviation between the solar radiation models directly affects the cooling load. Similar results were valid for electricity generated from PVs and useful heat gain of solar water heating system since they were directly proportional to the solar radiation and outdoor dry bulb temperature.

## 4.3 Energy performance rating

The total primary energy rating (PER) of the building system is given in Fig. 7. PER is classified according to the electricity consumption of zone cooling system, lighting, fan, pump, and other equipment and natural gas consumption of zone heating system and SWH. Calculated electricity consumption rate was always higher in ZHM model for all regions when compared with the other model. The exact opposite situation was obtained in natural gas consumption rate. For total PER, the highest deviation was 4.6% and 3.3% for Mersin and Muğla, respectively. For the other locations, this parameter deviates between 0.02% and 2.11%.

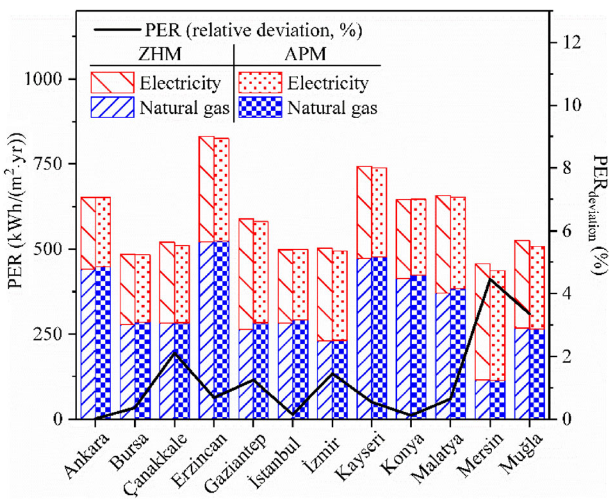


**Fig. 7** Total of primary energy ratings for each location

In Fig. 8, relative deviation in primary energy rating of APM simulation compared with ZHM model for each component is given. For Mersin, APM simulation overestimated the lighting (1.3%), pump (3.9%) and generator (1%) electricity consumptions when compared with the simulation with ZHM. The highest deviation is observed in SWH natural gas consumption (27%) and zone cooling electricity consumption (7.5%). For all locations, SWH natural gas consumption and zone cooling electricity consumption are underestimated in APM simulation. Moreover, the effect of solar radiation on SWH natural gas consumption, zone cooling, and fan electricity consumptions is obviously higher than the other parameters.

In Fig. 9, the renewable energy ratio (RER) simulated according to ZHM and APM and the relative deviation of

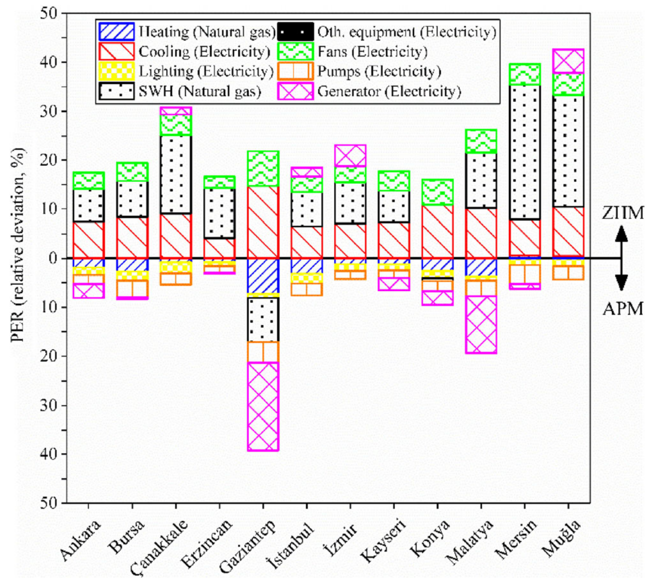


**Fig. 8** Relative deviation in primary energy ratings for each location

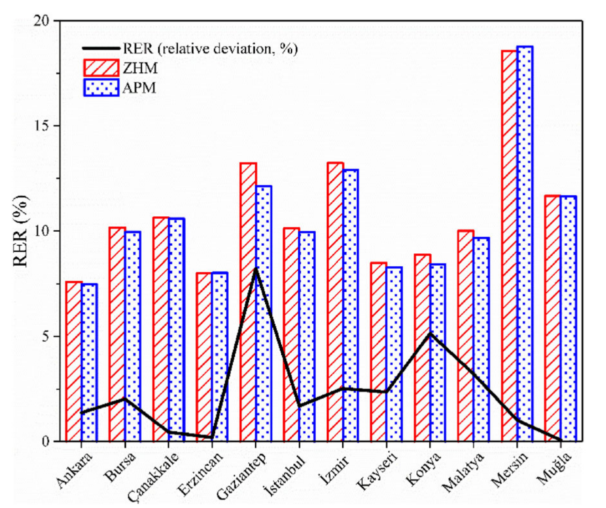


**Fig. 9** Renewable energy ratio and relative deviation for each location

obtained results for each location is given. According to the simulation with ZHM, the highest RER was obtained 18.6% for Mersin and the lowest one was obtained 7.6% for Ankara. The relative deviation of all locations except Gaziantep and Konya was less than 3.2% that is in a negligible level for building system designs.

## 5 Conclusion

In this study, the hourly energy simulation of a single-family house assisted with solar energy system was performed for 12 locations in Turkey. Building energy simulation tool was carried on EnergyPlus. To calculate building energy consumption rate, an hourly meteorological file of the region is required. Solar radiation is one of the most important parameters of that file. In order to eliminate the effect of parameters except for solar radiation, two different weather files were prepared by including APM and ZHM for each location. In the first model, the Angström-Prescott type (APM) solar radiation model was used to predict the global horizontal solar radiation and the diffuse fraction was calculated by using Erbs et al. (1982) correlation. The second model was prepared by adopting regression coefficient of Zhang and Huang (2002) (ZHM) model for different locations of Turkey. Direct normal radiation was calculated by using Perez et al. (1992) model. The effect of solar radiation models on building system was discussed in detail. The key results of this study are as follows:

(1) New regression coefficients of Zhang-Huang solar radiation model, which is not defined before, were developed for different locations of Turkey to predict hourly solar radiation with an acceptable accuracy ($R^2$=95.7%, RMSE= 55 Wh/m$^2$) according to measured solar radiation.

(2) For space heating intensity, the effect of solar radiation models is negligible since outdoor dry bulb temperature, relative humidity, and wind speed were more dominant. For space cooling intensity, relative deviation of simulation results of the solar radiation models was between 9% and 19%. Similar results were valid for electricity generated from photovoltaics and useful heat gain of the solar water heating system.

(3) The impact of solar radiation models in primary energy rating was more effective on SWH natural gas consumption. Average deviations of primary energy rating for SWH, space cooling intensity, equipment of HVAC (fans and pumps), generator, space heating intensity and lighting intensity, are 11.1%, 8.6%, 6.7%, 4.3%, 2.2%, and 1.4%, respectively.

(4) Highest renewable energy ratio (RER) was obtained for Mersin with 18.6% by using ZHM. Deviation of the RER was between 8.2% (Gaziantep) and 0.1% (Muğla).

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