Environmental Science and Pollution Research
https://doi.org/10.1007/s11356-022-24889-3

RESEARCH ARTICLE

# Advanced thermodynamics analysis for sustainable residential sector: a case study of Turkish residential sector

**Monirul Islam Miskat[1] · Salman Rahman[2] · Quddus Tushar[3] · Shishir Barai[4] · Nazia Hossain[3] · Fazleh Rabbi[5] · Nadia Sultana Nisha[5] · Sadiq Sait[6]**

Received: 17 May 2022 / Accepted: 16 December 2022


## Abstract

Energy sustainability plays a crucial role in the development of any country. With the booming economy of Turkey, it is necessary to ensure energy sustainability in every sector. The residential sector plays a vital role in energy consumption in Turkey and improving sustainability in this sector can foster Turkey's development. This study introduced first-time sustainability indicators of Turkey's residential sector to determine the energy and exergy analyses through a thermodynamics-derived approach based on the data from 2000 to 2017. Monte Carlo simulations have been performed for energy source variation. Possible distribution uncertainties show that natural gas (0.78–0.76), biofuels, and waste (0.39–0.43) are dominant parameters for energy and exergy. Improvement of biofuels and waste, renewable-based energy sources can be a feasible solution for fossil fuel replacement. In Turkey's residential sector, energy efficiency varies from 27.51 to 35.65%, while exergy efficiency ranges from 25.85 to 34.06%. The sustainability index for Turkey ranges from 1.34 to 1.51. In Turkey, around 65.93 to 74.14% of fossil fuel has been depleted in the last 18 years, which leads to lesser exergetic sustainability. Inefficient cooking, heating appliances, and lighting devices lead to higher exergy loss. Therefore, this study demonstrates the exergy analysis and prediction of the upcoming consequences of this analysis. In the future, Turkey can use higher efficient devices, especially in heating, lighting, and mechanical energy-related appliances, and electricity can be used to attain higher exergetic efficiency. Performed analysis and uncertainties of parameters will assist policymakers in selecting suitable alternative strategies in Turkey's residential sector for sustainable decision-making.

**Keywords** Turkey's residential sector · Fossil energy · Renewable energy · Energy sustainability · Monte Carlo simulation

## Abbreviations

| | |
|---|---|
| GHG | Greenhouse gases |
| EU | European Union |
| $T_o$ | Ambient temperature |
| $W$ | Work |
| $Q_k$ | Heat transfer |
| $ex_c$ | Chemical exergy |
| $\mathrm{Ex}_{\mathrm{loss}}$ | Exergy loss |
| $H_{ff}$ | Higher heating value (kJ/kg) |
| $\gamma$ | Exergy factor |
| IP | Irreversibility of process (IP) |
| $\varphi$ | Exergy efficiency |
| $\eta$ | Energy efficiency |
| $D$ | Depletion number |
| SI | Sustainability index |
| RF | Renewable fraction |

Responsible Editor: Philippe Garrigues

Monirul Islam Miskat, Salman Rahman, and Quddus Tushar are co-first authors.

✉ Nazia Hossain
bristy808.nh@gmail.com

[1] Department of Electrical and Electronic Engineering, Chittagong University of Engineering & Technology, Chattogram 4349, Bangladesh

[2] School of Mathematical and Statistical Sciences, The University of Texas Rio Grande Valley, Edinburg, TX 78539, USA

[3] School of Engineering, RMIT University, Melbourne, VIC 3001, Australia

[4] Department of Mechanical Engineering, The University of Texas Rio Grande Valley, Edinburg, TX 78539, USA

[5] Department of Geography and Environmental Studies, University of Chittagong, Chattogram 4331, Bangladesh

[6] King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia

Published online: 23 December 2022

NRF Non-renewable fraction
WER Waste exergy ratio
EDC Exergy destruction coefficient
IEA International Energy Agency
PJ Petajoule
LED Light-emitting diode

## Introduction

Energy is a critical component of an advanced and sustainable society. A robust and consistent energy supply is vital for technological and social development. The energy demand by various community sectors, such as industrial, residential, transportation, agricultural, and others, increases fossil fuel applications day by day (Chowdhury et al. 2020a). Therefore, fossil fuel is depleting. Due to fuel combustion, greenhouse gases (GHGs) are increasing and are responsible for tremendous environmental pollution (Utlu and Hepbasli 2005, 2007; Utlu et al. 2021). According to IEA (EXPAND IEA), the residential sector contributes to a significant portion of energy use, and every year, energy consumption in this sector increases rapidly. In 2017, 17% of the world's total $CO_2$ came from the residential sector (Tushar et al. 2019). A significant amount of energy is lost in this sector, and proper in-depth analysis is crucial for improving sustainability. To resolve this issue, exergy analysis has been demonstrated worldwide to analyze the overall energy strategy, simulation, and efficiency assessment of a thermal/thermo-chemical/thermo-dynamic system since exergy analysis is considered a meticulous approach to determine energy efficiency (Kanogˇlu et al. 2005). Exergy is defined as producing helpful work, and exergy cannot be conserved (Dincer et al. 2004a). In other words, exergy is a quality form of energy, and it is one of the most impactful methods that shed light on how much energy can be efficiently utilized from an existing system before reaching the final state of equilibrium of the external environment (Ahamed et al. 2011). Exergy analysis is also applied to precisely determine the location and amount of energy losses that are not available in energy analysis.

Exergy analysis done by Corre et al. found that exergy varies between 17 and 27% (Corre et al. 2013). Arslanoglu et al. performed an insightful study on the available solar exergy from the solar radiation in Turkey and found 0.93 for average exergy (Arslanoglu 2016). Researchers have performed exergy analysis for solar and other sectors to understand the system's actual energy efficiency and losses. Other studies by Koroneos et al. are considered various energy sources such as solar/electric, wind/electric, and other non-renewable energy resources for exergy analysis (Koroneos et al. 2011; Xydis et al. 2009). To gain accurate knowledge about the performance of wind power plants, exergy and energy analyses were done by Aghbashlo et al. (Aghbashlo et al. 2018). Recently, the exergetic sustainability approach has been applied in the sustainability analysis of industrial furnaces to the transportation section (Chowdhury et al. 2021a, 2021b). An earlier study by Açıkkalp et al. 2021 described a novel combined extended advanced exergy analysis method for assessing the thermodynamic system (Açıkkalp et al. 2021). Besides, Utlu et al. 2021 introduced a thermodynamic and artificial neural network (ANN) approach to evaluate the solar energy system (Utlu et al. 2021), but there is no study so far in the literature review that uses the Monte Carlo simulation to find the uncertainty of input variables and the possible best outcome.

Various researchers conducted sectoral exergy analysis to gain a broad outlook on energy utilization in multiple sectors (Dadsetani et al. 2019; Sarafraz et al. 2021). Many researchers have done numerous sectors such as the power generation sector, rural residential sector, residential sector, commercial sector, and the industrial sector's exergy analysis (Bühler et al. 2016, Maddah and Safaei 2021, Oladiran and Meyer 2007). The use of electricity for low-grade thermal applications was lower exergetic efficiency. Exergy analysis was done by Arango Miranda et al. to calculate Mexico's industrial sector's exergy and energy efficiencies. It is shown that exergy efficiency is significantly lower than energy efficiency, 23% and 73%, respectively (Arango-Miranda et al. 2018). This study was done on data from 2000 to 2015 in the industrial sector and considered electricity and fossil fuel as the primary energy sources. It is also shown that the iron and steel industries exhibit high exergetic efficiency due to electric arc furnaces. The sugar sector displays the highest energy efficiency as it uses cane bagasse as a renewable source. A previous study demonstrated the influence of dead state temperature on the exergetic efficiency of the industrial sector in Turkey (Utlu and Hepbasli 2008). In this context, exergy efficiency varies from 25.30 to 29.50% and 51.95 to 80.82%, while dead-state temperature ranges between 0 and 25 °C.

A study was done by Chowdhury et al. (Chowdhury et al. 2020a) on Bangladesh's commercial sector which found that exergy efficiencies vary in the range of 35.0 to 39.2%. Energy efficiencies vary from 34.9 to 36.3%. This study suggested using energy-efficient lighting and proper waste energy management and replacing gas-fired cooking stoves with electrical appliances to improve exergy efficiency. An earlier study performed an exergy analysis on residential, commercial, service, and public transport in Milano smart city planning (Causone et al. 2017). This study found that Milano's most significant share of primary energy relies on buildings. Exergy analysis for measuring sustainability is also evident in several studies (Amoo and Fagbenle 2014; Arunkumar et al. 2015; Brounen et al. 2013; Gong and Wall 2016; Kusiak et al. 2013; Li et al. 2020).

Among different sectors of exergy analysis, the industrial sector has been analyzed the most during the residential sector the least. According to an exergy analysis conducted in Malaysia, 70% energy and 28% exergy efficiencies have been identified. A similar methodology was implemented in the residential sector of Malaysia and Saudi Arabia to analyze exergy efficiency. This analysis presented overall 21%, 12%, 11%, 10%, and 8% exergy losses occurred by freezer refrigerator, air conditioner, washing machine, fan, and rice cooker, respectively, within eight years period from 1997 to 2004 (Chowdhury et al. 2019a). Another study presented that 18.96–31.53% and 4.86–8.42% of energy and exergy efficiencies, respectively, can be improved in the rural residential area in Bangladesh within 2010–2050, and 95% of fuel can be depleted from this sector. The study recommended biomass-based cookstoves for ensuring energy sustainability (Chowdhury et al. 2019a). A prediction study of energy and exergy analyses on the Turkish residential industry forecasted that this sector's total losses in energy and exergy from 2000 to 2022 would be 55.60–75.53% and 8.02–11.21%, respectively. It recommends using higher effective energy-exergy efficient process mechanisms for the utility policymakers in Turkey (Utlu and Hepbasli 2005). Several studies on various countries' urban residential sector and residential sectors are also available in these literature reviews (Al-Ghandoor et al. 2008; Armel et al. 2015; Badmus and Osunleke 2010; Dincer et al. 2004b; Fidelis et al. 2014; Liu et al. 2014).

Based on the energy and exergy analysis prediction, a study forecasted building without heating insulation requires 200–250kWh/m$^2$ while renovated, or new buildings with heating insulation will require only 100–150kWh/m$^2$ energy (Ozturk et al. 2004). The next largest share in energy consumption is space heating. Improvement of energy and exergy efficiencies of boilers in one of the most populated cities, Izmir city, Turkey, can save 12% fuel during the winter period (Hepbasli 2001). Therefore, a detailed energy-exergy study on the overall residential sector is essential for the country to determine the potential for efficiency improvement and possible approaches for policymakers for further development.

Most of the previous studies on energy and exergy analyses demonstrated in Turkey were either on the industrial sector or geothermal heating system by 2007 (Ozgener et al. 2005a, b; Utlu and Hepbasli 2004). The latest exergy analysis on actual data in Turkey was conducted on the Kizildere geothermal power plant, Turkey, in 2015 (Ozturk et al. 2006). All the experimental and forecasted investigations in Turkey presented only fossil-fuel-based exergy analysis, while the current study analyzed both fossil and renewable fuel-based exergy.

Sensitivity analysis is a systematic tool for developing models for observational study in energy and exergy analyses (Ege and Şahin 2014; Hossain et al. 2019). Therefore, sensitivity analysis has been extensively used to investigate various applications' energy and exergy performance characteristics. The sensitivity analysis methodology is the same for different sources of energy and exergy analyses. A typical implementation of sensitivity analysis consists of several parts: determining input variables, developing the relationship, performing the simulations, and collecting the results for design variables (Tian 2013; Tushar et al. 2021). The probabilistic distribution of input energy sources is often neglected in research applications. Process and operating data of energy sources in the residential sector can be considered a normal distribution to assign the uncertainties of production systems (Swan and Ugursal 2009). In this case, variations of inputs are equally uncertain due to the source of availability, energy production, and real scenarios. Uncertainties of input variables are feasible to combine to identify possible outcomes. From these perspectives, complicated two-dimensional Monte Carlo analysis is the probable solution to get the optimum result (Martoňák et al. 2002). Monte Carlo simulation depends on repeated random sampling and statistical analysis to compute the results. Monte Carlo algorithms are easy and efficient, transforming complex systems into a basic set of formulas that can be efficiently simulated in a computer. Monte Carlo simulation can find the uncertainty of input variables and the possible best outcome, which is utilized in this analysis (Tushar et al. 2021). Among different uncertainty analysis methods, Monte Carlo simulation has been implemented in the current study due to the higher practical guidance compared to others. According to earlier study, International Vocabulary of Metrology (VIM-JCGM 200:2012) presented the guide to the expression of uncertainty in measurement and mentioned that propagation of distributions implementing Monte Carlo simulation is one the best methods for providing practical guidance for the estimation of uncertainty (Couto et al. 2013). Besides, this simulation is well-established uncertainty estimation approach which had been applied commercially for diverse fields like science, finance, engineering, and supply chain (Couto et al. 2013).

The most prominent feature that distinguishes this study from previous studies is the identification of sustainable indicators based on exergy in the residential sector of Turkey for the first time. For this reason, this study will be critical in carrying previous studies to a further point and being a reference. The research aims to assess the application of sensitivity analysis in the Turkey residential sector for energy and exergy performances. The uncertainty analysis provides the remedy for possible increase and reduction in the effective use of energy sources. An exhaustive sensitivity analysis measures correlation between input variables and the confidence interval of probable outcomes. Moreover, no other study on the Turkish residential sector's exergy analysis is based on actual data from 2000 to 2017.

Moreover, thermal loss and system deviation are not adequately assessed in energy analysis, leading to misleading conclusions when decision-making is utterly dependent on energy analysis (Dincer and Rosen 2012). Exergy analysis can predict the energy loss forecast and assess insight for further development of the potential and efficiency of a specific system (Jeter 1981; Mehrdad et al. 2020). Renewable fuel in the residential sector is also analyzed in another study by Chowdhury et al. (Chowdhury et al. 2020a). This study utilized biofuel to find out the exergy analysis of the residential sector of Bangladesh. Using fossil fuel's renewable fuel-based exergy analysis is crucial because it provides a holistic view of the sector. Besides, in the national plan, it is stated that the government wants to reduce dependency on natural gas and focus on renewable energy-based fuel. Irreversibilities associated with renewable fuel utilization are generally lower than with fossil fuel. Improved exergy efficiency contributes to higher environmental sustainability and lower emission.

This study aims to determine the exergetic sustainability of the Turkish residential sector based on data from 2000 to 2017. This study has investigated how exergy flow is generated from different fuels such as coal, petroleum oil, natural gas, renewable fuel energy, and electricity implemented in the residential sector.

## Overview of Turkey residential sector

Urbanization in Turkey has reached 2% per year, contributing to growth in energy demand in the last ten years. The residential sector is the third-largest energy-consuming sector in Turkey among various sectors. The residential sector of Turkey consumed 19.1PJ energy in 2014, which was responsible for 22.3% of the country's total energy consumption. From 2014, the energy consumption of the Turkish residential sector manifested an annual 2% growth in 2016. By 2018, Turkey was heavily dependent on foreign energy sources by approximately 73%. Turkey's energy consumption in various sectors is shown in Fig. 1. It is shown that 25% of the total energy consumption goes to Turkey's residential and lighting sector (Öz and Alyürük 2020). It has been projected that the total energy consumption in Turkey will reach 170.3 Mtoe in 2020. Demand for energy in the residential sector rose by 5.8% between 2004 and 2014. For most cities in Turkey, the leading residential appliances are cooking appliances, washing, space heating and cooling, hot-tap water, refrigeration, light, TV, and other household appliances. Among these appliances, energy consumption by heating systems carries the most significant share of overall energy demand since most of the buildings in Turkey are without heating insulation (Bait 2019).

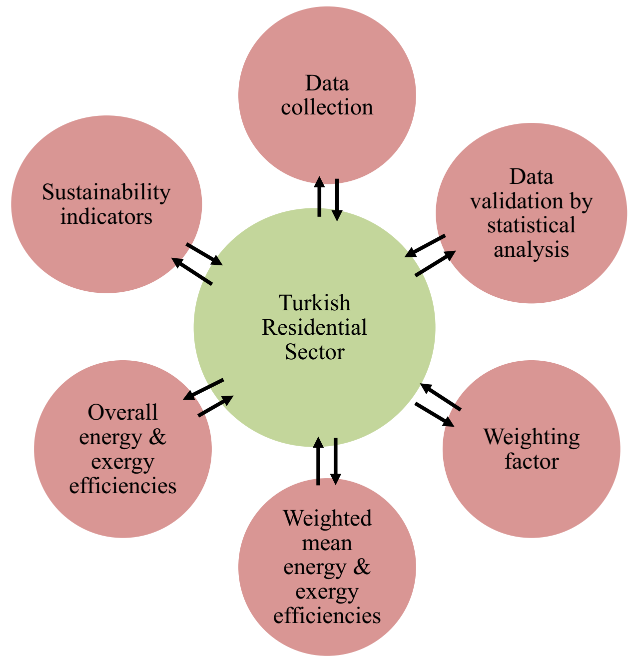


**Fig. 1** System boundary for the residential processes (outbound arrows from the residential sector describe the direction of the data flow, and the inbound arrows describe the implementation of the results of the thermodynamics analyses)

To decrease the energy dependency, the Turkey government released the National Energy Efficiency Action Plan covering the period 2017–23 on January 2, 2018. This plan aims to decrease the primary energy consumption of Turkey by 14% by 2023 through 55 actions defined in 6 categories: energy, agriculture, buildings and services, industry and technology, transport, and cross-cutting areas. The government anticipates that 23.9 Mtoe energy can be saved by 2023 after implementing this plan, resulting in an economic saving of $8.4 billion (Celik and Oktay 2019). In this plan, the government aims to promote energy efficiency in the existing buildings. The government also wants to establish a National Green Building Certificate System. Besides, the government wants to expand the buildings to produce their energy. From energy service systems, Turkey does not reap proportionate benefits. There are three significant reasons behind this. First of all, households have to pay a lot of money for natural gas and electricity. Moreover, equipment for cooling, lighting, and heating systems is inefficient. Last, insulation to protect people is not up to the mark. These three reasons lead to energy poverty in Turkey (Ucal and Günay 2022). Turkey has lower building energy standards than other EU countries. Furthermore, home renovation is under-developed in Turkey. Between 1980 and 2000, building standards were not updated. The share of residential buildings constructed with low energy efficiency standards between 1980 and 2000 in the current dwelling stock carries significant energy share

(Öz and Alyürük 2020). A huge potential energy was lost in that period. If these dwellings were improved, almost half of its current dwelling stock could be more energy-efficient today (Ucal and Günay 2022).

## Methodology

In this section, basic concepts of thermodynamics analysis, exergy, energy efficiency, and sustainability indictor for measuring the overall sustainability of the residential sector are analyzed.

### Thermodynamics analysis

Thermodynamics analysis is considered one of the crucial tools for analyzing the system's performance. Based on various performances evaluating criteria such as balance equations, thermal equilibrium conditions, and kinetic relationships in the system, it analyzes the impacts and effects of the energy in various parts of the system. It also deals with energy and exergy availability to determine the area of losses and how it can be improved. The necessary equilibrium equations within the scope of thermodynamics analysis of the housing sector are given below as Eqs. (1), (2), and (3), respectively (Szargut 2005).

$$\sum_{m_{\text{in}}} = \sum_{m_{\text{out}}} \tag{1}$$

$$\sum (mh)_{\text{in}} - \sum (mh)_{\text{out}} = W - Q \tag{2}$$

$$\sum ( m\ ex_c )_{\text{in}} - \sum ( m\ ex_c )_{\text{out}} + \sum \left(1 - \frac{T_o}{T_k}\right) Q_k - W = Ex_{\text{loss}} \tag{3}$$

where $m$ represents the mass, $T_o$ is the ambient temperature, $W$ is the work, $Q_k$ is the heat transfer, $T_k$ is the constant temperature, $\text{ex}_c$ is the chemical exergy, and $Ex_{\text{loss}}$ is the exergy loss.

Chemical exergy is the maximum work from the oxidation of fuel hydrocarbon's specific exergy shifts to chemical exergy in atmospheric temperature and pressure. Chemical exergy is the product of exergy grade function and higher heating value, delineated in Eq. (4).

$$ex_c = \gamma_{ff} H_{ff} \tag{4}$$

$H_{ff}$ represents the higher heating value (kJ/kg), and γ shows the exergy grade function. The values of γ for the energy sources analyzed in the present study are provided in Table 1.

**Table 1** Exergy factor of energy sources adapted from (Koroneos et al. 2011)

| Energy source | Exergy factor (γ) |
|---|---|
| Waterfall energy | 1 |
| Electrical energy | 1 |
| Natural gas | 1.04 |
| Coke | 1.05 |
| Oil and petroleum products | 1.06 |
| Coal | 1.06 |
| Bagasse | 1 |

### Improvement potential

Using exergy analysis, potential insights such as the system's energy consumption maximization and reduction of irreversibility can be achieved. Irreversibility of process (IP) indicates how much a system or process can be improved by reducing the irreversibility of a process. As a result, IP potential is utilized to analyze systems, shown in Eq. (5).

$$\text{IP} = (1 - \varphi)^2 \times \text{Exergy Input} \tag{5}$$

where φ is the exergy efficiency, and exergy efficiency is the ratio of output exergy to input exergy. This equation signifies that a sustainable system must have higher exergy efficiency and lesser improvement potential.

### Energy and exergy efficiencies

This subsection discusses energy and exergy efficiencies related to the system. As efficiency is the ratio of output and input, exergy efficiency is considered output exergy, and percentage of input exergy is provided in the system. Exergy potential is evaluated considering a stable environment. This study is carried out under the environmental conditions of $T_o = 10$ °C and $P_o = 1$ atm, as Utlu and Hepbasli (Utlu and Hepbasli 2008). The energy and exergy efficiencies for measuring the system's performance can be presented via Eqs. (6) and (7), respectively (Utlu and Hepbasli 2008).

$$\text{Energy efficiency}, \eta = \frac{\text{Energy output}}{\text{Total energy input}} \tag{6}$$

$$\text{Exergy efficiency}, \varphi = \frac{\text{Exergy output}}{\text{Total exergy input}} \tag{7}$$

The method utilized in this study has been developed based on previous studies (Chowdhury et al. 2019b; Koroneos et al. 2011). Koroneos et al. (2011) (Koroneos et al. 2011) utilized the average operation ratings represented Turkish residential sector processes. Process and operation data are shown in Table 2. In the analysis of the study, firstly, the weighting factors of energy and exergy consumption data of different energy sources were determined. Each energy source's energy and exergy consumption values equal the total energy and exergy consumption values. Then, each energy source's energy and exergy efficiencies were calculated by multiplying the calculated weight factors with the rating factors of the energy sources shown in Table 2.

The residential sector's overall energy and exergy efficiencies have been calculated by adding the weighted average energy or exergy efficiencies of each resource. Overall energy and exergy efficiencies can be calculated by Eqs. (8) and (9).

$$\textit{Overall energy efficiencies} = (\textit{Energy weighting factor}) \times (\textit{Average operation ratings}) \tag{8}$$

$$\textit{Overall exergy efficiencies} = (\textit{Exergy weighting factor}) \times (\textit{Average operation ratings}) \tag{9}$$

## Sustainability analysis

This subsection uses sustainability indicators for measuring the system's performance. By measuring systems' social, environmental, and economic aspects, better decisions can be made by using these sustainability indicators. Within the scope of this study, the exergetic sustainability index and environmental impact factor are calculated (Aydin et al. 2015, Midilli and Kucuk 2015, Rosen et al. 2008).

The depletion number shows the overall effectiveness of carbonaceous fossil fuel consumption. It is quite the opposite of the exergy efficiency, which indicates that to be more exergetic efficient, a system must have fewer depletion numbers. The depletion number is the exergy destroyed and exergy input ratio, shown in Eq. (10) (Rosen et al. 2008).

$$\text{Depletion number}, D = \frac{\text{Exergy Destroyed}}{\text{Exergy Input}} \tag{10}$$

$$D = (1 - \varphi) \tag{11}$$

The sustainability index is inversely proportional to the depletion number, a crucial indicator for sustainable development. The greater the value of the sustainability index, the more is the system's sustainability and less environmentally harmful impacts.

**Table 2** Process and operation data of the Turkish residential sector adapted from (Koroneos et al. 2011)

| | Coal | Renewable fuel | Oil | Gas | Electricity | Avg |
|---|---|---|---|---|---|---|
| Residential | | | | | | |
| Cooking | 0.14 | 0.10 | 0.22 | 0.27 | 0.60 | **0.27** |
| Washer, dishwasher | | | | 0.76 | | **0.76** |
| Space heating | 0.34 | 0.24 | 0.55 | 0.62 | 1.00 | **0.55** |
| Hot tap water | 0.18 | 0.12 | 0.44 | 0.45 | 0.67 | **0.37** |
| Space cooling | | | 0.46 | 0.60 | 0.88 | **0.65** |
| Refrigeration | | | | | 0.47 | **0.47** |
| Mechanical energy | | | 0.12 | 0.22 | 0.54 | **0.30** |
| Lighting | | | 0.02 | 0.03 | 0.04 | **0.03** |
| EDP, TV | | | | | 0.11 | **0.11** |
| Other household appliances | | | | 0.39 | 0.56 | **0.47** |
| Avg | 0.22 | 0.16 | 0.30 | 0.37 | 0.56 | **0.40** |
| Residential | | | | | | |
| (DIVIDED BY THE EXERGY FACTOR OF EACH FUEL) | | | | | | |
| Cooking | 0.14 | 0.10 | 0.20 | 0.26 | 0.60 | **0.26** |
| Washer, dishwasher | | | | | 0.76 | **0.76** |
| Space heating | 0.32 | 0.24 | 0.51 | 0.59 | 1.00 | **0.53** |
| Hot tap water | 0.17 | 0.12 | 0.41 | 0.44 | 0.67 | **0.36** |
| Space cooling | | | 0.43 | 0.58 | 0.88 | **0.63** |
| Refrigeration | | | | | 0.47 | **0.47** |
| Mechanical energy | | | 0.11 | 0.21 | 0.54 | **0.29** |
| Lighting | | | 0.02 | 0.03 | 0.04 | **0.03** |
| EDP, TV | | | | | 0.11 | **0.11** |
| Other household appliances | | | | 0.37 | 0.56 | **0.46** |
| **AVG** | **0.21** | **0.15** | **0.28** | **0.35** | **0.56** | **0.39** |

The bold entry is to highlight the final output

$$\text{Sustainability index, SI} = \frac{1}{\text{Depletion number}} \quad (12)$$

As an indicator of sustainability, Gong and Wall (Gong and Wall 2016) suggested a renewable fraction (RF), as given in Eq. (13). For a system to be more sustainable and have few environmental footprints, it is expected that RF should be higher. A higher renewable fraction indicates that the system's significant energy comes from sustainable renewable energy resources.

$$\text{Renewable Fraction, RF} = \frac{\text{Renewable exergy consumption}}{\text{Total exergy consumption}} \quad (13)$$

Non-renewable energy resources mainly indicate carbonaceous fossil fuels. High usage of non-renewable energy resources creates environmental concerns and reduces the system's sustainability. The non-renewable fraction (NRF) of the exergy is expressed by Eq. (14):

$$\text{NRF} = \frac{\text{Non} - \text{renewable exergy consumption}}{\text{Total exergy input}} \quad (14)$$

Waste exergy is considered a vital parameter to determine the system's performance. A sustainable system must reduce the waste exergy output and utilize these energies for better performance. The exergy destruction coefficient is the inverse of exergy efficiency.

Waste exergy ratio (WER) and exergy destruction coefficient (EDC) are defined in Eqs. (15) and (16), respectively.

$$WER = \frac{\text{Total outlet waste exergy}}{\text{Total input exergy}} \quad (15)$$

$$EDC = \frac{1}{\text{Exergy Efficiency}} \quad (16)$$

### Sensitivity analysis representation

Sensitivity analysis coupled with box plots and spider plots is rarely used to assess the performance of energy sources. Both types of charts have certain advantages in displaying the details of sensitivity analysis (Jordan et al. 2016). Box plots are the representatives of different input variations in sensitivity measures. Spider pots are performed to show the impact of input variables changes on outputs in detail. Additionally, a spider diagram can identify the linear and non-linear relationship between input and output variables. However, most energy and exergy analysis studies did not consider the changes in sensitivity indices of relative sources. The study performs an exhaustive simulation process to justify the effects of input variables on the outcome through scatter plots. Various system boundaries are associated with analyzing Turkey's residential sector shown in Fig. 1.

## Results and discussion

Exergetic sustainability indicators have been utilized for the first time in the residential sector of Turkey in this study. Analysis results covered the years between 2000 and 2017. The relevant data in the study were obtained from the International Energy Agency (IEA) (https://www.iea.org/data-and-statistics/data-tables 2021).

### Total energy and exergy efficiency scenario in Turkey's residential sector

In this section, energy and exergy efficiencies in the residential sector of Turkey from 2000 to 2017 are shown. Energy consumption data from Table 3 and exergy consumption data from Table 4 are utilized to determine the weighting factor.

Later, Eqs. (8) and (9) are used to determine the overall energy and exergy efficiencies. Energy, as well as exergy efficiencies, is delineated in Fig. 2. It is evident from Fig. 2 that energy efficiency ranges from 27.51 to 35.65%, and from 2000 to 2017, there is an upward trend in energy efficiencies except for 2009 and 2010. In 2009 and 2010, Energy consumption from natural gas was lower than in the successive years. In 2009 and 2010, energy from natural gas was 184.71PJ and 203.65PJ, while in 2008, it was 274.092PJ. In the context of exergy efficiency, it is always lower than the energy efficiency of the respective year, and the range is between 25.85 and 34.06%.

### Sensitivity indices of sources for energy and exergy efficiencies in Turkey

Monte Carlo simulations have been performed to quantify the associated uncertainties of different energy and exergy sources for decision-making (Lo et al. 2005). The exhaustive simulation process stimulates the decision-making with specific ranges of possible outcomes and the chances for the choice of each action. Natural gas is a significant source of energy production in Turkey. Pearson correlation ($r = 0.78$) of natural gas shows a higher association with total energy/exergy input. In contrast, the obtained correlation coefficients for other sources are relatively low compared to natural gas. The scatter plot shows the relative importance of sources in reducing energy and exergy consumption. Sensitivity analysis assists in selecting the priority of fossil fuels (natural gas, coal, and oil) and determines the amount of energy reduction possible by the existing system

**Table 3** Energy consumption (PJ) by Turkey's residential sector

| Year | Coal (PJ) | Oil (PJ) | Natural gas (PJ) | Biofuels and waste (PJ) | Wind, solar and others | Electricity (PJ) | Total input (PJ) |
|---|---|---|---|---|---|---|---|
| 2000 | 74.0 | 150.86 | 113.19 | 271.15 | 32.88 | 86.26 | 728.36 |
| 2001 | 52.12 | 121.50 | 126 | 260.82 | 35.95 | 85.09 | 681.49 |
| 2002 | 63.84 | 120.96 | 130.95 | 250.86 | 39.01 | 85.09 | 690.73 |
| 2003 | 75.64 | 116.67 | 156.53 | 241.37 | 42.63 | 90.97 | 723.82 |
| 2004 | 87.82 | 117.85 | 163.67 | 232.30 | 44.73 | 99.75 | 746.13 |
| 2005 | 92.86 | 121.12 | 200.97 | 223.60 | 49.98 | 111.72 | 800.26 |
| 2006 | 84 | 82.15 | 259.68 | 215.29 | 49.51 | 124.48 | 815.13 |
| 2007 | 92.48 | 73.29 | 289.92 | 209.37 | 50.73 | 131.71 | 847.51 |
| 2008 | 105.04 | 70.81 | 274.092 | 199.75 | 54.81 | 142.96 | 847.47 |
| 2009 | 139.39 | 67.87 | 184.71 | 192.23 | 65.05 | 141.37 | 790.65 |
| 2010 | 142.21 | 60.98 | 203.65 | 186.27 | 71.14 | 149.56 | 813.83 |
| 2011 | 127.38 | 53.55 | 303.53 | 148.30 | 79.96 | 159.89 | 872.63 |
| 2012 | 128.68 | 37.12 | 305.97 | 145.02 | 66.40 | 163.88 | 847.09 |
| 2013 | 91.14 | 42.714 | 329.86 | 137.80 | 67.15 | 162.41 | 831.096 |
| 2014 | 77.65 | 39.43 | 321.72 | 130.83 | 67.41 | 166.82 | 803.88 |
| 2015 | 82.65 | 14.07 | 380.39 | 117.76 | 78.41 | 172.99 | 846.3 |
| 2016 | 86.22 | 10.37 | 401.81 | 108.73 | 77.65 | 184.92 | 869.73 |
| 2017 | 82.36 | 9.99 | 467.33 | 99.20 | 75.55 | 195.93 | 930.38 |

**Table 4** Exergy consumption (PJ) by Turkey's residential sector

| Year | Coal (PJ) | Oil (PJ) | Natural gas (PJ) | Biofuels and waste (PJ) | Wind, solar, and others | Electricity (PJ) | Total input (PJ) |
|---|---|---|---|---|---|---|---|
| 2000 | 78.44 | 156.89 | 116.58 | 300.97 | 32.88 | 86.26 | 772.06 |
| 2001 | 55.24 | 126.36 | 129.78 | 289.51 | 35.95 | 85.09 | 721.94 |
| 2002 | 67.67 | 125.79 | 134.88 | 278.46 | 39.01 | 85.09 | 730.92 |
| 2003 | 80.18 | 121.34 | 161.23 | 267.92 | 42.63 | 90.97 | 764.28 |
| 2004 | 93.09 | 122.56 | 168.58 | 257.85 | 44.73 | 99.75 | 786.57 |
| 2005 | 98.43 | 125.97 | 206.99 | 248.20 | 49.98 | 111.72 | 841.31 |
| 2006 | 89.04 | 85.43 | 267.47 | 238.97 | 49.51 | 124.48 | 854.93 |
| **2007** | 98.03 | 76.22 | 298.62 | 232.40 | 50.73 | 131.71 | 887.72 |
| 2008 | 111.34 | 73.64 | 282.31 | 221.72 | 54.81 | 142.96 | 886.80 |
| 2009 | 147.76 | 70.58 | 190.25 | 213.37 | 65.05 | 141.37 | 828.41 |
| 2010 | 150.74 | 63.42 | 209.76 | 206.75 | 71.14 | 149.56 | 851.40 |
| 2011 | 135.02 | 55.69 | 312.64 | 164.61 | 79.96 | 159.89 | 907.83 |
| 2012 | 136.40 | 38.61 | 315.14 | 160.97 | 66.40 | 163.88 | 881.43 |
| 2013 | 96.60 | 44.42 | 339.76 | 152.96 | 67.15 | 162.41 | 863.32 |
| **2014** | 82.31 | 41.01 | 331.37 | 145.22 | 67.41 | 166.82 | 834.15 |
| 2015 | 87.61 | 14.63 | 391.80 | 130.72 | 78.41 | 172.99 | 876.18 |
| 2016 | 91.39 | 10.78 | 413.86 | 120.69 | 77.65 | 184.92 | 899.34 |
| 2017 | 87.30 | 10.39 | 481.35 | 110.11 | 75.55 | 195.93 | 960.65 |

The bold entry is to highlight the final output

in Turkey, as shown in Fig. 3. For example, the confidence interval (760–846 PJ) of coal as an energy source expresses a total reduction of 44.79 PJ (804.79PJ–760PJ) that is feasible from the mean. A maximum energy reduction will be 86 PJ that is possible within a certain degree of a confidence interval. The 95% confidence interval of probabilistic distribution for different sources shows the range of values for energy (586.80–1024.07 PJ) and exergy (613.13–1069.51 PJ), as shown in Table 5. Higher CI of natural gas for energy (628–968 PJ) and exergy (648–1031 PJ) can be replaced by

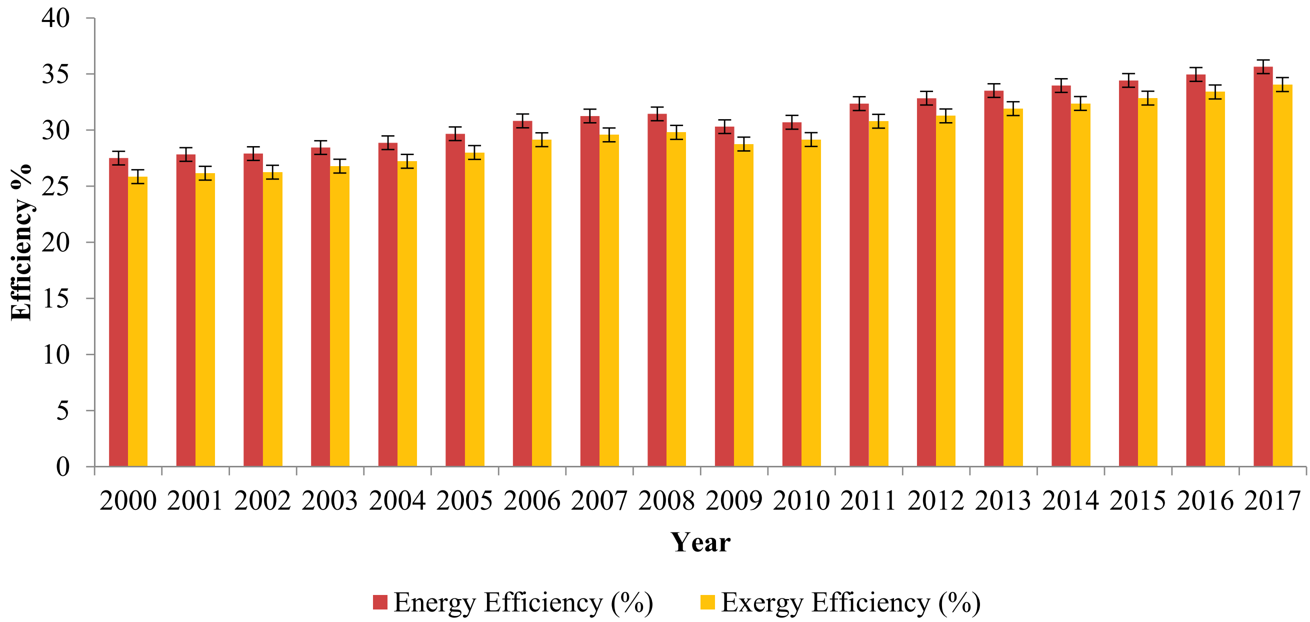


**Fig. 2** Energy and exergy efficiencies of the residential sector of Turkey

the possible expansion of biofuels and waste and renewable energy per the country's existing capacity.

## Energy and exergy loss in the residential sector of Turkey

Energy and exergy loss in the residential sector of Turkey for the year 2017 is depicted in Fig. 4 and Fig. 5. Figure 6 shows that energy loss from renewable fuels is around 112.46 PJ, whereas natural gas has a loss of 300.72 PJ. In 2017, exergy loss from natural gas was the highest, like energy loss in 2017. Around 317.4 PJ of exergy was lost from natural gas, 50% of the total exergy loss of 633.43 PJ.

Natural gas is used as a driving fuel for various processes in Turkey, such as cooking, mechanical energy, hot tap water, space cooling, space heating, washer, and dishwasher. Among these for cooking and mechanical purpose, energy efficiency is relatively low. As a result, a higher amount of energy and exergy is lost. Using more efficient cooking stoves and mechanical energy harvesting devices can undoubtedly improve the energy and exergy of turkey's residential sector. Cooking appliances run on electricity have higher energy efficiency than stoves run on gas or coal (Utlu and Hepbasli 2005). So, replacing these gas-driven cooking stoves with electric appliances can be a viable solution for improving Turkey's residential sector's overall energy and exergy efficiencies.

From Fig. 4 and Fig. 5, it is clear that the second leading source of energy and exergy destruction is the usage of electricity and for third is renewable fuels. In the residential sector of Turkey, renewable fuel is used mainly in space heating and hot tap water, but these appliances can transform a meagre amount of energy into efficient work, which leads to decreased overall exergy efficiency. Natural gas has higher energy efficiency for space heating and water heating of 84% and 80%, but it has lower energy efficiency in cooking appliances of 50%. As a result, for cooking activities, electricity usage should be increased to improve the energy and exergy efficiencies of the Turkish residential sector (Utlu and Hepbasli 2005). Therefore, policymakers should develop policies to increase the usage of highly energy-efficient appliances, especially space heating. Space heating contributes to the topmost use of renewable fuels, followed by water heating (Utlu and Hepbasli 2005). As Turkey has higher solar energy potential, solar energy can be utilized more in water heating activities to improve efficiency in this sector.

Electricity comprises 21% of the total energy consumption and 20.4% of exergy consumption in 2017. Electricity used in space, water, and cooking appliances has 98%, 90%, and 80% higher energy efficiency, respectively. They have higher exergy efficiency also (Utlu and Hepbasli 2005). In 2000, the lighting devices used in Turkey were 30% fluorescent, and the remaining were incandescent. Fluorescent lights had energy and exergy efficiencies of 20% and 18.5% in 2000, respectively (Utlu and Hepbasli 2004). In 2020, the lighting devices used in Turkey were 30% fluorescent, and the remaining were incandescent. As a result, replacing all incandescent devices with energy-efficient devices such as LED can improve exergy efficiency in this sector. Refrigeration utilizes a considerable share of electricity,

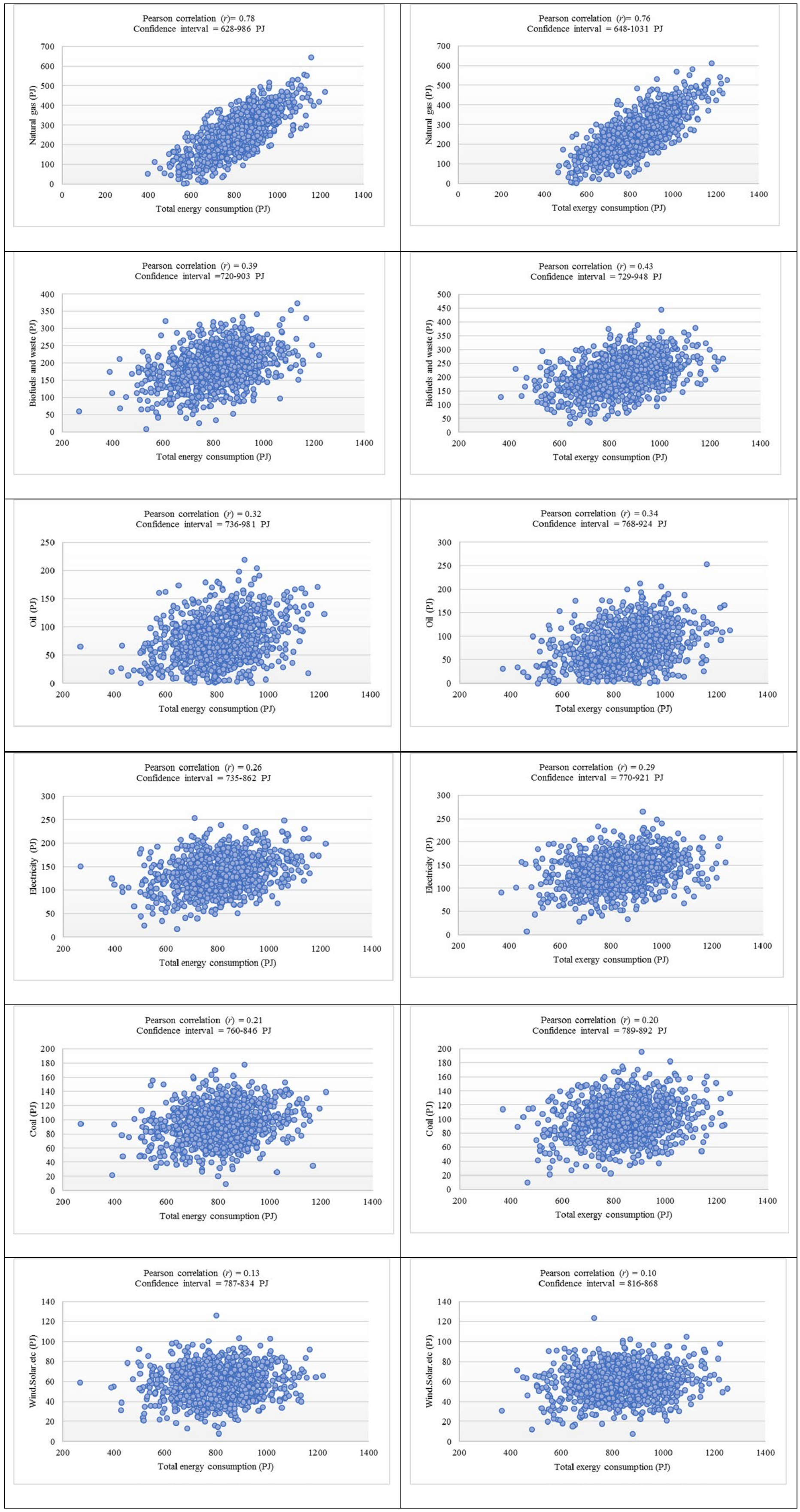


**Fig. 3** Scatter plots for energy and exergy consumption in Turkey's residential sector

**Table 5** Statistical analysis of energy and exergy consumption (PJ) by Turkey's residential sector

| Statistical inputs for energy and exergy consumption in petajoule (PJ) | | | | |
|---|---|---|---|---|
| Source of consumption | Energy (PJ) | | Exergy (PJ) | |
| | Mean | Std | Mean | Std |
| Natural gas | 256.33 | 102.78 | 264.02 | 105.89 |
| Biofuels and waste | 187.26 | 55.24 | 207.85 | 61.36 |
| Electricity | 136.43 | 36.26 | 136.43 | 36.26 |
| Coal | 93.64 | 25.40 | 99.25 | 26.91 |
| Oil | 72.85 | 43.58 | 75.76 | 45.31 |
| Wind, solar, and others | 58.28 | 15.62 | 58.28 | 15.62 |
| Statistical outputs for energy and exergy consumption in petajoule (PJ) | | | | |
| Source of consumption | Energy (PJ) | | Exergy (PJ) | |
| Mean | 804.79 | | 841.58 | |
| Standard deviation | 132.90 | | 139.22 | |
| 5th percentile | 586.80 | | 613.13 | |
| 95th percentile | 1024.07 | | 1069.51 | |

approximately 35 to 40% (Hepbasli and Utlu 2004), but the exergy efficiency in refrigeration is low. So, further exergy efficient devices should be employed to improve the exergetic sustainability of this sector as lighting and refrigeration contribute to the significant electricity usage. So, it is highly recommended that these devices should be replaced with exergy-efficient devices.

In 2000, 84.1% of residents used stoves, and 72.67% of these persons used coal-based stoves. Coal-based stoves have energy and exergy efficiencies of 45% and 3.2%. It was estimated that in 2020, coal used for water heating and cooking would have energy and exergy efficiencies of 60% and 4.3% (Aycik et al. 1986, Utlu and Hepbasli 2005). Instead of coal-based stoves, more exergy-efficient appliances should be used to improve exergetic efficiency.

## Improvement potential

Exergetic improvement potential from 2000 to 2017 in Turkey's residential sector is shown in Fig. 6. From Fig. 6, it is evident that its improvement potential increased for some years while it decreased for some years. The lowest exergetic improvement potential occurred in 2014, while the highest exergetic improvement potential was in 2007 at 440.09%. If exergy efficiency for a year is higher, that year's

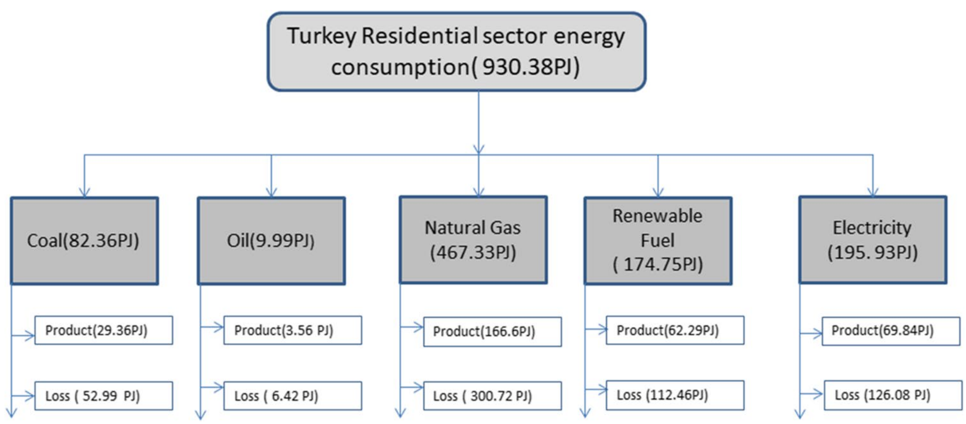


**Fig. 4** Energy flow in the residential sector of Turkey

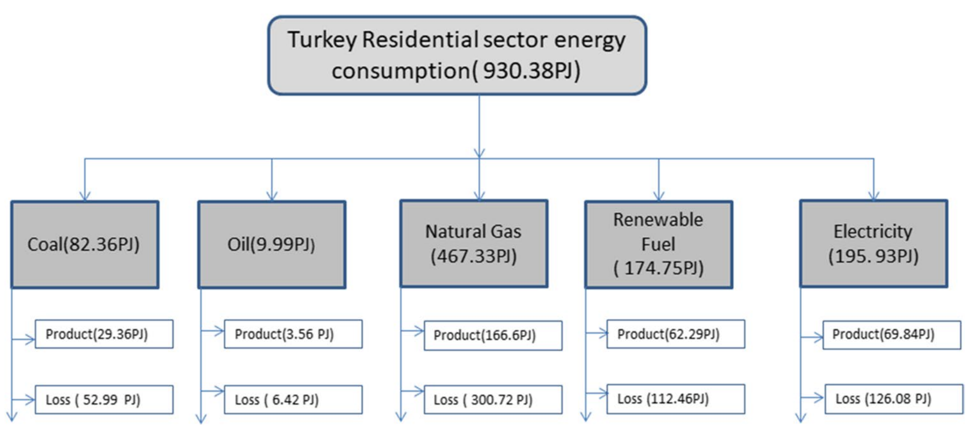


**Fig. 5** Exergy flow in the residential sector in Turkey

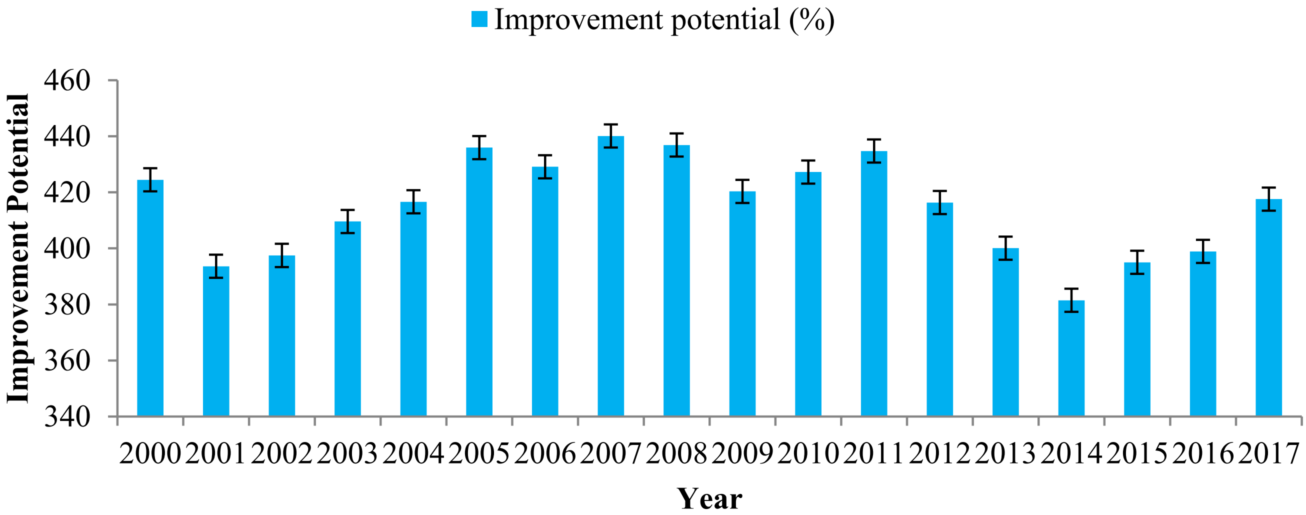


**Fig. 6** Exergetic improvement potential from 2000 to 2017 in the residential sector

improvement potential will be lower due to low exergy destruction. In 2007, exergy efficiency was lower than in other years. So, improvement potential will be the highest. Higher improvement potential indicates higher exergy destruction, which is not desired. Table 3 and Table 4 show that in 2014, total energy consumption in the residential sector was 803.88 PJ and 834.15 PJ, respectively. In 2000, Turkey's overall energy and exergy efficiencies of electrical appliances were 80.98% and 22.17%, respectively (Utlu and Hepbasli 2005). Inefficient heating appliances profoundly affect higher exergetic improvement potential, leading to higher exergy loss. Utilizing efficient LED lights will increase the exergy efficiency, thus reducing the improvement potential. Another significant reason for less exergy utilization is using renewable fuels in inefficient space heating and hot tap water application. If higher efficient appliances or renewable fuels replace these, electricity is used, and better exergetic efficiency can be achieved.

## Sustainability analysis of Turkey's residential sector

Various sustainability indicators are delineated, such as depletion number, SI, RF, NRF, and EDC in Fig. 7. The higher the depletion number, the higher the adverse effect on sustainability. The depletion number in Turkey's residential sector varies between 65.93 and7 4.14%. In 2017, the depletion number was 65.93%, 8.21 less than the depletion number in 2000. This shows a positive effect on exergetic sustainability, but for ensuring sustainable development, depletion number must be zero. So, policies must be updated to use efficient appliances with higher exergetic efficiency.

The sustainability index ranges from 1.34 to 1.51, indicating that sustainability in this sector is upbringing. The higher the sustainability index, the better is the exegetic sustainability of the system. In Turkey, around 65.93 to 74.14% of fossil fuel is depleted in 18 years, which leads to lesser exergetic sustainability. By depletion of fossil fuel, exergy is wasted, and it is recommended to utilize it to increase SI. Renewable fraction (RF), non-renewable fraction (NRF), and exergy destruction coefficient (EDC) are also shown in Fig. 7. RF and NRF are showing the opposite trend in these years. From 2000 to 2017, the share of renewable fractions in the residential sector decreased while non-renewable energy consumption increased. As a result, the residential sector of Turkey is less sustainable, considering exergetic sustainability. If the fraction of renewable energy can be improved with proper appliances, then the residential sector will be more sustainable from the exergetic point of view. The exergy destruction coefficient is the inverse of exergy efficiency. From 2000 to 2017, exergy destruction coefficient is decreased, but it is not up to the mark. Using efficient devices, especially cooking, lighting, and mechanical energy-related appliances, can significantly improve exergetic sustainability.

## Energy saving via efficient utilization

Turkey can save lots of energy in the residential sector by using efficient devices. For 2000, energy consumption in electricity was 86.26 PJ, shown in Table 3. Approximately 35–38% of all electrical use was for lighting. Considering 36.5% average consumption of electricity for lighting, 31.48PJ of energy was used in 2000. The energy and exergy efficiencies (%) of lighting components are shown in Table 6. Utilizing this, energy products from fluorescent, incandescent, and light-emitting diode (LED) devices can be found.

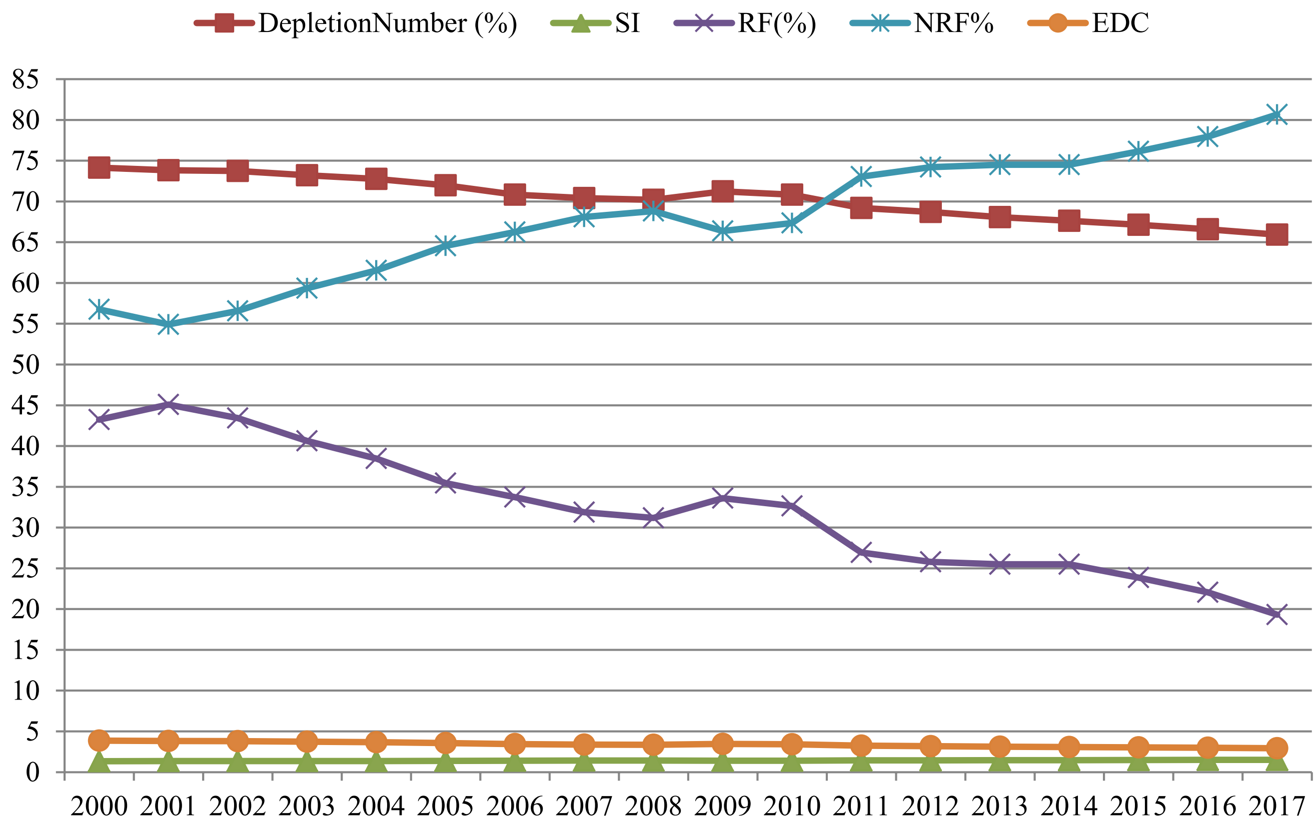


**Fig. 7** Sustainability indicators of Turkey's residential sector

**Table 6** Energy and exergy efficiencies (%) of lighting components (Arslanoglu 2016)

| Components | Energy efficiency (%) | Exergy efficiency (%) |
|---|---|---|
| Incandescent | 5 | 4.5 |
| Fluorescent | 20 | 18.5 |
| LED | 27.3 | 21.8 |

Lighting is assumed to be 80% incandescent and 20% fluorescent. Energy usage and energy product come from fluorescent, incandescent, and LED devices. If LED devices are only used for lighting, then (8.594–2.518) PJ = 6.08PJ energy can be saved.

## Global perspective of energy and exergy of the residential sector analyses

This section compares Turkey's residential sector's exergy and energy efficiencies with other countries. Energy and exergy efficiencies in the residential sector of several countries are shown in Table 7. In the case of Turkey, residential sector energy efficiency ranges from 27.51 to 35.65%, which is just higher than in Nigeria, but Turkey's residential sector exergy efficiency is between 25.85 and 34.06%, which is relatively higher than other countries. Bangladesh's energy

**Table 7** Global overview of energetic and exergetic comparison

| Countries | Year | Energy efficiencies % | Exergy efficiencies % | References |
|---|---|---|---|---|
| Saudi Arabia | 2007–2017 | 145 | 11.38 | (Almasri et al. 2020) |
| Bangladesh | 2000–2015 | 25.54–37.77 | 6.35–9.04 | (Chowdhury et al. 2020b) |
| Nigeria | 2006–2011 | 20.19 | 4.4 | (Fidelis et al. 2014) |
| China | 2002–2011 | 70.30 | 12.2 | (Liu et al. 2014) |
| Japan | 1990–2005 | 62.35 | 6.3 | (Kondo 2009) |
| Malaysia | 1997–2004 | 70 | 28 | (Saidur et al. 2007) |

efficiency in the residential sector is almost the same as Turkey's, but Bangladesh has lower exergy than Turkey due to the higher dependency on biofuel and natural gas-based inefficient devices. However, Turkey can further improve its exergy efficiencies via implementing energy-efficient heating apparatus, replacing lighting devices, and utilizing renewable resources.

### Overview of the sustainability of the Turkish residential sector

Turkey's demand for buildings grows with its increasing urbanization, population, and industrialization. As it transpires, the sector must embrace possibilities to curtail the stress on the environment since it puts significant pressure on the environment. The harmful impact of the building sector on the environment can be minimized through waste minimization, energy efficiency, recycling and savings, and encouraging the utilization of renewable energy resources. The goal can be highly achievable because of Turkey's abundance of natural resources that allows a chance to use sustainable energy sources such as wind, solar, and geothermal. It has been reported that heating and cooling systems in Turkey consume 70–90% of total building energy, and the rest is by lighting. Besides, the modern fuel infrastructure for space heating is also missing in Turkey. Another study found that old houses adopted conventional fuel (coal) rather than clean fuel due to their lack of environmental knowledge (Celik and Oktay 2019). Aslanoğlu et al. stated that the majority of the households in Turkey use incandescent and halogen lamps due to the high cost of LED (Aslanoğlu et al. 2021). These lamps are not energy-efficient and reduce the sustainability of the building sector since they have higher energy loss. Besides, natural gas is used for cooking and mechanical purposes, with relatively low energy efficiency. Our analysis shows how LED devices can lead to energy and exergy savings, which is also validated by Aslanoğlu et al. (Aslanoğlu et al. 2021). Diffusion of electric cooking stoves needs to be happened in Turkey to enhance the sustainability of the residential sector. Moreover, people need to be educated more on clean cooking fuel to choose the best environmentally friendly fuel. Modern space heating system infrastructure should also be developed throughout the country.

### Limitations of the study and future recommendations

The study has some limitations. The data utilized in this study has been collected from a secondary source (IEA). Some of the appliance's energy and exergy efficiencies data were taken from published literature. Nevertheless, these restrictions do not influence the estimation of energy and exergy efficiencies, as other analyses also followed the same method to study this sector. A comprehensive survey should be conducted to estimate energy consumption data and fuel use behaviour patterns in the residential sector of Turkey. The survey-based study may provide more precise results about overall energy loss. Therefore, more accurate forecasting of energy analysis can be demonstrated for new buildings to minimize energy loss. This approach may help better planning for future infrastructure in the country. Besides, the study is done in a steady-state condition but varying the pressure and temperature leads to future studies for better results (Muller and Yan 2018).

### Research, practical, and social implications of the study

One of the promising solutions is the insulation of buildings to tackle these issues. For example, a well-insulated roof can reduce heat loss by 20% compared to no insulation. Heat loss was reduced to 15%, comparing exterior wall insulation to no insulation. Similarly, heat loss will be reduced by up to 15% if doors, as well as windows, are well insulated (Turan Bıyık 2018). Especially for multi-family apartment buildings, the renovation of Turkish homes is underdeveloped. To reduce cooling and heating use, it is fundamental to create programs to deal with current apartment management cooperatives and homeowner associations to retrofit their buildings by improving access to proper financing, introducing incentives, and providing technical support on reinforcement. More than 8 million buildings need energy performance certification (Utlu et al. 2021). Moreover, building certificate systems are essential to improving public awareness. To incorporate energy-efficient technologies in new infrastructure or eco-friendly homes, mortgages or loans should be given.

## Conclusions

It is an essential factor for countries to sustain their energy consumption needs. Energy is a critical component of an advanced and sustainable society. For Turkey's booming economy, the energy needs to become sustainable which is very important. There is an important energy consumption place in the residential sector in Turkey. In this study, for the first time, sustainable indicators of Turkey have been determined based on exergy for the residential sector and analyzed comprehensively. Analysis results covered the years between 2000 and 2017. In this study, sustainability indicators of Turkey's residential sector have been identified with the first time thermodynamic-based approach. The sustainability index for Turkey ranges from 1.34 to 1.51. The higher the sustainability index, the better is the exegetic sustainability of the system. In Turkey, around 65.93 to 74.14% of fossil fuel is depleted in 18 years, which leads to lesser energetic sustainability.

Associative uncertainties of Monte Carlo simulations for energy and exergy sources showed that in maximum energy reduction, 86 PJ can be achieved annually by implementing renewable energy in the residential sector.

Turkey can improve its exergy efficiencies by implementing energy-efficient heating apparatus, replacing lighting devices, and utilizing renewable resources. For future studies, how exergy efficiency improvement methods based on the recommendations from this study influences other sectors of Turkey can be explored. This will give an overview of overall exergetic sustainability in various sectors of Turkey. Furthermore, developing models to predict future energy situations in the residential sector of Turkey, along with more indicators such as waste-exergy ratio, environmental effect factor, and exergy economic indicators, can be employed for better energy sustainability in Turkey. The analysis results of this study will be an essential source of data for policies to be followed by government bodies in the housing sector. As a result, Turkey's residential sector identifies numerical findings as an essential source of reference literature in terms of sustainability.

**Author contribution** MIM-formal analysis and original draft—writing. SR-conceptualization, methodology, formal analysis, and original draft—writing. QT-sensitivity analysis and original draft—writing (supporting). SB-formal analysis. NH-original draft—writing, review, and editing. FR and NSN-software. SS-proofreading.

**Data availability** The data that support the findings of this study are available from the corresponding author, Nazia Hossain, upon reasonable request.

## Declarations

**Consent for publication** We undertake and agree that the manuscript submitted to your journal has not been published elsewhere and has not been simultaneously submitted to other journals.

**Competing interests** The authors declare no competing interests.

**Disclaimer** The facts and views in the manuscript are solely ours, and we are totally responsible for the authenticity, validity, and originality. We also declare that this manuscript is our original work, and we have not copied from anywhere else. There is no plagiarism in my manuscript.

## References


Açıkkalp E, Caliskan H, Altuntas O, Hepbasli A (2021) Novel combined extended-advanced exergy analysis methodology as a new tool to assess thermodynamic systems. Energy Convers Manage 236:114019

Aghbashlo M, Tabatabaei M, Hosseini SS, Dashti BB, Soufiyan MM (2018) Performance assessment of a wind power plant using standard exergy and extended exergy accounting (EEA) approaches. J Clean Prod 171:127–136

Ahamed JU, Saidur R, Masjuki HH, Mekhilef S, Ali M, Furqon M (2011) An application of energy and exergy analysis in agricultural sector of Malaysia. Energy Policy 39:7922–7929

Al-Ghandoor A, Al-Hinti I, Akash B, Abu-Nada E (2008) Analysis of energy and exergy use in the Jordanian urban residential sector. Int J Exergy 5:413–428

Almasri RA, Almarshoud A, Omar HM, Esmaeil KK, Alshitawi M (2020) Exergy and economic analysis of energy consumption in the residential sector of the Qassim region in the kingdom of Saudi Arabia. Sustainability 12:2606

Amoo LM, Fagbenle RL (2014) A thermodynamic performance analysis of the transport sector of Nigeria. Int J Exergy 14:441–458

Arango-Miranda R, Hausler R, Romero-López R, Glaus M, Ibarra-Zavaleta SP (2018) An overview of energy and exergy analysis to the industrial sector, a contribution to sustainability. Sustainability 10:153

Armel TKF, Vidal AKC, René T (2015) Energy analysis and exergy utilization in the residential sector of Cameroon. Energy Power Eng 7:93

Arslanoglu N (2016) Empirical modeling of solar radiation exergy for Turkey. Appl Therm Eng 108:1033–1040

Arunkumar T, Denkenberger D, Velraj R, Sathyamurthy R, Tanaka H, Vinothkumar K (2015) Experimental study on a parabolic concentrator assisted solar desalting system. Energy Convers Manage 105:665–674

Aslanoğlu R, Kazak JK, Yekanialibeiglou S, Pracki P, Ulusoy B (2021) An international survey on residential lighting: analysis of winter-term results. Build Environ 206:108294

Aycik I, Turkseven K, Bulhaz K (1986) Position of high efficiency stove in Turkish economy and studies on this subject, Proceedings of Fourth Turkish Energy Congress. World Energy Council-Turkish National Committee, Izmir, Turkey, pp. 269–276

Aydin H, Turan O, Karakoc TH, Midilli A (2015) Exergetic sustainability indicators as a tool in commercial aircraft: a case study for a turbofan engine. Int J Green Energy 12:28–40

Badmus I, Osunleke AS (2010) Application of energy and exergy analyses for efficient energy utilisation in the Nigerian residential sector. Int J Exergy 7:352–368

Bait O (2019) Exergy, environ–economic and economic analyses of a tubular solar water heater assisted solar still. J Clean Prod 212:630–646

Brounen D, Kok N, Quigley JM (2013) Energy literacy, awareness, and conservation behavior of residential households. Energy Economics 38:42–50

Bühler F, Nguyen T-V, Elmegaard B (2016) Energy and exergy analyses of the Danish industry sector. Appl Energy 184:1447–1459

Causone F, Sangalli A, Pagliano L, Carlucci S (2017) An exergy analysis for milano smart city. Energy Proc 111:867–876

Celik AK, Oktay E (2019) Modelling households' fuel stacking behaviour for space heating in Turkey using ordered and unordered discrete choice approaches. Energy and Buildings 204:109466

Chowdhury H, Chowdhury T, Chowdhury P, Islam M, Saidur R, Sait SM (2019a) Integrating sustainability analysis with sectoral exergy analysis: a case study of rural residential sector of Bangladesh. Energy and Buildings 202:109397

Chowdhury H, Chowdhury T, Thirugnanasambandam M, Farhan M, Ahamed JU, Saidur R, Sait SM (2019b) A study on exergetic efficiency vis-à-vis sustainability of industrial sector in Bangladesh. J Clean Prod 231:297–306

Chowdhury T, Chowdhury H, Ahmed A, Park Y-K, Chowdhury P, Hossain N, Sait SM (2020a) Energy, exergy, and sustainability analyses of the agricultural sector in Bangladesh. Sustainability 12:4447

Chowdhury T, Chowdhury H, Chowdhury P, Sait SM, Paul A, Ahamed JU, Saidur R (2020b) A case study to application of

exergy-based indicators to address the sustainability of Bangladesh residential sector. Sustainable Energy Technol Assess 37:100615
Chowdhury H, Chowdhury T, Hossain N, Chowdhury P, Salam B, Sait SM, Mahlia TMI (2021a) Exergetic sustainability analysis of industrial furnace: a case study. Environ Sci Pollut Res 28:12881–12888
Chowdhury H, Chowdhury T, Rashedi A, Banik SC, Khanam T, Saidur R, Sait SM, Rosen MA (2021b) Energy and exergy assessment with updated Reistad estimates: a case study in the transportation sector of Bangladesh. Energy Sci Eng
Corre OL, Broc JS, Dincer I (2013) Energetic and exergetic assessment of solar and wind potentials in Europe. Int J Exergy 13:175–200
Couto PG, Damasceno JC, Oliveira Sd, Chan W (2013) Monte Carlo simulations applied to uncertainty in measurement. Theory and applications of Monte Carlo simulations, 27–51
Dadsetani R, Sheikhzadeh GA, Safaei MR, Alnaqi AA, Amiriyoon A (2019) Exergoeconomic optimization of liquefying cycle for noble gas argon. Heat Mass Transf 55:1995–2007
Dincer I, Rosen MA (2012) Exergy: energy, environment and sustainable development. Newnes
Dincer I, Hussain M, Al-Zaharnah I (2004a) Energy and exergy utilization in transportation sector of Saudi Arabia. Appl Therm Eng 24:525–538
Dincer I, Hussain M, Al-Zaharnah I (2004b) Energy and exergy use in residential sector of Saudi Arabia. Energy Sources 26:1239–1252
Ege A, Şahin HM (2014) Determination of uncertainties in energy and exergy analysis of a power plant. Energy Convers Manage 85:399–406
Fidelis I, Ohunakin OS, Nwankwojike BN, Ekwe B (2014) End-use energy utilization efficiency of Nigerian residential sector. Front Energy 8(3):322–334
Gong M, Wall G (2016) Exergy analysis of the supply of energy and material resources in the Swedish society. Energies 9:707
Hepbasli A (2001) Energy conservation studies on residential heating systems: an application for Izmir, Turkey. Int J Global Energy Issues 15:247–263
Hepbasli A, Utlu Z (2004) Evaluating the energy utilization efficiency of Turkey's renewable energy sources during 2001. Renew Sustain Energy Rev 8:237–255
Hossain N, Mahlia TMI, Zaini J, Saidur R (2019) Techno-economics and sensitivity analysis of Microalgae as commercial feedstock for bioethanol production. Environ Prog Sustainable Energy 38:13157
https://www.iea.org/data-and-statistics/data-tables S (2021)
Jeter SM (1981) Maximum conversion efficiency for the utilization of direct solar radiation. Sol Energy 26:231–236
Jordan DC, Kurtz SR, VanSant K, Newmiller J (2016) Compendium of photovoltaic degradation rates. Prog Photovoltaics Res Appl 24:978–989
Kanogˇlu M, Işık SK, Abuşogˇlu A (2005) Performance characteristics of a diesel engine power plant. Energy Convers Manage 46:1692–1702
Kondo K (2009) Energy and exergy utilization efficiencies in the Japanese residential/commercial sectors. Energy Policy 37:3475–3483
Koroneos CJ, Nanaki EA, Xydis GA (2011) Exergy analysis of the energy use in Greece. Energy Policy 39:2475–2481
Kusiak A, Zhang Z, Verma A (2013) Prediction, operations, and condition monitoring in wind energy. Energy 60:1–12
Li Z, Zhang D, Chen X, Li C (2020) A comparative study on energy saving and economic efficiency of different cooling terminals based on exergy analysis. J Build Eng 30:101224
Liu Y, Li Y, Wang D, Liu J (2014) Energy and exergy utilizations of the Chinese urban residential sector. Energy Convers Manage 86:634–643
Lo S-C, Ma H-w, Lo S-L (2005) Quantifying and reducing uncertainty in life cycle assessment using the Bayesian Monte Carlo method. Sci Total Environ 340:23–33
Maddah S, Safaei MR (2021) Determination of the optimal discharge pressure of the transcritical CO 2 heat pump cycles for heating and cooling performances based on new correlation. Journal of Thermal Analysis and Calorimetry 1–10
Martoňák R, Santoro GE, Tosatti E (2002) Quantum annealing by the path-integral Monte Carlo method: The two-dimensional random Ising model. Phys Rev B 66:094203
Mehrdad S, Dadsetani R, Amiriyoon A, Leon AS, Reza Safaei M, Goodarzi M (2020) Exergo-economic optimization of organic rankine cycle for saving of thermal energy in a sample power plant by using of strength pareto evolutionary algorithm II. Processes 8:264
Midilli A, Kucuk H (2015) Assessment of exergetic sustainability indicators for a single layer solar drying system. Int J Exergy 16:278–292
Muller C, Yan H (2018) Household fuel use in developing countries: review of theory and evidence. Energy Economics 70:429–439
Oladiran M, Meyer J (2007) Energy and exergy analyses of energy consumptions in the industrial sector in South Africa. Appl Energy 84:1056–1067
Öz S, Alyürük M (2020) Energy sector overview and future prediction for Turkey. Journal of Industrial Policy and Technology Management 3:59–69
Ozgener L, Hepbasli A, Dincer I (2005a) Energy and exergy analysis of geothermal district heating systems: an application. Build Environ 40:1309–1322
Ozgener L, Hepbasli A, Dincer I (2005b) Energy and exergy analysis of the Gonen geothermal district heating system, Turkey. Geothermics 34:632–645
Ozturk HK, Canyurt OE, Hepbasli A, Utlu Z (2004) Residential-commercial energy input estimation based on genetic algorithm (GA) approaches: an application of Turkey. Energy and Buildings 36:175–183
Ozturk HK, Atalay O, Yilanci A, Hepbasli A (2006) Energy and exergy analysis of kizildere geothermal power plant, Turkey. Energy Sources, Part A 28:1415–1424
Rosen MA, Dincer I, Kanoglu M (2008) Role of exergy in increasing efficiency and sustainability and reducing environmental impact. Energy Policy 36:128–137
Saidur R, Masjuki HH, Jamaluddin M (2007) An application of energy and exergy analysis in residential sector of Malaysia. Energy Policy 35:1050–1063
Sarafraz MM, Goodarzi M, Tlili I, Alkanhal TA, Arjomandi M (2021) Thermodynamic potential of a high-concentration hybrid photovoltaic/thermal plant for co-production of steam and electricity. J Therm Anal Calorim 143:1389–1398
Swan LG, Ugursal VI (2009) Modeling of end-use energy consumption in the residential sector: a review of modeling techniques. Renew Sustain Energy Rev 13:1819–1835
Szargut J (2005) Exergy method: technical and ecological applications, 18. WIT press
Tian W (2013) A review of sensitivity analysis methods in building energy analysis. Renew Sustain Energy Rev 20:411–419
Turan Bıyık Ş (2018) Otellerde sürdürülebilir çevre yönetimi ve Eskişehir örneği, Anadolu Üniversitesi
Tushar Q, Bhuiyan M, Sandanayake M, Zhang G (2019) Optimizing the energy consumption in a residential building at different climate zones: towards sustainable decision making. J Clean Prod 233:634–649
Tushar Q, Bhuiyan MA, Zhang G, Maqsood T (2021) An integrated approach of BIM-enabled LCA and energy simulation: the optimized solution towards sustainable development. J Clean Prod 289:125622
Ucal M, Günay S (2022) Household happiness and fuel poverty: a cross-sectional analysis on Turkey. Appl Res Qual Life 17:391–420

Utlu Z, Hepbasli A (2004) Turkey's sectoral energy and exergy analysis between 1999 and 2000. Int J Energy Res 28:1177–1196

Utlu Z, Hepbasli A (2005) Analysis of energy and exergy use of the Turkish residential–commercial sector. Build Environ 40:641–655

Utlu Z, Hepbasli A (2007) A review and assessment of the energy utilization efficiency in the Turkish industrial sector using energy and exergy analysis method. Renew Sustain Energy Rev 11:1438–1459

Utlu Z, Hepbasli A (2008) Energetic and exergetic assessment of the industrial sector at varying dead (reference) state temperatures: a review with an illustrative example. Renew Sustain Energy Rev 12:1277–1301

Utlu Z, Tolon M, Karabuga A (2021) Modelling of energy and exergy analysis of ORC integrated systems in terms of sustainability by applying artificial neural network. International Journal of Low-Carbon Technologies 16:156–164

Xydis G, Koroneos C, Loizidou M (2009) Exergy analysis in a wind speed prognostic model as a wind farm sitting selection tool: a case study in Southern Greece. Appl Energy 86:2411–2420