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Residential-commercial energy input estimation based on genetic algorithm (GA) approaches: an application of Turkey

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Abstract

The main objective of the present study is to develop the energy input estimation equations for the residential-commercial sector (RCS) in order to estimate the future projections based on genetic algorithm (GA) notion and to examine the effect of the design parameters on the energy input of the sector. For this purpose, the Turkish RCS is given as an example. The GA Energy Input Estimation Model (GAEIEM) is used to estimate Turkey's future residential-commercial energy input demand based on GDP, population, import, export, house production, cement production and basic house appliances consumption figures. It may be concluded that the three various forms of models proposed here can be used as an alternative solution and estimation techniques to available estimation techniques. It is also expected that this study will be helpful in developing highly applicable and productive planning for energy policies.

Keywords: Residential; Genetic algorithm; GA; Energy; Energy use; Energy planning; Energy modelling; Future projections; Turkey

1. Introduction

There are a large number of factors external to the energy sector which are considered to be significant for determining the future level of the energy consumption and production in both developed and developing countries. Such factors include population growth, economic performance, consumer tastes and technological developments. Furthermore, government policies concerning the energy sector and developments on the world energy markets will play a key role in the future level and pattern of energy production and consumption [1].

Residential energy consumption depends mainly on the available amounts of local resources, which are closely connected with the present rural economy and living standards [2]. In the EU residential sector, about 57% of the total final energy consumption is used for space heating, 25% for domestic hot water and 11% for electricity [3].

Energy modelling is a subject of widespread current interest among engineers and scientists concerned with problems of energy production and consumption. Modelling in some areas of application is now capable of making useful contributions to planning and policy formulation [4]. In this regard, energy planning is not possible without a reasonable knowledge of past and present energy consumption and likely future demands [5].

Genetic algorithms (GAs) are well known types of evolutionary computation methods today and have been adapted for a large number of applications in different areas. These include from image processing in medicine [6] to the optimal power flow [7] and determination of heat transfer coefficients [8]. Interest is also growing within the studies performed in the energy-related fields, such as nuclear energy [9], solar energy [10], low energy design in buildings [11], optimization of building thermal design [12] and cogeneration [13]. However, its use in modelling and estimating the energy demands is very limited [14].

In this study, the residential energy input estimation equations are developed in order to better analyze energy use and make future projections based on GA notion. In this regard, Turkey is given as an illustrative example and GA Energy Input Estimation Model (GAEIEM) is used to estimate Turkey's future residential energy input based several essential design criteria.

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2. Genetic algorithms (GAs)

GAs were first proposed by Holland in 1975 [15] and further developed for engineering applications by Goldberg [16]. They manipulate concepts derived from biology and are philosophically based on the Darwin's theory of survival of the fittest [17]. Similar to the natural evolution process where a population of a given race adapts to a natural environment, a population of designs is created and then allowed to evolve in order to adapt to the design environment under consideration. These algorithms encode a possible solution to a specific problem on simple chromosome string like data structure and apply specified operators to these structures so as to preserve important information, and to produce a new set of population with the purpose of generating strings which map to high function values.

GAs were characterized by bit string representations of potential solutions for a presented problem and these bit string representations change and improve these coded solutions by using GA operations. The basic operations of GA, a selection, a crossover of genetic information between reproducing parents and a mutation of genetic information affect the binary strings characteristic in natural evolution. The binary representation and the basic operations of GAs can be summarized as follows.

Genetic operations manipulated the bit string representations of possible solutions to considered problem. The representation of the coefficients into binary strings requires determining the bit string length, and then using scaling procedures to associate design variable values to binary coding. The lower and upper bound values of the associate design variables appointed into the corresponding binary number of $X_{\min} = 0000000$, $X_{\max} = 1111111$, while assuming that there is a seven-digit binary number. The values between the lower and upper bounds are scaled and converted to the corresponding binary strings using several scaling methods. For instance, 2 bit string representations using linear scaling method can be shown as follows.

Actual values	0.00	0.33	0.67	1.00
Binary representation	00	01	10	11

Each string represents one design, and multiple strings constitute the entire set of designs. Multiple designs can be represented by head-to-tail stacking in any given order. By taking w_i as the coefficients of the GAEIEM, the stacking of weighting variables can be represented as follows.

Weighting variables	w_1	w_2	w_i	...
Binary string representation	000 ... 11	001 ... 01	111 ... 00	...

A sequence of such strings can be introduced to construct a population of designs, with each design having a corresponding fitness value, which is the sum of squared error SSE. The three basic operations of GA are performed based on the fitness function evaluation.

Once obtaining set of strings, the GA selects the new designs with higher level of fitness than members of the current population by performing selection operation. Selection operator biases the search process in favour of the more fit members based on their fitness values. More fit members of the population can participate more than once, while less fit members may entirely suppressed that lead to an increase in average fitness. The fitness value of the ith member in the population can participate in this operation based on its probability. The probability of the ith member in population is computed as follows.

$$P_i = \frac{f_i}{\sum_{k=1}^{m} f_k} \tag{1}$$

The next essential part of GA is referred to as crossover operation. The crossover operation allows for an exchange of design characteristics among the mating members. The crossover operation is performed by randomly choosing two sites on each of the chromosomal strings of selected two mating parents, and swapping strings between the sites among the pair based on a designer choice of crossover probability pc. Typical probability values range from 0.5 to 0.8. An illustration of the crossover operation for string length of 12 by displaying crossover sites indicated by under line is as follows.

Parent 1 = $01010\underline{1}0110\underline{1}1$ → Child 1 = $01010\underline{0}010111$
Parent 2 = $10001\underline{0}0101\underline{1}1$ → Child 2 = $10001\underline{1}0110\underline{1}1$

Mutation operation is another essential operation in GA process, and is one safeguards the process from a premature loss of valuable genetic information in the population during selection and crossover operation. In both selection and crossover operations, the search process would heavily depend on the initial population. Therefore, there is a risk of premature loss of some genetic information from the population. The mutation operator is invoked with a low probability (pm) at a randomly selected site on chromosomal string of the randomly chosen design. The operation consists of a switching of a 0–1 or vise versa. Low values of mutation probability (∼0.01–0.03) are recommended, as higher values tend to be disruptive to the convergence process. An illustration of the mutation operation in the population is as follows.

Initial population	New population
$100\underline{0}100100\underline{1}0011$	$100\underline{\mathbf{1}}100100\underline{\mathbf{0}}0011$
$00100\underline{0}100010010$	$00100\underline{\mathbf{1}}100010010$
$11\underline{1}000\underline{1}0010\underline{1}001$	$11\underline{\mathbf{0}}000\underline{\mathbf{0}}0010\underline{\mathbf{0}}001$
$101\underline{1}001100101\underline{0}0$	$101\underline{\mathbf{0}}001100101\underline{\mathbf{1}}0$
$010100\underline{1}11000110$	$010100\underline{\mathbf{0}}11000110$

The operations described above are performed for successive number of generation. Successive number of generation continues to produce new design with improved fitness until a specified number of function evaluations.

The GA works according to rules as defined by the laws of evolutionary genetics based on fitness evaluation. The model seeks the "*fittest*" model to the observed values. In the GAEIEM, the model parameters of gross domestic product (GDP), population, import, export, house production, cement production, basic house appliances consumption figures produce the estimation of the residential energy input values of Turkey, which is best match the measured demand and reference values. The fitness function $F(x)$, takes the following form:

$$\min F(x) = \sum_{j}^{m} S_j (E_{\text{actual}} - E_{\text{predicted}})^2 \tag{2}$$

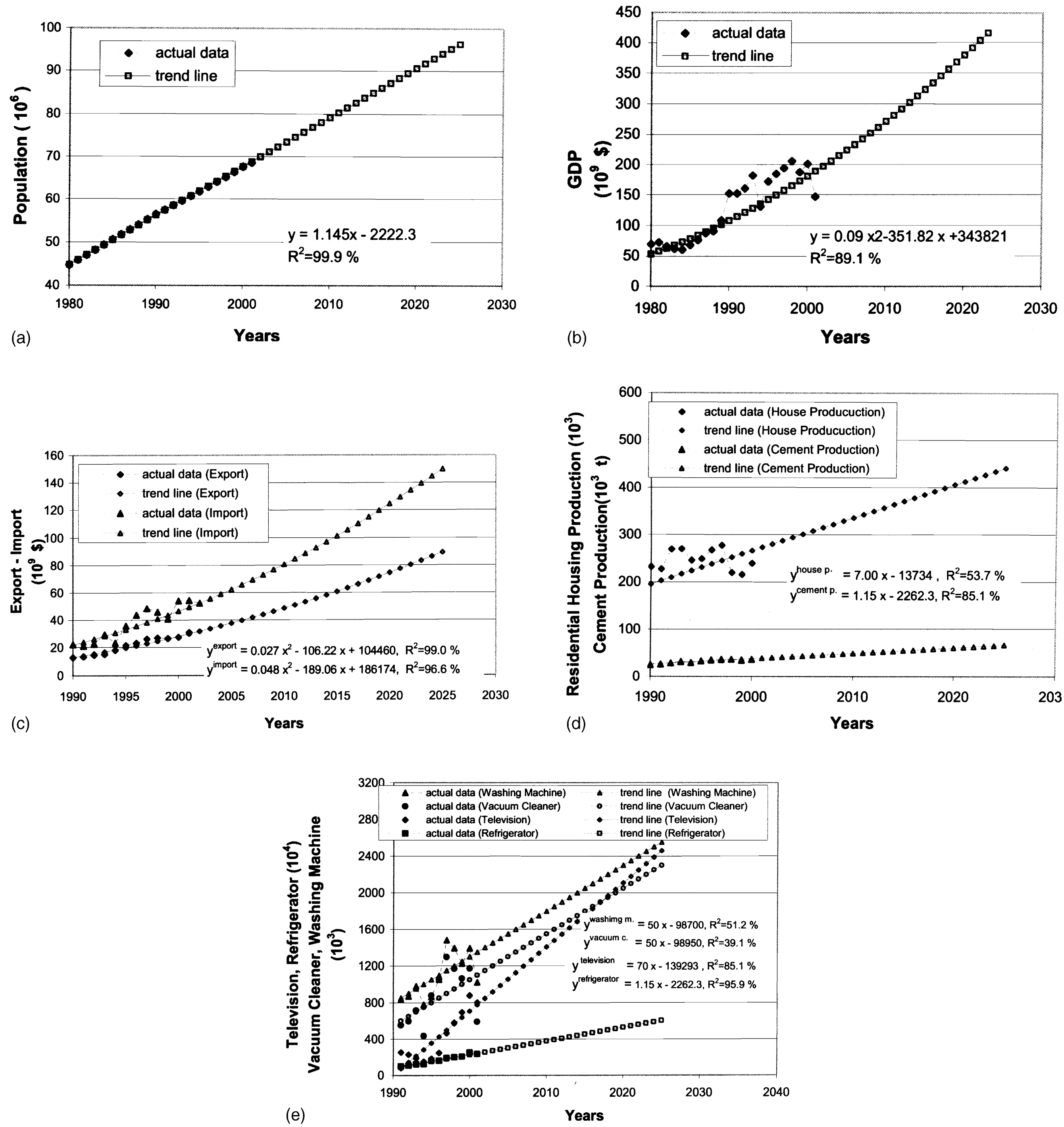

Fig. 1. (a) Population trend. (b) GDP and its corresponding fitted polynomial trends. (c) Import and export trends. (d) Residential housing and cement production trends. (e) Television, refrigerator, vacuum cleaner and washing machine trends.

where E_{actual} and $E_{\mathrm{predicted}}$ are the observed and predicted energy values, respectively, m the number of observations and s_j the weighting factor.

The genetic processes continue to search new designs with enhanced fitness until a specified number of function evaluations.

Iterative search after many generations of evolution leads the population to an optimal design. A set of design in the population is altered in structure and constitution based on the fitness, and searches after many generations of evolution towards to an optimal design. The fitness indicates the *goodness* of design, and therefore, the objective function is a logical choice for the fitness measure. The GAEIEM searches the most fitted members by minimizing the error. The algorithm randomly selects a set of models by minimizing error and evolves them to create the best model. The quadratic forms of the GAEIEM can be written as follows:

$$\begin{aligned} E = {} & w_1 + w_2X_1 + w_3X_2 + w_4X_3w_5X_4w_6X_5w_7X_6 \\ & + w_8X_1X_2 + w_9X_1X_3 + w_{10}X_1X_4 + w_{11}X_1X_5 \\ & + w_{12}X_1X_6 + w_{13}X_2X_3 + w_{14}X_2X_4 + w_{15}X_2X_5 \\ & + w_{16}X_2X_6 + w_{17}X_3X_4 + w_{18}X_3X_5 + w_{19}X_3X_6 \\ & + w_{20}X_4X_5 + w_{21}X_4X_6 + w_{22}X_1^2 + w_{23}X_2^2 \\ & + w_{24}X_3^2 + w_{25}X_4^2 + w_{26}X_5^2 + w_{27}X_6^2 \end{aligned} \tag{3}$$

where X_i represents the population, GDP, population, export, import, residential housing production, cement production, house appliances sales of refrigerator, washing machine, television and vacuum cleaner, while w_i is the corresponding design variables.

3. Illustrative example

The model developed in this study is applied to the Turkish residential-commercial sector (TRCS), of which energy utilization structure is summarized below.

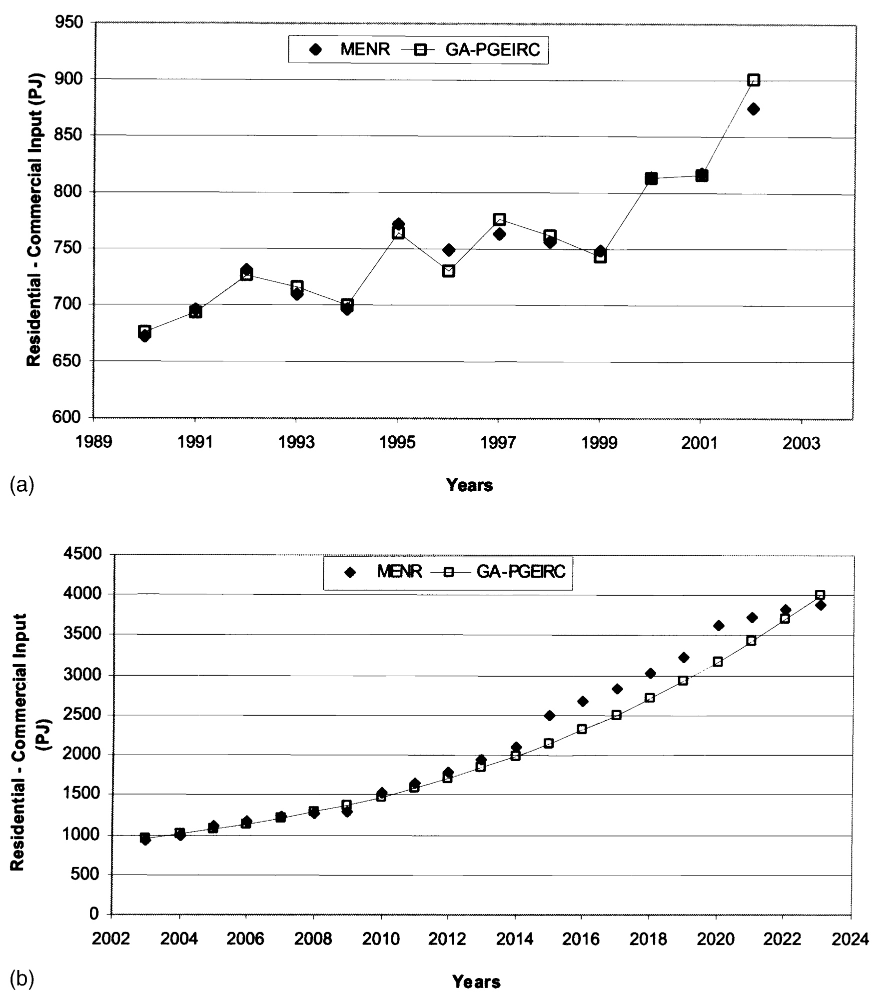

Fig. 2. (a) Actual and fitted data obtained from GA-PGEIRC scenario 1 of the residential-commercial energy input values of Turkey. (b) Comparison of GA-PGEIRC scenario 1 and MENR for future residential-commercial energy input value projections of Turkey.

3.1. A brief overview of the Turkish residential-commercial sector

The TRCS includes residential, commercial public and agriculture activities. About 39% and 34% of total energy resources were used in this sector in 1990 and 2000, respectively. The highest contributions came from renewable energy with 389.25 PJ in 1990 and liquid fuel with 253.75 in 1999. However, natural gas usage has continuously increased in the residential sector for space heating, water heating and cooking purposes in several cities. Natural gas constituted 23.73 PJ of used energy in this sector in 1990, while this value was 103.73 PJ in 2000. In addition, utilization of renewable energy is spread in the TRCS, especially from sunlight for water heating, from geothermal for water heating and space heating and from bio waste for general usage [18]. In 2001, of Turkey's end use energy, 34.48% was used by the residential-commercial sector. The share of this sector in this breakdown is expected to continue to decrease at approximately 9–12% per year and to reach 28 and 26% in 2005 and 2010, respectively. The energy efficiency value for the TRCS is found to be 55.75%, while the exergy efficiency value for that is obtained to be 8.98% in the same year [19]. In the TRCS, energy consumption for heating is too high (more than 70% of the energy consumed) since buildings have almost no insulation [20].

Energy use per unit of building area in Turkey could be reduced by nearly half through the application to all buildings of the new Heat Insulation Standards on building envelopes [21], issued in 2000. While existing buildings require 200–250 kWh/m^2, the new standards could bring requirements down to 100–150 kWh/m^2. At current rates of building stock turnover, the estimated energy efficiency gains could take several decades to materialize [20,21].

Estimating the energy demands in Turkey has been executed by the Minister of the Energy and Natural Resources (MENR). Every 5 years in Turkey, the State Planning Organization (SPO) prepares a *Development Plan* with the assistance of expert organizations for all sectors including the energy sector. The MENR prepares energy production and demand projections in accordance with the growth targets given by the SPO in Turkey. Energy demand projections based on various factors, including development, industrialization, urbanization, technology and conservation. The

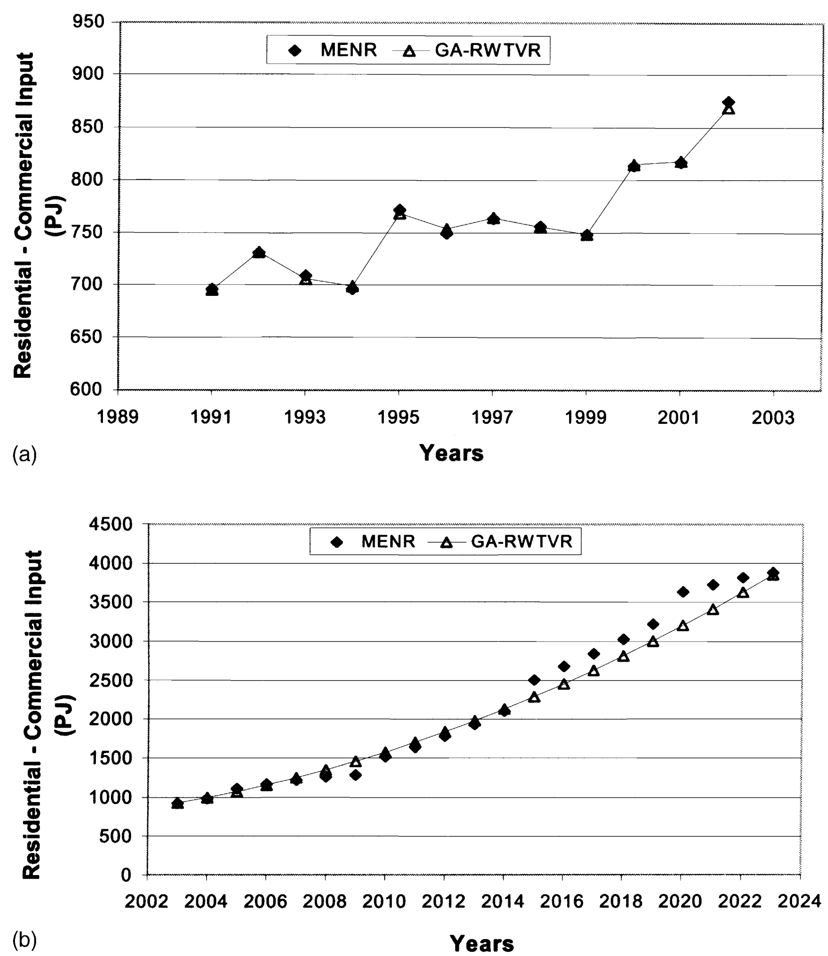

Fig. 3. (a) Actual and fitted data obtained from GA-RWTVR scenario 2 of the Turkish residential-commercial energy input values. (b) Comparison of GA-RWTVR scenario 2 and the MENR for the future residential-commercial energy input value projections of Turkey.

figures are revised each year in the light of the performance over the past year [22,23].

3.2. Data used

The data related to the design parameters are collected from a variety of sources and covers the period from 1990 to 2023 for energy input values. The GDP and total final energy consumption data are collected from the World Energy Council—Turkish National Committee [24] and the MENR [25]. Turkey's general population, GDP, import, export, residential housing production, cement production, house appliances sales of refrigerator, washing machine, television and vacuum cleaner figures are obtained from the State Statistics Institute [26]. Besides this, the future estimation of the residential-commercial energy input is taken from both the MENR [25] and Utlu [27], which will be stated only the MENR projections throughout this study, since the values up to 2020 are based on the estimations of the MENR. All the data used are also calculated by Utlu [27], with the projected figures between 2020 and 2023.

3.3. The GAEIEM scenarios developed

Observation of X_i values shows that the growth of the Turkish population (P), GDP (G), export (E), import (I), residential housing production (R), cement production (C), house appliances sales of refrigerator (R), washing machine (W), television (T) and vacuum cleaner (V) have been increasing according the social development in Turkey.

The scenarios are made in order to perform better predictions of the residential-commercial energy input of Turkey. In the first two scenarios, two sets of design parameters/indicators have been used in the GA; then important parameters were selected and used in the third scenarios.

Scenario 1 (*GA-PGEIRC*): It is assumed that the values for population (X_1), GDP (X_2), export (X_3), import (X_4), residential housing production (X_5) and cement production (X_6) of Turkey increase with time. These increment trends are plotted in Figs. 1a–d.

Scenario 2 (*GA-RWTVR*): Residential housing production (X_1), house appliances sales of washing machine (X_2), television (X_3), vacuum cleaner (X_4) and refrigerator (X_5) have been used as a design parameter/indicator. These parameters

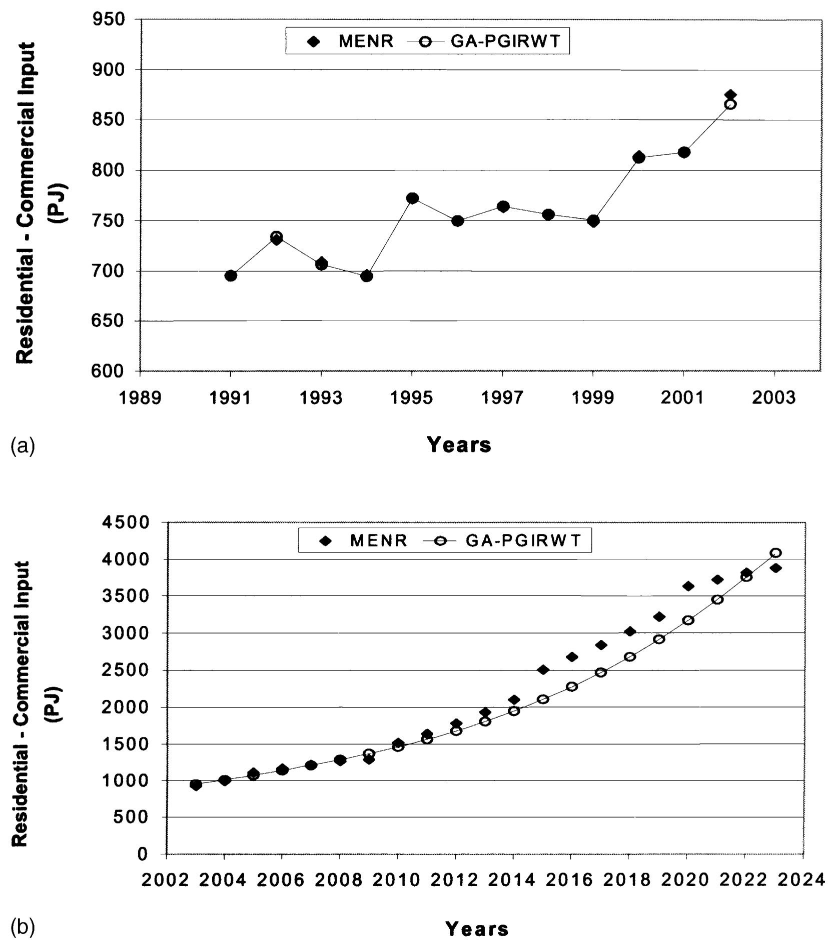

Fig. 4. (a) Actual and fitted data obtained from GA-PGIRWT scenario 3 of the Turkish residential-commercial energy input values. (b) Comparison of GA-PGIRWT scenario 3 and the MENR for the future residential-commercial energy input value projections of Turkey.

give valuable important information related to the social and economic development changes in Turkey. It is assumed that there is a linear increase in these design parameters for the future energy input prediction. Trends of these parameters are plotted in Figs. 1d–e.

Scenario 3 (*GA-PGIRWT*): The important design parameters of population (X_1), GDP (X_2), import (X_3), residential housing production (X_4), washing machine (X_5) and television (X_6) were selected as a residential-commercial energy input indicator. There is a strong relation among the residential-commercial energy and indicators.

3.4. Application of the GAEIEM model and results

By providing the upper and lower bounds of parameters the GAEIEM is performed using the following user-specified parameters.

Population size (n)	100
Generation number (k)	450
Probability of crossover (p_c)	0.8
Probability of mutation (p_m)	0.02

The convergence of the objective function was examined in the GAEIEM. The obtained model converges in an acceptable number of generations. The convergence of the algorithms can be obtained from Canyurt [28].

After the application of the GAEIEM, the following parameter values are obtained, which result in the minimum SSE between the experimental data and estimated results. The forms of the GAEIEM developed for three different kinds of approaches are given by the following equations:

$$E_{\text{input}}^{\text{GA1-PGERC}} = w_1 + w_2X_1 + w_3X_2 + w_4X_3 + w_5X_4 + w_6X_5 + w_7X_6 + w_8X_1X_2 + w_9X_1X_3 + w_{10}X_1X_4 + w_{11}X_1X_5 + w_{12}X_1X_6 + w_{26}X_5^2 \quad (4)$$

$w_1 = -5772.332$, $w_2 = 10.221$, $w_3 = 11.084$, $w_4 = -81.955$, $w_5 = -146.059$, $w_6 = 28.414$, $w_7 = 294.541$, $w_8 = -0.133$, $w_9 = 1.156$, $w_{10} = 2.852$, $w_{11} = 0.210$, $w_{12} = -4.809$ and $w_{26} = -0.082$; remaining w_i parameter values are found zero from the GA results.

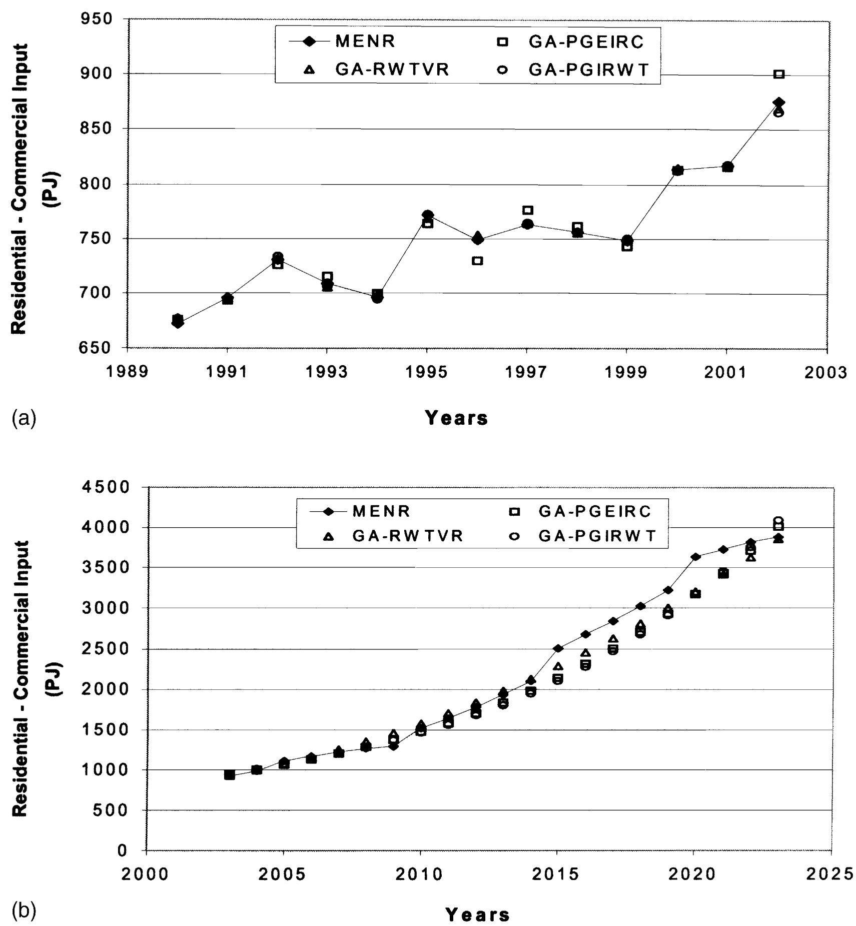

Fig. 5. (a) Comparison of MENR, GA-PGEIRC scenario 1, GA-RWTVR scenario 2 and the GA-PGIRWT scenario 3 for the Turkish residential-commercial energy input values between 1990 and 2002. (b) Comparison of MENR, GA-PGEIRC scenario 1, GA-RWTVR scenario 2 and the GA-PGIRWT scenario 3 for the future residential-commercial energy input value projections of Turkey.

$$E_{\text{input}}^{\text{GA2-RWTVR}} = w_1 + w_2X_1 + w_3X_2 + w_4X_3 + w_5X_4 + w_6X_5 + w_8X_1X_2 + w_{11}X_1X_5 + w_{15}X_2X_5 + w_{18}X_3X_5 + w_{20}X_4X_5 + w_{22}X_5^2 \quad (5)$$

$w_1 = 4870.636$, $w_2 = -22.751$, $w_3 = -3.992$, $w_4 = 0.100$, $w_5 = 2.130$, $w_6 = -0.165$, $w_8 = 0.003$, $w_{11} = -0.002$, $w_{15} = 0.002$, $w_{18} = -0.0001$, $w_{20} = -0.001$ and $w_{22} = 0.048$; remaining w_i parameter values are found zero from the GA results.

$$E_{\text{input}}^{\text{GA2-RWTVR}} = w_1 + w_2X_1 + w_3X_2 + w_4X_3 + w_5X_4 + w_6X_5 + w_7X_6 + w_8X_1X_2 + w_9X_1X_3 + w_{10}X_1X_4 + w_{11}X_1X_5 + w_{12}X_1X_6 + w_{17}X_3X_4 + w_{20}X_4X_5 \quad (6)$$

$w_1 = -38477.375$, $w_2 = 752.116$, $w_3 = 221.263$, $w_4 = -566.735$, $w_5 = 185.187$, $w_6 = -38.694$, $w_7 = 9.125$, $w_8 = -3.526$, $w_9 = 6.114$, $w_{10} = -3.450$, $w_{11} = 0.616$, $w_{12} = -0.172$, $w_{17} = 0.776$ and $w_{20} = -0.001$; remaining w_i parameter values are found zero from the GA results.

The three forms of the GAEIEM are applied for estimating the Turkish residential-commercial energy input values and the results are compared with the MENR projections [25,27], as shown in Figs. 2–5. As can be seen from the figures of GA results, the MENR [25,27] results between 1990 and 2002 are very close the comparative error is less than 1%. GA scenarios are also capable of locating the economic crisis at 1994 and 1999. It may be concluded that all the three scenarios considered seem to be capable of predicting the Turkish residential-commercial energy input values as an alternative to the MENR.

4. Conclusions

Use of GAs has been growing exponentially since Holland proposed them in 1975 and a number of studies have been performed by many researchers since that time. In this study, GA was composed in order to predict the future energy trends for the residential-commercial energy input values of Turkey, which was selected as an example, while the effect of the design parameters on the energy input of the sector considered was examined. The three types of models were developed in quadratic forms for making future predictions. It may be concluded that the GA can be used as an alternative solution algorithm to estimate the future energy values of Turkey as well as any other countries, while the use of GA is easy and does not need many parameters for future projections, therefore it is preferable. The results of the present study are also expected to give a new direction to engineers, scientists, and policy makers in estimating energy consumption values and implementing energy planning studies as a potential tool.

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