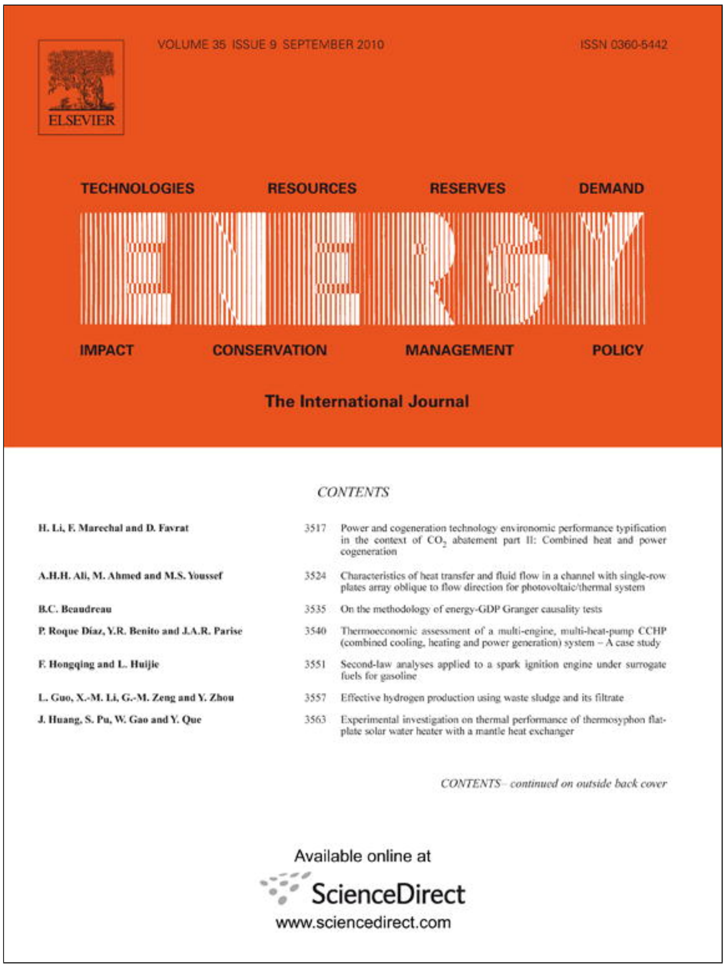

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# An analytical method for the measurement of energy system sustainability in urban areas

Marina Jovanovic [a,*], Naim Afgan [b,1], Vukman Bakic [a]

[a] Laboratory for Thermal Engineering and Energy, VINCA Institute of Nuclear Sciences, P.O. Box 522, Belgrade 11001, Serbia
[b] Mechanical Engineering Department, Instituto Superior Tecnico, Lisbon 35121, Portugal

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A B S T R A C T

Assessing the sustainability of urban energy systems and forecasting their development are important topics that have been the focus of recent research. In this paper, an approach for the measurement the sustainability of an urban energy system is introduced. The approach is based on prediction of the future energy needs within the consuming sectors of a city by specification of energy system development scenarios and validation of the scenarios by a multi-criteria decision method. Prediction of energy needs for the area of the city using the simulation model, model for analysis of the energy demands (MAED) is done. Finish the last level of aggregation, using the method of multi-criteria analysis, is getting the General Index of Sustainability (GIS), which shows a measure of the validity or viability, or quality of the investigated scenarios. In this way, the mathematical and graphical made a synthesis of all the indicators that are relevant to sustainable development. The accuracy in determining the mean of the GIS is checked by calculating the standard deviation. Also, a measure of reliability of the preference when watching a few consecutive scenarios was performed. The defined scenarios take into account the utilization of different energy sources, the exploitation of existing energy plants and infrastructure, and the building of new plants. The sustainability criteria are described by a unique set of economic, social and ecological indicators. The new approach was used to forecast the development of sustainable energy system in Belgrade, Serbia.



## 1. Introduction

Energy is essential for economic and social development and improves the quality of life. It is very important for the development of society. Presently, most of the world's energy production and consumption is performed in a way that cannot be sustained given existing technologies. The world's consumption of primary energy has increased at an average rate of 2.0% per year since 1973 [1].

Analysis of an energy system on the local level may support the use of different forms of sustainable development in different regions. The estimation, research and categorization of sustainability in different regions using standardised indicators are the focus of most investigations of local level energy system sustainability. These indicators and sub-indicators numerically express the environmental, social and economic conditions of a region. They are useful tools that support the planning of sustainable regional or national energy strategies [2,3]. To measure the sustainability of a city energy system, it is necessary to define and calculate specific energy indicators [4]. To aggregate multidimensional indicators into a general index, which represents the quality or sustainability of energy system options, the methodology of multi-criteria analysis is often used. This methodology provides a mathematical and graphical synthesis of all of the indicators that are relevant to sustainable development [5,6].

In this paper, a method for the measurement of the sustainability of the energy system is proposed. It is based on forecasting future energy requirements, defining various urban energy system development scenarios, and validating these scenarios using the multi-criteria decision method. This new approach was applied to the energy system of the city of Belgrade.

## 2. Sustainability and indicators of sustainable development

Countries around the world formulate energy and economic policies on the local level. These policies should have a minimum impact on the environment, and they should provide a framework

*Abbreviations:* ISD, indicators of sustainable development; MAED, model for analysis of the energy demands; GDP, gross domestic product; EISD, energy indicators of sustainable development; GIS, general index of sustainability; ASPID, analysis and synthesis parameters under information deficiency.

* Corresponding author. Tel.: +381 11 3408250; fax: +381 11 2453670.
*E-mail addresses:* marinaj@vinca.rs (M. Jovanovic), afgan@sbb.rs (N. Afgan), bakicv@vinca.rs (V. Bakic).
[1] Tel.: 35121 8478082; fax: 3512 18475545.

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**Nomenclature**

| | |
|---|---|
| $x(j)$ | complex objects (–) |
| $q_i(x)$ | quality of the objects (–) |
| $q_i(x_i;\theta)$ | normalised function (–) |
| $w_i$ | weight-coefficients (–) |
| $Q(q; w)$ | general index of sustainability (–) |
| $W(m, n)$ | finite set of weight-coefficients (–) |
| $S(q^j; I)$ | standard deviation (–) |
| $P(j, l, I)$ | probability (–) |
| Eclec | economy sub-indicator of energy cost ($/kWh) |
| Eclinv | economy sub-indicator of investment ($/kWh) |
| Eclef | economy sub-indicator of plant efficiency (%) |
| Eclei | economy sub-indicator of energy intensities (kWh/$) |
| Soleh | social sub-indicator of energy use per household (kWh/hh) |
| SoIsi | social sub-indicator of share of household income spent on fuel and electricity (%) |
| SoIni | social sub-indicator of number of injured per energy produced (1/kWh) |
| SoIwh | social sub-indicator of working hours per energy produced (h/kWh) |
| $EkIco_2^{(1)}$ | ecology sub-indicator $CO_2$ emission per energy produced ($kgCO_2$/kWh) |
| $EkINO_x^{(1)}$ | ecology sub-indicator $NO_x$ emission per energy produced ($kgNO_x$/kWh) |
| $EkIco_2^{(2)}$ | ecology sub-indicator $CO_2$ emission per capita ($kgCO_2$/cap.) |
| $EkINO_x^{(2)}$ | ecology sub-indicator $NO_x$ emission per capita ($kgNO_x$/cap.) |

for sustainable development. Hence, the economic, environmental and social objectives of sustainable development may be effectively achieved by acting on the local level, such as within the energy systems of cities.

The World Commission on Environment and development [7] established new modalities for measuring progress in defining and achieving energy system sustainability. This was also mentioned at the 1992 Earth Summit in Rio de Janeiro, Brazil [8]. A better understanding of different dimensions or aspects of sustainable development, and the complex mutual relations between these aspects, is achieved with the Indicators of Sustainable Development (ISD) [9]. Energy indicators are defined from a combination of basic economic data, social activities, technological characteristics and measurements or estimates of energy production or consumption. Energy indicators represent the basic connecting tools between energy targets and sustainable development in the formation of a sustainable development policy used for institutional dialogue [10].

## 3. Energy management in urban areas with the aim of sustainable development

The energy system in an urban environment has a complex structure: on the one hand, it has a large number of suppliers of different types of energy, and on the other hand, a large number of consumers. Analysis of the energy system of a metropolitan city is often concentrated on the social and economic aspects of the system. It is necessary to develop a methodology for this analysis and an estimation of energy consumption to satisfy the needs of consumers, secure environmental protection, ensure the reliability and sufficiency of energy resources, and assess budget limitations and economic efficiency [11–13].

The environmental, economical and social sustainability of cities are the most urgent challenge for humanity in the 21st century, but each city has its own vision of sustainability. The key issues of sustainable development of urban areas were presented in the agenda of "Habitat II" the UN Summit of Cities [14].

Planning the sustainable development of a city is a very complex process. It begins with determination of indicators and calculations that aggregate the indicators at all levels before the final level is reached. Thus final level shows the general sustainability index of the complex system. The key issues that will define the shape and future use of energy in cities are the sustainability of the energy, the efficiency of the energy process and the accessibility of different forms of energy.

## 4. Assessment of city energy needs with the simulation model, model for analysis of the energy demands (MAED)

The simulation model MAED is used to estimate the energy requirements of a city in accordance with the potential development of economic, social and technological factors [15]. The model MAED is available software for prediction of energy needs. The projection plan of the future total energy needs is determined based on the current development and assumptions about the future evolution of economic activities, technological development and life style of the city's population.

The simulation model MAED systematically relates specific energy demands with sets of social, economic and technological factors that influence energy consumption. Six economic sectors are considered: manufacturing, agriculture, construction, mining, energy and services. The service sector includes many sub-sectors (trade services, restaurants and hotels, transport services, storage and communication, finance insurance, real estate and business services, community and personal services). The manufacturing sector includes four sub-sectors: basic materials, machinery and equipment, nondurable and miscellaneous.

There are two sets of input parameters that are needed for forecasting future energy needs, initial parameters and constants that refer to current energy status and time dependent parameters that predict future energy needs. The current status of the city energy system should be based on a selected basis year and a few years preceding the basis year. It is necessary to have information about different characteristics including statistical data on energy consumption, energy supply, energy sectors and end-use categories. The basis year should belong to a past period when there were no sudden increases in energy consumption, no natural or national catastrophes, and it should be close to the beginning of the period for which the forecasting analysis is to be performed. Next, the future economic, social and technological development of the city must be described analytically. Economic and social development is described by demographic data (population, population growth rate, active labourer force), GDP (Gross Domestic Product), GDP per capita, annual GDP growth rate, numbers of public transport users in urban and suburban areas, average total distance travelled by a person using public transport, the average dwelling size, the heated area of dwelling, *etc.* The technology factors used in the calculation of energy requirements are the efficiency of the energy carriers, the market penetration of the energy carriers, the fuels demanded for the transport of passengers and goods by vehicles, the insulation of buildings, other building related factors for both existing and new buildings, *etc.*

The preparation of input data for the simulation model of the energy system requires synthesis, linking and compliance of necessary data from various sources as well as calculation of derived complex input parameters. A vast amount of data and information at the local level needed. Some data must be reconstructed due to the lack of statistical evidence.

## 5. Total energy requirements for three main energy consumers in the city

Total energy requirements are calculated and disaggregated into energy forms and a large number of end-user categories (each one corresponding to a given energy sector) for each defined year in the projection plan. The derived results provide information about the total annual energy needs and the average annual growth rate of the energy demands. The overall results express the final energy needed.

Demographic input data are prepared for the basis year, the historic years (before the basic year) and the projected years. These data are grouped into population growth rate, capita per household, share of the potential labour force, share of the participating labour force, share of the population outside the community of Belgrade and the share of the rural population.

The GDP is projected for the years in the future period based on the economic development plans in Serbia and on the experience of other developing countries, while the GDP data for the basis year and the historic years are specified according to statistical evidence in Serbia. Changes in the parameters concerning GDP or GDP growth rate (the structure of GDP formation and the structure of value added formation) in the manufacturing and service sectors are also defined as a part of the projection plan. The derived values are the monetary values per capita of the major economic sectors of the manufacturing and service industries and their sub-sectors.

The energy demands of agriculture, construction, mining and manufacturing within the industry sector are calculated based on energy intensities (consumption of energy per added value unit) for three energy forms: electricity (lighting, electrolysis, *etc.*), heat (space and water heating, steam generation, furnace and direct heat) and motor fuels. The input data of the energy intensities of the four manufacturing sub-sectors are calculated based on statistical evidence and future projection. In addition, the shares of various energy forms on the energy market and the average efficiencies of the energy consumption technologies are taken into account.

The energy demands of the transport sector are calculated as a function of performed duty (e.g. ton-kilometres or passenger-kilometres), demand breakdown according to transportation device (cars, trucks, train, plane, *etc.*), the specific energy needs of each device, and the load factors of each transportation mode. The total energy demand for transportation is calculated separately for freight and for passengers, according to macroeconomic and life style factors. Energy consumption is calculated on the basis of the energy intensities of the transportation modes expressed in kWh/100 km; the energy consumption according to mode of transportation and fuel type (diesel, electricity).

For the calculation of the energy demands in passenger transportation, the following input data are required, [6,9,16]: the average intercity distance travelled per person per year; the average intra-city (in urban areas) distance travelled per person per day; the average load factor of cars, buses and trains in intercity and intra-city travel (persons per car, bus, train); the average load factor of the intra-city electric mass transit system (persons in trolleys, trams); a model of the public intercity passenger transport distribution (share of buses, electric and diesel trains); a model of intra-city passenger transport distribution (share of cars and urban public passenger transportation); various factors for intercity passenger transportation (ratio of population to total number of cars, average intercity distance driven per car and per year) and the average intensity of passenger transport (in natural units).

The obtained results were as follows: 1) passenger kilometres (passenger transport per 1 km distance) by mode of transportation (car, bus, train) in intercity transport; 2) passenger kilometres by car or public transport; 3) energy intensity of passengers transportation: gasoline consumption of cars in intra-city and intercity travel, electricity consumption in intra-city travel, diesel consumption of intra-city buses, diesel consumption and electricity consumption of trains and electricity consumption of intra-city electric mass transport (trams and trolleys); 4) energy consumption of passenger intercity and intra-city transportation by mode; 5) energy consumption of passenger intercity and intra-city transportation by fuel (motor fuels and electricity); 6) energy consumption of international transportation, and 7) total energy consumption of passenger transportation by fuel.

The energy demands of the household sector are calculated based on demographic data (population, number of dwellings, *etc.*), whereas for the service sector energy demands are related to the level of economic activity. For the household and the service sectors, a further division is made according to the type of construction. The groups are "old" (traditional construction) and "new" (identifying the modern type of construction complying with new insulation standards which were built after the defined basis year in the model).

The categories of energy usage considered in the household sector are space heating, air-conditioning, water heating, cooking and electricity for secondary appliances (refrigerators, lighting, washing machines, *etc.*). For the final energy calculation in the household sector the following data are required: number of dwellings for the basis, historic and projected years; the percentage of dwellings in the areas requiring space heating; degree days for the considered area; and the demolition rate. Three types of input data are required: 1) those which enable the final energy demands in the household sector required for space heating, hot water cooking, air-conditioning and the specific use of electricity for appliances to be calculated; 2) data on the penetration of different energy carriers (electricity, heat pumps, solar, district heat, non-commercial fuels, fossil fuels) into their respective heat markets associated with space heating, water heating and cooking components of the final heat demand, and 3) data such as efficiencies/coefficients of performance of different energy carriers when used in the household sector for various applications (space heating, domestic hot water production, air-conditioning, *etc.*)

In the case of dwellings, a distinction is made between single family houses with central heating, apartments with central heating, dwellings with room heating only and dwellings without heating. Input data were provided separately for old and new buildings. These factors represent the general structure of each dwelling. The factors of old and new buildings that are taken into the calculation, as input data are, average dwelling size, the percent of the area heated, specific heat loss rate, the percent of dwellings with air-conditioning, specific cooling requirements of dwellings, percent of dwellings with hot water production relative to total number of dwellings, specific energy consumption for cooking per dwelling/year, specific electricity consumption for appliances per dwellings/year and electricity supply to households for appliances. Furthermore, some of the input data are related to the penetration of non-commercial fuels (wood, *etc*), the district heating system, solar energy and fossil fuels for space heating, domestic hot water production, or cooking and air-conditioning.

The input data for the service sector require the same pattern as that for the household sector but in much less details. The end-use categories considered for the service sector are, thermal uses (space/water heating), air-conditioning and specific uses of electricity (motive power for small motors, computers, lighting, *etc.*).

The contribution of various energy carriers and the efficiency of each energy form on a potential energy market are important parameters for assessing final energy needed. These are specified in the projection plan. The input parameters for this calculation are, the contribution of the service sector to the total labour force, the area requiring space heating, the floor area per employee, the total labour force and the total floor area in the service sector. The remaining values and factors, which are used in the final energy calculation are, the percent of the service sector floor area requiring space heating that is actually heated, the specific heat requirements of old and new service sector buildings, the percent of air-conditioned service sector floor area and specific cooling requirements.

## 6. Measuring the sustainability of energy scenarios

Energy system sustainability is quantified by analysing possible energy scenarios, which provide the framework for investigating the future of energy perspectives, including various combinations of technological options [17].

The quality of selected scenarios are defined by energy indicators of sustainable development (EISD), which are represented by three sets of economical, social and ecological sub-indicators. The methodology of multi-criteria analysis is applied to estimate the sustainability of proposed energy scenarios. The results are then compared using the General Index of Sustainability (GIS), which is the measure of system complexity [16,18,19]. For this purpose, a mathematical model and corresponding computer code are developed based on the fuzzy sets theory for the new multi-criteria decision-making technique analysis and synthesis parameters under information deficiency (ASPID) [20,21].

### *6.1. Estimation of energy system sustainability by multi-criteria analysis using the fuzzy sets of synthesis technique*

The fuzzy sets of synthesis technique are used as a mathematical tool in the decision-making process for the evaluation of different complex systems under uncertain conditions. The main benefit of this methodology is its ability to work with the non-numerical (ordinal), inexact (interval) and incomplete information (*nnn*-information). It is based on stochastic models of uncertainty, which enable the GIS to be obtained using *nnn*-information from various sources having different reliability and probability [11,22,23].

### *6.2. The synthesis technique of fuzzy sets*

Fuzzy sets theory is applicable to the multi-criteria assessment of various energy systems. If an alternative (scenario) of an energy system is observed as an object, than all alternatives that are taken in consideration make the finite set:

$$X = \{x(j), j = 1, \ldots k\} \tag{1}$$

where $X$ is the finite set of all considered objects, and $k$ is the total number of objects.

First, we must presume, that complex objects are identified with vectors:

$$x(j) = (x_1(j), \ldots\ldots, x_m(j)) \tag{2}$$

$$x_i(j) \in E^1, x(j) \in E^k, i = 1, \ldots\ldots, m; \; j = 1, \ldots\ldots, k,$$

where $k$ is the number of objects under investigation, component $x_i(j)$ of vector $x(j)$ refers to a value of an indicator $x_i$ of an object $x(j)$, $E^1$ represents the set of real numbers, while $E^k$ represents $k$ sets of real numbers. The finite set of objects $X$ shows the basis set for all fuzzy sets that are determined later. It is supposed that each value of indicator $x_i$ is necessary and all defined indicators are sufficient for an estimation of a fixed quality of an object, respectively for the sustainability assessment of an object configured over the set of indicators.

The quality of the objects $x(j)$, $j = 1,\ldots\ldots,k$, is estimated by a number of specific criteria $q_1,\ldots,q_m$ where each criteria is a function of a corresponding indicator:

$$q_i = q_i(x_i), i = 1, \ldots m; \tag{3}$$

where $m$ is the number of indicators.

The function $q_i = q_i(x_i)$ may be treated as a particular membership function of a fuzzy set PREF$\subseteq X$ of objects which are preferable from the point of '$i$'-th criterion's view. The quality level (degree of preferability) of the '$j$'-th object is estimated by the value $q_i(j) = q_i(x_i(j))$ of function $q_i(x_i)$ from the point of '$i$'-th criterion's view.

In the next step, it is assumed that all of the specific criteria are normalised without a loss in generality. Normalisation of the specific criteria is done on the basis of the values of the indicators. The sustainability indicators are not suitable for use because they have different dimensions and ranges ($/kWh, kg/kWh, kWh/$, etc.), so they could not be compared.

For each object $x(j) \in X$, quality estimation is performed by many criteria $q_i(j) = (q_1(j), \ldots, q_m(j)), 0 \le q_i(j) \le 1$, that can be treated as a vector-criterion $q = (q_1,\ldots q_m)$. This level means defining of monotonous of each normalised function type $q_i(x_i)$ (decreasing or increasing function).

The specific criteria are described by a power law function. If the value of $q_i$ increases when the value of the indicator $x_i$ increases, then the function $q_i(x_i)$ is defined by Eq. (4a). However, the function $q_i(x_i)$ is defined by Eq. (4b) if the value of $q_i$ decreases when the value of argument $x_i$ increases. MIN and MAX are used to indicate the upper and lower bounds of a given indicator.

$$q_i(x_i;\Theta) = \left\{ \begin{array}{cc} 0 & x_i \le \mathrm{MIN}_i, \\ \left(\dfrac{x_i - \mathrm{MIN}_i}{\mathrm{MAX}_i - \mathrm{MIN}_i}\right)^{\Theta} & \mathrm{MIN}_i < x_i < \mathrm{MAX}_i, \\ 1 & x_i > \mathrm{MAX}_i. \end{array} \right\} \tag{4a}$$

$$q_i(x_i;\Theta) = \left\{ \begin{array}{cc} 1 & x_i \le \mathrm{MIN}_i, \\ \left(\dfrac{\mathrm{MAX}_i - x_i}{\mathrm{MAX}_i - \mathrm{MIN}_i}\right)^{\Theta} & \mathrm{MIN}_i < x_i < \mathrm{MAX}_i, \\ 0 & x_i > \mathrm{MAX}_i. \end{array} \right\} \tag{4b}$$

The convexity of curve $q_i = q_i(x_i)$ is defined by the exponent $\Theta$ which is chosen by the researcher based on experience. The derivations of function $q_i(x_i)$ defined with Eq. (4a) are as follows:

$$q_i^{'} = \Theta\left(\frac{x_i - \mathrm{MIN}_i}{\mathrm{MAX}_i - \mathrm{MIN}_i}\right)^{\Theta-1}\frac{1}{\mathrm{MAX}_i - \mathrm{MIN}_i}\Theta \tag{5}$$

$$q_i^{''} = \Theta(\Theta-1)\left(\frac{x_i - \mathrm{MIN}_i}{\mathrm{MAX}_i - \mathrm{MIN}_i}\right)^{\Theta-2}\frac{1}{(\mathrm{MAX}_i - \mathrm{MIN}_i)^2} \tag{6}$$

For $\Theta > 1$ the function $q_i(x_i)$ is concave, as can be concluded from Eq.(6) and $q_i'' > 0$, Fig. 1a. For $0 < \Theta < 1$ the function is convex, from Eq. (6) $q_i'' < 0$, Fig. 1b. For the special case, when $\Theta = 1$, the function $q_i(x_i)$ is a linear equation between $\mathrm{MIN}_i$ and $\mathrm{MAX}_i$, Fig. 1c. For the decreasing function described by Eq. (4b), similar results are obtained as presented in Fig. 2a–c.

In practice the most popular normalised function is a linear function. As such, in this paper the following normalised function $q_i(x_i; =\Theta)$, $\Theta = 1$ is adopted. In this way, normalised values of indicators are obtained by the linear normalisation. The set of

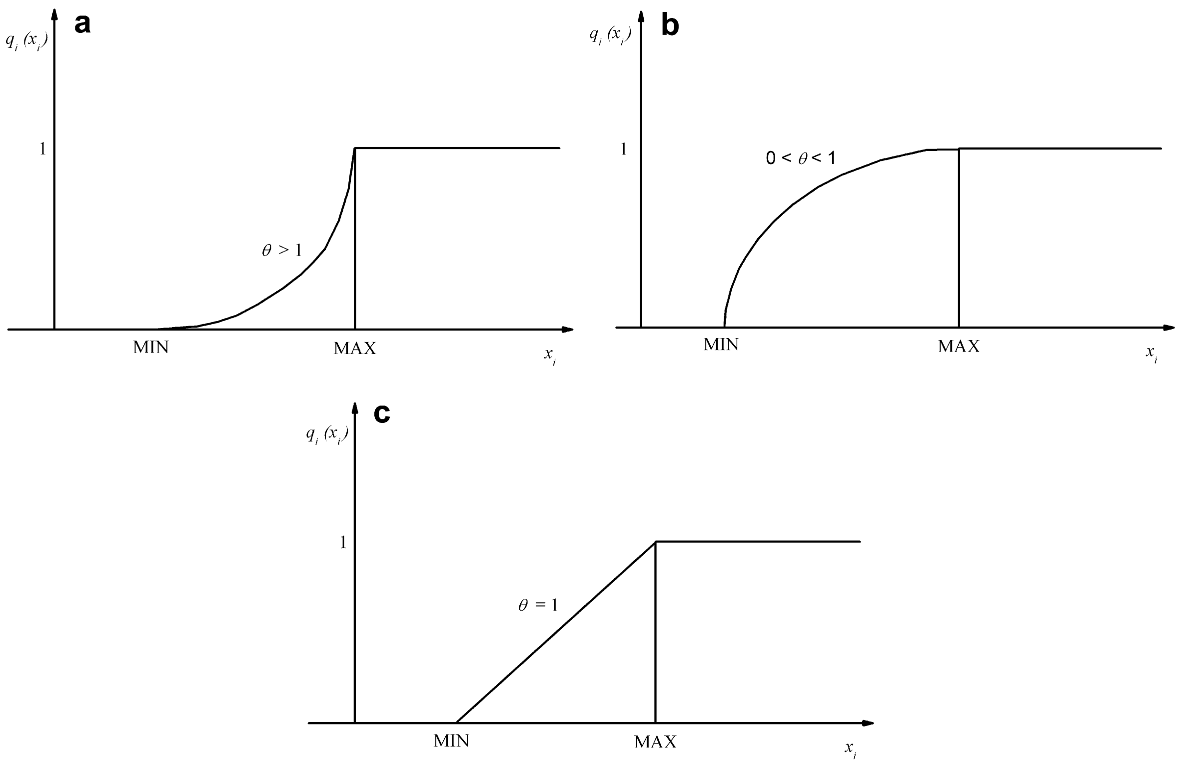


**Fig. 1.** The cases for an increasing function (a)–(c).

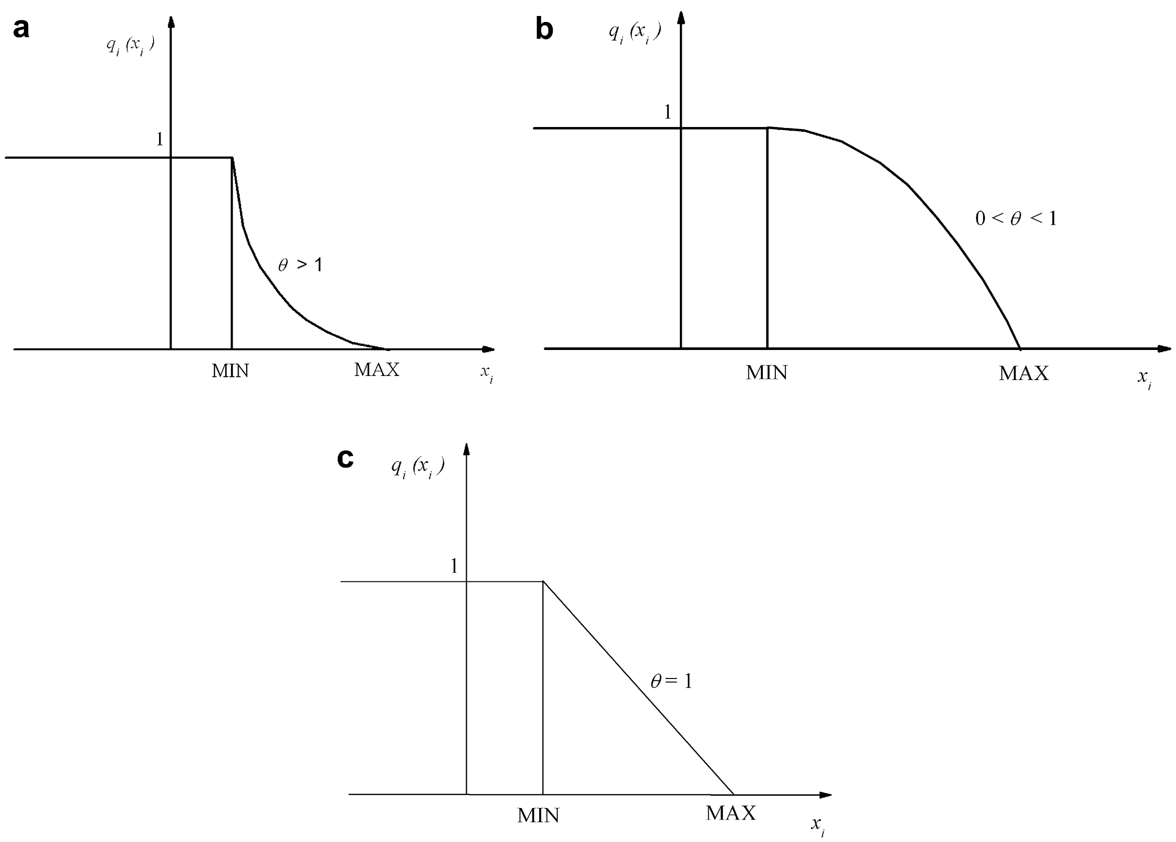


**Fig. 2.** The cases for a decreasing function (a)–(c).

numerical values for each indicator for all considered energy scenarios, is converted into a fuzzy set of normalised indicators, as presented with the following matrix

$$\begin{vmatrix} q_1^1 & q_2^1 & q_3^1 & q_4^1 & \ldots q_m^1 \\ q_1^2 & q_2^2 & q_3^2 & q_4^2 & \cdot \\ q_1^3 & q_2^3 & q_3^3 & q_4^3 & \cdot \\ q_1^4 & q_2^4 & q_3^4 & q_4^4 & \cdot \\ q_1^5 & q_2^5 & q_3^5 & q_4^5 & \cdot \\ \cdot & & & & \cdot \\ q_1^k & q_2^k & q_3^k & q_4^k & \ldots q_m^k \end{vmatrix} \quad (7)$$

where the element $q_i(j)$ is the measure of *i-th* indicator for the *j-th* scenario. Due to the performed normalisation process, each criterion fulfills the inequality $0 \le q_i(j) \le 1$.

After the normalisation process, the minimum value $q_i(j) = 0$ indicates that the estimated '*j*'-*th* object has a minimal preference from the '*i*'-*th* specific criterion point of view. The maximum value $q_i(j) = 1$ indicates that the estimated '*j*'-*th* object has a maximal preference from the '*i*'-*th* specific criterion point of view.

The objects from the set *X* can be compared under the following conditions:

$$\forall x^{(j)}, x^{(l)} \in X\left(x^{(j)} > x^{(l)}\right) \Leftrightarrow \left(\left(\forall i\, q_i^{(j)} \ge q_i^{(l)}\right)\left(\exists s : qs^{(j)} > qs^{(l)}\right)\right) \quad (8)$$

In other cases objects are incomparable, if any criterion of the second object is higher than the specific criteria of the first object. Two objects cannot be compared under the following condition:

$$\left(\exists r : q_r^{(j)} > q_r^{(l)}\right)\left(\exists s : q_s(j) < q_s(l)\right) \quad (9)$$

These set of incomparable pair of objects makes part of set *X* of all possible pair objects. Hence, the comparison of complex objects on multi-criteria bases may face the problem of incomparable objects pairs. Assume that two objects are independently taken by chance from an infinite set of all possible objects determined by corresponding criteria-vector $q_i = (q_1, \ldots, q_m), 0 \le q_i \le 1$, then the probability of these two objects being incomparability is equal to:

$$P(m) = 1 - \frac{1}{2^{m-1}} \quad (10)$$

This problem is solved by synthesis or aggregation of particular criteria, $q_1, \ldots, q_m$ into one General criterion or General Index-Q determined by a scalar-valued synthesising function.

The weight-coefficient $w_i (i = 1, \ldots, m)$ indicates how important a particular criterion $q_i$ is when the General Index-Q($q$; $w$) is formed. The weight-coefficients $0 \le w_i \le 1$ for each $i = 1, \ldots m$ are called the relative "weights" of specific criteria $q_i$. Specific criterion $q_i$ have more influence on the value of the General Index-Q($q$) at increasing values of $w_i$. By varying the coefficient $w_i, (\sum_{i=1}^m w_i = 1; w_i \ge 0)$, the influence of $q_i = q_i(x_i)$ on the General Index-Q($q$; $w$) is changed. In other words the importance that is given to the specific criteria $q_i$ is changed within the formation of the General Index. The importance of each criterion in each level is assessed by weight-coefficients before the overall evaluation is carried out. The weights are proportional to the importance of the criteria evaluated by each indicator. In the fuzzy sets synthesis technique the stage of vector estimation $w = (w_1, \ldots, w_m)$ is delicate because researchers do not have enough information to exactly determine the weight-coefficients $w_i$ in practice. From experience and from theoretical arguments it is known that in these circumstances the most suitable approach is to have non-numeric information. The process of randomisation is used when instead of one vector *w*, the vector set $W(I)$ is introduced. This set is defined based on the group of all available information ($I$). For example, if interval information is known, then the set $I$ of all relations in the form of $a_i \le w_i \le b_i$ is made. If ordinal information is available, then the set $I$ of all relations in the form of $w_i = w_j$, $w_i > w_s$ is made. However, some of the weight-coefficients do not belong to equality and inequality systems. In this case, the information $I = \mathrm{OI} \cup \mathrm{II}$ is incomplete.

Non-numeric, inexact and incomplete information may be used for the reduction of the set $W(m,n)$ of all possible weight vectors with discrete components into a set:

$$W(I;m,n) = \left\{w^{(s)}, s = 1, \ldots, N(I;m,n) \le N(m,n) \subseteq W(m,n)\right\} \quad (11)$$

of all admissible weight vectors, weight vectors which meet the requirements implied by the information *I*.

The weight-coefficients are chosen from the finite set $W(m,n)$, [24]:

$$\left\{0, \frac{1}{n}, \frac{2}{n}, \frac{n-1}{n}, 1\right\}$$

where *N* represents the number of possible weight-coefficients from the set $W(m,n)$ and it can be calculated by the formula:

$$N(m,n) = \frac{(n+m-1)!}{n!(m-1)!} \quad (12)$$

where *n* is the number of the pieces of divided segments from 0 to 1, and *m* is the number of initial specific criteria.

The following synthesis function is chosen:

$$Q_\varphi(q) = Q_\varphi(q;w) = Q_\varphi(q_1, \ldots, q_m; w_1, \ldots\ldots, w_m) = \\ = \varphi^{-1}\left(\sum_{i=1}^m w_i \varphi(q_i)\right) \quad (13)$$

where $\varphi$ is a monotonically increasing random function, and $w = (w_1, \ldots., w_m)$, $w_i \ge 0$, $w_1 + w_2 + \ldots.. + w_m = 1$ is a vector of weight-coefficients.

If the function $\varphi$ is defined as an exponential function:

$$\varphi(z) = z^\lambda, \; z \ge 0, \lambda > 0$$

then the exponential weighted mean function is obtained, which is the base of a popular synthesising function:

$$Q_\lambda(q;w) = \left(\sum_{i=1}^m w_i q^\lambda\right)^{\frac{1}{\lambda}} \quad (14)$$

If $\lambda = 1$, then $Q_\lambda(q;w)$ transforms into the additive aggregative function or weighted arithmetical mean function.

$$Q_+(q;w) = Q_1(q;w) \sum_{i=1}^m w_i q_i \quad (15)$$

The additive synthesising function is the most popular type of synthesising functions. There are several reasons for the popularity of this type of synthesising function ($Q_+(q;w)$). Firstly, it is the most simplest synthesising function and it is easy to interpret. Secondly, this function presents a natural form for the aggregation of particular criteria for the majority of real decision-makers. Thirdly, this function can be represented as an arbitrary linear extension $\succ$ (when priority is given to certain criterion among the order relation $>$).

There are a number of synthesis functions but a simple modification is usually used (aggregative synthesis function):

$$Q = Q(q) = Q(q, w) = q_1 w_1 + q_2 w_2 + \ldots\ldots\ldots.. + q_m w_m \quad (16)$$

This selected function, $Q(q)$, is linear per variable $q_1,\ldots,q_m$, at $w_1$, $w_2,\ldots w_m$. According to Eq. (15), the General Index-$Q(q,w)$ has the following characteristics:

1. Monotony: if an estimation of two objects or alternatives is realised, and if $q^{(1)} = (q_1^{(1)}, \ldots q_m^{(1)})$ and $q^{(2)} = (q_2^{(2)}, \ldots q_m^{(2)})$ are vectors of specific criteria for the first and the second object, therefore if $q_i^{(1)} \geq q_i^{(2)}$, at $i = 1,2,3,\ldots m$, then:

$$Q\left(q^{(1)};\, w\right) \geq Q\left(q^{(2)};\, w\right)$$

2. If $q_i = 0$ for each $i = 1,\ldots,m$ when $Q(q,w) = 0$, and if $q_i = 1$ for each $i = 1,\ldots,m$ when $Q(q,w) = 1$. These characteristics are the direct result of the linear function $Q(q,w)$ and the facts that $w_1 + w_2 + \ldots + w_m = 1$, and $w_i \geq 0$.

The inequality $Q(q^{(j)}) > Q(q^{(l)})$ means that the '*j*'-*th* object is more preferable than the '*l*'-*th* object from the point of view of the general criterion '*Q*'. Now, all objects are comparable by the General Index. There are only three possibilities for any pair of objects, these are:

$$Q\left(q^{(j)}\right) > Q\left(q^{(l)}\right); Q\left(q^{(j)}\right) < Q\left(q^{(l)}\right); Q\left(q^{(j)}\right) = Q\left(q^{(l)}\right)$$

Thus, the following set is derived:

$$Q^{+}(I;m,n) = \left\{Q_{+}^{(s)}(q) = Q^{+}\left(q;w^{(s)}\right), s = 1,\ \ldots\ldots,\ N(I;m,n)\right\} \tag{17}$$

where the function $Q_{+}^{(s)}(q)$ from the set $Q^{+}(I;m,n)$ determines the corresponding general fuzzy set $\mathrm{PREF}^{(s)} \subseteq X, s = 1,\ \ldots,\ N(I;\ m,n)$.

By this reasoning the average members function is introduced:

$$\begin{aligned} -Q_{+}(q;I) &= \frac{1}{N(I;m,n)} \sum_{s=1}^{N(I;m,n)} Q_{+}^{s}(q) \\ &= \frac{1}{N(I;m,n)} \sum_{s=1}^{N(I;m,n)} Q_{+}\left(q;w^{(s)}\right) \end{aligned} \tag{18}$$

where $w^{(s)} \in W(I;m,\ n)$.

The function $-Q_{+}(q;I)$ implicitly contains non-numeric, inexact and incomplete information and specifies the corresponding average value of the fuzzy set $\overline{\mathrm{PREF}}(I) \subseteq X$. Hence, the following values: $-Q_{+}(q^{(j)};I),\ \ldots\ldots,\ -Q_{+}(q^{(k)};I)$ may be treated as the desired average values of the objects $x(j),\ldots,x(k)$ for the preferred (quality) estimation, and which are defined because of the missing numerical information of the weight-coefficients $w_1,\ldots,w_m$.

The exactness of an average general estimation of the preferences of the '*j*'-*th* objects may be measured by the standard deviation:

$$S\left(q^{j};I\right) = \frac{1}{N(I;m,n)} \sum_{s=1}^{N(I;m,n)} \left[Q_{+}^{s}\left(q^{j}\right) - -Q_{+}\left(q^{(j)}\right)\right]^{2} \tag{19}$$

The standard deviation measures the 'uncertainty' in the process of estimating the weight-coefficients. An object shows high 'uncertainty' in the forecasting when the standard deviation has a large value.

In the process of linearisation of the numerical values of the indicators, dispersion is registered. Dispersion depends on $n$; the dispersion is less for higher values of $n$. When a pair of successive objects is considered, the probability of the domination of a single object is included as an additional factor in the estimation.

'Probability', a measure of reliability of the preference, is calculated as follows:

$$P(j,\ l;\ I) = \frac{\left|\left\{s:\ Q_{+}^{(s)}(q^{(j)}) \rangle Q_{+}^{(s)}\left(q^{(l)}\right)\right\}\right|}{N\ (I;\ m,\ n)} \tag{20}$$

where $|\{s: Q^{(s)}(q^{(j)}) > Q^{(s)}(q^{(l)})\}|$ is number of the element of a finite set.

For the considered pair of objects, the 'probability', indicates whether a given combination is a real case, compared to the total number of combinations, $P > 0.5$. In other cases, a small value of the probability indicates that the case of these pairs of objects is improbable.

## 7. Measurement of the sustainability the energy system in urban areas

Previously, multi-criteria methods for the estimation of energy systems with only one energy carrier were applied. This study shows a methodology that was developed for the assessment of an urban energy system. The methodology addresses situations in which there are complex interdependencies between the energy systems and energy consumption as well as between economic developments, standards of living, available energy and technology resources, and environmental impacts of energy consumption. In this situation it was necessary to assign criteria and respective indicators that could be employed as measures for the calibration of different factors in the evaluation of an energy system. The necessary data for the definition of the energy systems scenarios which were used in the process of multi-criteria evaluation of the sustainability of the urban energy system, were ensured by a set of energy indicators. In this paper, the multi-criteria assessment was extended to a procedure with several levels of evaluation. In this way, accurate outcomes were provided when several different criteria were used simultaneously and when non-numeric information was used in the estimations. The weight-coefficients for the criteria were mathematically defined based on mutual relations between particular values of each alternative (scenario) and criterion with a predefined constraint. The mutual relations of the weight-coefficients with respect to different aspects of sustainable development, when priority is given to certain criterion, were investigated.

In the applied ASPID method, certain information, which can be very important for some estimation levels, cannot be lost as a consequence of the normalisation process of the indicators. Likewise, this method provides a better knowledge of results from the practical point of view of the application of multi-criteria methods. In this paper, the described methodology was applied to the complex urban energy system of Belgrade, Serbia. The algorithm for the assessment of the city's energy scenarios is shown in Fig. 3.

The mathematical description of the defined levels of the hierarchical scheme, in the case of theGIS, was obtained by a multi-criteria method according to the following steps:

(1) Formation of the '0' level of the hierarchical scheme

$Q[1;0],\ \ldots\ldots,Q[m(0);0]$, where m is the number of initial criteria (sub-criteria), $m(0) = 4$.

The complex energy system was described by values of the criteria $m(0)$, namely vectors of the criteria (sub-criteria) at the '0' level.

$$Q[1;0],\ Q[2;0],\ Q[3;0],\ Q[4;0]$$

| | |
|---|---|
| $0 \leq Q[m(0);\ 0)] \leq 1$, per $Q[m(0);\ 0)] = 0$. | Minimal values of $m(0)$-*th* criterion which has minimal degree of quality in the estimation. |
| $0 \leq Q[m(0);\ 0)] \leq 1$, per $Q[m(0);\ 0)] = 1$. | Maximum values of $m(0)$-*th* criterion which has maximum degree of quality in the estimation |

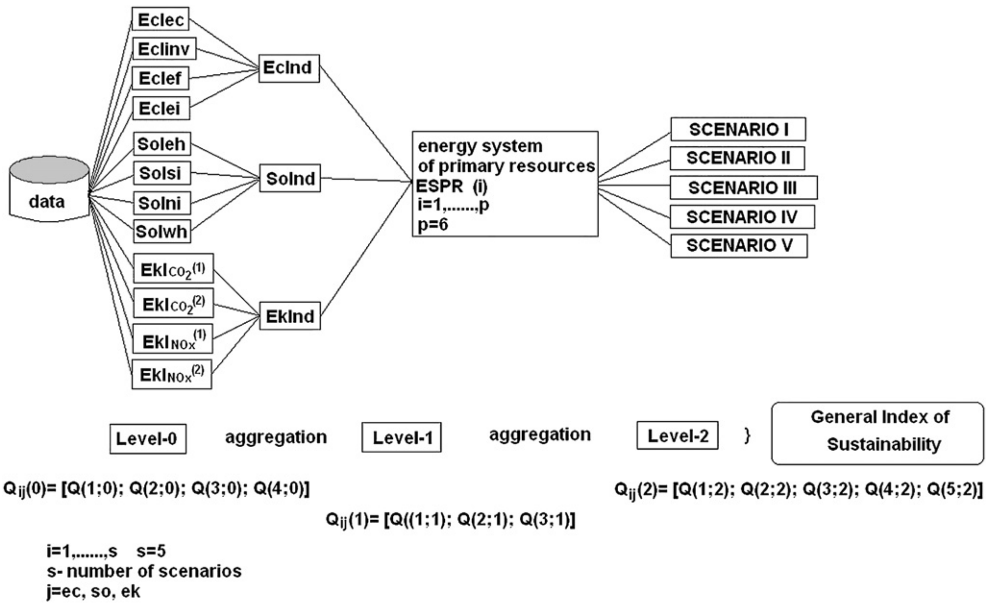


**Fig. 3.** Graph based approach of the algorithm for an estimate of the energy scenarios of the energy system of Belgrade.

$$Q_{ij}[0] = Q_i[Q_{EC}(0); Q_{SO}(0); Q_{EK}(0)] = Q_{ij}[Q[1;0];\ Q[2;0]; Q[3;0];\ Q[4;0]] \quad (21)$$

$i = 1,\ldots,5, s = 5$ – the number of scenarios
$j$ = EC, SO, EK

$$Q_{ij}[0] = \begin{vmatrix} q_{11} & q_{12} & q_{13} & q_{14} \\ q_{21} & q_{22} & q_{23} & q_{24} \\ q_{31} & q_{32} & q_{33} & q_{34} \\ q_{41} & q_{42} & q_{43} & q_{44} \\ q_{51} & q_{52} & q_{53} & q_{54} \end{vmatrix}$$

(2) Formation of the ‘1’ level of the hierarchical scheme
At the first level, the aggregation of the initial values of the criteria in the GIS was presented in the form of an $m(1)$ dimensional vector, where the *i-th* component of $Q[i(1);\ 1]$ of the vector $Q_{ij}(1)$ shows the synthesis function of vector $Q_{ij}[0]$ of the initial criteria at the 0-*th* level.

$$Q[i(1); 1] = Q_i[Q_{ij}[0]; i(1); 1] = Q_i[Q_{EC}(0); Q_{SO}(0); Q_{EK}(0); i[1]; 1] = Q_i[Q(1;0); Q(2;0); Q(3;0); Q(4;0); i[1]; 1] \quad (22)$$

At the ‘1’ level of aggregation, four conditions for the criteria (sub-criteria) were assigned in the definition of the weight-coefficients. To obtain an average value of the weight-coefficients from the finite set of all possible weight-coefficients, the non-numerical values had to be included based on predefined conditions. Considering the conditions (constraints), the weight-coefficients which fulfilled these requirements were chosen.

The conditions were determined by the following the non-numerical information: Four economic indicators:

*Condition1* EcIec > EcIinv = EcIef = EcIei
*Condition2* EcIinv > EcIec = EcIef = EcIei
*Condition3* EcIef > EcIec = EcIinv = EcIei
*Condition4* EcIei > EcIec = EcIinv = EcIef

Four social indicators:

*Condition1* SoIeh > SoIsi = SoIni = SoIwh
*Condition2* SoIsi > SoIeh = SoIni = SoIwh
*Condition3* SoIni > SoIeh = SoIsi = SoIwh
*Condition4* SoIwh > SoIeh = SoIsi = SoIni
Four ecological indicators:
*Condition1* $EkI^{(1)}_{co2} > EkI^{(2)}_{co2} = EkI^{(1)}_{nox} = EkI^{(2)}_{nox}$
*Condition2* $EkI^{(2)}_{co2} > EkI^{(1)}_{co2} = EkI^{(1)}_{nox} = EkI^{(2)}_{nox}$
*Condition3* $EkI^{(1)}_{nox} > EkI^{(1)}_{co2} = EkI^{(2)}_{co2} = EkI^{(2)}_{nox}$
*Condition4* $EkI^{(2)}_{nox} > EkI^{(1)}_{co2} = EkI^{(2)}_{co2} = EkI^{(1)}_{nox}$
Finally, ‘1’ level of aggregation was completed as

$$Qi[1] = [Q(1;1); Q(2;1); Q(3;1)]$$

(3) Formation of the ‘2’ level of the hierarchical schema
The synthesis function $Q[i(2);\ 2]$:

$$Q[i(2); 2] = Qi[Qi[1]; i(2); 2) = Qi[Q(1;0); Q(2;0); Q(3;0); i[2]; 2] \quad (23)$$

At the ‘2’ level of aggregation to obtain the weight-coefficients, fifteen constraints were defined by the following non-numerical information:

*Constraint 1* EcInd (condition1) > SoInd (condition 1) = EkInd (condition 1)
*Constraint 2* EcInd (condition 2) > SoInd (condition 3) = EkInd (condition 2)
*Constraint 3* EcInd (condition 3) > SoInd (uslov 2) = EkInd (condition 3)
*Constraint 4* SoInd (condition 2) > EcInd (condition 1) = EkInd (condition 4)
*Constraint 5* SoInd (condition 4) > EcInd (condition 2) = EkInd (condition 1)
*Constraint 6* EkInd (condition 1) > EcInd (condition 4) = SoInd (condition 3)
*Constraint 7* EkInd (condition 3) > EcInd (condition 3) = SoInd (condition 2)

*Constraint 8* EkInd (condition 2) > EcInd (condition 1) = SoInd (condition 4)
*Constraint 9* EcInd (condition 4) > EkInd (condition 1) = SoInd (condition 2)
*Constraint 10* EcInd (condition 3) > SoInd (condition 4) > EkInd (condition 4)
*Constraint 11* EcInd (condition 1) > EkInd (condition 2) > SoInd (condition 2)
*Constraint 12* SoInd (condition 2) > EkInd (condition 3) > EcInd (condition 2)
*Constraint 13* SoInd(condition 3) > EcInd (condition 4) > EkInd (condition 1)
*Constraint 14* EkInd (condition 2) > EcInd (condition 4) > SoInd (condition 3)
*Constraint 15* EkInd (condition 4) > SoInd (condition 1) > EcInd (condition 1)

‘2’ level of aggregation was completed as:

$$Q[2] = [Q(1;2); Q(2;2); Q(3;2); Q(4;2); Q(5;2)]$$

### *7.1. Sustainable development of the energy system in an urban area: The Belgrade, case study*

Scenarios of the development of the energy system in the city of Belgrade were formed from the current year through 2020. These scenarios were based on projections of the energy requirements in the city for the consuming sectors: industry, transportation, household and services as described in chapter 4. The future needs of electricity, heat and fuels are satisfied from existing and new energy sources and plants. In accordance with the calculation of the energy needs, five scenarios were formed. Energy scenarios for 2010 predict technological modernisation of the energy systems, revitalisation of existing power plants and heating plants to increase reliability, improved energy efficiency, and additional production of electricity and thermal energy. The substitution of the use of fossil fuels (wood and coal) and electricity for thermal supply are proposed by increasing the number of users of the district heating system. In addition, the development of local thermal resources (small and medium power) for biomass use is foreseen. According to the development strategy through 2015, liquid fossil fuel will remain predominant, but this tendency will decline. Likewise, increasing use of natural gas and a gradual decrease in the use of electricity are predicted. Energy scenarios for 2020 predict the construction of new energy production facilities, such as, a combined heat and power generation plant, a natural gas combined cycle power plant, and a nuclear and coal power plant. Solar thermal systems in the ‘household’ and ‘service’ sectors, and useful thermal energy in the ‘industry’ sector, for hot water production are also predicted for 2020.

For each developed scenario, the energy system of the primary resources (ESPR) was determined. This should satisfy the predicted differences in the consumption of electricity, thermal energy and motor fuels for the time intervals of 2005–2010, 2010–2015 and 2015–2020. *Scenario I* (“business-as-usual”) shows the traditional method in a scenario formation. From the aspect of energy generating technology, the ESPR in *Scenario I* for 2010, 2015 and 2020 are the same (coal). Additional electricity and thermal production from hydro-potential, gas and biomass are proposed in *Scenario II*. Additionally, in *Scenario II*, the motor fuels consumed in the sectors of transportation are predicted and the introduction of fuel cells is proposed. Fuel cells would replace the total additional amount of motor fuels needed in 2020 in the sector of public transport. Additional production of electricity and thermal energy from gas and crude oil is predicted in *Scenario III*. Additionally, in this scenario, the introduction of fuel cells is proposed (10% in 2010 and 20% in 2020). *Scenario IV* proposes the supply of electricity from coal, gas and biomass, and thermal energy from gas, biomass and solar collectors. In the transportation sectors, the consumptions of motor fuels would remain at current levels. Instead of building new thermal power plants, the importation of electricity is adopted as a solution in *Scenario V* and the supply of thermal energy is provided by gas. The amount of energy obtained by fuel cells increases to 20% of the total required in *Scenario V*.

To calibrate the developed energy model of the city of Belgrade, a database of the energy consumption in a few past decades was formed. A database of the consumption of different energy forms was determined, such as, a) electricity of all energy sectors, from 1981 to 2002, b) gasoline, diesel, kerosene and heating oil in the period from 1980 until 2002, c) natural gas in the household sector, service sector and in the industry sector, as well as liquefied natural gas in the industry sector from 1996 to 2003, d) liquefied natural gas in the household and service sectors from 2000 to 2003 and e) coal in the household, service and industry sectors from 1980 to 2002 [25–30]. In the period from 1990 until 2000 the economy and energy consumption of the country were under very irregular conditions. All data connected with this period are presented only to give a general view and time line of previous decade. Calibration of the simulation model was performed based on the basis year, which was 2002, and several surrounding years.

The required data were obtained from the following sources: the City Bureau of Informatics and Statistics, the Statistical Office of the Republic of Serbia, the City Department of Energy, the Public Utility Company for the District Heating System and the Ministry of Mining and Energy. As an example, the results suggest that by the year 2020 the number of inhabitants in the administrative area of Belgrade will reach 2,230,000 living in 919,000 households, Fig. 4. An average annual population growth rate of 1.5% is projected. On the basis of the foreseen projection plan, the obtained results suggest consumptions of electricity, motor fuels and heat in the main energy consumption sectors, as shown in Fig. 5a–c.

### *7.2. Discussion*

Until now, the multi-criteria methods, as well as ASPID method, have been applied for the assessment of system with a single carrier of energy [31–35]. In this paper, the method of multi-criteria analysis for assessing the sustainability of complex energy system with more carriers of energy in urban areas is performed. Also, multi-criteria analysis procedure has been extended to several levels of evaluation, which was not the case when this method is applied before.

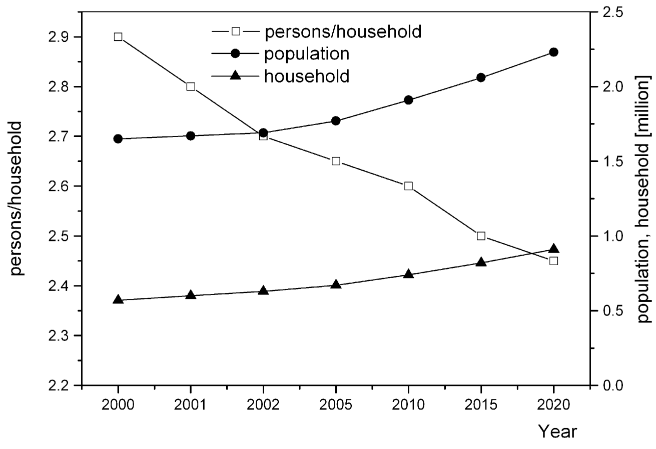


**Fig. 4.** Demographic data.

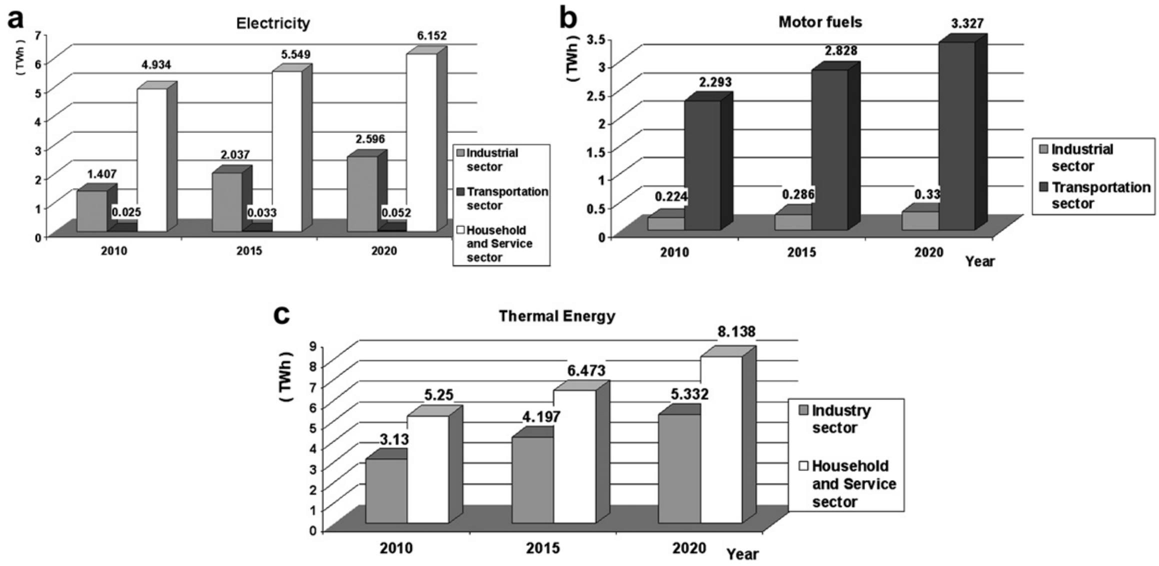


**Fig. 5.** Predicted consumptions of (a) electricity (b) motor fuels (c) thermal energy.

Application of multi-criteria evaluation enables selection of the best scenario in terms of sustainability according to defined constrains and in that way gives help experts in decision-making. Three distinctive cases (A–C) are presented, and constraints that give priority to one of the energy indicators are defined for each case. Different rating of scenarios in priority lists is obtained when different priority to certain indicator is assigned.

For **Case A** the constraint was defined so as to give priority to the economic indicator (weight-coefficient = 0.68). All other indicators were given a weight-coefficient of 0.16. For this case, in assessing the weight-coefficients, the standard deviation was 0.196. In the process of the agglomerations of sub-indicators according to the defined conditions, the following had priority: the economic sub-indicator of energy cost (EcIec), the social sub-indicator of energy use per household (SoIeh) and the ecology sub-indicator of $CO_2$ emission per energy production ($EkI^{(1)}_{CO2}$). Standard deviation for GIS of scenario *I–V* was calculated (standard deviation = 0.167, 0.098, 0.093 0.048, 0.192, respectively). The priority list for the defined constraint is shown in Fig. 6. If the economy indicator had priority, then scenario *II* is optimal and *Scenarios III* and *V* perform the worst.

Case A: Constrain 1

EcInd (condition 1) > SoInd (condition 1) = EkInd (condition 1)

$EcInd(EcIec > EcIinv = EcIef = EkIei) > SoInd(SoIeh > SoIsi = SoIni = SoIwh) = = EkInd(EkI^{(1)}_{CO2} > EkI^{(2)}_{CO2} = EkI^{(1)}_{NOx} = EkI^{(2)}_{NOx})$

(a) Sustainability Index
(b) Weight-coefficient

Case B: Constrain 13

SoInd (condition 3) > EcInd (condition 4) > EkInd (condition 1)

$SoInd(SoIni > SoIeh = SoIsi = SoIwh) > EcInd(EcIei > EcIec = EcIinv = EkIef) > EkInd(EkI^{(1)}_{CO2} > EkI^{(2)}_{CO2} = EkI^{(1)}_{NOx} = EkI^{(2)}_{NOx})$

(a) Sustainability Index
(b) Weight-coefficient

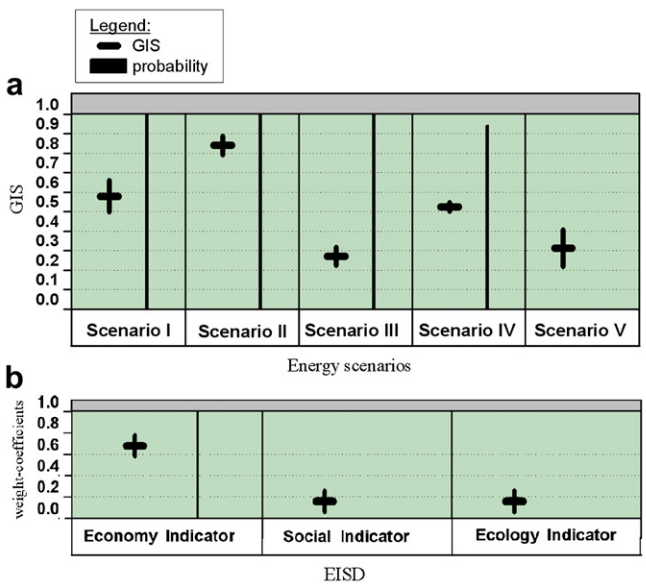


**Fig. 6.** Sustainability Index of *Scenarios I–V* of 2015 when priority was given to the economy indicator: (a) Sustainability Index (b) Weight-coefficient.

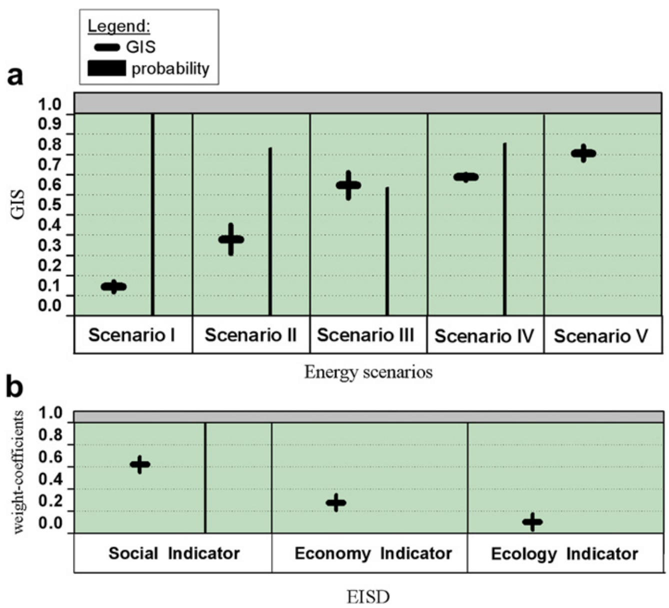


**Fig. 7.** Sustainability Index of *Scenarios I–V* of 2015 when priority was given to the social indicator: (a) Sustainability Index (b) Weight-coefficient.

In **Case B**, constraints were defined to give priority to the social indicator (weight-coefficient = 0.621). The economic and ecologic indicators were given weight-coefficients of 0.278 and 0.101, respectively, Fig. 7. For **Case B**, in assessing the weight-coefficients, the standard deviation was 0.141. In the process of agglomerations of the sub-indicators according to the defined conditions, the following had priority: the social sub-indicator of the number of injured per energy production (SoIni), the economy sub-indicator of industrial, household and commercial energy intensities (EcIei) and the ecology sub-indicator of $CO_2$ emission per energy production ($EkI^{(1)}_{CO2}$). Standard deviation for GIS of scenario *I–V* was calculated (standard deviation = 0.054, 0.142, 0.128 0.033, 0.073, respectively). The list of priorities for this case is presented in Fig. 7. If priority was given to the social indicator then scenario *V* is the most sustainable and Scenario *I* is the list sustainable, *Scenario V* was the worst performer in Case A and in the best performer here.

Case C: Constrain 6

EkInd (condition 1) > EcInd (condition 4) = SoInd (condition 3)
EkInd($EkI^{(1)}_{CO2} > EkI^{(2)}_{CO2} = EkI^{(1)}_{NOx} = EkI^{(2)}_{NO}$)>EcInd(EcIei > EcIec = EcIinv = EkIef) = SoInd (SoIni > SoIeh = SoIsi = SoIwh)

(a) Sustainability Index
(b) Weight-coefficient

In Case C, the constraint gave priority to the ecology indicator (weight-coefficient = 0.66). Economic and social indicators were given weight-coefficients of 0.16, Fig. 8. For this case, in assessing the weight-coefficients, the standard deviation was 0.098. In the process of agglomerations of sub-indicators according to the defined conditions, the following had priority: the ecological sub-indicator of $CO_2$ the emission per energy production ($EkI^{(1)}_{CO2}$), the economic sub-indicator of industrial, household and commercial energy intensities (EcIei) and the social sub-indicator of number of injured per energy production (SoIni). Calculated values of standard deviation for scenario *I–V* were: 0.121, 0.233, 0.114, 0.097, 0.164, respectively. The GIS rating list of priorities for the defined constraint is presented in Fig. 8. In first places on, the GIS rating list are *Scenarios II* and *V*, while scenario *I* was in last place.

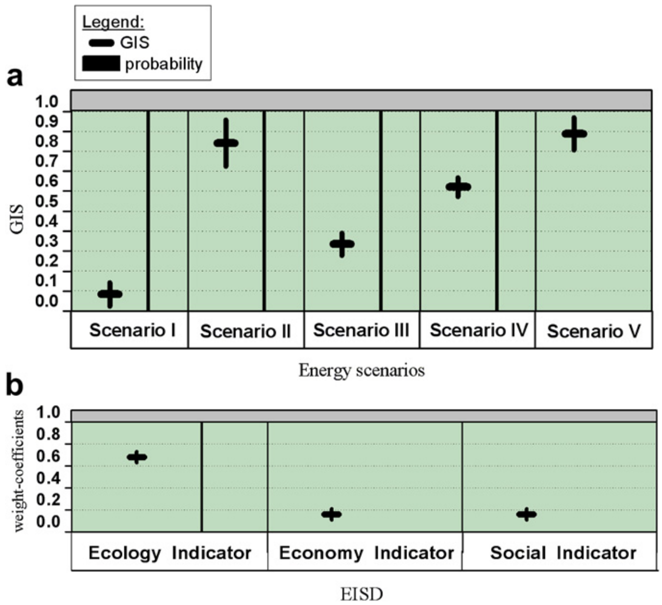


**Fig. 8.** Sustainability Index of *Scenarios I–V* of 2015 when priority was given to the ecology indicator: (a) Sustainability Index (b) Weight-coefficient.

## 8. Conclusions

Long term trends in the development of sustainable energy systems were investigated using a model for the prediction and analysis of energy demands that was based on the mathematical method for multi-criteria decisions. Possible developments of the city energy system are described by various scenarios, where the sustainability of the scenarios are described by a set of economic, social and environment indicators. Using the multi-criteria decision method, the synthesised index of the sustainability of each energy system scenario was derived and calculated. The synthesised index accounts for all estimated aspects, thereby giving an indication of the overall sustainability. Different weights were assigned to the indicators. The criteria for the estimation weights were based on expert opinion and on the measurement scale by which the relative weighting was expressed, numerically or verbally. Application of the presented method provides an objective evaluation because randomisation of the uncertainty in the weight-coefficient vector was performed.

Unlike other methods, this method has the following advantages, a) allows obtaining accurate results when several criteria were used simultaneously in estimations, b) small possibility of subjective decision-making, c) normalisation of indicators do not lose some information that may be very important on some level evaluation (which is not the case with other methods), d) its ability to work with the non-numerical, inexact and incomplete information, e) examined the mutual relationships of all weight-coefficients of criteria in relation to different aspects of the sustainable development so that the advantage given to one of the criteria over the weights by the decision-maker, f) weights are calculated mathematically, g) from the perspective of practical implementation this method of multi-criteria analysis provides better understanding and viewing the results.

In this paper, a valid evaluation tool for measurement of the sustainability of urban energy systems in different contexts, and based on various simultaneous indicators were demonstrated. For this analysis, several sets of indicators and sub-indicators, in the appropriate context, were adopted and calculated using the available data needed. The proposed new method was applied to the energy system of Belgrade. The study was used to compare different energy scenarios for Belgrade through 2020.

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