An Analytical Method for the Measurement of Energy Systems Sustainability in Urban Areas

Marina Jovanović
Research Scientist
Institute of Nuclear Sciences "Vinča"

The assessment of sustainability of the city energy systems is an important topic in the current research and forecasting of development of various countries. In this paper the new approach for the measurement of the sustainability of the city energy system is introduced. It is based on the prediction of the future energy needs within the city consuming sectors, on the specification of scenarios of the city energy system development and on the validation of scenarios with a multicriteria decision method. The defined scenarios take into account utilization of different energy sources, exploitation of existing energy plants and infrastructure and building of new plants. The sustainability criteria are described with the new unique set of economical, social and ecological indicators. The new approach is applied to the forecasting of the sustainable development of the energy system of the city of Belgrade.

Keywords: *sustainable development, energy indicators, multicriteria decision method.*

1. INTRODUCTION

Energy is essential to economic and social development and improves quality of life. It is very important for the developing society. Presently, the largest part of the world's energy production and consumption is performed in a way that can not be sustainable if existing technologies remain the same and total quantities of polluters significantly increase. The world's consumption of primary energy is increased from 1973 with the average rate of 2.0 % per year [1].

The analysis of the energy system on the local level could significantly support different forms of the sustainable development. Estimation, research and categorization of sustainability in different regions using standardized indicators is the most important task with in the framework of these investigations. Indicators and subindicators numerically express the environmental, social and economical conditions and features of an area or region. They are a useful tool that supports planning of the sustainable development of regional or national energy strategies [2,3].

In order to measure a sustainable development of the city energy system, it is needed to define and calculate specific energy indicators [4]. In order to aggregate multidimensional indicators to a general index, which represents the quality or sustainability of energy system options, the methodology of multicriteria analysis is used. This methodology provides mathematical and graphical synthesis of all indicators relevant to the sustainable development, and it is a tool for the measurement of urban energy system sustainability [5,6].

Received: November 2008, Accepted: December 2008
Correspondence to: Marina Jovanovic, M.Sc.
Institute of Nuclear Sciences "Vinča",
Laboratory for Thermal Engineering and Energy,
P.O. Box 522, Serbia
E-mail: marinaj@vinca.rs

In this paper a method for the measurement of the city energy system sustainability is proposed. It is based on the forecasting of the future energy needs, defining of the various scenarios of the city energy system developments and the validation of the scenarios sustainability with the multicriteria decision method. This new approach is applied to the energy system of the city of Belgrade.

2. SUSTAINABILITY AND INDICATORS OF SUSTAINABLE DEVELOPMENT

Nowadays, countries around the world formulate energy and economic policies on the local level that should lead to a minimum impact on the environment and should provide 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 the cities.

The World Commission on Environment and development (Bruntland Commission, 1987) has established the new modalities of measuring progress in defining and achieving the energy system sustainability [7]. The same is mentioned by the 1992 Earth Summit in Rio de Janeiro, Brazil [8].

Better understanding of different dimensions or aspects of sustainable development and complex mutual relation of these aspects is achieved by using the Indicators of Sustainable Development (ISD) [9]. Energy indicators are defined from the combination of basic economy data, social activities, technological characteristics, measurements or estimations of energy production or consumption. Energy indicators represent basic connecting tool between energy targets and sustainable development in forming sustainable development policy, and are 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 one side, it has a large number of suppliers of different types of energy and a large number of consumers, on the other. The analysis of energy systems in metropolitan cities is also concentrated on the social and economic aspect of the system. Also, it is necessary to develop a methodology for this analysis and estimation of energy consumption in order to satisfy the needs of consumers, to secure environmental protection, reliability and sufficiency of energy resources, as well as the necessary budget and economic efficiency [11-13].

Each city has its own vision of sustainability and the city environmental, economical and social sustainability is humanity's most urgent challenge for the 21st century. The key issues of sustainable development of urban areas are presented in agenda of “'Habitat II'” the UN Summit of Cities [14].

The planning of sustainable development of a city is a very complex process. It begins with a determination of indicators and calculations that aggregate indicators at all levels before final level is reached to show the general sustainability index of the complex system.

The key issues which will define the shape and future using of energy in cities are sustainability of energy, efficiency of energy process as well as accessibility and availability of different energy forms, Fig. 1.

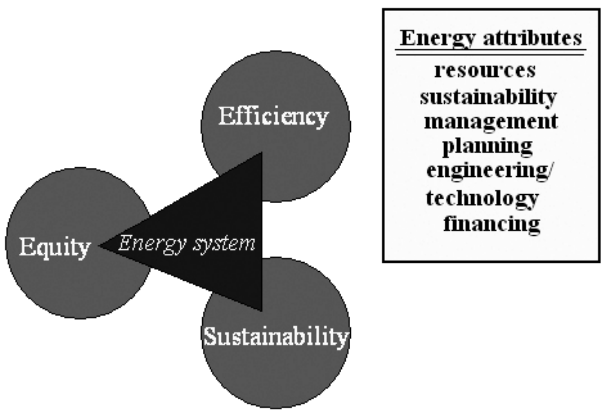

Figure 1. The key issues which will define the future using of energy

4. ASSESSMENT OF CITY ENERGY NEEDS WITH THE SIMULATION MODEL MAED

The simulation model MAED [15] is used for the estimation of the city energy needs in accordance with the potential development of economical, social and technological factors. The projection plan of the future total energy needs is determined based on the current development and assumptions about future evolution of the economic activities, technological development and life style of the city population.

Simulation model MAED systematically relates the specific energy demand with the sets of social, economical and technological factors which influence the energy consumption. Six economy sectors are considered: manufacturing, agriculture, construction, mining, services (considering subsectors: trade services, restaurants and hotels; transport services, storage and communication; finance insurance, real estate and business services; community and personal services) and energy sector. Manufacturing sector has four subsectors: basic materials, machinery and equipment, nondurable and miscellaneous.

Sets of input parameters for the forecasting of future energy needs consist of initial parameters and constants that refer to the basic years and time depending parameters which determine input data for considered future years that are included in the projection plan. First, it is need to describe the city energy system for a chosen basic year and a set of previous years that should be close to the basic year. It is necessary to have information about different characteristics and statistical data on the energy consumption, the supply of energy carriers, the energy sectors and the end-use categories. A basic year should belong to the past period when there were no sudden increases in energy consumption, no natural or national catastrophes, as well as that it should be close to the beginning of the period for which the analysis is carried out. The following step is to describe analytically the future economical, social and technological development of the city. The economical and social development is described with the following parameters: the demography data (population, population growth rate, active labor force), GDP (Gross Domestic Product), GDP per capita, annual GDP growth rate, numbers of public transport users in urban and suburban traffic, average total distance traveled by person using public transport, average dwelling size, heated area of dwelling, etc. The technology factors used in the calculation of energy needs are the efficiency of energy carriers, the market penetration of energy carriers, the fuels demanded for transport of passengers and goods by vehicles, the insulation in buildings, the different factors of existing and new buildings, etc.

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

5. TOTAL ENERGY NEEDS FOR THREE MAIN ENERGY CONSUMERS IN THE CITY AND THE INPUT VALUES FOR CALCULATION

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

Demographic input data are prepared for the basic year, the historical years (that should be close to the basic year) and the projected years in the projection plan. These data are grouped into population growth rate, capita per household, share of potential labour force, share of participating labour force, share of population outside settlement of Belgrade, share of rural population.

Gross domestic product (GDP) is projected for the years in the future period based on the economic developing plans in Serbia and on the experience of other developing countries, while GDP data for the basic year and the historical years are specified according to the statistical evidence in Serbia. Changes of parameters dealing with GDP or GDP growth rate (the structure of GDP formation and the structure of value added formation) in the manufacturing and services 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 manufacturing and services and their subsectors.

The energy demand of agriculture, construction, mining and manufacturing within the industry sector is 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 energy intensities of the four manufacturing subsectors are calculated based on the statistical evidence and future projection. Also, the share of various energy forms on the energy market is taken into account, as well as the average efficiencies of the energy consumption technologies.

The energy demand of transport sector is calculated as a function of performed duty, such as ton-kilometers, passenger-kilometers, the breakdown of this demand by transportation devices (cars, trucks, train, plane, etc.), and their specific energy needs and load factors of each mode. The total energy demand for transportation is calculated separately for freight and passengers according to macroeconomic and life style factors. The energy consumption is calculated on the bases of energy intensities of transportation modes expressed in kWh/100km; and energy consumption by mode of transportation as well as by fuel type (diesel, electricity).

For the calculation of energy demand in the passenger transportation the following of input data are needed [6,9,16]: the average intercity distance traveled per person and per year; the average intracity (in urban areas) distance traveled per person and per day; average load factor of cars, buses, trains in intercity and intracity travel (persons per car, bus, train); average load factor of electric mass transit system of intracity (persons in trolleys, trams); model split of public intercity passenger transport (share of buses, electric and diesel trains); model split of intracity passenger transport (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 average intensity of passenger transport (in natural units).

Respectively, obtained results represent: 1) passenger kilometers (passenger transport per one kilometer distance) by mode of transportation (cars, buses, train) in intercity transport; 2) passenger kilometers by cars or public transport; 3) energy intensity of passengers transportation: gasoline consumption of cars in intracity and intercity travel, electricity consumption in intracity travel, diesel consumption of intracity buses, diesel consumption and electricity consumption of trains and electricity consumption of intracity electric mass transport (trams and trolleys); 4) energy consumption of passenger intercity and intracity transportation by mode; 5) energy consumption of passenger intercity and intracity 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 demand of the household sector is calculated on the basis of the demographic data (population, number of dwellings, etc.), whereas in the service sector it is related to the level of economic activity.

For both, households and service sector, further breaking is made for the type of construction, separating them into "'old" (traditional construction) and "new" (identifying modern type of construction complying with new insulation standards) which are built after defined basic year in the model.

The categories of energy use considered in the household are: space heating, air conditioning, water heating, cooking and electricity for secondary appliances (refrigerators, lighting, washing machines, etc.). For the final energy calculation in household sector the following data are needed: number of dwellings for basic year, historical and projected years; share of dwellings in areas requiring space heat; degree days for considered area; and demolition rate. The three types of input data are required: 1) those which calculate final energy demands in the household sector for space heating, hot water cooking, air conditioning and the specific use of electricity for appliances; 2) data on penetration of different energy carriers (electricity, heat pumps, solar, district heat, noncommercial fuels, fossil fuels) into their respective heat markets associated with the space heating, water heating and cooking components of the final heat, 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.).

Also, 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. The input data have been provided separately for old and new construction. These factors represent shares of each dwelling type in general structure. The factors of old and new buildings which are taken in calculation, as input data are: average dwelling size, share of area heated, specific heat loss rate, share of dwellings with air conditioning, specific cooling requirements of dwellings, share 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 dwelling/year and electricity penetration in households for appliances.

Likewise, some of input data are in regard to non-commercial fuels penetration (wood, etc), district heating system, solar energy and fossil fuels for space heating, domestic hot water production, 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: the thermal uses (space/water heating), air-conditioning and specific uses of electricity (motive power for small motors, computers, lighting, etc.).

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

6. MEASURING OF ENERGY SCENARIOS SUSTAINABILITY

The energy system sustainability is measured by analyzing the possible energy scenarios, which provide the frame in researching the future of energy perspectives, including various combinations of technological options [17].

The quality of selected scenarios is defined by energy indicators of sustainable development (EISD), which are represented by three sets of economical, social and ecological subindicators. The methodology of multicriteria analysis is applied in order to estimate the sustainability of proposed energy scenarios. Obtained results are compared by General Index of Sustainability which is the measure of system complexity [16,18,19]. For this purpose, the mathematical model and corresponding computer code are developed based on the fuzzy sets theory for the new multicriteria decision making technique ASPID [20,21].

6.1 Estimation of energy system sustainability by multicriteria 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 issue of this methodology is 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 obtaining General Index of Sustainability using *nnn*-information from various sources having different reliability and probability [20,21].

6.2 The synthesis technique of fuzzy sets

The fuzzy sets theory is applicable to the multicriteria assessment of various energy systems. If an alternative (scenario) of an energy system is observed as an object, then all alternatives that are taken in consideration make the finite set:

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

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

First, it is presumed that complex objects are identified with vectors:

$$x(\mathrm{j}) = (x_1(\mathrm{j}),\ldots,x_\mathrm{m}(\mathrm{j}))$$
$$x_\mathrm{i}(\mathrm{j}) \in E^1,\ x(\mathrm{j}) \in E^\mathrm{k},\ \mathrm{i} = 1,\ldots,\mathrm{m},\ \mathrm{j} = 1,\ldots,\mathrm{k}, \tag{2}$$

where k is the number of objects under investigation, component $x_\mathrm{i}(\mathrm{j})$ of vector $x(\mathrm{j})$ refer to a value of indicator x_i of an object $x(\mathrm{j})$, 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 base 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.

A validation of quality of the objects $x(\mathrm{j})$, j = 1,...,k, is estimated by a number of specific criteria $q_1,\ldots, q_\mathrm{m}$ where each of them being a function of corresponding indicator:

$$q_\mathrm{i} = q_\mathrm{i}(x_\mathrm{i}),\ \mathrm{i} = 1,\ldots,\mathrm{m}, \tag{3}$$

where m is the number of indicators.

The function $q_\mathrm{i} = q_\mathrm{i}(x_\mathrm{i})$ 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 $q_\mathrm{i}(\mathrm{j}) = q_\mathrm{i}(x_\mathrm{i}(\mathrm{j}))$ of function $q_\mathrm{i}(x_\mathrm{i})$ from the point of 'i'-th criterion's view.

In the next step, it is assumed that all the specific criteria are normalized without the loss in generality.

Normalization of the specific criteria is done on the basis of the values of indicators. The sustainable indicators are not suitable for use because they have different dimensions and interval of range ($/kWh, kg/kWh, kWh/$,...), so they could not be compared.

For each object $x(\mathrm{j}) \in X$, the quality estimation is performed by many of the criteria $q_\mathrm{i}(\mathrm{j}) = (q_1(\mathrm{j}),\ldots,q_\mathrm{m}(\mathrm{j}))$, $0 \le q_\mathrm{i}(\mathrm{j}) \le 1$, that could be treated as the vector-criterion $q = (q_1,\ldots,q_\mathrm{m})$. This level means defining of monotonous of each normalized function type $q_\mathrm{i}(x_\mathrm{i})$ (decreasing or increasing function).

The specific criteria are described by power law function and they are defined as follows. The value of indicator could change in interval from *MIN* to *MAX*. If the value of q_i increases when the value of indicator x_i increases, then the function $q_\mathrm{i}(x_\mathrm{i})$ is defined by (4a). However, the function $q_\mathrm{i}(x_\mathrm{i})$ is defined by (4b) if the value of q_i decreases when the value of argument x_i increases.

$$q_i(x_i;\Theta)=\begin{Bmatrix} 0 & x_i \le MIN_i \\ \left(\dfrac{x_i-MIN_i}{MAX_i-MIN_i}\right)^{\Theta} & MIN_i < x_i < MAX_i \\ 1 & x_i > MAX_i \end{Bmatrix}, \quad (4a)$$

$$q_i(x_i;\Theta)=\begin{Bmatrix} 1 & x_i \le MIN_i \\ \left(\dfrac{MAX_i-x_i}{MAX_i-MIN_i}\right)^{\Theta} & MIN_i < x_i < MAX_i \\ 0 & x_i > MAX_i \end{Bmatrix}. \quad (4b)$$

The convexity of curve $q_i = q_i(x_i)$ is defined by exponent Θ and it is chosen by the researcher experience. The derivations of function $q_i(x_i)$ defined with (4b) are as follows:

$$q'_i=\Theta\left(\frac{x_i-MIN_i}{MAX_i-MIN_i}\right)^{\Theta-1}\frac{1}{MAX_i-MIN_i} \quad (5)$$

$$q''_i=\Theta(\Theta-1)\left(\frac{x_i-MIN_i}{MAX_i-MIN_i}\right)^{\Theta-2}\frac{1}{\left(MAX_i-MIN_i\right)^2} \quad (6)$$

For $\Theta > 1$ the function $q_i(x_i)$ is downward convex, as it can be concluded from (6) and $q_i'' > 0$, Fig. 2a. For $0 < \Theta < 1$, the function is upward convex, since from (6) holds that $q_i'' < 0$, Fig. 2b. For the special case, when $\Theta = 1$, the function $q_i(x_i)$ is linear equation between MIN_i and MAX_i, Fig. 2c. In the other case, for the decreasing function described by (4b), similar results are obtained as presented in Figure 3.

In the praxis the most popular normalized function is a linear function, so in this paper the following normalized function $q_i(x_i;\Theta)$, $\Theta = 1$ is adopted. In this way, normalized values of indicators are obtained by the linear normalization. The set of numerical values of indicators for all considered energy scenarios would be converted in fuzzy set of normalized indicators, as presented with the following matrix

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

where the element $q_i(j)$ is the measure of 'i'-th indicator for the 'j'-th scenario. As stated, due to the performed normalization process, each criterion has to fulfill the inequality $0 \le q_i(j) \le 1$.

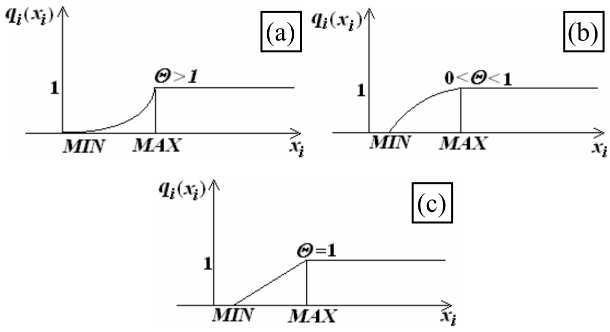

Figure 2. The cases for increasing function

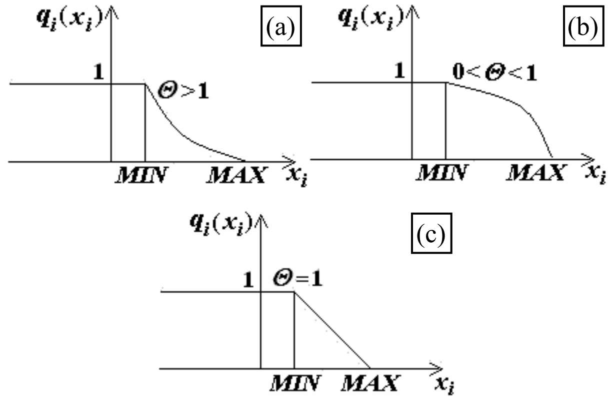

Figure 3. The cases for decreasing function

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

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

$$\forall x^{(j)}, x^{(l)} \in X(x^{(j)} > x^{(l)}) \Leftrightarrow ((\forall i\ q_i^{(j)} \ge q_i^{(l)})\ \&$$

$$\&\ (\exists s{:}\ q_s^{(j)} > q_s^{(l)}). \quad (8)$$

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

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

This set of incomparable pair of objects makes part of set X of all possible pair objects. Hence, the comparison of complex objects on multicriteria bases can meet the problem of incomparable pair of objects. Assume that two objects are independently taken by chance from an infinite set of all possible objects determined by corresponding criteria-vector $q_i = (q_1,...,q_m)$, $0 \le q_i \le 1$, the probability of these two objects 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, $q_1,...,q_m$ into one General criterion or General Index-Q determined by a scalar-valued synthesizing function.

The weight-coefficient w_i (i = 1,...,m) shows which importance is given to the particular criterion q_i when the General Index $Q(q;w)$ is formed. The weight-coefficients $0 \leq w_i \leq 1$, for each i = 1,...,m, is called the relative "weight" of specific criteria q_i. Specific criterion q_i have more influence on the value of General Index $Q(q)$ at increasing of value w_i. Varying of coefficient w_i, ($\sum_{i=1}^{m} w_i = 1$; $w_i \geq 0$), the influence of $q_i = q_i(x_i)$ on the General Index $Q(q;w)$ is changed, respectively the importance which 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 $w = (w_1,...,w_m)$ is delicate because researchers do not have enough information for the exact determination of the weight coefficients w_i in practice. From experience and from theoretical arguments it is known that in these circumstances the most suitable is to have so called nonnumerical information. Process of randomization is used when instead of one vector w, the vector set $W(I)$ is introduced. This set is defined with group of all available information (mark as I). For example, if interval information is known, then set I of all relations in the form $a_i \leq w_i \leq b_i$ is made. If ordinal information is available, then set I is made of all relations in the form of $w_i = w_j$, $w_i > w_s$.

However, some of weight coefficients do not belong to equalities and inequalities systems. In this case the information $I = OI \cup II$ is incomplete.

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

$$W(I;\mathrm{m,n}) = \{w(\mathrm{s}),\ \mathrm{s} = 1,...,N(I;\mathrm{m,n}) \leq N(\mathrm{m,n}) \subseteq \subseteq W(\mathrm{m,n})\} \quad (11)$$

of all admissible weight vectors, i.e. weight vectors witch meet the requirements implied by the information I.

The weight coefficients are chosen from the finite set W(m,n) [22]:

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

Number N presents number of all possible weight coefficients from set W(m,n) and it can be calculated by the formula:

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

where is: n – number of the pieces of divided segment from 0 to 1, and m – number of the initial specific criteria.

The following synthesis function is chosen:

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

where is: φ – monotonically random increasing function, and $w = (w_1,...,w_m)$, $w_i \geq 0$, $w_1 + w_2 + ... + w_m = 1$ is a vector of weight coefficient.

If the function φ is defined as exponential function:

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

then exponential weighted mean function is obtained which is the base of very popular synthesizing 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 in the additive aggregative function or weighted arithmetical mean function

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

Additive synthesizing function is the most popular type of synthesizing functions There are some reasons for such popularity of this type of synthesizing function ($Q_+(q;w)$). First of all, it is the simplest and easiest interpretable synthesizing function. Thereafter, this function presents a quite natural form of particular criteria aggregation for majority of real decision makers. The third argument is its ability to represent an arbitrary linear extension $\succ$ (when priority is given to certain criterion among the order relation $>$).

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

$$Q = Q(q) = Q(q,w) = q_1w_1 + q_2w_2 + ... + q_mw_m. \quad (16)$$

This selected function $Q(q)$ is linear per variables $q_1,...,q_m$, e.t. at $w_1,w_2,...,w_m$. According to (15) General Index $Q(q,w)$ has the following characteristics:

1. Monotony: if estimation of two objects or alternatives is done, and if $q^{(1)} = (q_1^{(1)},...,q_m^{(1)})$ and $q^{(2)} = (q_2^{(2)},...,q_m^{(2)})$ 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,...,m, when is:

$$Q(q^{(1)};w) \geq Q(q^{(2)};w).$$

2. If $q_i = 0$ for each i = 1,...,m when is $Q(q,w) = 0$, and if $q_i = 1$ for each i = 1,...,m when is $Q(q,w) = 1$.

These characteristics are directly the result of linear function $Q(q,w)$ and facts that is $w_1 + w_2 + ... + w_m = 1$, $w_i \geq 0$.

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

$$Q(q^{(j)}) > Q(q^{(l)});\quad Q(q^{(j)}) < Q(q^{(l)});\quad Q(q^{(j)}) = Q(q^{(l)}).$$

The following set is derived:

$$Q^+(I;\mathrm{m,n}) = \{Q_+^{(s)}(q) = Q_+(q;w^{(s)}),\ \mathrm{s} = 1,...,N(I;\mathrm{m,n})\} \quad (17)$$

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

For this reason the average members of function is introduced:

$$\bar{Q}_+(q;I) = \frac{1}{N(I;\text{m,n})}\sum_{s=1}^{N(I;\text{m,n})} Q_+^s(q) = = \frac{1}{N(I;\text{m,n})}\sum_{s=1}^{N(I;\text{m,n})} Q_+(q;w^{(s)}) \quad (18)$$

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

The function $\bar{Q}_+(q;I)$ implicitly contains nonnumeric, inexact and incomplete information and specifies corresponding an average value of fuzzy set $\overline{\text{PREF}}(I) \subseteq X$. So, the following values: $\bar{Q}_+(q^{(j)};I),...,\bar{Q}_+(q^{(k)};I)$ may be treated as the desired average values of the objects x(j),…,x(k) at preferability (quality) estimation, and which are defined because of missed numerical information of weight coefficients $w_1,...,w_m$.

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

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

Standard deviation measures "uncertainty" in the process of weight coefficients estimation. The object shows high "uncertainty" in the forecasting when the standard deviation has the huge value.

In the process of linearization of the numerical values of indicators dispersion is notified. It depends on number n, respectively dispersion is less for higher values of number n. When pair of the successive objects is considered, probability of domination of single object is included as additional factor in estimation.

"Probability" or "measure of reliability (reliability of preference)" is calculated:

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

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

For the considered pair of objects the huge value of "probability" means that this combination is a real case compared to total number of combination, $P > 0.5$. In other cases, a small value of "probability" means that the case of these pair of objects is not probable.

7. SUSTAINABLE DEVELOPMENT OF ENERGY SYSTEM IN URBAN AREA: THE CASE STUDY OF THE BELGRADE CITY

Scenarios of the development of the energy system in the city of Belgrade are formed for the time period till the year 2020. These scenarios are based on the projections of the energy needs in the city within industry, transportation, household and services consuming sectors, as described in section 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 energy needs, five scenarios are formed. For each scenario, the energy system of primary resources (ESPR) is determined, which should satisfy the predicted differences in 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 traditional method in scenario forming. From the aspect of energy generating technology, the ESPR in *scenario I* for 2010, 2015 and 2020 are the same (from coal). The additional electricity and thermal production from the hydro potential, gas and biomass is proposed in *scenario II*. Also, in *scenario II* the motor fuels consumed in the sectors of transportation are predicted. Besides the motor fuels, the introduction of fuel cells is proposed, which would replace the total additional motor fuels amount needed in 2020 in the sector of public transport. The additional production of electricity and thermal energy from gas and crude oil is predicted in *scenario III*. Also, 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 transportation sectors the motor fuels consumptions would remain. Instead of building new thermal power plants, import of electricity is adopted as a solution in *scenario V* and supply of thermal energy is provided by the gas. Share of energy obtained by fuel cells increases to 20 % in *scenario V.*

In order to calibrate the developed energy model of the city of Belgrade, the database about the energy consumption in a few past decades is formed. The database of consumption of different energy forms is 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 till 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) liquified natural gas in the household and service sectors, from 2000 to 2003, and e) coal in household, service and industry sectors, from 1980 to 2002, [23-28]. In the period from 1990 to 2000 the country economy and energy consumption were under very irregular conditions. All data connected with this period are presented only to give general view and time connection with the previous decade, while calibration of the simulation model for the energy system of the city of Belgrade is done for the basic year 2002 and years close to the basic year.

In this research, all needed data are 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, the Ministry of Mining and Energy. As an example, obtained results express that in the year 2020 the number of inhabitants in the administrative area of Belgrade will reach 2,230,000 living within 919,000 households, Fig. 4. The average annual population growth rate of 1.5 % is projected. On the basis of the foreseen projection plan, obtained results present consumptions of electricity, motor fuels and heat in the main energy consumption sectors, Fig. 5.

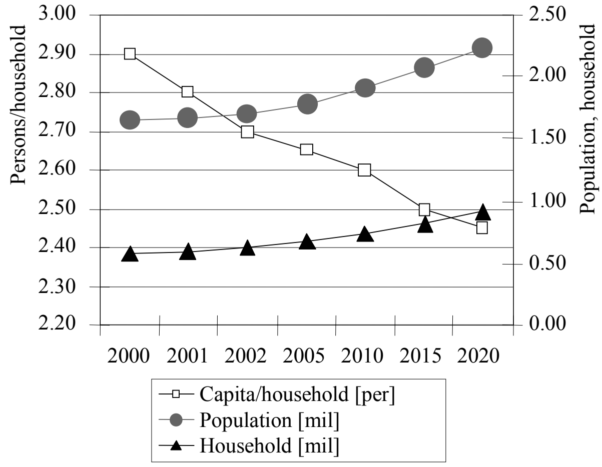

Figure 4. Demographic data (population and households)

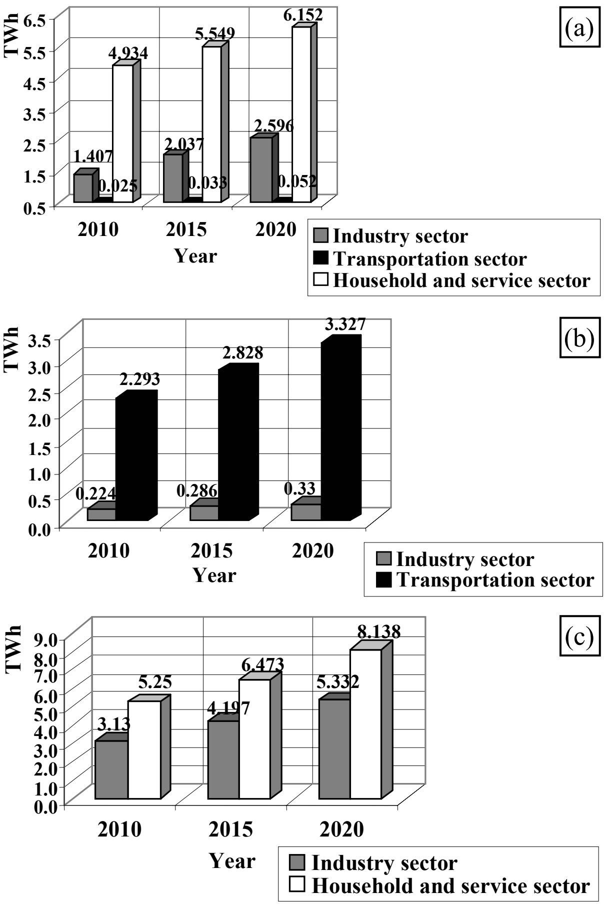

Figure 5. Predicted consumptions of: (a) electricity, (b) motor fuels and (c) thermal energy

In the case study of the Belgrade city, three groups of standardized indicators in accordance to aspects of sustainable development (economical, social, environmental) are taken. Each group of indicators consist of subindicators set which describe specific characteristics in compliance with defined energy option. These indicators and subindicators are defined and calculated for the time series of observed past and future years. Different priorities are given to certain indicator, according to the procedure presented in section 6, which results in a different rating of scenarios in sustainability assessment.

For **Case A** the constraint is defined so as to give priority to the economy indicator (value of weight coefficient is 0.68), while the other indicators have the same value of weight coefficient (0.16). In the process of subindicators agglomerations, according to the defined conditions, the following has priority: the economy subindicator of energy cost (EcIec), the social subindicator of energy use per household (SoIeh) and the ecology subindicator of CO_2 emission per energy production ($EkI_{CO2}^{(1)}$). Figure 6 shows priority list for defined constraint. If the economy indicator has a priority, than *scenario II* is in the first place on the list and groups of *scenarios* (*III* and *V*) are the last on the list.

Case A_1: Constraint 1.
EcInd(condition1) > SoInd(condition1) = EkInd(condition1)
EcInd(EcIec > EcIinv = EcIef = EkIei) >
> SoInd (SoIeh > SoIsi = SoIni = SoIwh) =
= $EkInd(EkI_{CO2}^{(1)} > EkI_{CO2}^{(2)} = EkI_{NOx}^{(1)} = EkI_{NOx}^{(2)})$

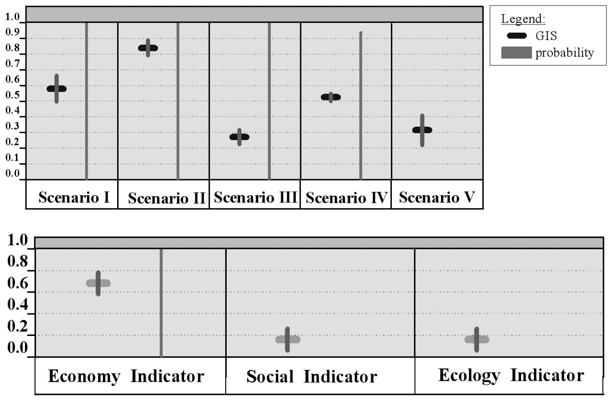

Figure 6. Sustainability Index of *scenarios I* to *V* of 2015 when priority is given to economy indicator: (a) sustainability Index and (b) weight coefficient

Case B: Constraint 13.
SoInd(condition3) > EcInd(condition4) > EkInd(condition1)
SoInd(SoIni > SoIeh = SoIsi = SoIwh) >
> EcInd(EcIei > EcIec = EcIinv = EkIef) >
> $EkInd(EkI_{CO2}^{(1)} > EkI_{CO2}^{(2)} = EkI_{NOx}^{(1)} = EkI_{NOx}^{(2)})$

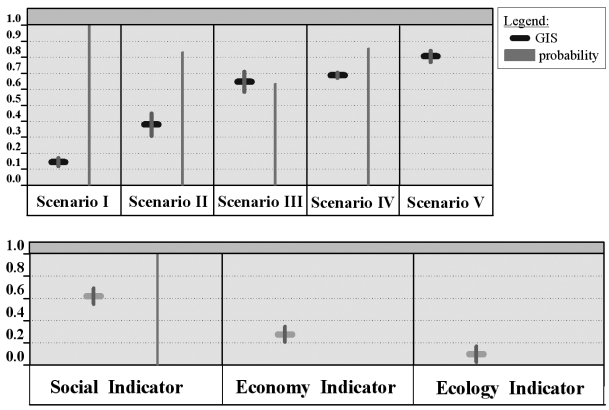

Figure 7. Sustainability Index of *scenarios I* to *V* of 2015 when priority is given to social indicator: (a) sustainability Index and (b) weight coefficient

In **Case B**, the constraint is defined to give priority to the social indicator (the value of weight coefficient is

0.621), while the economy and ecology indicators have the value of weight coefficient (0.278, respectively 0.101), Fig. 7. In the process of subindicators agglomerations, according to the defined conditions, the following has priority: the social subindicator of number of injured per energy production (SoIni), the economy subindicator of industrial, the household and commercial energy intensities (EcIei) and the ecology subindicator of CO_2 emission per energy production ($EkI_{CO2}^{(1)}$). The list of priorities for this case is presented in Figure 7. If the priority is given to the social indicator, it is noticeable that *scenario V* shows the best level of sustainability. *Scenario I* is at the bottom of the GIS rating list as the scenario with the respective sustainability level. *Scenario V* which is in the previous case at the last place, in this case ranks the first.

In **Case C**, the constraint gives priority to the ecology indicator (the value of weight coefficient is 0.66), while the economy and social indicators have the same values of weight coefficients (0.16), Fig. 8. In the process of subindicators agglomerations, according to the defined conditions, the following has priority: the ecology subindicator of CO_2 the emission per energy production ($EkI_{CO2}^{(1)}$), the economy subindicator of industrial, household and commercial energy intensities (EcIei) (EcIec) and the social subindicator of number of injured per energy production (SoIni). The GIS rating list of priorities for the defined constraint is presented in Figure 8. At the first place of the GIS rating list are *scenarios II* and *V*, while the *scenario I* is on the lower position.

Case C: Constraint 6.
EkInd(condition1) > EcInd(condition4) = SoInd(condition3)
$EkInd(EkI_{CO2}^{(1)} > EkI_{CO2}^{(2)} = EkI_{NOx}^{(1)} = EkI_{NOx}^{(2)}) >$
$> EcInd(EcIei > EcIec = EcIinv = EkIef) =$
$= SoInd(SoIni > SoIeh = SoIsi = SoIwh)$

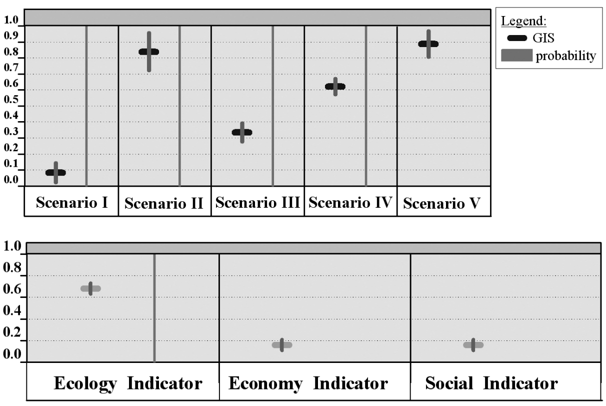

Figure 8. Sustainability Index of *scenarios I* to *V* of 2015 when priority is given to ecology indicator: (a) sustainability Index and (b) weight coefficient

8. CONCLUSION

Sustainable development trends of the city energy system in the long term are investigated by using the model for the prediction and analysis of energy demands and by the mathematical method for the multicriteria decision. Possible developments of the city energy system are described by various scenarios, where the sustainability of the scenarios are described with the set of economic, social and environment indicators. By the multicriteria decision method the synthesized index of energy system sustainability is derived and calculated. The synthesized index sums up all estimated aspects giving an indication of the overall sustainability. Different weights are assigned to indicators. The criteria for the weights estimation is based on the expert opinion and on the measurement scale by which the relative weighting is expressed numerically or verbally. But, the application of the presented mathematical tool provides an objective evaluation, since the randomization of uncertainty of the weight coefficient vector is performed.

In this paper the valid evaluation tool in measuring energy system sustainability in urban area in different contexts and analyzing many indicators simultaneously is demonstrated. So, for this analysis several set of indicators and subindicators in appropriate context are adopted and calculated using available data needed. The proposed new method is applied to the energy system of the city of Belgrade. The study is used to compare different energy scenarios defined for the time period till 2020.

REFERENCES

[1] *Key World Energy Statistics*, The International Energy Agency, Paris, 2007.

[2] Holden, M., Roseland, M., Ferguson, K. and Perl, A.: Seeking urban sustainability on the world stage, Habitat International, Vol. 32, No. 3, pp. 305-317, 2008.

[3] Pohekar, S.D. and Ramachandran, M.: Application of multi-criteria decision making to sustainable energy planning – A review, Renewable and Sustainable Energy Reviews, Vol. 8, No. 4, pp. 365-381, 2004.

[4] Mega, V., Pedersen, J.: *Urban Sustainability Indicators*, Office for Official Publications of the European Communities, Luxembourg, 1998.

[5] Hobbs, B.F. and Meier, P.M.: Multicriteria methods for resource planning: an experimental comparison, IEEE Transactions on Power Systems, Vol. 9, No. 4, pp. 1811-1817, 1994.

[6] Huang, J.P., Poh, K.L. and Ang, B.W.: Decision analysis in energy and environmental modeling, Energy, Vol. 20, No. 9, pp. 843-855, 1995.

[7] Bruntland, G.: *Our Common Future: The World Commission on Environment and Development*, Oxford University Press, Oxford, 1987.

[8] Science for Sustainable Development, in: *Agenda 21 – The Report of the United Nations Conference on Environment and Development (UNCED)*, 03-14.06.1992, Rio de Jeneiro, Brazil, Chapter 35.

[9] Energy Indicators for Sustainable Development: Guidelines and Methodologies, International Atomic Energy Agency, Vienna, 2005.

[10] *Indicators of Sustainable Development*, United Nations, New York, 1999.

[11] Carlsson-Kanyama, A., Dreborg, K.H., Moll, H.C. and Padovan, D.: Participative backcasting: A tool

for involving stakeholders in local sustainability planning, Futures, Vol. 40, No. 1, pp. 34-46, 2008.

[12] Zhang, Y., Zhao, Y.W., Yang, Z.F., Chen, B. and Chen, G.Q.: Measurement and evaluation of the metabolic capacity of an urban ecosystem, Communications in Nonlinear Science and Numerical Simulation, Vol. 14, No. 4, pp. 1758-1765, 2009.

[13] Afgan, N.H. and Carvalho, M.G.: *Quality, Sustainability and Indicators of Energy Systems*, Begell House, Redding, Connecticut, USA, 2007.

[14] *An Urbanizing World: Global Report on Human Settlements, 1996*, Oxford University Press, Oxford, 1996.

[15] *Model for Analysis of the Energy Demand (MAED)*, International Atomic Energy Agency, Vienna, 2002.

[16] Jarrar, O.M. and Al-Zoabi, A.Y.: The applicability of sustainable city paradigm to the city of Jerusalim: Criteria and indicators of efficiency, Building and Environment, Vol. 43, No. 4, pp. 550-557, 2008.

[17] Goldemberg, J., Johansson, T.B., Reddy, A.K.N. and Williams, R.: *Energy for a Sustainable World*, Wiley Eastern, New Delhi, 1988.

[18] Scipioni, A., Mazzi, A., Mason, M. and Manzardo, A.: The dashboard of sustainability to measure the local urban sustainable development: The case study of Padua Municipality, Ecological Indicators, Vol. 9, No. 2, pp. 364-380, 2009.

[19] Gagliardi, F., Roscia, M. and Lazaroiu, G.: Evaluation of sustainability of a city through fuzzy logic, Energy, Vol. 32, No. 5, pp. 795-802, 2007.

[20] Afgan, N.H. and Carvalho, M.G.: *Sustainable Assessment Method for Energy Systems*, Kluwer Academic Publisher, Boston, 2000.

[21] Hovanov, N.V.: *Analysis and Synthesis of Parameters under Information Deficiency*, St. Petersburg University Press, St. Petersburg, 1996, (In Russian).

[22] Barnard, G.A. and Bayes, T.: Studies in the history of probability and statistics: IX. Thomas Bayes's essay towards solving a problem in the doctrine of chances, Biometrika, Vol. 45, No. 3-4, pp. 293-315, 1958.

[23] *Statistical Yearbook of Belgrade 2003*, Bureau of Informatics and Statistics, Belgrade, 2004, (in Serbian).

[24] *Statistical Yearbook of Belgrade 1981-2003*, Bureau of Informatics and Statistics, Belgrade, 2003, (in Serbian).

[25] *Review of Electricity and Fuel Consumption*, Energy Statistical Office in Belgrade, Belgrade, 2004, (in Serbian).

[26] *Statistical Yearbook of Republic of Serbia from 2000 to 2003*, Statistical Office of the Republic of Serbia, Belgrade, 2004, (in Serbian).

[27] *Transport and Communication Builten from 1981 to 2003*, Statistical Office of the Republic of Serbia, Belgrade, 2004, (in Serbian).

[28] *Energy Sector Strategy and Development up to 2015*, Ministry of Energy and Mining, Belgrade, 2004, (in Serbian).

АНАЛИТИЧКИ МЕТОД ЗА МЕРЕЊЕ ОДРЖИВОСТИ ЕНЕРГЕТСКИХ СИСТЕМА У УРБАНИМ СРЕДИНАМА

Марина Јовановић

Важан предмет текућих истраживања и предвиђања развоја у различитим земљама је процена одрживости енергетског система града. У овом раду представљен је нов начин мерења одрживости енергетског система града. Он је заснован на предвиђању будућих енергетских потреба свих сектора потрошње енергије у граду, одређивању сценарија развоја енергетског система града и вредновању тих сценарија коришћењем методе вишекритеријалног одлучивања. У сценарије се укључује коришћење различитих извора енергије, постојећих енергетских постројења и инфраструктуре, као и изградња нових постројења. Критеријуми одрживости су описани јединственим скупом економских, социјалних и еколошких индикатора. Развијени поступак је примењен за предвиђање одрживог развоја енергетског система града Београда.