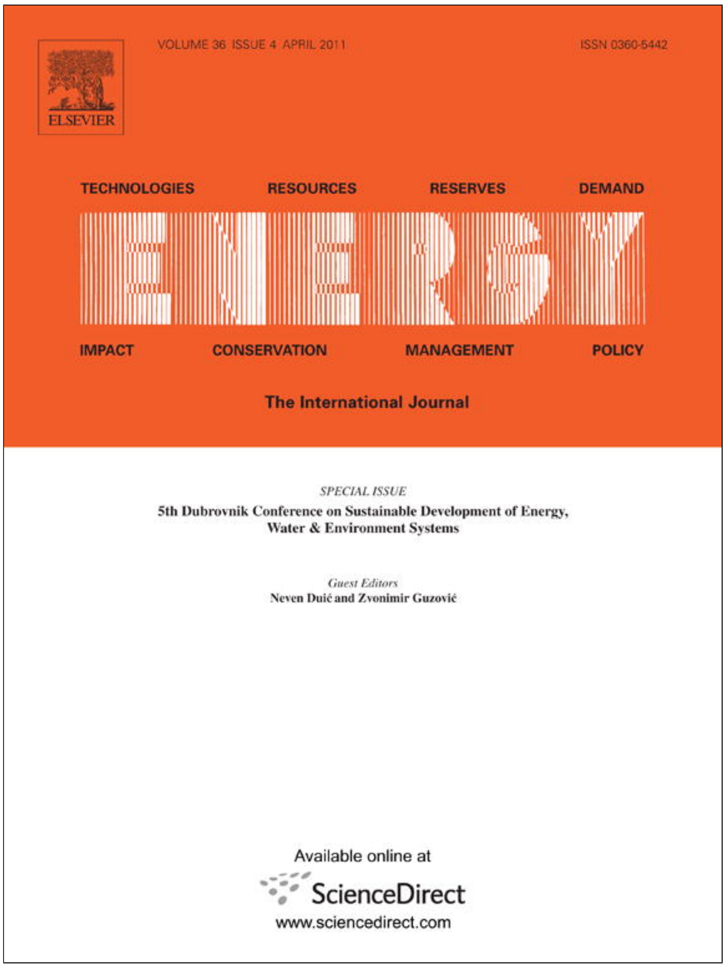
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# Sustainability estimation of energy system options that use gas and renewable resources for domestic hot water production

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ABSTRACT

Two possible substitutions for fossil fuel used in heat production are biomass and solar energy. This paper presents an evaluation of various energy sources for hot water production in a heating plant. The heating plant was situated in one of the largest municipalities in the city of Belgrade, Serbia. It produces and delivers domestic hot water and energy for heating to approximately 17,000 households. It is possible to use of using renewable energy instead of fossil fuel for producing the thermal energy for the supply of domestic hot water. Hence, in this paper, an evaluation of the sustainability of different energy options for obtaining thermal energy was considered: 1) from gas combustion; 2) from gas combustion and solar collection 3) from biomass combustion 4) from gas and biomass combustion, and 5) from gas and biomass combustion and solar collection. To compare the different energy systems, the method of multi-criteria analysis was utilised. This method integrates various multi-dimensional criteria and provides an efficient method of estimating the sustainability of complex systems. The obtained results were compared by the General Index of Sustainability which is a measure of the complexity of a system. A basic set of energy indicators that relate to different aspects of sustainable development was defined. In this way, the results in the assessment of sustainability of energy options do not depend on the various analysts in decision making.



## 1. Introduction

According to the available data (in 2007), the total annual energy consumption worldwide exceeds 131–138 PWh or 473–500 EJ. Of this total amount, oil generates 35%, natural gas generates 20.7%, nuclear generates 6.3%, hydro energy generates 2.2%, biomass and residue generates 10%, coal generates 25.3% and other sources provide the remaining 0.5% [1]. The increased use of fossil fuels has led to air pollution problems, climate change and a constant growth in oil and gas prices on the world market. This has resulted in a worldwide expansion in the usage of renewable energy sources. The utilisation of renewable energy sources such as water, wind, sun, waves, biomass, and others is rapidly replacing the conventional methods of energy production by fossil fuels [2].

The scope and structure of Serbian energy resources are highly unfavourable. The reserves of high quality energy-generating products, such as oil and gas, are symbolic and represent less than 1% of the total energy reserves in Serbia and, the remaining 99% were comprised of various types of coal, with low-quality lignite amounting to 92% of the total reserves.

The energy potential of the renewable energy resources in Serbia is important, and it amounts to over 3 Mtoe per year (with the potential of small hydro power plants being approximately 0.4 Mtoe). Approximately 80% of the total potential lies in biomass, to which biomass from wood sources contributes 1.0 Mtoe (wood cutting and wooden biomass residue during its primary and/or industrial processing), and over 1.5 Mtoe arises from agricultural biomass (agricultural and field crops residues including liquid manure). The energy potential of the existing geothermal resources in Serbia amounts to nearly 0.2 Mtoe [3].

The Renewable Energy Resources category in the Strategy of Energy Development of Serbia until 2015 includes biomass, the hydro-potential of small water streams (with structures up to 10 MW), geothermal and wind and solar radiation energy. It should be emphasised that special benefits and requirements exist for the organised usage of these renewable sources in decentralised heat production (by biomass combustion and solar radiation "collection") and electrical energy production (by construction of small hydro power plants with power potential up to 10 MW and wind generators with power potential up to 1 MW) to satisfy the requirements of local consumers [3].

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**Nomenclature**

Mtoe million tons of oil equivalent
O & M operation and maintenance
EISD energy indicators of sustainable development
EcIec (€/kWh) economic sub-indicator of energy cost
EcIinv (€/kWh) economic sub-indicator of investment
EcIef (%) economic sub-indicator of efficiency
EcIei (kWh/€) economic sub-indicator of energy intensity
GIS General Index of Sustainability
SoIsre (kWh/h) social sub-indicator of renewable energy share per household
SoIsi (%) social sub-indicator of the share of household income spent on hot water
SoIni (1/kWh) social sub-indicator of the number of injured per energy produced
SoIwh (h/kWh) social sub-indicator of working hours per energy produced
$EkI^{(1)}_{CO_2}$ and $EkI^{(1)}_{NO_x}$ ($kgCO_2$/kWh and $kgNO_x$/kWh) ecological sub-indicators of $CO_2$ and $NO_x$ emission per energy produced, respectively
$EkI^{(2)}_{CO_2}$ and $EkI^{(2)}_{NO_x}$ ($kgCO_2$/cap. and $kgNO_x$/cap.) ecological sub-indicators of $CO_2$ and $NO_x$ emission per capita, respectively

## 2. Various energy options for domestic hot water production

This paper presents an evaluation of various energy system options for hot water production in a heating plant. Additionally, an analysis of solar energy and biomass utilisation as substitutes for fossil fuels was considered [4–6].

The heating plant under consideration was situated in one of the largest municipalities in the city of Belgrade, Serbia and represents an integral part of the Public Utility Company. It produces and delivers domestic hot water and energy for heating to approximately of 17000 households. The current fuels used in the plant are natural gas and fuel oil. The total installed boiler capacity is 244 MW, and the utilised capacity for heating and hot water is 230 MW. The designed output and input temperature is 60/40 °C, with a flux of 250 $m^3$/h for sanitary hot water production. The analysis was made with a boiler life-time of 15 years. An average hot water (45 °C) consumption of a household was assumed to be 2.8 kWh/day [7,8]. In the calculation, the following emission coefficients for gases were adopted: $k_{ECO_2} = 50.33$ $kgCO_2$/GJ and $k_{ENO_x} = 0.00561$ $kgNO_x$/kggas. When using biomass briquettes as the fuel, the following emission coefficients for gases were adopted: $k_{ECO_2} = 49.5$ $kgCO_2$/GJ and $k_{ENO_x} = 0.000544$ $kgNO_x$/kggas, [9]. The calculated numerical values of several sub-indicators of the ecology indicator were shown in Table 3 and include the $CO_2$ emission per energy produced ($EkI^{(1)}_{CO_2}$) and per capita ($EkI^{(2)}_{CO_2}$) as well as; the $NO_x$ emission per energy produced ($EkI^{(1)}_{NO_x}$) and per capita ($EkI^{(2)}_{NO_x}$). They also represent the input data of the mathematical model in which the average value of the GIS (General Index of Sustainability) for each energy option was calculated.

### 2.1. *Thermal energy obtained from gas combustion (Gas energy option)*

This energy option represents the generation of thermal energy by gas combustion in the heating plant. The installed 10 MW boiler produces thermal energy. The heating value of the gas is 34 MJ/$m^3$, or 45.5 MJ/kg, and the required annual volume of gas is $606 \times 10^4$ $m^3$. The amount of heat injected with the fuel into boiler (chemical gas energy) is 206 TJ/year. The output and input temperature is 60/40 °C with a flux of 250 $m^3$/h for sanitary hot water production obtained from the Public Utility Company. Based on this, the total calculated amount of energy required to heat the water to the specified temperature is 183 TJ/year. In heating plants in Serbia, boilers of this type work 7000–7500 h/year for hot water production. There are two 10 MW boilers in this heating plant; however, one is always in reserve [19]. According to the literature, the gas price for business consumers is 0.393 €/$m^3$. In accordance with statistical data on the variation in gas prices during the period 1991–2006, an annual gas price increase of 6% was used in this study. Likewise, a boiler efficiency of 89% and an investment cost of $20 \times 10^4$ € were assumed [10–12].

### 2.2. *Thermal energy obtained from a combined system (Gas + Solar energy option)*

This energy option employs both gas combustion in a boiler and a solar thermal system for thermal energy production. The heat quantity obtained by the collectors and from the boiler in the combined system was calculated by simulation in the programme (TRNSYS16) Transient Energy System Simulation Tool, version 16, [13]. The total energy production from gas combustion was 164 TJ/year, and the overall gas consumption was $544 \times 10^4$ $m^3$/year. The solar energy calculations were made for an Apricus collector with a total collector surface area of 5000 $m^2$. An evacuated collector was chosen with a collector area of 4.35 $m^2$/pcs, a total absorption area of 2760 $m^2$ and a unit price of 154 €/$m^2$ [14]. The total amount of energy obtained from the collectors was 19 TJ/year, which accounted for 10% of the total thermal production required to satisfy the demand. These solar panels were installed as a centralised solar plant in the vicinity of the heating plant. The costs were calculated based on component prices obtained from the manufacturer and the estimated installation cost [15,16]. The total costs of the produced thermal energy for the combined system were calculated as the sum of the costs of the required gas, operation costs and maintenance costs of the combined thermal system (the O & M is $3.92 \times 10^{-3}$ €/kWh and $1.11 \times 10^{-3}$ €/kWh for the gas and solar system, respectively) [14,17]. The necessary costs for the collectors and the other parts of the solar thermal system were approximately $80 \times 10^4$ €. Combined system efficiency of 83% was assumed. A reduction in the price of the produced hot water was anticipated when renewable energy provides 10% of thermal energy production [14,18,19].

### 2.3. *Thermal energy obtained from biomass combustion (Biomass energy option)*

This is the option in which thermal energy was provided from the combustion of biomass briquettes in a boiler with an installed capacity of 10 MW. In the calculation the following values were used: the price of briquette 0.09 €/kg, the costs for O & M is $1.64 \times 10^{-3}$ €/kWh, investment costs of 70 €/kW, the efficiency of the biomass boiler of 77% and the heating value of the biomass 13.9 MJ/kg. Total obtained thermal energy was 183 TJ/year and the overall required quantity of biomass was $1713 \times 10^4$ kg/year. Where biomass energy source used, a reduction in the price of sanitary hot water of 40% was assumed [18,20,21].

### 2.4. *Thermal energy obtained from a combined system (Gas + Biomass energy option)*

This energy option refers to a combined thermal energy production system in which gas combustion and biomass combustion were used and account for 49.2% and 50.8% of the total production. The amount of heat injected with the gas into the boiler was 101 TJ/year and with the biomass was 121 TJ/year, respectively. The total amount of energy obtained from gas and biomass was 90 TJ/year and 93 TJ/year, respectively. The required volume of gas for one year was 298 × $10^4$ $m^3$ and the overall consumption of biomass was 870 × $10^4$ kg/year. The following parameters were used in the computation: a combined system efficiency of 83% and a 20% reduction in the price of hot water. Based on the total heat energy produced and the efficiency coefficients for the two independent systems (gas and biomass boiler), an efficiency coefficient of 0.83 was used. The data relating to the costs of hot water, hot water consumption and data on the assessment of cost reduction were taken from references [18,19].

### *2.5. Thermal energy from a combined system (Gas + Biomass + Solar energy option)*

This option considers reducing the share of production by gas to 39% while still meeting the total required thermal energy for a sanitary hot water for the predicted operating mode by introducing a biomass boiler and central solar system, which account for 51% and 10% of the total energy produced, respectively. A 3 MW biomass boiler was installed for *Gas + Biomass + Solar* and *Gas + Biomass* energy options, and a 10 MW unit was installed when the thermal energy was obtained solely from biomass. The boilers need to meet the same demand for different energy options to more favourably compare with other energy options using the MCDA (Multi-criteria decision analysis) method.

This energy option refers to a combined system in which gas combustion accounts for 39% of the total energy produced, biomass combustion accounts for 51% and solar energy for the remaining 10%. The total amount of produced energy obtained from gas, biomass and solar collectors was: 71 TJ/year, 93 TJ/year and 19 TJ/year, respectively. The overall gas consumption was 234 × $10^4$ $m^3$/year and the overall consumption of biomass was 877 × $10^4$ kg/year. A combined system efficiency of 76% and a 20% reduction in the price of hot water were used in the computation.

The price of hot water using only gas for the production of thermal energy was taken from reference [18]. The prices for hot water were derived based on a techno-economical analysis for the cases in which the amount of gas was reduced and renewable energy sources were introduced for obtaining heat energy [19,17]. The costs of gas and biomass boilers were taken from references [22,23].

## 3. Measurement of the sustainability of the energy options

The quality of the examined energy options was defined by EISD (energy indicators of sustainable development) , which was represented by economic, social and ecological sub-indicators. To quantify the criteria for the sustainability assessment based on several aspects, the core set of sub-indicators was defined and calculated.

**Table 1**
Economy sub-indicators data.

| Energy options | EcIec (€/kWh) | EvIinv (€/kWh) | EcIef (%) | EcIei (kWh/€) |
|---|---|---|---|---|
| 1. Gas | 0.0779 | 0.000262 | 89 | 0.00175 |
| 2. Gas + Solar | 0.0699 | 0.001030 | 83 | 0.00175 |
| 3. Biomass | 0.0263 | 0.000920 | 77 | 0.00175 |
| 4. Gas + Biomass | 0.0537 | 0.001180 | 83 | 0.00175 |
| 5. Gas + Solar + Biomass | 0.0472 | 0.001310 | 76 | 0.00175 |

**Table 2**
Social sub-indicators data.

| Energy options | SoIsre (kWh/h.) | SoIsi (%) | SoIni (1/kWh/year) | SoIwh (h/kWh) |
|---|---|---|---|---|
| 1. Gas | 0 | 1.35 | 3.927 × 10E-08 | 6.011 × 10E-05 |
| 2. Gas + Solar | 332.631 | 1.31 | 3.918 × 10E-08 | 5.997 × 10E-05 |
| 3. Biomass | 3183.21 | 0.80 | 3.927 × 10E-08 | 7.213 × 10E-05 |
| 4. Gas + Biomass | 1616.48 | 1.08 | 3.927 × 10E-08 | 8.415 × 10E-05 |
| 5. Gas + Solar + Biomass | 1960.05 | 1.06 | 3.918 × 10E-08 | 8.396 × 10E-05 |

The EcIec (economic sub-indicator of energy cost) represents the busbar cost per kW-h of thermal energy. It includes the costs of fuel, plant operation and maintenance. The EcIinv (economic sub-indicators of investment) shows the total amount of EUR invested in the energy system divided by the energy produced during its life-time. The EcIef (economic sub-indicator of efficiency) refers to the efficiency of the system. It is a relation between the total amount of produced energy and total amount of input fuel energy. The EcIei (economic sub-indicator of energy intensity) presents the total energy consumption per (GDP) gross domestic product. The SoIsre (social sub-indicator of the renewable energy share) reflects the renewable energy use per household. The SoIsi (social sub-indicators of share of household income) spent on hot water shows the share of income needed to satisfy the minimum household commercial energy requirements. The SoIni (social sub-indicators of the number of injured per energy produced) relates the number of injured and the annual energy produced. The SoIwh (social sub-indicator of the working hours per energy production) refers to the number of working hours divided by the total energy produced in the energy system. The ecological sub-indicators, which provide a measure of the state of the environment are the ecological sub-indicators of $CO_2$ emission per energy produced ($EkI^{(1)}_{CO_2}$) and per capita ($EkI^{(2)}_{CO_2}$) and $NO_x$ emission per energy produced ($EkI^{(1)}_{NO_x}$) and per capita ($EkI^{(2)}_{NO_x}$).

The calculation was performed with the selected sub-indicators, as shown in Tables 1–3 [24,25].

### *3.1. Ecology sub-indicators data*

The methodology of multi-criteria analysis was applied to estimate the sustainability of the proposed energy options. The obtained results were compared by the energy options' respective GIS, which was a measure of system complexity. For this purpose, a mathematical model was developed based on the fuzzy sets theory, which is applicable to the multi-criteria assessment of the various energy systems (ASPID methodology). The main advantage of the multi-criteria decision making technique, ASPID, is its ability to work with non-numerical (ordinal), inexact (interval) and incomplete information (*nnn*-information) [26].

At the first level of the calculation, specific sub-criteria normalisation was performed on the basis of the values of the sub-indicators. The sustainable indicators are not suitable for use or

**Table 3**
Ecology sub-indicators data.

| Energy options | $EkI^{(1)}_{CO_2}$ ($kgCO_2$/kWh) | $EkI^{(2)}_{CO_2}$ ($kgCO_2$/cap.) | $EkI^{(1)}_{NO_x}$ (kgNOx/kWh) | $EkI^{(2)}_{NO_x}$ (kgNOx/cap.) |
|---|---|---|---|---|
| 1. Gas | 0.204 | 61.53 | 0.000499 | 0.151 |
| 2. Gas + Solar | 0.162 | 49.13 | 0.000447 | 0.135 |
| 3. Biomass | 0.231 | 69.94 | 0.000183 | 0.055 |
| 4. Gas + Biomass | 0.218 | 65.80 | 0.000338 | 0.102 |
| 5. Gas + Solar + Biomass | 0.196 | 59.54 | 0.000286 | 0.087 |

**Table 4**
Normalised values of economic sub-indicators.

| Energy option | Eclec > Eclinv = Eclef = Eclei | Eclinv > Eclec = Eclef = Eclei | Eclef > Eclec = Eclinv = Eclei | Eclei > Eclec = Eclinv = Eclef |
|---|---|---|---|---|
| 1.Gas | 0.360000 | 0.880000 | 0.880000 | 0.880000 |
| 2. Gas + Solar | 0.303611 | 0.473581 | 0.595233 | 0.778048 |
| 3. Biomass | 0.828335 | 0.598061 | 0.314726 | 0.828335 |
| 4. Gas + Biomass | 0.556244 | 0.344317 | 0.614724 | 0.797539 |
| 5. Gas + Solar + Biomass | 0.578129 | 0.205899 | 0.205899 | 0.725899 |

comparison because they have different dimensions and their values cover different ranges. The introduction of the technique of fuzzy sets results in non-dimensional sets that can be added, subtracted, etc. The normalised values of the sub-indicators were obtained by linear normalisation ($q_i(x_i;\Theta)$, $\Theta = 1$). Members of the fuzzy sets range from 0 to 1 and were obtained by the linear function. A set of numerical values of the indicators for all of the energy options was converted into a fuzzy set of normalised indicator values [25–28].

Likewise, the aforementioned conditions for the sub-criteria were assigned in the defining of weight coefficients. It was assumed, that all of the specific criteria were normalised without a loss in generality. The set of numerical values of the sub-indicators for all of the considered energy options was converted into a fuzzy set of normalised indicators, as shown in Tables 4–6.

### 3.2. *Normalised values of ecology sub-indicators*

At the second level of the calculation, eight constraints were defined by non-numerical information to obtain weight coefficients. Aggregation of the particular multi-dimensional indicators (criteria) into one general criterion or GIS was realised by a scalar-valued synthesizing function: $I_{agi} = \sum_{i=1}^{m} w_i q_i$, where: $I_{agi}$ are the aggregated values of the indicators, $w_i$ are the weight coefficients and $q_i$ are the normalised values of the sub-indicators. The importance of each criterion in each level was assessed by the weight coefficients before the overall evaluation was performed. The weight coefficients assigned to each indicator were consistent with the examined context. The weights were proportional to the importance of the criteria evaluated by each indicator and demonstrate how willing decision-makers are to accept the trade-offs between the criteria [29,30].

The weight coefficients of the criteria can be subjectively determined using a measurable scale where they can be presented numerically or by linguistic expressions. There are a large number of combinations that describe possible relationships between the weights. In this paper, the weight coefficients were mathematically determined to provide an objective assessment. The weight coefficient vector was determined from the set of weights because the process of uncertainty randomisation was performed [31]. The quality assessment of the examined energy options by the GIS depends on giving priority to a certain weight (for the different cases and constraints) [28]. The cases were selected, compared and modelled according to the demands and needs of end users (Public Utility Company in this case).

The methodology of the multi-criteria analysis was applied to estimate the sustainability of the various energy system options [32–36]. For this purpose, the mathematical model and corresponding computer code were developed based on the fuzzy sets theory for the multi-criteria decision making technique ASPID. The multi-criteria assessment method was based on the decision-making procedure reflecting the combined effect of all of the considered criteria and is expressed in the form of the GIS. The application of this method in the cases of information deficiency enables the evaluation of the various energy system options. Nonnumeric, inexact and incomplete information may be used for the reduction of the set $W(m,n)$ of all the possible weight vectors with discrete components to a set of admissible weight vectors, i.e. weight vectors that meet the requirements implied by the information $I$.

An accounting for the discrete nature of the weights and normalisation $w_1 + w_2 + \ldots + w_m = 1$, the values of the weights were calculated. At the first level of the calculation, total values of each indicator were obtained using a linear summation Eq. (1).

$$I_{agi} = \sum_{i=1}^{m} w_i q_i \tag{1}$$

where: $I_{agi}$ represent the summed values of the indicators, $w_i$ represent the weight coefficient for the sub-indicators, $q_i$ represent the normalised values of the sub-indicators. The second step in the calculation considered the normalisation of all of the indicators for each energy options and under the conditions of the pre-defined constrains and calculated the GIS using the additive synthesis function shown in Eq. (2).

$$\overline{Q}_+(q;I) = \frac{1}{N(I;m,n)} \sum_{s=1}^{N(I;m,n)} Q_+\left(q;w^{(s)}\right),\ w^{(s)} \in W(I;m\,n) \tag{2}$$

where: $\overline{Q}_+(q\,;\,I)$ is the average value of the GIS; $q$ is the criteria, $N(I;\ m,n)$ is the number of elements in the set $W(m,n)$; $w$ is the weight coefficient; $W(m,n)$ is the infinite set of all possible weight coefficients; $m$ is the number of criteria; $n$ is a positive integer; $I$ is the non-numerical and inexact information.

The energy system options ‘probability’ and ‘measure of reliability’ (reliability of preference)’ were calculated to indicate

**Table 5**
Normalised values of social sub-indicators.

| Energy option | Solsre > Solsi = Solni = Solwh | Solsi > Solsre = Solni = Solwh | Solni > Solsre = Solsi = Solwh | Solwh > Solsre = Solsi = Solni |
|---|---|---|---|---|
| 1.Gas | 0.13101 | 0.131009 | 0.178714 | 0.651009 |
| 2. Gas + Solar | 0.26093 | 0.256836 | 0.765962 | 0.765962 |
| 3. Biomass | 0.83064 | 0.830640 | 0.358345 | 0.569042 |
| 4. Gas + Biomass | 0.45817 | 0.465883 | 0.201140 | 0.153435 |
| 5. Gas + Solar + Biomass | 0.66855 | 0.625025 | 0.806353 | 0.286354 |

**Table 6**
Normalised values of ecology sub-indicators.

| Energy option | $EkI^{(1)}_{CO_2} > EkI^{(2)}_{CO_2} = EkI^{(1)}_{NO_x} = EkI^{(2)}_{NO_x}$ | $EkI^{(2)}_{CO_2} > EkI^{(1)}_{CO_2} = EkI^{(1)}_{NO_x} = EkI^{(2)}_{NO_x}$ | $EkI^{(1)}_{NO_x} > EkI^{(1)}_{CO_2} = EkI^{(2)}_{CO_2} = EkI^{(2)}_{NO_x}$ | $EkI^{(2)}_{NO_x} > EkI^{(1)}_{CO_2} = EkI^{(2)}_{CO_2} = EkI^{(1)}_{NO_x}$ |
|---|---|---|---|---|
| 1.Gas | 0.352455 | 0.359784 | 0.112459 | 0.112459 |
| 2. Gas + Solar | 0.777565 | 0.777565 | 0.294228 | 0.297018 |
| 3. Biomass | 0.240000 | 0.240000 | 0.760000 | 0.760000 |
| 4. Gas + Biomass | 0.257780 | 0.262446 | 0.460715 | 0.463788 |
| 5. Gas + Solar + Biomass | 0.664848 | 0.657021 | 0.737241 | 0.740443 |

whether the combination was considered a realistic case compared to all of the combinations. Also, the standard deviation, which measures 'uncertainty' in the process of the weight coefficients estimation, was calculated and shows a measure of the accuracy in the evaluation of the GIS [26,37].

## 4. Results and analysis

A sustainability assessment of the various combinations of the technological options for thermal energy production was performed. When priority was given to different aspects of sustainability as well as to various sub-indicators, a ranking of the energy options was performed. This was shown by priority lists for the four cases with respect to the pre-defined constraints, and their graphical presentations were shown in Figs. 1–4. Figs. 1 and 2 were shown the cases in which the economic and ecological indicators had priority, respectively. The process of summing of the economic, social and ecological sub-indicators was performed at pre-defined condition 1, in which priority was given to the following sub-indicators: the economic sub-indicator of energy cost, the social sub-indicator of the share of renewable energy and the ecologic sub-indicator of $CO_2$ emission per energy production. Constraint 1 was defined when priority was given to the economic indicator ($w = 0.680$) while the social and ecologic indicators have the same value of the weight coefficient ($w = 0.160$). In the case when the economic indicator had priority, the best options on the list were the *Biomass* and the *Gas + Solar + Biomass* energy options (Fig. 1). The results of the GIS showed a low level of sustainability for the *Gas* and the *Gas + Solar* options.

*Constraint 1.* EcInd(condition 1) > SoInd(condition 1) = EkInd (condition 1)

EcInd (EcIec > EcIinv = EcIef = EkIei) >SoInd(SoIsre > SoIsi = SoIni = SoIwh) = EkInd($EkI^{(1)}_{CO_2} > EkI^{(2)}_{CO_2} = EkI^{(1)}_{NO_x} = EkI^{(2)}_{NO_x}$)

(a)

(b)

*Constraint 2.* EkInd(condition1) > SoInd(condition1) = EcInd (condition1)

EkInd($EkI^{(1)}_{CO_2} > EkI^{(2)}_{CO_2} = EkI^{(1)}_{NO_x} = EkI^{(2)}_{NO_x}$) > SoInd(SoIsre > SoIsi = SoIni = SoIwh) = EcInd(EcIec > EcIinv = EcIef = EkIei)

(a)

(b)

In the next case, for the pre-defined constraint, the ecological indicator had priority ($w = 0.680$), while the social and economic indicators had the same weight coefficient ($w = 0.160$), as shown in Fig. 2. When the ecological indicator had priority, the *Gas + Solar + Biomass* and *Gas + Solar* energy options showed the best level of sustainability. The *Biomass* energy option, which was on the top of the rating list in the previous constraint, was in the group of energy options with low levels of sustainability in this case. This is most likely due to the calculation of the ecological indicator, in which the atmospheric concentrations of $CO_2$ emitted were calculated for combustion of $257 \times 10^3$t of biomass in lifetime of boiler. It is assumed that the carbon from biomass is not entirely 'biogenic'.

*Constraint 3.* SoInd(condition 2) > EkInd(condition 4) > EcInd (condition 2)

SoInd(SoIsi > SoIsre = SoIni = SoIwh) > EkInd($EkI^{(2)}_{NO_x} > EkI^{(1)}_{NO_x} = EkI^{(1)}_{CO_2} = EkI^{(2)}_{CO_2}$) > EcInd(EcIinv > EcIec = EcIef = EkIei)

(a)

(b)

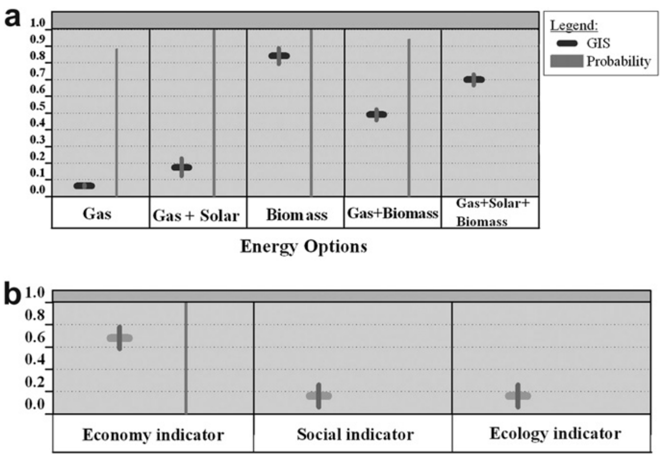


**Fig. 1.** (a) General Index of Sustainability of the considered energy options when priority was given to the economic indicator; (b) Weight coefficients.

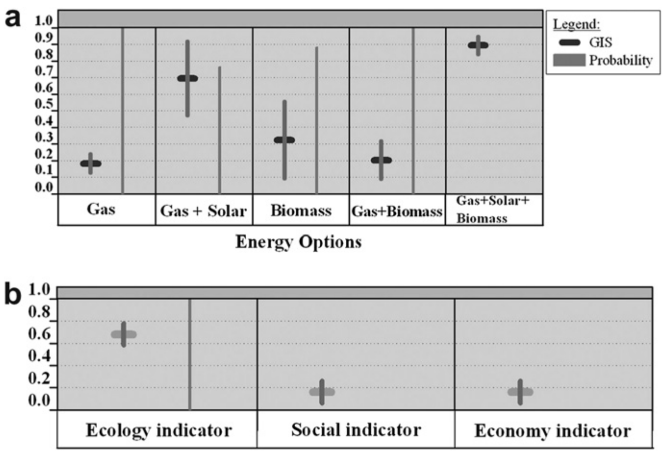


**Fig. 2.** (a) General Index of Sustainability of the considered energy options when priority was given to the ecological indicator; (b) Weight coefficients.

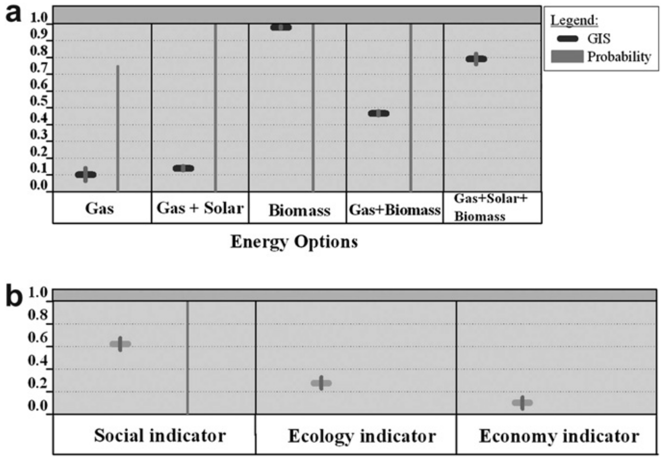


**Fig. 3.** (a) General Index of Sustainability of the energy options when the highest priority was given to the social indicator; (b) Weight coefficients.

The priority list of the energy options when the social indicator had the highest value of the weight coefficient ($w = 0.621$) and the ecological indicator had priority over the economic indicator (the values of the weight coefficients were 0.278 and 0.101, respectively) was shown in Fig. 3. In the process of calculating the sub-indicators, the following had priority: the social sub-indicator of the share of household income spent on hot water, the ecological sub-indicator of $NO_x$ emission per capita and the economic sub-indicator of investment. The derived value of the GIS, which represents the quality of a given energy option when the social indicator had priority with respect to the ecological and economic indicators, showed that the *Biomass* energy option is the most favourable option on the list, Fig. 3. In addition, the *Gas* + *Solar* + *Biomass* energy option showed a high level of sustainability as in the case with the first pre-defined constraint 1. The *Gas* + *Biomass* energy option had a medium level of sustainability while the *Gas* and *Gas* + *Solar* energy options showed the lowest levels of sustainability.

*Constraint 4.* EkInd(condition 4) > EcInd(condition 2) > SoInd (condition 2)

EkInd $(EkI^{(2)}_{NO_x} > EkI^{(1)}_{NO_x} = EkI^{(1)}_{CO_2} = EkI^{(2)}_{CO_2}) >$ EcInd (EcIinv > EcIec = EcIef = EkIei) > SoInd(SoIsi > SoIsre = SoIni = SoIwh)

(a)

(b)

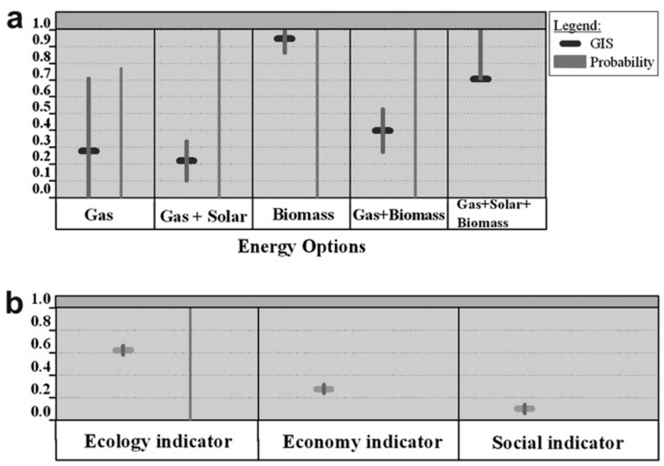


**Fig. 4.** (a) General Index of Sustainability of the energy options when the highest priority was given to the ecological indicator; (b) Weight coefficients.

Constraint 4 was defined to give priority to the ecological indicator ($w = 0.621$) over the economic and the social indicators (the values of the weight coefficients were 0.278 and 0.101, respectively). In the process of summing the sub-indicators, the following had priority: the ecological sub-indicator of $NO_x$ emission per capita, the economic sub-indicator of investment and the social sub-indicator of the share of household income spent on hot water. Fig. 4 shows the results, with the *Biomass* and *Gas* + *Solar* + *Biomass* energy options having level of sustainability and the *Gas*, *Gas* + *Solar*, and *Gas* + *Biomass* occupying the lowest positions.

## 5. Conclusion

In this paper, a sustainability assessment of various energy options was performed. The ASPID methodology was used as a mathematical tool and applied in the analysis and synthesis of the general criteria of the energy options that lacked information.

First, economic, social and environmental criteria were defined and calculated using the basic set of energy sub-indicators. Then, made the assessment of energy systems sustainability using the methodology that demonstration of method or procedure of multicriteria analysis. In this paper, the values of GIS that show the quality or validity of energy systems were calculated. The systems were then ranked based on their GIS score with the different constraints. In this study several cases were analysed, and each case had one constraint. This allows compare different energy options when priority was given to certain criteria over the weight coefficients. The *Biomass* and *Gas* + *Solar* + *Biomass* energy options showed a high level of sustainability with constraints 1, 3 and 4. For these constraints priority was given to EcIec, SoIsi, and $EkI^{(2)}_{NO_x}$, respectively. The *Gas* + *Solar* and *Gas* + *Solar* + *Biomass* were the best options for constraint 2 when priority was given to $EkI^{(1)}_{CO_2}$. The *Gas* energy option was in the group of options heading the list (one of the worst). The quality estimation of the examined energy options by the GIS depended on which weight coefficient had priority.

This approach for the measurement of the sustainability of energy options allows obtaining accurate results when several criteria were used simultaneously in estimations and weights were calculated mathematically. In addition, paper presents the use of renewable energy resources (solar and biomass) and, their organised usage in thermal energy production and, it compares the renewable energy options with the classic energy option to make a contribution to sustainable development. This means using combined systems for water heating to achieve a reduction in $CO_2$ emissions and promote nature recovery.

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