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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.

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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 606×10^4 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 20×10^4 € were assumed [10–12].

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

This energy option employes 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 544×10^4 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 3.92×10^{-3} €/kWh and 1.11×10^{-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 80×10^4 €. 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 1.64×10^{-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 1713×10^4 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

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