ТЕРМОДИНАМИЧКА И ЕКОНОМСКА АНАЛИЗА КОРИШЋЕЊА РАЗЛИЧИТИХ ЕНЕРГЕНАТА НА ПРИМЕРУ СТАМБЕНЕ ЗГРАДЕ

THERMODYNAMIC AND ECONOMIC ANALYSIS OF DIFFERENT FUELS USAGE ON EXAMPLE OF RESIDENTIAL BUILDING

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На основу података Енергетског биланаса Републике Србије за 2017. годину, потрошња финалне енергије је процењена на 8429 Mtoe, од чега је 48% укупне потрошње у сектору домаћинства, пољопривреда и јавно-комуналне делатности. У укупној структури коришћења финалне енргије, обновљиви извори енергије (само геотермална енергија и биомаса заједно) учествују са 12%. Осим квантитативне (енергијске) анализе, за потпуно разумевање свих важних аспеката коришћења енергије и успостављања одговарајуће енергетске политике, потребно је извршити и квалитативну (ексергијску) анализу, као и анализу утицаја коришћења различитих енергената на животну средину. Цене енергената треба да одражавају вредност искористивог дела, односно квалитет, њихове енергије, тј. ексергије. У раду је приказана термодинамичка и економска анализа коришћења различитих енергената у стамбеној згради грејане површине око 160 m², за климатско подручје Београда. Поређени су различити енергенти за грејање и припрему санитарне топле воде: електрична енергија, природни гас, даљинско грејање, угаљ и обновљиви извори енергије. Дат је упоредни приказ потребне примарне енергије, емисије угљен-диоксида, ексергије, као и цена енергије и ексергије за различите енергенте.

Кључне речи: *Енергија; ексергија; цене енергената; обновљиви извори енергије; емисија* CO_2

According to the energy balance for Republic of Serbia for 2017, the total final energy needs for 2017 for Republic of Serbia are estimated as 8429 Mtoe, with a share of 48% estimated for households, agricultural, public and commercial sectors. In the structure of final energy consumption by fuel for 2017 in Serbia, the renewable energy sources are participating with a share of 12% (only geothermal energy and biomass). In order to provide better understanding of all important aspects of energy usage, beside the quantitative (energetic) analysis, it is necessary to perform also qualitative (exergetic) analysis, together with the analysis of different fuels usage impact on environment. Fuel costs should take into a consideration the value of usable part, with other words the quality of their energy, namely exergy. The paper presents thermodynamic and economic analysis of different fuels usage, for residential building, with net heated area cca 160 m², for Belgrade weather data. Results are presented as a comparison between different fuels used for heating and domestic hot water preparation, such as: electricity, natural gas, district heating, coal and renewable energy sources. The comparison is shown for primary energy consumption, CO_2 *emission, exergy consumption and energy and exergy costs for different fuels.*

Key words: *Energy; exergy; fuel costs; renewable energy sources;* CO_2 *emission*

1 Introduction

According to the energy balance for Republic of Serbia for 2015 the total primary energy needs were 16.206 Mtoe, which is 11% more than it was estimated for 2014. The total final energy needs for 2015 for Republic of Serbia were estimated as 9.556 Mtoe, with a share of 47% estimated for households, agricultural, public and commercial sectors [1]. Data from 2017, according to the energy balance for Republic of Serbia, indicate that total estimated final energy needs are lower, namely 8429 Mtoe, but the estimated share for estimated for households, agricultural, public and commercial sectors is 48% [2]. The estimated final energy consumption for energy purposes for 2018 is 8989 Mtoe [3], which is a bit higher than in previous year.

The share of 30% of final energy consumption goes on industry, and the rest of 23% is estimated for transport. European final energy consumption by sector for 2014 shows similar trend, with a share of about 33% for transport, 26% for industry, 25% for households, 13% for services and the rest for agricultural sector [4]. In the structure of final energy consumption by fuel for 2015 in Serbia, the share of 29.7% was estimated for liquid petroleum products, the electricity takes 25.4%, coal 11.8%, natural gas 14%, derived heat 8.1% and geothermal and biomass together with a share of 10.8% [1].

According to data given by European environmental agency for 2015, the highest final energy consumption households per capita are located in Finland, with about 893.9 kg of oil equivalent/capita, while Malta is targeted as the lowest one, with about 180.6 kg of oil equivalent/capita [5].

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Energy consumption by building sector approach takes into account only the quantity of energy used in buildings, without actual quality of the used energy, which is further possible to achieve using also exergy analysis [6]. Sartor and Dewallef [6] studied four selected buildings, using energy performance building software, and compared both specific energy and exergy use. Their results showed that the best system from the energy and exergy perspective is domestic heat network connection followed with heat pumps. Hu et al. [7] analyzed energy and exergy losses for ground source heat pump system for building in China using different control strategies. The study showed that the adequate control strategy can reduce exergy losses, which are mostly from the auxiliary equipment, such as circulation pumps. Adequate control strategy can increase the annual exergy efficiency up to 1.5% [7]. Heating systems through the exergy approach are also analyzed by Yildiz and Gungor [8] on the example of an office in Izmir, Turkey. They compared natural gas conventional boiler, natural gas condensing boiler and air to air heat pump. The results showed that the total energy efficiency is the highest for the heat pump, about 80.9%, while the total exergy efficiency is the highest for the conventional gas boiler, with about 8.68% [8].

Sangi and Muller [9] proposed three approaches for renewable and non- renewable building systems which can be used for exergy analysis. Schlueter and Thesseling [10] also suggested exergy approach implementation in building modeling proposing a prototype tool for exergy modeling.

Various authors analyzed exergy for different systems worldwide, but there are a limited data for Balkan countries. This paper analyzes energy and exergy consumption and costs for Serbian case, for heating season.

2 Building and systems description

The observed building is located in Belgrade, Serbia. It has a total heated area of 162 m^2. The building is well insulated, and U-values of thermal envelope are below the maximal values prescribed by Serbian rulebook on the energy efficiency [11]. Heating system is designed as two pipes, radiator central heating system. For the purpose of analyzes, different heating sources were observed: a) electrical boiler, b) water to water heat pump, c) natural gas boiler, d) coal boiler and e) district heating system. For domestic hot water (DHW) preparation, different sources are observed, and combinations are shown in table 1.

Table 1. Different cases observed in analysis

Case	Heating	DHW	electrical appliances	auxiliary
1	coal	electricity	electricity	electricity
2	natural gas	natural gas	electricity	electricity
3	electricity	electricity	electricity	electricity
4	district heating	electricity	electricity	electricity
5	heat-pump	heat-pump	electricity	electricity

3 Methodology

3.1 Determination of energy demand for case building

The energy analysis was performed using actual methodology prescribed in Serbian Regulations regarding energy efficiency in buildings [11], [12]. The total final energy needs for building can be calculated using following equation:

$$Q_{H,nd} = Q_{H,ht} - \eta_{H,gn} \cdot Q_{H,gn}, \tag{1}$$

where:

$Q_{H,nd}$ - annual final energy for heating [kWh/a],

$Q_{H,ht}$ - annual energy for heat losses [kWh/a],

$\eta_{H,gn}$ - gain utilization factor for heating [-].

Heating is observed with 8h break during the night, so the reduction factor for heating systems working with break is calculated according to the standard SRPS EN 13790.

Total delivered energy for all cases and all systems was calculated also according to the [11], as sum of final energy and losses in generation, emission and heat distribution sub-system. Primary energy was defined using conversional factors prescribed in [11], together with CO2 emission.

3.1.1 Domestic hot water, light and appliances

Energy demands for domestic hot water preparation (Q_w), for light and also for appliances (E_{el}) were calculated in accordance with the literature [11]. Taking into a count the losses, delivered energies were obtained ($Q_{w,d}$ and $E_{el,d}$), and then, using the appropriate conversion factor for each fuel, the primary energy needs were calculated. Also, the exergy values were calculated depending from defined fuel, where the energy for lighting and appliances were always considered as electrical energy from the grid.

3.1.2 Carbon-dioxide emission

Carbon-dioxide emission was obtained using the specific emission data for different fuels prescribed by [11] and based on primary energy needs for building, with a respect to the consumption of different energy sources for heating, DHW and electrical appliances, as it is given in tab. 1.

3.1.3 Energy costs analyzes

The energy cost analyzes was done only for used energy for all system combinations given in tab. 1, and not for the investment costs and maintenance of systems. In this analysis, the actual costs for different fuels and tariff systems were used, as it is given in references [13], [14], [15]. The cost for electricity takes into account the monthly calculations, having in mind that the electricity costs depends on the different tariffs by energy consumption. Prices are given in Serbian dinars, with a currency rate of approximately 119 dinars for 1 euro (Oct. 2018).

3.2 Exergy analyzes for case building

Different forms of energy don't have the same transformation possibility into the other forms of energy, thus don't have the same possibility for use, in other words, their quality is different. In thermodynamics theory the exergy is usually defined as maximal useful work, which could be obtained by existence of thermodynamic non-equilibrium between the observed system and environment. As it is that non-equilibrium bigger, the bigger is also the exergy. Unlike of the energy, in energy processes the exergy can be lost, destroyed, which means that the energy losses it's quality (the degradation of energy). Exergy analysis locates the processes and devices in which the energy loses its quality and gives the possibility to design the suitable strategies and measures for thermodynamic improvement of process. It is a question how to improve the energy usage in buildings in order to obtain more efficient consumption. Beside the energy needs reduction (by insulation, more efficient appliances etc.), the proper choice of energy source, respectively the energy quality is crucial. In buildings, many energetic processes are present and a large part of the total energy is used as a heat at relatively low temperatures. In spite of this, energy sources for buildings are almost exclusively high-quality, such as electricity or natural gas and coal. The energy analysis is not capable to illustrate properly this mismatch between the quality of the energy demand and the source quality. Exergy analysis clearly shows this as a thermodynamic mismatch. High exergy overall efficiencies mean exploiting all the available exergy content and energy usage in the most rational way. The exergy output in buildings is defined by the energy demand and appropriate levels of temperatures for the different energy needs. The exergy optimization here must be addressed to the input in the system and the exergy efficiency can be increased only by reducing exergy input.

3.2.1 Heating system

In order to calculate the exergy flow through the heating chain, first the energy flow has to be estimated. As energy for heating is transformed from the heat generation to emission into the room, losses occur at each step of the transformation. The losses are dependent on factors such as construction of the envelope, choice of heating system components and their operation. In this analysis, the losses were considered by defining the corresponding efficiencies values (generation, distribution and automation).

The monthly demand for indoor air heating is Q_h. The air temperature in the building is maintained at a temperature of 20°C (T_i = 293K) while the average outside air temperature for a given month is T_o, see ref.[11] . The exergy load i.e. the exergy demand to maintain inside air temperature is given by:

$$Ex_i = \left(1 - \frac{T_o}{T_i}\right) Q_h \quad (2).$$

Heating temperature regime, together with the district heating temperature regime in substation is defined as a function of the outdoor air temperature. The exergy demand of the heating emission system calculated from

$$\Delta Ex_{es} = mc_p\left(T_{in} - T_{ret} - T_o \ln\frac{T_{in}}{T_{ret}}\right) = Q_h\left(1 - \frac{T_o}{T_{in} - T_{ret}} \ln\frac{T_{in}}{T_{ret}}\right) \quad (3),$$

where T_{in} is inlet fluid temperature and T_{ret} is return fluid temperature. Taking into a consideration the heat generation energy efficiency, the efficiencies of distribution system and automation system, heat demands of the distribution (Q_d) and generation system (Q_g=Q_{del}) and inlet ($T_{in,d}$) and return fluid temperature ($T_{ret,d}$) of the distribution system were calculated. Expression for exergy demand of the distribution system is similar to the emission system, but with appropriate fluid temperatures, i.e:

$$\Delta Ex_d = mc_p\left(T_{in,d} - T_{ret,d} - T_o \ln\frac{T_{in,d}}{T_{ret,d}}\right) = Q_d\left(1 - \frac{T_o}{T_{in,d} - T_{ret,d}}\ln\frac{T_{in,d}}{T_{ret,d}}\right) \quad (4).$$

Expression for exergy demand of the generation system (i.e. delivered exergy) in general has a form:

$$Ex_g = \gamma_s Q_g \quad (5),$$

where γ_s is a quality factor of the appropriate energy source (fossil fuel, electricity,...). Electrical energy is the highest quality energy and it could be completely transformed into a different forms of energy, which means that its quality factor is γ_e=1. The total exergy of the fuel, at a specified state, is a sum of the thermo-mechanical and chemical exergies. The evaluation of chemical exergy is explained in details in numerous books and articles. For hydrocarbon fuels specific standard chemical exergy, at defined standard conditions, can be written as ([16],[17],[18],[18]):

$$e_x^{ch} = \gamma_h H_h = \gamma_l H_l \quad (6),$$

where γ_h and γ_l are corresponding quality factors of the fuel or exergy coefficients, H_h is the higher and H_l is the lower heating value of the fuel. The values γ_h and γ_l depend on the composition of the fuels and in literature there are some models for their determination. For a conventional fuel composition, for lignite is γ_h=1.03 while for natural gas isγ_l=0.93. Usually, the specific standard chemical exergy of a fuel is approximately equal to higher heating value [16] ie. the quality factor of the fossil fuels is around 1, which means they have high quality.

The necessary primary exergy (Ex_p) for the heating system are given by:

$$Ex_p = \gamma_s \cdot Q_g \cdot f_p + \gamma_{aux} \cdot E_{aux} \cdot f_{p,aux} \quad (7),$$

where: E_{aux} is a necessary auxiliary energy (electricity) for heating system operation, f_p is primary energy factor of the energy source, $f_{p,aux}$ is primary energy factor of the auxiliary energy (given in [11]) and γ_{aux}=1 is a quality factor of the electricity. Energy and exergy efficiencies were defined in the usual way, as ratio of useful value and input value. For heating system useful values are Q_h and Ex_i while input values depend on borders of analyzed thermodynamic system. The exergy efficiencies for generation and primary subsystem are

$$\eta_{ex,g} = \frac{Ex_i}{\gamma_s \cdot Q_g + \gamma_{aux} \cdot E_{aux}} \quad (8),$$

and

$$\eta_{ex,p} = \frac{Ex_i}{\gamma_s \cdot Q_g \cdot f_p + \gamma_{aux} \cdot E_{aux} \cdot f_{p,aux}} \quad (9).$$

3.2.2 Total energy and exergy demands

Summing corresponding values of primary energy and exergy needs for DHW preparation, lighting and appliances, together with auxiliary equipment, and heating, total primary energy or exergy for building can be calculated. Further, the total demand of the primary energy for building is:

$$E_{p,tot} = Q_g \cdot f_p + E_{aux} \cdot f_{p,aux} + E_{el} \cdot f_{p,el} + Q_{w,d} \cdot f_{p,w} \quad (10),$$

and the overall (total) demand of the primary exergy is:

$$Ex_{p,tot} = \gamma_s \cdot Q_g \cdot f_p + \gamma_{aux} \cdot E_{aux} \cdot f_{p,aux} + \gamma_{el} \cdot E_{el} \cdot f_{p,el} + \gamma_w \cdot Q_{w,d} \cdot f_{p,w} \quad (11).$$

where $f_{p,w}$ and $f_{p,el}$ are primary energy conversion factors, while γ_{el}=1 and γ_w are quality factors of the of the considered energy energy sources.
The total exergy efficiency of the building for primary subsystem is

$$\eta_{p,tot} = \frac{Ex_{build}}{Ex_{p,tot}} = \frac{Ex_i + Ex_w + Ex_{el}}{\gamma_s \cdot Q_g \cdot f_p + \gamma_{aux} \cdot E_{aux} \cdot f_{p,aux} + \gamma_{el} \cdot E_{el} \cdot f_{p,el} + \gamma_w \cdot Q_{w,d} \cdot f_{p,w}} \quad (12).$$

4 Results and discussion

In this study, the indoor air is considered to be heated up to 20ºC and DHW up to 55ºC. In literature, the similar analysis are usually done at the constant reference condition for the whole season (project conditions, or average season conditions), which is relatively far from the real cases. In this article, the analysis was carried out on the monthly basis, for the monthly based reference conditions of environment which are closer to the real situation. The difference between the seasonal final exergy value for heating based on monthly conditions and value determined for seasonal average conditions is about 12%.

Energy and exergy flows are calculated in reverse order, from final, over delivered to primary, taking into a consideration the corresponding losses in distribution, generation and automation. For the purpose of exergy flow determination, the appropriate temperature regimes were determined in every part of the system. Temperature regime in emission system in substation was determined based on heating curve which is designed in function of outdoor air temperature.

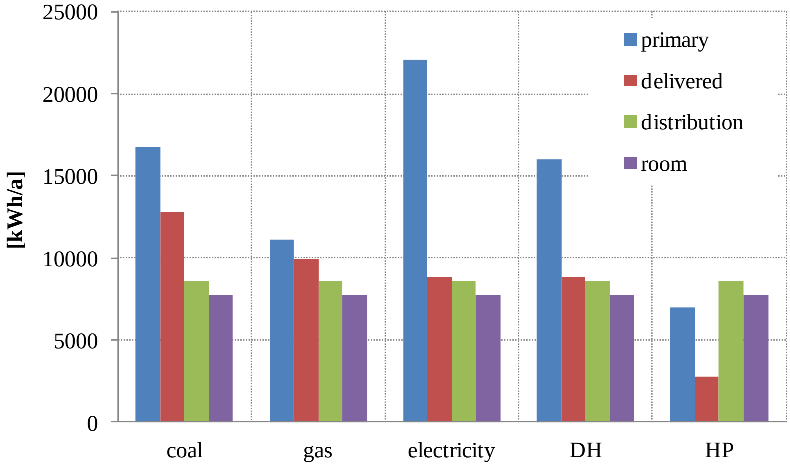

Fig. 1. Energy flow through process (primary, delivered, distribution, final) for different energy sources for heating[2]

The energy flow in building heating system is shown in fig. 1. for different energy sources. Energy flow is given from primary energy, over delivered energy, then for energy transferred to the distribution system (after the generation) to the final energy transferred to the indoor air in building. Energy flow diagram gives the clear information regarding the energy efficiency of energy transformation in observed process or source. Final energy, the same as energy transferred to the distribution system, is the same for every considered case, thus to the same radiator system for all cases, while the delivered energy is directly dependent on the efficiency of generation system. Value of delivered energy is the highest for coal usage as a fuel, because the generation system (boiler) has the lowest efficiency from all observed cases. The primary energy values are strongly depended of primary energy conversion factor for each fuel, which is the highest for electrical energy [11]. Observing the energy aspects, the electrical energy is the most unfavorable source for heating, exactly because the highest primary energy loss during the transformation from fossil fuel to electricity. Also, in case of district heating system, which is based on fossil fuel, the primary energy conversion factor has a significant value, and thus the difference between the primary and delivered energy is also significant. In case of coal, the primary energy has a high value due to the two reasons: relatively moderate value of primary energy conversion factor and the lowest energy efficiency of the generation system (boiler). The values of primary and delivered energy are the lowest for heat pump, while the difference between the energy transferred to the distribution system, and the delivered energy represents the energy obtained from the environment.

Fig. 2. shows the exergy flow for building heating system. The flow is shown from primary, over delivered and exergy transferred to the distribution system, to the final air exergy in room. The primary exergy values are almost equal to the primary energy values having in mind the high quality of primary energy sources. In case of district heating, the delivered exergy value is significantly lower from the primary exergy. The cause of that is the relatively low temperature of hot water delivered to the building substation, so the delivered exergy is also low. Looking at the quality of energy flows within the building boundaries, from delivered to the final energy, the district heating is the most favorable case, having in mind the highest exergy efficiency of delivered energy (see fig.3). With other words, for heating purpose, low temperature and low quality heat was delivered. In case of waste heat utilization from the process, or looking just at the part of distribution chain, it is possible to say that the delivered energy and building energy needs are well balanced for district heating system. But, the problem in this case would be the high thermodynamic price paid in heat plant, combusting the high quality fuel for the generation of low quality thermal energy. Looking at the whole chain of energy transfer, the exergy efficiency for DH primary energy is lower than for heating using heat pump or natural gas as a source (Fig.3). Using the natural gas and coal as fuel, in combustion, for the purpose of low quality heat generation is also thermodynamically unadjusted, and due to that the energy quality decrease is significant. Further, the exergy loss is clearly visible from delivered to the value transferred to the distribution (see Fig.2).

[2] In case of heat pump, the energy received from the environment was not showed in diagram.

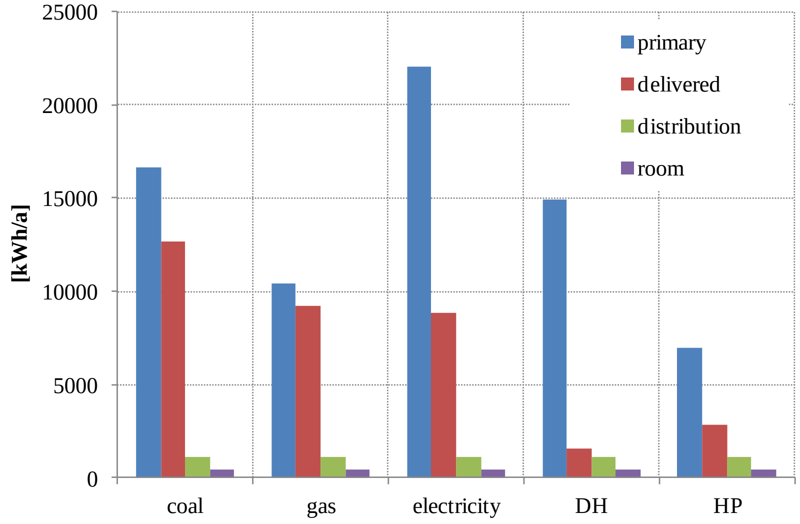

Fig.2. Exergy flow through process (primary, delivered, distribution, final) for different energy sources for heating

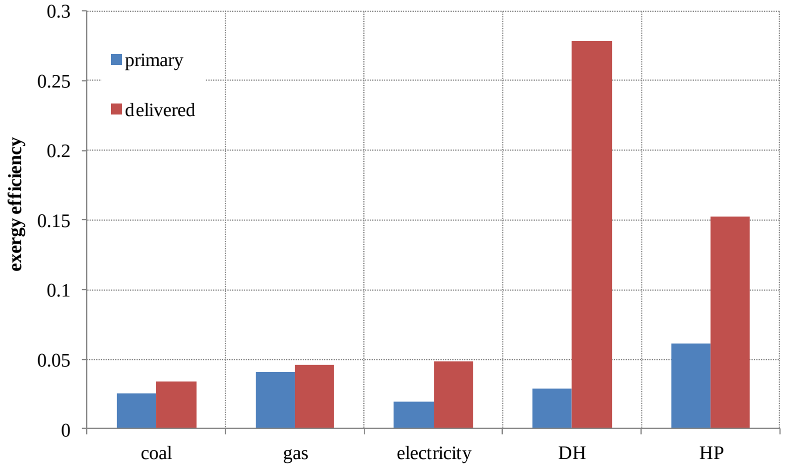

Fig. 3. Seasonal values of exergy efficiency (primary and delivered) for different energy sources for heating

Generally, it is clear that the exergy efficiency is very low in all cases, which further implies poor thermodynamic compatibility of energy quality from the supplied side and the energy used for building heating. The main problem for all cases is the process of combusting the high quality fuels for low temperature heat generation (coal, natural gas, district heating on fossil fuel, electrical energy generation in power plant). The highest exergy efficiency is for the case of heat pump utilization (about 6%), due to the energy used from renewable source, from environment.

Fig. 4 and 5 show the prices of energy and exergy for heating, for different fuels in [din/kWh]. In fig. 4. the comparison of prices for primary energy and primary exergy can be seen.

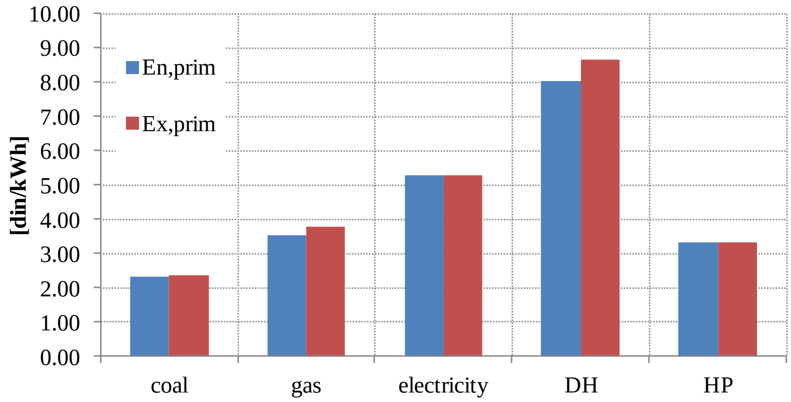

Fig.4. Prices of primary energy and exergy for heating

Fig. 5. shows the prices for delivered values. According to the thermodynamic price logic, the price of the fuel should be directly proportional to its quality, which further implies that the customer should pay for the exergy. It is not

logical to buy high quality energy for the low quality utilization, in other words to buy much more exergy than it is actually necessary. From the price politics point of view, both the supplier and the customer should be motivated to save the fuel exergy, by using it, for example, for electricity generation or in technological process which demands high exergy, and that the waste heat from these processes should be used for heating.

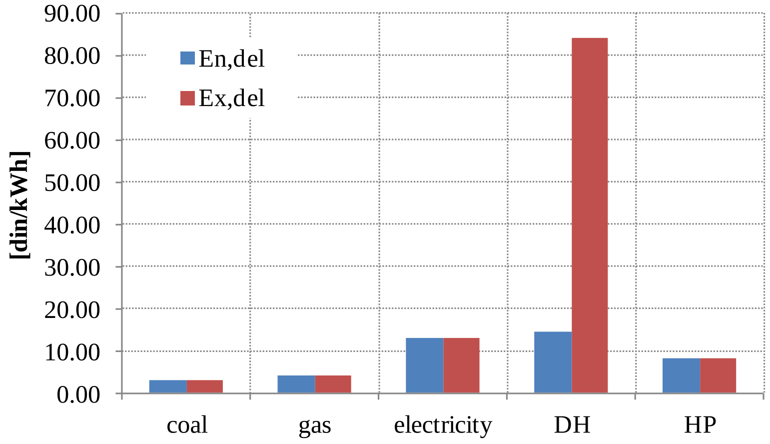

Fig. 5. Prices of delivered energy and exergy for heating

In fig. 6. the values of exergy efficiency are shown, averaged for whole season, for different fuels used for hot water preparation. Values are higher than for heating, because of the higher temperature of water which has to be prepared for DHW, but still reasonably low for primary values.

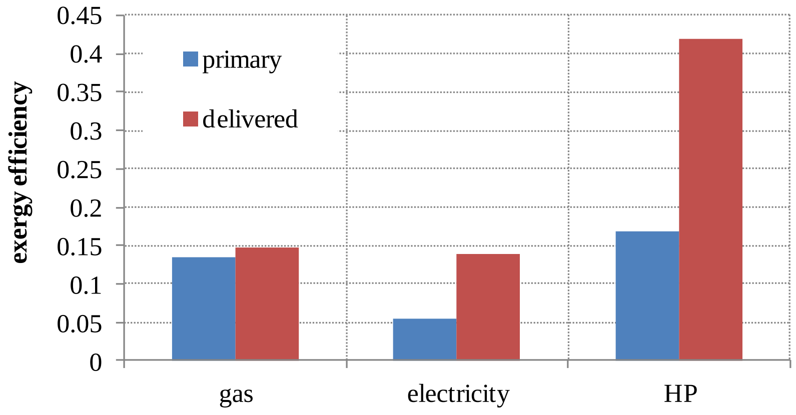

Fig. 6. Exergy efficiency (primary and delivered) for different energy sources for DHW

Total values of primary energy, primary exergy, CO_2 emission and total energy costs for cases from 1 to 5 are given in fig. 7. Looking at the results, as it was expected, usage of renewable energy sources was shown as energy and exergy the most favorable.

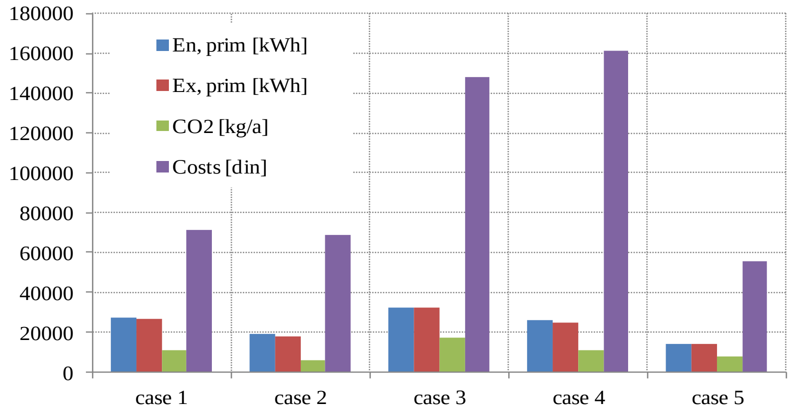

Fig. 7. Total primary energy, total primary exergy, CO_2 emission and costs for different cases

5 Conclusions

The aim of this paper was not to emphasize the best fuel, neither the combination of fuels for usage in buildings, but to show thermodynamic method of fuel and cost valorization. Speaking about heating and DHW preparation for analyzed cases for building, the results suggest that there is not adequate compatibility among energy quality from supplied side and its usage. Thermodynamically, there is no adequate justification for high quality fuels usage for heating and DHW preparation, because of their low exergy efficiency. Waste heat, energy from heat pumps and other renewable energy sources better fulfill this purpose. It is important to emphasize that whole chain of energy transfer has to be analyzed, starting from primary energy, because that is the only manner to get the appropriate conclusion. From exergy analysis it is possible to draw out the important conclusion such is that in an exergy efficient energy system, combustion processes should not be used for direct production of low temperature heat.

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