Evacuated tube heat pipe solar water heating system

1. Introduction

Market instability of fossil fuels, import resources dependency and the continuous increase in the fuel price cause more and more consumers to turn to the use of biomass for residential heating. In Romania, the government action to support the purchase of efficient residential heating boilers on biomass and promote the use of renewable energy resources, resulted in boosting the use of combined biomass and solar heating systems also called solar-biomass hybrid heating system or solar combisystems.

Biomass burning for heat production is the oldest and most common way of converting solid biomass into energy. There are currently on the European market a wide span of different power boilers that use firewood, chips, briquettes and pellets made of wood or agricultural residues. They can be manually or automatically fed, with normal or downdraft combustion. Besides thermal performance, the pollutant emissions from the heating system are important evaluation criteria. In the EU, legislative regulations and incentives are used for continuous improvement of biomass boilers performance. The European Standard EN 303-5: 2012 (Heating boilers - Part 5: Heating boilers for solid Fuels, manually and automatically stoked, nominal heat output of up to 500 kW - Terminology, Requirements, testing and marking) deals with performance requirements of solid fuel boilers for five classes (class 1-5) for the requirements of efficiency and defines the emission limits. Using the staged combustion, fuels with low water content (only 22.5% for wood chips and 14.5% for wood), the minimum requirements for thermal efficiency, and sophisticated control that optimizes combustion, the first 25% of the European best commercially available technologies far exceed the performance requirements (thermal efficiency and emissions) even for classes 4 and 5 of EN 303-5: 2012 [1, 2].

The use of solar thermal energy in combination with a pellet heating system reduces burner on/off-cycling rates, fuel use and electricity consumption considerably, because the solar heat gain reduces the boiler inefficient operation during the spring, summer and autumn [3]. It has been shown that using the solar heat store to buffer heat from a small pellet boiler is not advantageous from an energy efficiency point of view and that over dimensioning of the boiler has strong negative impacts on the overall system efficiency and on the on/off-cycle rates [3].

The use of a combined solar - biomass heating system instead of the conventional one (biomass heating system) in a building with high heating demand can result in higher savings and shorter payback period than the ones with better thermal insulation [4].

The hybrid solar thermal-biomass heating systems have the advantage of easily integration in any existing heating system, combination with conventional heating components (radiators, fan coils, floor heating, etc.) and replacement of the conventional heating source [5].

To optimize the hybrid solar-heating biomass systems, many studies were conducted with different objectives such as: annual energy cost, payback time, solar fraction, energy performance in the operation stage, energy performances in all stages (eg, production, operation and maintenance), embedded energy, carbon monoxide emission, pollutant emissions (NO_x, dust), energy saving etc. The optimum functioning parameters of the systems were determined by experiments or numerical simulations. Among the most widely used simulation tools are: TRNSYS, EnergyPlus, CIBSE, RESET, Equest, Polysun, Homer, SUNREL, Energy-10 etc. All these studies are necessary because oversizing the system components leads to high costs of investment and operation, while the undersizing the systems leads to uncovering of the heating demand or hot water demand, or to low solar heat gain.

The design of hybrid solar-biomass heating systems must start from knowing the variation of heating and domestic hot water demands to avoid as much as the energy mismatch, which usually causes the system performance to be overestimated. About 40% of the harvested solar heat gain is wasted due to the energy mismatch between the heating load demands and solar energy supply [6].

In the life-cycle studies of these systems has been found out that the optimized volume of heat storage tank is strongly dependent on the collector area while the impact of tank volume on the optimization of collector area is very limited [6].

An optimisation performed for a combined objective function-primary energy use and CO emissions with non-zero weighting factors revealed that the results are higher than if the optimisation is performed individually for primary energy use and CO emissions (2% higher primary energy use and 7% higher CO emissions). The study suggested the use and equal weighting of the annual primary energy use in MWh and CO emissions in kg for future optimisations [7].

Some works evaluated, based on the exergoenvironmental analysis, the renewable energy system-related environmental impact per kWh exergy demand expressed in Impact 2002+ points per unit of time [8] or in Eco-indicator99 impact factors [9]. The analyses generate information on environmental impacts associated with thermodynamic inefficiencies (exergy destruction) and on impacts associated with the construction, operation, maintenance and disposal of components.

The environmental performance in terms of kg CO_2 equivalent of solar biomass hybrid systems is the highest in comparison with the other fuels, while the performance in terms of energy pay-back time is the lowest, because biomass is the fuel with lowest environmental impact and associated embodied energy and therefore the avoided embodied energy due to the solar contribution in solar hot water system is the lowest in the biomass case [10].

In work [11] a solar biomass hybrid system with thermal storage was optimised using as objectives the annual costs during the calculation period, emissions, fuel consumption and utilization of renewable energy, and their combinations. It was noted that the use of solar collectors leads to the boiler size decrease and storage volume increase. The CO_2 emissions increase with the storage volume and decrease with the size of solar collectors.

In paper [12] it is shown that the heat storage enables higher primary energy savings for higher average outdoor temperatures and that during the period with small heat load it is sometimes necessary to have two small boilers to reduce the time when the boiler is not working.

The life cycle assessment of the solar water heating systems revealed that the energy spent for the manufacture and installation of the solar systems is recovered in few months, whereas the payback time with respect to emissions produced from the embodied energy required for the manufacture and installation of the systems varies from a few months to few years depending on the fuel type and the particular pollutant considered [13].

In the environmental impact assessment of a building heating with biomass and solar energy a CO_2 emission of 0.023 kg-CO_2/kWh was considered for the biomass material (soft wood) during its collection, transportation and processing and 0.00647 kg-CO_2/kWh was considered for the flat plate solar collector manufacturing [14].

In this paper it is presented a combined energy, economic and environmental analysis of an optimally sized and configured solar combisystem for residential heating. The analysis starts with the evaluation of heating and domestic hot water demands and takes into account the recommendations for optimal plant configuration selection to avoid oversize and to obtain the minimum total yearly operation cost, cost which includes capital cost, maintenance and operation cost and environmental cost. The analysis is useful for designers who should develop eco-labelled products with a reduced environmental impact throughout their life cycle and also for consumers who, when buying equipment, want to know the total operation cost, and recently the cost related to carbon tax and pollutant emissions. The purpose of the paper is also to summarize the current progress in combined solar-biomass heating systems.

2. Heating and domestic hot water demand

The specifications of considered building are presented in Table 1. The calculation of heating and domestic hot water demand requires data on site weather and on building occupancy and specification. The weather data for the building site is given in Table 2.

Table 1. Building parameters

Parameter	Value	Parameter	Value
South wall area	96 m^2	Type of insulation material	polyurethane
North wall area	96 m^2	Total surface of the windows	15 m^2
East wall area	36 m^2	Window frame	aluminium
West wall area	36 m^2	Window type	double glass
Temperature outside of the building	-18°C	Occupancy	5 people
Temperature inside of the building	20°C	Wall and roof transmittance	2 W/m^2K
The floor surface	96 m^2	Window transmittance	3 W/m^2K
Building volume	576 m^2	Lighting load	15 W/m^2
Thickness of the insulation layer	10 cm	Equipment load	30 W/m^2
Thickness of the main structure	20 cm	People load	130 W/person

Table 2. Weather data for considered site (Galati, Romania) [15]

Month	Average ambient temperature [°C]	Average water temperature, t_{wc} [°C]	Average daily radiation on South facing surface set at a 45° angle [$kWh/m^2 \cdot d$]	Solar irradiance on South facing surface set at a 45° angle [W/m^2]	Degree-days for heating, HDD [°C·d]
January	-1.70	5	2.77	115.42	611
February	-0.60	8	3.65	146.84	521
March	5.00	10	4.34	180.83	403
April	11.10	12	5.24	218.33	207
May	16.70	15	5.53	230.42	40
June	20.00	18	5.87	244.58	0
July	21.70	20	5.91	246.25	0
August	21.70	18	5.79	241.25	0
September	17.80	15	5.26	212.10	6
October	11.70	12	4.51	187.92	195
November	5.00	10	2.98	120.16	390
December	0.60	7	2.29	95.42	539

At European level there is the Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings which set a methodology to calculate energy performance of buildings. The EU member states can use this methodology or can adopt their own methodology. In Romania there is a standard for calculation of the annual heat demand for heating for residential buildings based on the global thermal insulation coefficient [16].

According to this method the monthly heat demand for heating is given by the following equation:

$$Q_{mh} = \frac{24}{1000} F \cdot HDD \cdot G - \left(Q_i + Q_s\right), \text{ kWh/m}^3 \qquad (1)$$

where: Q_i – heat generated by occupants, electrical and electronic devices; Q_s – solar heat gain:

$$Q_s = 0.4 \sum_{ij} I_{Gj} \cdot g_i \frac{A_{Fij}}{V}, \text{ kWh/m}^3 \quad (2)$$

I_{Gj} – global solar radiation available to the cardinal orientation "j"; g_i – transmittance of window type "i"; A_{Fij} – area of window type "i" facing the cardinal orientation "j";

The daily necessary heat amount for domestic hot water is calculated by the equation:

$$Q_{dhw} = c_p \frac{G_{hw}^N \cdot N}{3600} (t_{wh} - t_{wc}), \text{ kWh} \quad (3)$$

The monthly heating demand and domestic hot water demand for considered building are shown in Fig. 1.

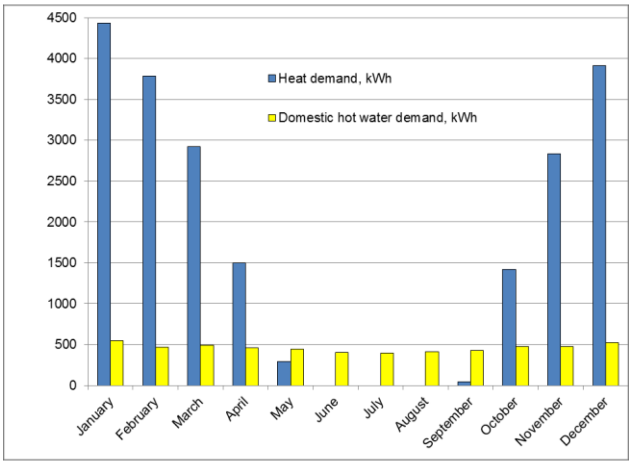

Fig. 1. Heat demand for heating and domestic hot water.

The building heating process starts in September and ends in May. The lowest heat demand is in September (43.546 kWh) and the highest heat demand is in January (4434.394 kWh). The domestic hot water demand is almost constant during a year, with soft lower values during summer.

3. System description

The hybrid solar-biomass heating system includes a biomass heating boiler, two evacuated-tube solar collectors, a heat storage tank, a buffer tank, a variable-speed pump (P1) for solar collector loop and two fixed-volume pumps for boiler loop (P2) and for heating loop (P3), respectively (Fig. 2). Pump P1 was chosen with variable flow rate to improve the heat transfer from the solar collectors. The buffer tank was included in the system in order to reduce the number of boiler start/stops, during which high CO emissions occur [17]. Also to reduce the CO emissions the boiler control system must achieve modulating boiler output. It was observed that a larger buffer volume does not lead to a significant decrease in CO emissions even if the number of start/stops can be further reduced, but it leads to increased heat losses which in turn should be covered by the boiler and the solar collector. In paper [17] it was found out that the optimum buffer volume is about 140 l [17]. In paper [12] the recommended buffer volumes is (0.04-0.08) m^3/kW. The volume of heat storage tank was selected according to the recommendation given in [18] as function of the area of the solar collectors (50 l/m^2) in order to achieve a good plant thermal balance. In paper [15] it is recommended a storage capacity of 37.5 litres per m^2 of solar collector and an 80% efficient heat exchanger can be assumed. The power of circulation pump (P1) is assumed to be about 5 W per m^2 of solar collector and the heat losses in the collector are estimated at 2% in the collector and 3% in the balance of system [15]. The minimum temperature of water of 60°C in heat storage tank is used to ensure that sufficient hot water is available at any time and to avoid growth of Legionella bacteria.

The efficiency of the selected evacuated-tube solar collectors is given by the following equation:

$$\eta_{sc} = 0.825 - 1.19\frac{T_i - T_a}{I_T} - 0.009\frac{(T_i - T_a)^2}{I_T} \tag{4}$$

The monthly amount of heat produced by the solar collectors is:

$$Q_{sc} = \eta_{sc} \cdot A_{sc} \cdot G_T \text{, kWh} \tag{5}$$

A comparison between the total heat demand and the amount of heat produced by the solar collectors is given in Fig. 3.

The selected biomass boiler has 15 kW power and 0.91 thermal efficiency.

The monthly amount of heat produced by the heating boiler is:

$$Q_b = \frac{\eta_b \cdot m_f \cdot LHV}{3600} \text{, kWh} \tag{6}$$

Two solar collectors with area of 3 m^2 each were chosen to cover the domestic hot water demand only during summer. The solar gains cover partially the heat demand during March, may, September and October.

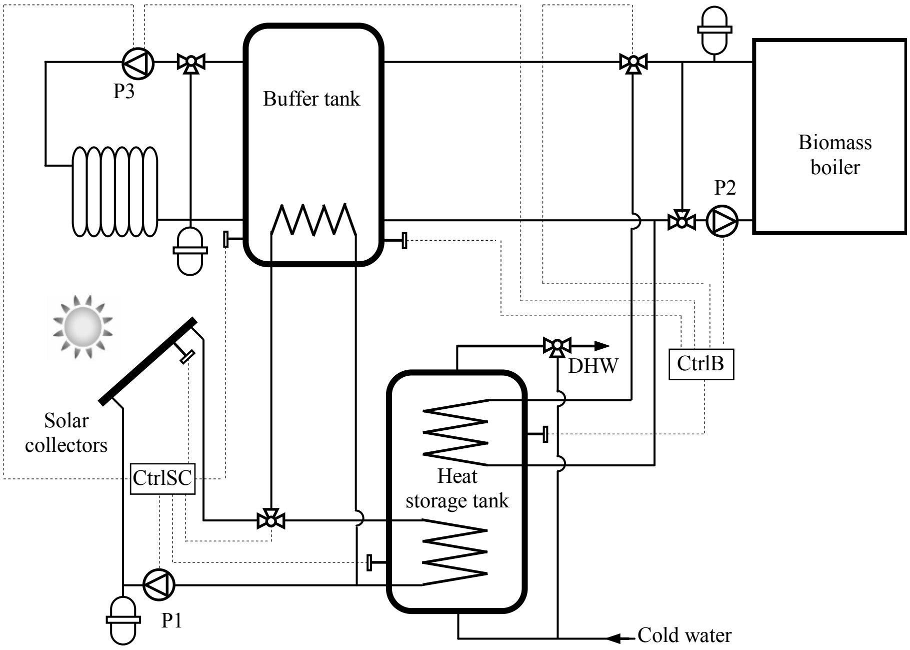

Fig. 2. Schematic diagram of the combined solar-biomass heating system.

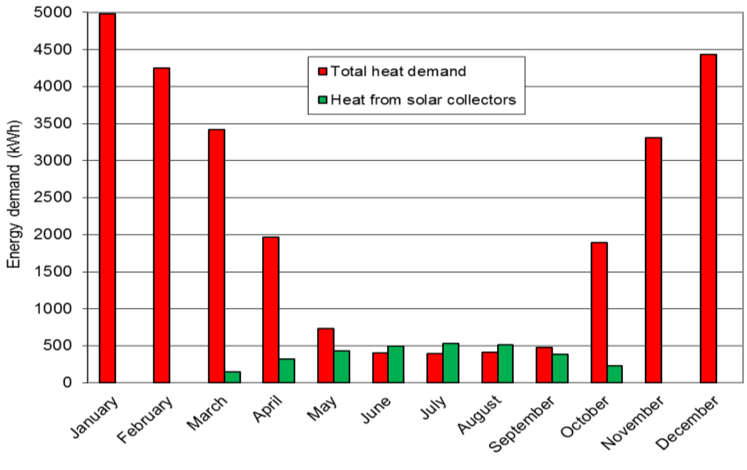

Fig. 3. The monthly heat demands and heat generated by solar collectors.

4. Exergy analysis

Exergy expresses the quality of an energy source. The exergy efficiency of the heating system is the ratio of the total (annual) exergy demands of the building to the total exergy supplied to building [19]:

$$\varepsilon = \frac{Ex_{demand}}{Ex_{solar} + Ex_{biomass} + W_{pumps}} \tag{7}$$

where:

$$Ex_{demand} = Q_{ah}\left(1 - \frac{T_0}{T_{ia}}\right) + Q_{adhw}\left(1 - \frac{T_0}{T_{dhw}}\right) \tag{8}$$

Q_{ah}, Q_{adhw} – annual demand for heating and domestic hot water respectively; T_{ia} - inside air temperature, K; T_{dhw} – domestic hot water temperature, K;

$Ex_{biomass}$ - biomass exergy estimated as function of lower heating values and elemental analysis [20]:

$$Ex_{biomass} = m_{af} \cdot e_f = m_{af}\{4.1868[8177.79C + 5.25N + 27.892H - 3173.66O +$$
$$+ 0.15O(7837.67C + 33888.89H - 4236.1O)]\} \tag{9}$$

m_{af} – annual fuel consumption, kg; C, H, O, N, S - mass fractions of elements, wt%.

Ex_{solar} - exergy received by solar collector [25]:

$$Ex_{solar} = A_{sc} G_T \left[1 - \frac{4T_0}{3T_s} + \left(\frac{4T_0}{3T_s}\right)^4\right]$$

T_s – solar temperature.

4. Environmental analysis

The environmental impact analysis of the building heating system takes into consideration the CO_2 emission and energy rates based on its life cycle assessment (LCA) and the pollutant emissions generated during operation. The CO_2 emissions of heating boiler are omitted as the biomass is a CO2 neutral energy source.

According to LCA, the CO_2 emissions released during the manufacturing is 0.023 kg CO_2/kWh for biomass fuel and 0.00647 kg CO_2/kWh for solar collector [14]. The CO_2 amount released from natural gas fired thermal power station for electricity generation is 0.712 kg CO_2/kWh [14].

The pollutant emissions of the selected biomass heating boiler (automatic pellet boiler with 15 kW power) are: 500 mg CO/m^3 and 40 mg dust/m^3 at 10 vol% O_2 according to the EN 303-5:2012 - class 3 [21], and 150 mg NO_x/m^3 at 10 vol% O_2 according to the eco-labels Blauer Engel-mark [14].

5. Economic analysis

The total yearly cost related to the combined solar-biomass heating system includes cost of fuel (C_f), cost associated with capital investment (Z^{CI}), operating and maintenance (Z^{OM}) and environmental cost (C_{env}):

$$C_{tot} = C_f + Z^{CI} + Z^{OM} + Z_{env},\ € \tag{10}$$

The fuel cost is:

$$C_f = m_{af} \cdot c_f,\ € \tag{11}$$

where:

c_f – specific cost of fuel, €/kJ. For biomass pellets c_f=0.037 €/kWh;

The cost associated with capital investment is given by the following equation:

$$Z^{CI} = \varphi \cdot i \cdot \frac{(1+i)^n - j}{(1+i)^n - 1} \sum_k C_k \quad , € \tag{12}$$

φ =1.06 is maintenance factor; i =10% is annual rate of return; j =12% is effective rate of return; n =20 years is the heating system life period;

$$\sum_k C_k = C_{boiler} + C_{SC} + C_{TK1} + C_{TK2} + C_{P1} + C_{P2} + C_{P3}, € \tag{13}$$

C_{boiler}, C_{SC}, C_{TK1}, C_{TK2}, C_{P1}, C_{P2}, C_{P3} – initial investment cost of boiler, solar collectors, storage tank, buffer tank, circulation pump P1, circulation pump P2 and circulation pump P3 respectively (Tab. 3);

$$Z^{OM} = Z_{el} + Z_{SC}^{M} , € \tag{14}$$

Z_{el} - cost associated to electricity consumption:

$$Z_{el} = W_{pumps} c_{el} \ , € \tag{15}$$

Z_{SC}^{M}- cost associated to solar collector maintenance: Z_{SC}^{M}=265 €/an (annual inspection and replacement of the water/glycol mixture every 7 to 10 years) [15];

$$Z_{env} = m_{CO} c_{CO} + m_{NO_x} c_{NO_x} + m_{CO2} c_{CO_2} + m_{dust} c_{dust}, € \tag{16}$$

m_{CO} – carbon monoxide amount released by the biomass heating boiler in a year, kg; m_{NOx} – nitrogen oxide amount released by the biomass heating boiler in a year, kg; m_{CO2} – sum of CO_2 amount corresponding to biomass production, CO_2 amount released during solar collector manufacturing and CO_2 amount released at electricity generation in a year, kg; c_{CO}, c_{NOx}, c_{CO2}, c_{dust} – damage or external cost of CO, NO_x, CO_2 and dust respectively, €/kg (Tab. 4).

Table 3. Initial investment of the components.

Component	Cost, €	Source
Pellet boiler	$180P + 431$	[11]
Evacuated – tube solar collector	$141.6 A_{GSC}$ A_{GSC} – gross solar collector area, m^2	[11]
	$700 A_{SC}$	[18]
Thermal storage tank (TK1 and TK 2)	$1805.8 \ln V + 4082.9$	[11]
Heat storage tank	50 l/m^2	[18]
	37.5 l/m^2	[15]
Buffer tank	140 l	[17]
	(0.04-0.08) m^3/kW	[12]
Variable-volume pump (P1)	$389 \ln\left(\frac{\dot{m}_{p1}}{1000}\right) + 717$ $\dot{m}_{p1} = \varphi_{P1} A_{SC}$; φ_{P1} = 222kg/(h·m^2)	[18]
Fixed-volume pump (P2 and P3)	$389 \ln\left(\frac{\dot{m}_p}{1000}\right) + 283.15$	[18]

Table 4. Damage costs (external costs).

Pollutant	Cost	Source

CO	0.002 €/kg	[13]
	0.52 $/kg	[24]
	0.029 €/kg	[13]
CO_2	(0.013-0.016) $/kg	[14]
	0.02086 $/kg	[23]
NO_x	6.853 $/kg	[23]
	2.8 $/kg	[24]
Dust	4.3 $/kg	[24]

6. Results and discussion

The analysis results for both combined solar-biomass heating and biomass heating systems are given in Table 5 and Fig. 4. The exergy efficiency is lower by 13 % for combined biomass-solar heating because the exergy of solar gain is higher than the exergy of biomass saved by using the solar collector. The yearly total cost of combined solar-biomass heating is 1564.617 € with 5.8% lower than the total cost corresponding to the biomass heating. The environmental cost is higher for combined solar –biomass heating due to CO_2 cost related to electricity generation in gas-fired power plants. Even the capital cost is higher for the combined solar-biomass heating with 34.28% compared to the biomass heating, the yearly total cost is lower in first case due to the lower cost of fuel and electricity.

Table 5. Energy, exergy and economic analysis result for combined solar-biomass heating and biomass heating.

Parameter	Combined solar – biomass heating	Biomass heating
Exergy efficiency	6.281	7.229
Fuel consumption, kWh	26957.483	29304.810
Fuel & electricity cost, €	1463.078	1590.476
Capital cost, €	86.828	56.976
Environmental cost, €	14.711	13.653
Total cost, €	1564.617	1661.105

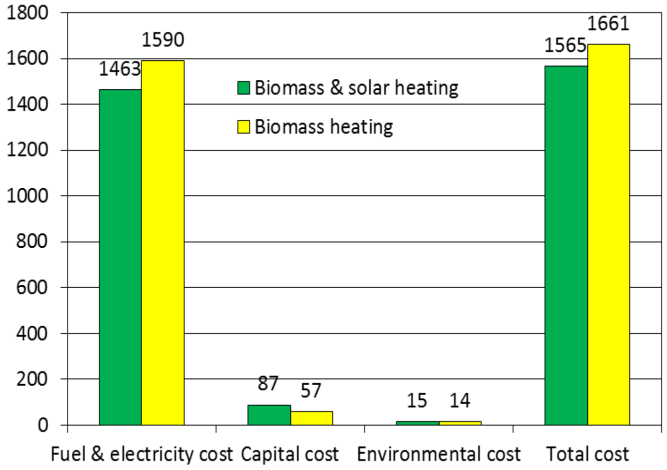

Fig. 4. Cost for combined biomass-solar heating and biomass heating.

Fig. 5 shows the participation of different types of costs to the total cost formation for combined solar-biomass heating.

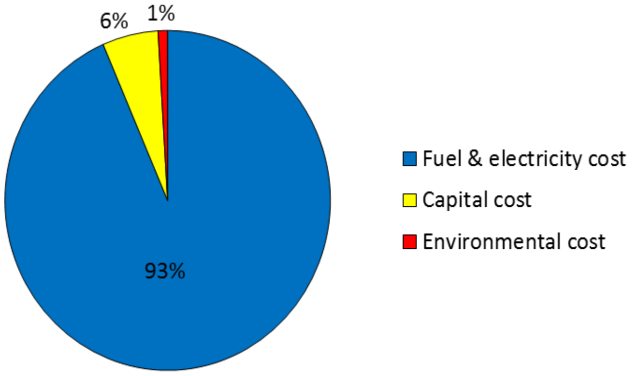

Fig. 4. The weight of different costs in the total cost of combined solar-biomass heating.

It can be seen in Fig. 4 that the cost of fuel and electricity has the highest weight (93%), followed by the capital cost (6%) and environmental cost (1%).

The performed analysis provides information about the possibilities for design improvements of the boiler furnace related to energy efficiency and environmental impact.

6. Conclusions

The combined solar-biomass heating and biomass heating options are analysed from energy, exergy and economic point of view. The analysed building has the following characteristics: floor area is 96 m^2, volume 576 m^3, inside building temperature is 20°C and the outside average temperature is -18°C. The heating system was designed taking into the consideration the recommendations from the previous optimisations studies. The pellet boiler has 15 kW power, the evacuated-tube solar collector has the total surface of 6 m^2, the storage tank has a volume of 300 l and the buffer tank has a volume of 140 l. Two storage tanks were used in order to reduce the CO and NO_x emissions during the start/stop events of biomass heating boiler. The solar collector surface and tilt angle was chosen 6 m^2 and 45° respectively in order to cover the domestic hot water during the summer season. The use of solar energy in the biomass heating system leads to a lower exergy efficiency (6.281 instead of 7.229), lower total cost (with 5.8%) and saving in fuel cost of about 8.7 %. The cost of fuel and electricity has the highest share (93%) in the total cost, followed by the capital cost (6%) and environmental cost (1%).

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Nomenclature

C	cost
c	specific cost
c_p	specific heat of water at constant pressure, kJ/(kg·°C)
F	correction factor (depends on *HDD*)
G_T	global solar radiation on the collector surface, Wh/m^2
G_{hw}^{N}	daily consumption of hot water per person, l/person
g_i	transmittance of window type "i"
HDD	monthly number of degree-days for heating, °C·days
I_{Gj}	global solar radiation available to the cardinal orientation "j", kWh/(m^2·an)

LHV – lower heating value, kJ/kg.

m	mass, kg
N	number of people in the building;
Q_i	heat generated by occupants, electrical and electronic devices
Q_s	solar heat gain, kWh/m^3
T	temperature, K
t	temperature, °C

Greek symbols

η	thermal efficiency
ε	exergy efficiency
φ	maintenance factor

Subscripts and superscripts

a	annual/ambient air
b	boiler
dhw	domestic hot water
el	electricity
env	environment
f	fuel
i	solar collector inlet
ia	inside air
m	monthly
sc	solar collector
wc	cold water
wh	hot water
tot	total
CI	capital investment
OM	operation and maintenance

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