Efficiency of biomass energy used for heating purposes in a residential building in comparison with other energy sources

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Summary. This paper discusses the results of analyses investigating the energy efficiency of biomass in comparison with other popular energy carriers used for heating, ventilation and water heating in residential buildings. The compared energy sources were lignite, natural gas, heating oil and electricity produced by conventional and integrated power generation plants. The most efficient variant relying on biomass and the least efficient variant that involves electricity generated by a conventional power plant were described in detail for the harsh climate zone of Suwałki region in Poland (climate zone V).

The demand for energy in a residential building was analyzed, taking into account six variants of heating. Primary energy consumption ranged from 82.65 kWh×(m²×year)$^{-1}$ for biomass to 481.05 kWh×(m²×year)$^{-1}$ for electric energy generated in the grid system. Intermediate values were obtained for the other energy carriers analyzed in the study. Biomass-generated energy accounts for approximately 17% of the primary energy from the public grid that is needed to power the studied building.

Key words: biomass, energy efficiency, residential building, primary energy carriers, microgeneration.

SYMBOLS AND ABBREVIATIONS

A_f – heated area in a building or apartment, m²,
c_w – specific heat of water - 4.19 kJ×(kg×K)$^{-1}$,
$E_{el,pom,H}$ – annual demand for final electric energy to supply auxiliary heating and ventilation devices, kWh×(year)$^{-1}$,
$E_{el,pom,W}$ – annual demand for final electric energy to supply auxiliary water heating devices, kWh×(year)$^{-1}$,
EK – index of annual demand for final energy in a building, kWh×(m²×year)$^{-1}$,
EP – index of annual demand for primary energy in a building, kWh×(m²×year)$^{-1}$,
j.o. – unit of reference (person),
k_t – correction factor for hot water temperature other than 55°C,
L_i – number of units of reference (persons)
$Q_{H,nd}$ – demand for energy in a residential building, kWh×(year)$^{-1}$,
$Q_{H,gn}$ – monthly indoor heat gain and solar gain, kWh×(month)$^{-1}$,
$Q_{H,ht}$ – monthly heat loss caused by heat transfer and ventilation, kWh×(month)$^{-1}$,
q_{int} – thermal load of premises with indoor gain, W×m^{-2},
Q_{int} – monthly indoor heat gain, kWh×(month)$^{-1}$,
$Q_{K,H}$ – annual demand for final energy in heating and ventilation systems, kWh×(year)$^{-1}$,
$Q_{K,W}$ – annual demand for final energy in the water heating system, kWh×(year)$^{-1}$,
Q_P – annual demand for primary energy in heating, ventilation, water heating systems and auxiliary devices, kWh×(year)$^{-1}$,
$Q_{P,H}$ – annual demand for primary energy in heating and ventilation systems, kWh×(year)$^{-1}$,
$Q_{P,W}$ – annual demand for primary energy in the water heating system, kWh×(year)$^{-1}$,
Q_{s1} – solar gain through windows in vertical partitions, kWh×(month)$^{-1}$,
Q_{s2} – solar gain through roof windows, kWh×(month)$^{-1}$,
Q_{sol} – solar gain, kWh×(month)$^{-1}$
$Q_{W,nd}$ – demand for water heating energy, kWh×(year)$^{-1}$,
t_M – number of hours per month, h×(month)$^{-1}$,
t_{UZ} – operating time (day),
V_{CWi} – unitary daily consumption of hot water, dm³×(day×j.o.)$^{-1}$,
w_{el} – index of non-renewable primary energy expenditure required to generate and supply electric energy to the analyzed building,
w_H – index of non-renewable primary energy expenditure required to generate and supply heating energy to the analyzed building,
w_W – index of non-renewable primary energy expenditure required to generate and supply water heating energy to the analyzed building,

$\eta_{H,d}$ – annual seasonal distribution efficiency of a heat carrier in a building,
$\eta_{H,e}$ – annual seasonal efficiency of heat control and heat consumption in a building,
$\eta_{H,g}$ – annual seasonal efficiency of heat generation from the energy supplied to a building's boundary layer (final energy),
$\eta_{H,gn}$ – heat gain index in heating mode,
$\eta_{H,s}$ – mean annual efficiency of heat storage in capacitators of the building's heating system (within or outside the boundary layer),
$\eta_{H,tot}$ – total efficiency of a building's heating system,
$\eta_{W,d}$ – mean annual efficiency of hot water distribution in a building,
$\eta_{W,e}$ – mean annual heat efficiency (equal to 1.0),
$\eta_{W,g}$ – mean annual efficiency of heat generation from the energy supplied to a building's boundary layer (final energy),
$\eta_{W,s}$ – mean annual efficiency of hot water storage in capacitators of the building's hot water system (within or outside the boundary layer),
$\eta_{W,tot}$ – total efficiency of the water heating system,
Θ_{CW} – hot water temperature in the feed valve, 55°C,
Θ_{O} – cold water temperature, 10 °C,
ρ_{W} – water density, 1000 kg×m^{-3}.

INTRODUCTION

The looming danger of depletion of non-renewable energy sources, rapid climate change, the advances made in technologies that rely on alternative energy sources, including biomass [11, 19, 25], and environmental pollution [5, 28] spur new research into the energy efficiency of biomass [1, 2, 3, 14, 25, 27]. The Act on Energy Efficiency of 15 April 2011 (Journal of Laws No. 94, item 551) defines energy efficiency as *the ratio of total energy input to a building, machine or equipment under standard operating conditions to the amount of energy consumed by that building, machine or equipment to deliver the anticipated effect*. In this paper, the concept of energy efficiency is understood as the amount of non-renewable primary energy required to meet heating, ventilation and hot water needs of a building. The methodological aspects of energy efficiency have been discussed in detail by Patterson [20]. According to the law of energy conservation in a closed system, generation capacity (or reserve energy from an energy store) is needed for the required amount of energy to be supplied to a recipient at any given moment. This requirement is apparently easy to fulfill, but in practice, it is fraught with numerous technical, logistic and transport problems. To illustrate, the transport of large quantities of raw materials, such as bituminous coal, lignite, crude oil, natural gas or biomass (Table 1), requires complex logistic (coordination of deliveries), transport (geographic distance) and technical (infrastructure) processes. Those requirements often pose a substantial barrier due to high investment costs, ineffective distribution systems or environmental concerns [10].

In view of the above, the energy efficiency of various sources should be analyzed in a broader context. The selection of optimal generation methods and energy sources requires comprehensive evaluations [13] that account for legal and economic aspects [8, 9], physical properties [12]

Table 1. Percentage of primary energy sources used in Poland

No.	Energy source \ Year	2000	2005	2007	2008	Unit
1	**Bituminous coal**					
	Domestic consumption	84890	78722	84587	80415	×10^6 kg
	Consumption in electric power plants, CHP plants and heat plants	51628	50903	52937	48968	×10^6 kg
2	**Lignite**					
	Domestic consumption	59487	61589	57528	59371	×10^6 kg
	Consumption in electric power plants, CHP plants and heat plants	59149	61075	56895	58646	×10^6 kg
3	**Crude oil**					
	Domestic consumption	18081	18191	20024	21036	×10^6 kg
4	**Methane-rich natural gas**					
	Domestic consumption	10119	12694	12728	13036	hm^3
	Household consumption	3052	3414	3341	3347	hm^3
5	**Nitrogen-rich natural gas**					
	Domestic consumption	3028	3514	3535	3386	hm^3
	Household consumption	699	450	462	432	hm^3

Source: Own study based on [Directive 2002/91/CE]

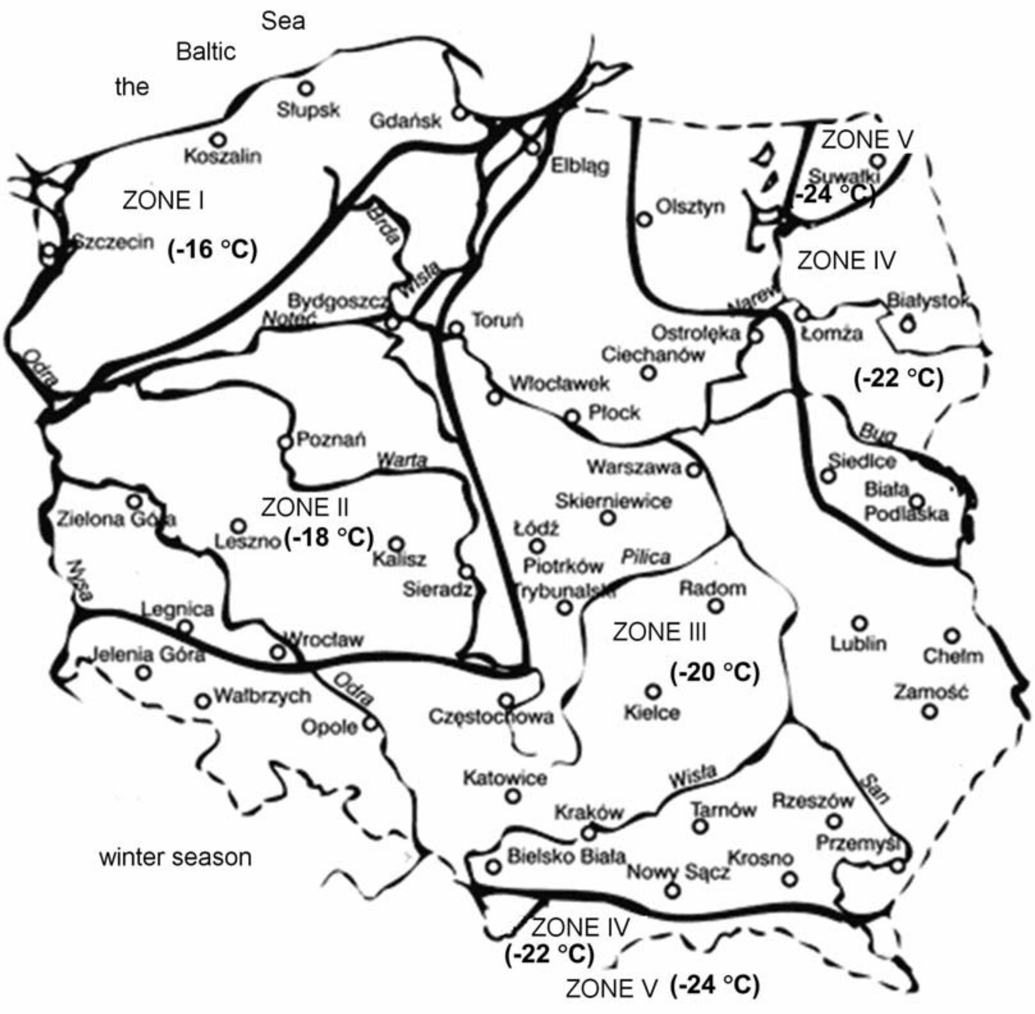

Fig. 1. Climate zones in Poland in the winter season, from October to March (as per standard PN-76/B-03420)

and the latest technological solutions [6, 7]. Alternative sources of energy should play an important part in this process, especially because they eliminate logistic and transport concerns in the generation process (energy is generated at the site of use). Unconventional energy sources should deliver additional benefits to justify their use. At present, alternative sources of energy have a low output, therefore, their use is generally limited to small buildings or sites with low energy requirements.

According to the available data, Polish housing and service sectors are responsible for more than 40% of final energy consumption, and this value is growing. The above can be attributed to the relatively low level of awareness about energy saving measures and energy performance of residential buildings. The energy efficiency of biomass and other energy sources under severe climatic conditions has never been compared in Polish literature.

The objective of this study was to present and discuss the results of energy efficiency analyses of biomass and popular energy carries used for heating purposes in a typical single-family house. The article focuses on both scientific and utilitarian aspects of the analyzed problem. The materials and methods are overviewed in the first part of this paper, whereas the second part discusses the results and proposes practical solutions.

MATERIALS AND METHODS

The energy efficiency analysis of the Polish housing sector was performed on the example of a typical single-family house (Table 2) in the city of Suwałki (this information is needed to calculate solar gains) in Poland's most energy-intensive climate zone V (Fig. 1).

The reference building used in this study was a single-family, two-storey house inhabited by a family of five (this information is needed to determine hot water demand). The structure and technical systems in the analyzed building were consistent with the requirements and guidelines of the relevant laws, in particular the Regulation of the Minister of Infrastructure of April 2009 amending the regulation on the technical requirements set for buildings and their surroundings (Journal of Laws of 7 April, 2009, No. 75, item 690).Various calculations were performed to determine the benefits delivered by the analyzed energy sources in the building (Table 2) [21, 22, 23, 24]. The calculation procedure was consistent with the provisions of the Regulation of the Minister of Infrastructure of 6 November 2008 on the calculation methodology for determining the energy performance of a building or an apartment or a part of a building that constitutes a technically integral whole and the manner of developing energy performance certificates and templates (Journal of Laws of 2008, No. 201, item 1240).

In line with the above regulation, the demand for energy is determined by a number of factors, including thermal insulation of walls, structural parameters, performance of energy supply systems and functional properties (for example, the number of inhabitants, temperatures and air exchange rates in the building). An analysis of demand for energy from various sources (at a constant level of energy consumption in the building) supports the determination of differences in primary energy expenditures, defined as the amount of non-renewable energy supplied by technical systems, for heating, ventilation and water heating purposes in the building.

Table 2. Main parameters of the analyzed building.

Building parameters	
Built-up area	116 m^2
Cubic capacity	535.1 m^3
Net floor area with controlled temperature	184.6 m^2
Location	climate zone V
Air-conditioning system	none
Ventilation system	natural
Cubic capacity of heated rooms	458.6 m^3

The measured parameters were expressed as follows:

– index of annual demand for final energy in the building:

$$EK = (Q_{K,H} + Q_{K,W}) \cdot A_f^{-1},$$

– primary energy index:

$$EP = Q_p \cdot A_f^{-1},$$

– total efficiency of the building's heating system:

$$\eta_{H,tot} = \eta_{H,g} \cdot \eta_{H,s} \cdot \eta_{H,d} \cdot \eta_{H,e},$$

– total efficiency of the water heating system:

$$\eta_{W,tot} = \eta_{W,g} \cdot \eta_{W,s} \cdot \eta_{W,d} \cdot \eta_{W,e},$$

– annual demand for final energy in heating and ventilation systems:

$$Q_{K,H} = Q_{H,nd} \cdot \eta_{H,tot}^{-1},$$

– annual demand for final energy in the water heating system:

$$Q_{K,W} = Q_{W,nd} \cdot \eta_{W,tot}^{-1},$$

– annual demand for primary energy in heating and ventilation systems:

$$Q_{P,H} = w_H \cdot Q_{K,H} + w_{el} \cdot E_{el,pom,H},$$

– annual demand for primary energy in the water heating system:

$$Q_{P,W} = w_W \cdot Q_{K,W} + w_{el} \cdot E_{el,pom,W}$$

– annual demand for primary energy:

$$Q_P = Q_{P,H} + Q_{P,W},$$

– solar gain:

$$Q_{sol} = Q_{s1} + Q_{s2},$$

– monthly indoor heat gain:

$$Q_{\text{int}} = q_{\text{int}} \cdot A_f \cdot t_M \cdot 10^{-3},$$

– annual demand for water heating energy:

$$Q_{W,nd} = V_{CWi} \cdot L_i \cdot c_w \cdot \rho_W \cdot$$
$$\cdot(\Theta_{CW} - \Theta_O) \cdot k_t \cdot t_{UZ} \cdot (1000 \cdot 3600)^{-1},$$

– annual demand for heating and ventilation energy:

$$Q_{H,nd} = \sum_n (Q_{H,ht} - \eta_{H,gn} \cdot Q_{H,gn}).$$

The discussed method may be applied to analyze the consumption of primary energy from various sources and to evaluate the resulting benefits. The following variants were analyzed to determine the demand for primary energy and energy consumption in the studied building:

– *variant* 1 – the source of energy for central heating and water heating systems was lignite with calorific value of 2.680 kWh/kg (9.648 MJ/kg),
– *variant* 2 – the source of energy for central heating and water heating systems was grid electricity,
– *variant* 3 - the source of energy for central heating and water heating systems was biomass with calorific value of 4.280 kWh/kg (15.408 MJ/kg),
– *variant* 4 – the source of energy for central heating and water heating systems was natural gas with calorific value of 9.970 kWh/m^3 (35.892 MJ/m^3),
– *variant* 5 – the source of energy was heat produced in an integrated cycle combining lignite firing in the central heating system with solar energy supplied by thermal solar collectors in the water heating system,

– *variant* 6 – the source of energy for central heating and water heating systems was heating oil with calorific value of 10.080 kWh/l (36.288 MJ/l).

RESULTS

Owing to the vast abundance of material produced by the analyses (*variant* 1 ÷ *variant* 6), only two extreme cases (representing the highest – *variant* 2, and the lowest – *variant* 3, consumption of primary energy) are described in the successive parts of this paper. For easier interpretation, the obtained results were sorted in view of the adopted technical configuration, i.e. they were described separately for heating and ventilation systems and the water heating system. The results illustrating the demand for heating and ventilation energy and water heating energy are presented in Table 3.

Table 3. The results of heat calculations for the analyzed building.

Results of heat calculations for the analyzed building	
Air flow rate	566.5 $m^3 \times h^{-1}$
Seasonal demand for heat	26330.9 kWh×year^{-1}
Index of seasonal demand for heat	57.4 kWh(m^3×year)
Shape factor	0.7 m^{-1}
Limiting factor of seasonal demand for heating energy	34.5 kWh×(m^3×year)$^{-1}$
Solar gain	9561.1 kWh×year^{-1}
Indoor solar gain	430.1 kWh×year^{-1}
Annual demand for water heating energy	2408.73 kWh×year^{-1}

Source: own study

BIOMASS ENERGY

The results of comprehensive calculations that account for the use of auxiliary energy to power circulating pumps in the central heating system and automated boiler controls clearly indicate that biomass energy is the most efficient of the analyzed variants (with the lowest consumption of primary energy at 82.65 kWh×(m^2×year)$^{-1}$). The input values and the results of the analysis of the heating and ventilation system are presented in Table 4. The results reported for the water heating system are shown in Table 5.

The physical parameters representing the demand for primary energy relative to a unit of area in the evaluated building constitute important information in the light of the Regulation of the Minister of Infrastructure (2008) [23, 22]. The value, percentage share and demand for primary energy for heating, ventilation, water heating and auxiliary devices are given in Table 6. The calorific value and the use of various types of biomass have also been discussed by [15, 16, 17].

Table 4. Use of biomass energy for heating and ventilation in the analyzed building

Input values		
1	Energy carrier	Fuel - biomass
2	Selected generation variant	Biomass (straw) boiler with rated output of up to 100 kW, manually operated
3	Selected control variant	Water-circulating heating system with column or panel radiators – in a central heating system
4	Selected transmission variant	Water-circulating heating system with a local generation source and insulated installation
5	Selected storage variant	No buffer tank
6	Overall system efficiency	0.49
Results of analysis		
1	Demand for final energy	53859.63 kWh×year^{-1}
2	Demand for auxiliary energy	1107.6 kWh×year^{-1}
3	Demand for primary energy	14094.73 kWh×year^{-1}

Source: own study

Table 5. Use of biomass energy for the water heating system

Input values		
1	Energy carrier	Fuel - biomass
2	Selected generation variant	Low-temperature boiler with rated output of up to 50 kW
3	Selected control variant	Centrally controlled water heating system with circulation, limited operating time and full piping insulation
4	Selected transmission variant	Small systems with up to 30 water supply points
5	Selected storage variant	Energy-efficient water tank
6	Overall system efficiency	0.58
Results of analysis		
1	Demand for final energy	4167.92 kWh×year^{-1}
2	Demand for auxiliary energy	108.82 kWh×year^{-1}
3	Demand for primary energy	1160.05 kWh×year^{-1}

Source: own study

Table 6. Demand for primary energy in the analyzed building

No.	Primary energy	Heating and ventilation	Hot water	Auxiliary devices	Total
1	Value [kWh×(m^2×year)$^{-1}$]	58.36	4.52	19.77	82.65
2	Share [%]	70.61	5.46	23.92	100

Source: own study

The high share of primary energy needed to power auxiliary devices in the building (Table 6) results from the use of automatic control systems which are supplied solely by grid electricity.

GRID ELECTRICITY

The use of grid electricity is the least energy efficient variant which requires the highest expenditure of primary energy (481.05 kWh×(m^2×year)$^{-1}$). Detailed data for the applied technologies and the reported demand for heating and ventilation energy are presented in Table 7. The input values and the noted results for the water heating system are shown in Table 8 (solutions that would increase the overall demand for energy in the building were not analyzed).

Table 7. Use of grid electricity for heating and ventilation in the analyzed building

Input values		
1	Energy carrier	Electricity – integrated generation
2	Selected generation variant	Electric heaters: convection, surface and radiation heaters, electric floor heating
3	Selected control variant	Electric heaters: convection, surface and radiation heaters
4	Selected transmission variant	Heat source in the room
5	Selected storage variant	No buffer tank
6	Overall system efficiency	0.97
Results of analysis		
1	Demand for final energy	27139.66 kWh×year^{1}
2	Demand for auxiliary energy	0 kWh×year^{1}
3	Demand for primary energy	81418.98 kWh×year^{1}

Source: own study

Table 8. Use of grid electricity for the water heating system

Input values		
1	Energy carrier	Electricity – integrated generation
2	Selected generation variant	Electric storage heater (with lossless storage tank)
3	Selected transmission variant	Water is heated locally at supply points. No water circulation in the system.
4	Selected storage variant	No tank
5	Overall system efficiency	0.98
Results of analysis		
1	Demand for final energy	2457.88 kWh×year^{1}
2	Demand for auxiliary energy	0 kWh×year^{1}
3	Demand for primary energy	7373.65 kWh×year^{1}

Source: own study

The demand for primary energy in the studied building is presented in Table 9, separately for every type of energy use.

Table 9. Demand for primary energy in the analyzed building

No.	Primary energy	Heating and ventilation	Hot water	Auxiliary devices	Total
1	Value [kWh/(m^2×year)]	441.10	39.95	0	481.05
2	Share [%]	91.70	8.30	0	100

Source: own study

The results shown in Table 9 indicate that nearly 92% of energy is used for heating and ventilation, and that the relevant energy expenditure is more than seven times higher in comparison with the biomass variant (Table 6). Such a high demand for electricity can be attributed to a high index of renewable energy expenditure which is set at 3.0 pursuant to the cited Regulation of the Minister of Infrastructure (2008). The above solution was probably introduced by the legislator with the aim of reducing electricity consumption in residential buildings because the public power grid has a relatively low generation efficiency (0.36 ÷ 0.44). High levels of consumption deplete non-renewable sources of energy (mostly coal) and significantly increase harmful emissions to the natural environment, including CO_2 emissions.

CONCLUSIONS

The two extreme cases analyzed in this study were biomass, an unconventional source of energy (with primary energy consumption of 82.65 kWh×(m^2×year)$^{-1}$), and electricity supplied by the public power grid (with primary energy consumption of 481.05 kWh×(m^2×year)$^{-1}$). With regard to the remaining energy carriers, energy consumption values were noted in between the above extremes. The results reported for all tested variants are compared in Figure 2. This comparison points out at significant variations in the quantity of primary energy needed to supply identical residential buildings. Biomass-generated energy accounts for only 17% of the primary energy from the public grid that is needed to power identical buildings. The above fact implies that the demand for primary energy can be reduced by approximately 83%. Measures aiming to economize energy consumption would be particularly valuable in sites located far from generation sources because they would eliminate transfer losses [18]. Such solutions would also limit the depletion of primary energy sources and lower harmful emissions to the environment.

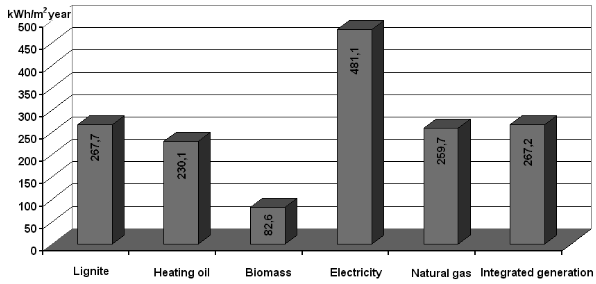

Fig. 2. Primary energy consumption values for all the analyzed variants in a residential building.

Source: own study.

Due to accelerating climate changes and their adverse consequences, the search for the most efficient sources of energy will be a key global challenge in the coming years. The efficiency of energy carriers used for heating, ventilation and water heating in residential buildings is an issue of particular concern. The results of analyses examining the most popular to the most technically demanding solutions (*variant* 1 ÷ *variant* 6), also in the harshest climate zone (V), indicate that biomass is the most efficient energy carrier. The results of our analysis can significantly contribute to planning processes in agriculture and the power industry by illustrating that the consumption of primary sources of energy can be modified and, consequently, economized. They can also provide a valuable input for administrative decisions regarding preferential treatment for selected energy-saving solutions and sources of renewable energy.

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WYDAJNOŚĆ ENERGII BIOMASY STOSOWANEJ DO CELÓW GRZEWCZYCH W BUDYNKU MIESZKALNYM W PORÓWNANIU Z INNYMI ŹRÓDŁAMI ENERGII

S t r e s z c z e n i e. W artykule omówiono wyniki analiz badających efektywność energetyczną biomasy w porównaniu z innymi popularnymi nośnikami energii wykorzystywanymi do ogrzewania, wentylacji i ogrzewania wody w budynkach mieszkalnych. Porównywane źródła energii to: węgiel brunatny, gaz ziemny, olej opałowy i energia elektryczna produkowana przez konwencjonalne i zintegrowane elektrownie. Najbardziej efektywny wariant wykorzystujący biomasę i najmniej efektywny wariant oparty na energii elektrycznej wytworzonej przez konwencjonalną elektrownię zostały szczegółowo opisane dla strefy nieprzyjaznego klimatu Suwalszczyzny w Polsce (klimat strefa V).

Zapotrzebowanie na energię w budynku mieszkalnym było analizowane, biorąc pod uwagę sześć wariantów ogrzewania. Zapotrzebowanie energii zawierało się w zakresie od 82,65 kWh×(m^2×rok)$^{-1}$(w przypadku nośnika energii - biomasy) do 481,05 kWh×(m^2×rok)$^{-1}$) (energia elektryczna – wytworzona w systemie elektroenergetycznym). Pozostałe nośniki energii dotyczą stanów pośrednich. Biomasa stanowi około 17% energii pierwotnej, która byłaby wymagana do zasilenia budynku, w przypadku jej doprowadzania z krajowego systemu elektroenergetycznego.

S ł o w a k l u c z o w e: biomasa, wydajność energetyczna, budynek mieszkalny, nośniki energii, mikrowytwarzanie.