Original Research

Reducing Air Pollutant Emissions from the Residential Sector by Switching to Alternative Energy Sources in Single-Family Homes

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Abstract

Our paper discusses a scenario for adapting residential buildings to the requirements of the EU climate and energy package. It analyzes the option of reducing pollutant emissions to ambient air by switching to alternative energy sources in a typical single-family residential building. The most common sources of energy in central heating and ventilation systems and water heating systems were compared, and the analyzed energy carriers were brown coal, electricity supplied by the electric power grid, biomass, natural gas, heating oil, and combined production (which relies on various energy carriers). In the examined scenarios, special emphasis was placed on carbon dioxide emissions and the value of the equivalent emission factor.

Keywords: energy sources in residential buildings, reduction of pollutant emissions, carbon dioxide, equivalent emission factor, European Union

Introduction

Global economic growth and reports of alarming levels of environmental pollution [1-3], in particular high CO_2 emission levels [4], make rational and effective use of fuels and energy resources the key challenge for the coming years [5-10]. Environmental concerns have been addressed by the Kyoto Protocol [11] and ratified by the European Union and Poland in 2002, which is an international agreement on reducing pollutant emissions to ambient air by increasing the global share of renewable energy sources [12]. The Kyoto Protocol paved the way for further legal regulations on emission reduction, which are implemented by the European Parliament [13] and EU member states, including Poland [14-18].

Despite those efforts and initiatives, on 31 May 2011 the chief economist of the International Energy Agency in Paris, Dr. Fatih Birol, stated that 80% of projected emissions from the power sector in 2020 were already locked in [4]. This seriously challenges the provisions of the Cancun climate change conference in 2010, during which world leaders agreed to reduce emissions to minimize the adverse effects of global warming. According to the IEA, a nearly 5% increase in global emissions from the record-high level in 2008 resulted from an economic revival, and the temporary drop in 2009 was a consequence of the global crisis [4]. These data clearly indicate that the provisions of the 2008 climate and energy package are not being met [19]. The above package of measures aimed to achieve a 20% reduction in CO_2 emissions by 2020, and countries that failed to meet the above target would be faced with serious consequences (Poland would have to spend 2 billion Euros on

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certificates legalizing additional emissions of 50 million tons CO_2).

The alarming increase in emission levels was validated by research studies that indicate that Poland is one of the leading producers of greenhouse gases in the European Union. According to published sources, the most toxic pollutants are emitted during the generation and distribution of electricity, water steam and hot water, the manufacture of metals and chemicals [20-23], and road transport, which is one of the main sources of nitrogen oxide, carbon monoxide, and dust emissions [24-26]. Other sources [20, 27] indicate that the greatest environmental risk is posed by carbon dioxide produced by electric power plants, combined heat and power plants and heat plants fuelled by lignite and brown coal. Polish plants burn 47,071,000 tons of lignite, which accounts for 63.6% of national consumption, and 56,059,000 tons of brown coal, which accounts for 98.85% of national consumption [20]. Emission levels can be reduced through more efficient use of chemical energy in coal, but the relevant measures would require massive spending and long-term investment schemes in the power generation system. The above goal could also be reached by cutting energy consumption, but this is not a likely scenario in a country that boasts rapid economic growth [28]. An alternative solution involves implementing various support measures for projects that promote the use of renewable energy sources. Such measures would contribute to quick, effective, and uniform reduction of pollutant emissions, mostly carbon dioxide, without the need to lower energy production levels in a developing economy.

An analysis of electricity consumers, who share the responsibility for the adverse consequences of power generation, indicates that Polish residential and retail sectors have more than a 40% share of final energy consumption [20]. The level of emissions generated by those consumers continues to increase due to the operation of outdated and inefficient power generation and distribution systems. Energy efficiency improvements require urgent attention in residential and retail sectors, including single-family residential buildings, to minimize their negative environmental impacts. The majority of Polish single-family homes use energy for the needs of central heating, water heating, and lighting. Air-conditioning systems are still rare in residential buildings, and they have a much smaller share of total energy consumption. There exists a narrow category of homes whose energy needs are completely met by grid-supplied electricity. In most residential buildings, grid electricity is used mainly for lighting purposes, and the remaining energy needs are satisfied by other sources, including lignite, brown coal, natural gas, heating oil, biomass, and combined production (where the above energy carriers are used in various proportions). There also is a small group of historical buildings that do not meet the requirements of energy regulations because energy-efficient solutions cannot be implemented for conservation reasons [17]. By contrast, newly built houses have to conform to the latest and the most stringent energy performance requirements.

In view of the above problems and the general scarcity of comprehensive studies analyzing various scenarios for reducing pollutant emissions through the use of alternative energy sources in single-family residential buildings, the aim of this paper was to discuss the results of quantitative research comparing emission levels from various energy sources in typical single-family detached homes. Our findings could have significant practical applications in the process of designing energy performance requirements for single-family homes.

The presented analysis could contribute to the rational use of the existing sources of primary energy, an increase in the share of renewable energy sources and a reduction in pollutant emissions to ambient air. Projects aiming to achieve the above goals have been implemented in Poland, and most of them involve upgrades of outdated energy generation and distribution systems in residential buildings. In view of the general scarcity of comprehensive scientific analyses and regulatory guidelines, this paper also attempts to determine the measurable benefits, both quantitative and qualitative, of implementing energy-efficient solutions in single-family homes.

Materials and Methods

The object of our analysis of pollutant emission levels in the residential sector was a typical single-family home situated in the third climate zone, which is most representative of average weather conditions in Poland (according to [29], Poland is divided into five climate zones in the winter). The analysis will determine the minimum average environmental benefits generated by the compared heat sources. We analyzed six variants representing the most common heating, ventilation (central heating), and water heating solutions [30] in a typical Polish single-family home:

- variant 1 – central heating and water heating systems are powered by brown coal
- variant 2 – central heating and water heating systems are powered by electricity supplied by the electric power grid
- variant 3 – central heating and water heating systems are powered by biomass
- variant 4 – central heating and water heating systems are powered by natural gas
- variant 5 – combined production, which relies on heat generated by lignite fired in the central heating system and solar energy generated by solar thermal collectors in the water heating system
- variant 6 – central heating and water heating systems are powered by heating oil

The analyzed heat sources were described using the following parameters (Table 1): total power system efficiency $\eta_{H,tot}$ (for the central heating system, CHS) and $\eta_{W,tot}$ (for the water heating system, WHS), and the calorific value of the compared energy sources H_u. Based on the procedure described in [14], the above parameters were processed by specialist software to determine the values of: annual final energy consumption $Q_{K,H}$ (for the central heating system) and $Q_{K,W}$ (for the water heating system), and consumed fuel

Table 1. Energy efficiency of the analyzed sources.

Variant	System	$\eta_{H,tot}$, $\eta_{W,tot}$	H_u	$Q_{K,H}$, $Q_{K,W}$	B
I	CHS	0.66	2.68 kWh·kg^{-1} (9.648 MJ·kg^{-1})	31215.6 kWh·year^{-1}	11647.6 kg·year^{-1}
	WHS	0.5	2.68 kWh·kg^{-1} (9.648 MJ·kg^{-1})	4779.2 kWh·year^{-1}	1783.3 kg·year^{-1}
II	CHS	0.97	1.00 kWh·kWh^{-1}	21106.4 kWh·year^{-1}	21106.4 kWh·year^{-1}
	WHS	0.98	1.00 kWh·kWh^{-1}	2457.9 kWh·year^{-1}	2457.9 kWh·year^{-1}
III	CHS	0.49	4.28 kWh·kg^{-1} (15.408 MJ·kg^{-1})	41886.4 kWh·year^{-1}	9786.5 kg·year^{-1}
	WHS	0.58	4.28 kWh·kg^{-1} (15.408 MJ·kg^{-1})	4167.9 kWh·year^{-1}	973.8 kg·year^{-1}
IV	CHS	0.73	9.97 kWh·m^{-3} (35.892 MJ·m^{-3})	28051.3 kWh·year^{-1}	2813.6 m3·year^{-1}
	WHS	0.58	9.97 kWh·m^{-3} (35.892 MJ·m^{-3})	4167.9 kWh·year^{-1}	418.0 m3·year^{-1}
V	CHS	0.78	1.00 kWh·kWh^{-1}	26119.2 kWh·year^{-1}	26119.2 kWh·year^{-1}
	WHS	1	1.00 kWh·kWh^{-1}	2408.7 kWh·year^{-1}	2408.7 kWh·year^{-1}
VI	CHS	0.85	10.08 kWh·l^{-1} (36288 MJ·l^{-1})	24091.1 kWh·year^{-1}	2390.0 l·year^{-1}
	WHS	0.58	10.08 kWh·l^{-1} (36.288 MJ·l^{-1})	4153.0 kWh·year^{-1}	412.0 l·year^{-1}

B (expressed as the ratio of final energy consumption to the calorific value of energy source). The adopted procedure is described in detail in our previous work [31].

The data presented in Table 1 were used to evaluate the level of pollutant emissions from each analyzed variant. We relied on guidelines [32, 33] to estimate the emissions of the most common pollutants, including sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), total dust, soot and benzopyrene (BaP) concentrations, which are an indicator of exposure to polycyclic aromatic hydrocarbons. The measured values were expressed in terms of [33]:

- sulfur dioxide emissions

$$SO_2 = B \cdot SO_{2x} \cdot m$$

- nitrogen oxide emissions

$$NO_x = B \cdot NO_{xx} \cdot m$$

- carbon monoxide emissions

$$CO = B \cdot CO_x \cdot m$$

- carbon dioxide emissions

$$CO_2 = B \cdot CO_{2x} \cdot m$$

- total dust emissions

$$P_l = B \cdot P_{lx} \cdot m$$

- soot emissions

$$S_A = B \cdot S_{Ax} \cdot m$$

- benzopyrene emissions

$$BaP = B \cdot BaP_x \cdot m$$

...where: SO_{2x}, NO_{xx}, CO_x, CO_{2x}, P_{lx}, S_{Ax}, BaP_x – are pollutant emission factors, *m* – dimensionless adjustment factor for a given energy carrier, *B* (Table 1) – consumed fuel.

The above formulas do not account for the cumulative effect and toxicity of all substances released into ambient air (excluding carbon monoxide), therefore they fail to illustrate the full magnitude of pollution. The equivalent emission factor E_r was used to compensate for that deficiency. Its value is determined by adding up the actual emissions of all pollutants produced by a given source (sulfur dioxide SO_2, nitrogen oxides NO_x, total dust P_l, soot S_A, and benzopyrene BaP) and multiplying their sum by toxicity factor K_t, as defined by regulation [34] (where *t* is the type of the analyzed pollutant), according to the following formula:

$$E_r = SO_2 \cdot K_{SO_2} + NO_x \cdot K_{NO_x} + P_l \cdot K_{P_l} + S_A \cdot K_{S_A} + BaP \cdot K_{BaP}$$

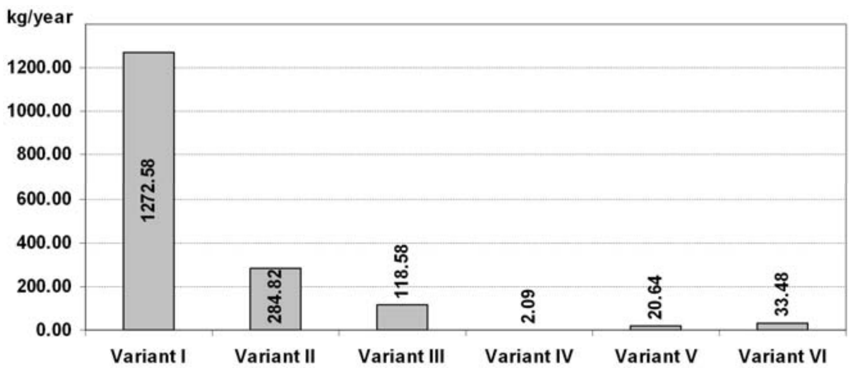

Fig. 1. Values of equivalent emission factors.

Table 2. Pollutant emission levels in the analyzed variants.

Variant	System	SO_2	NO_x	CO	CO_2	Dust	Soot	BaP
I	CHS	745.45	17.47	291.19	27954.26	698.86	0.0000	0.0000
	WHS	114.13	2.67	44.58	4279.90	107.00	0.0000	0.0000
	∑	*859.58*	*20.14*	*335.77*	*32234.16*	*805.86*	*0.0000*	*0.0000*
II	CHS	192.07	48.54	14.56	21106.39	31.66	0.0570	0.0011
	WHS	22.37	5.65	1.70	2457.88	3.69	0.0066	0.0001
	∑	*214.44*	*54.19*	*16.26*	*23564.27*	*35.35*	*0.0636*	*0.0012*
III	CHS	6.75	195.44	11.45	0.00	6.75	0.0000	0.0000
	WHS	0.67	19.45	1.14	0.00	0.67	0.0000	0.0000
	∑	*7.42*	*214.89*	*12.59*	*0.00*	*7.42*	*0.0000*	*0.0000*
IV	CHS	0.00	3.60	1.01	5525.85	0.0422	0.0000	0.0000
	WHS	0.00	0.54	0.15	821.04	0.0063	0.0000	0.0000
	∑	*0.00*	*4.14*	*1.16*	*6346.89*	*0.0485*	*0.0000*	*0.0000*
V	CHS	8.88	20.11	3.40	9726.78	3.40	0.0000	0.0000
	WHS	0.00	0.00	0.00	0.00	0.00	0.0000	0.0000
	∑	*8.88*	*20.11*	*3.40*	*9726.78*	*3.40*	*0.0000*	*0.0000*
VI	CHS	20.43	11.99	1.43	3943.48	4.30	0.0000	0.0000
	WHS	3.52	2.06	0.25	679.80	0.74	0.0000	0.0000
	∑	*23.95*	*14.05*	*1.68*	*4623.28*	*5.04*	*0.0000*	*0.0000*

Results and Discussion

In each of the analyzed variants (Table 1), emission levels were determined separately for the central heating and ventilation systems, the water heating system, and total emissions in the building. The results illustrating the share of every pollutant in the studied variants are expressed in kg·year^{-1} (Table 2). The values of equivalent emission factors are presented in Fig. 1.

The direct environmental impact can be determined by subtracting emission values in two select variants (Table 2). A positive environmental impact suggests a drop in the emission levels of a given pollutant (positive value of difference), whereas a negative effect implies a rise in the relevant emission levels (negative value of difference).

The results of a quantitative evaluation of CO_2 emissions (Table 2) indicate that brown coal is the greatest source of pollution. Brown coal firing in residential buildings also is responsible for the highest SO_2 emissions (one of the causes of acid rain), the highest emissions of toxic CO, and one of the highest emission levels of total dust. Electricity supplied by the electric power grid has an almost equally toxic effect on the environment. Electricity generation leads to emissions of soot and benzopyrene, a highly carcinogenic compound. Cigarette smoke, a source of highly carcinogenic substances, contains only 0.15-0.16 μg BaP [35], whereas a single-family building (Table 2) emits 1.2 g BaP per year, which is equivalent to smoking 7.5 million cigarettes.

Carbon dioxide emissions in the analyzed variants were compared with the most toxic scenario (lignite burning) to

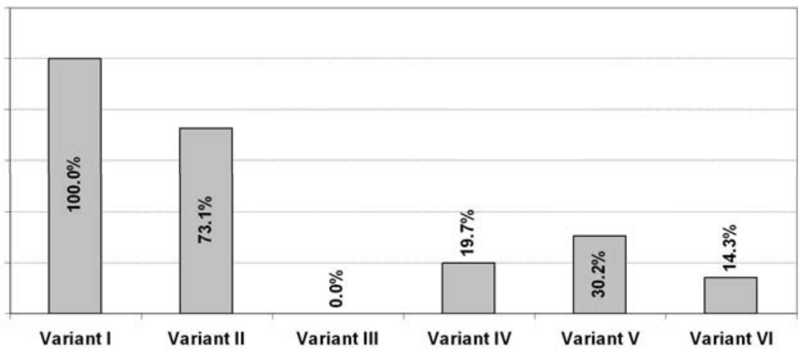

Fig. 2. Carbon dioxide emissions relative to the lignite burning variant.

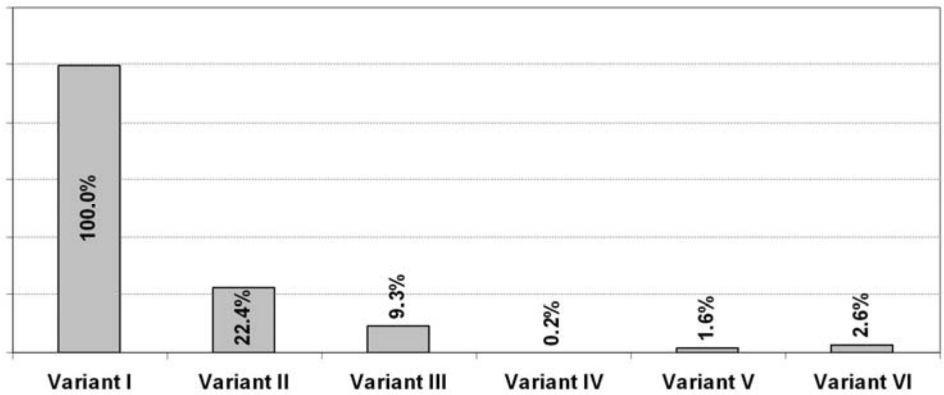

Fig. 3. Theoretical reduction in the values of equivalent emission factors.

estimate the possible reduction in CO_2 emission levels that could be achieved by switching to alternative energy sources in a single-family home. The results of the analysis are presented in Fig. 2.

An analysis of the data in Fig. 2 indicates that the greatest reduction in CO_2 emissions can be achieved by burning biomass, an increasingly popular energy source [36-42]. Satisfactory levels of carbon dioxide emissions also were noted in variants relying on heating oil, natural gas, and combined production (lignite burning in the central heating system and energy generated by solar thermal collectors in the water heating system). According to recent reports of the Central Statistical Office in Warsaw [20], total electric energy consumption of Polish households reached 28,684 GWh, and it had an estimated 20.1% share of national consumption. Statistical data can be used to predict the reduction in carbon dioxide emissions in a scenario where grid-supplied electricity is replaced with renewable energy sources (biomass, wind farms, etc.). Polish power plants are characterized by 33% energy efficiency, and they emit 2.61 tons of CO_2 per 2.2 MWh of generated electricity [28]. The proposed solution would reduce CO_2 emissions by approximately 34 million tons, which accounts for 11% of national emissions. If around 10% of the electricity generated nationwide is used in central heating and water heating systems in single-family homes, then based on the data presented in Fig. 1, we can conclude that the switch to alternative sources of energy would significantly limit CO_2 emissions to ambient air. The replacement of conventional energy sources with biomass would reduce emission levels by around 16.93 million tons (5.46% of national emissions), with heating oil – by 9.95 million tons (3.21%), with natural gas – by 9.04 million tons (2.92%), and with combined production – by 7.26 million tons (2.34%). The above results clearly indicate that the proposed measures would deliver considerable environmental benefits.

A theoretical reduction in the value of the equivalent emission factor, an indicator of the cumulative toxicity of the analyzed pollutants, is proposed in Fig. 3 relative to the most environmentally harmful variant that relies on brown coal (Fig. 1). The switch from lignite to natural gas in a residential building would reduce the value of the equivalent emission factor by an impressive 99.8%.

Conclusions

The proposed measures to maximize the efficiency of primary energy sources in single-family homes take on a special significance in light of the latest EU guidelines, which promote renewable energy sources to reduce toxic emissions into ambient air.

The results of our analysis demonstrate that the above goals can be achieved by initiating various measures to improve the thermal efficiency of residential buildings in Poland and other EU countries. Such schemes involve switching to alternative energy sources in the building, and promoting energy-efficient technologies (solar panels, solar collectors, compact fluorescent lamps) and many others. In addition to delivering environmental benefits, these measures will eliminate other problems, including logistical requirements for the transport and storage of materials in the energy supply chain and transmission losses between sources of supply and end users. As a result, the proposed solutions will enable Poland to comply with EU requirements and the priority action plan for reducing CO_2 emissions by 2020.

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