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SELECTION OF A RELIABLE ENERGY SOURCE SUPPLYING DOMESTIC HOT WATER (DHW) SYSTEM IN THE KINDERGARTEN – A CASE STUDY

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ABSTRACT: Renewable energy sources (RESs) are used more and more frequently as energy sources for heating and domestic hot water (DHW). However, there are many factors influencing energy efficiency, thus also ecological benefits. Before making a decision on what kind of RES is useful and reliable, a comprehensive analysis should be conducted, taking into account technical, financial and ecological factors. This paper discusses different variants of energy sources that could be applied in a kindergarten building to prepare hot water in place of existing solutions (district heating system, DHS). An air heat pump (AHP) with photovoltaic panels (PV) was considered the most reliable energy source in the analysed building in terms of economic and environmental considerations. The simple payback time (SPBT) for this investment was estimated to be 14.55 years. This solution causes the lowest CO_2 emissions. Another system with solar collectors supplying hot water preparation in the heat centre can also be recommended. The simple payback time in this case was slightly higher (14.94 years), and a decrease in CO_2 emissions was observed compared to the actual conditions.

KEYWORDS: kindergarten, heat pump, solar energy, SPBT, CO_2 emissions

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Introduction

Each owner of the building faces the decision about the energy source for heating, ventilation and cooling (HVAC), domestic hot water (DHW) and lighting. Despite the fact that we need to choose between renewable (RES) and non-renewable energy sources, there is also a variety of kinds of RESs to be considered the best solution in the case of each building and user. Renewable energy sources are naturally replenished, sustainable, and eco-friendly. The major types of RES are:

- Solar energy,
- Wind energy,
- Geothermal energy,
- Hydropower from flowing water,
- Ocean energy,
- Biomass.

RESs are frequently used. However, non-renewable energy sources like natural gas, coal or oil play a crucial role in the generation of energy for different purposes (IEA, 2022). Thinking about the safety of each solution, we take into account the safety of delivering energy (in the context of existing circumstances), maintaining the source by users (including the financial side of this issue) and for the surroundings. As shown by Sadowska et al. (2022), the emission of pollutants strictly depends on the combustion technology or type of fuel used.

An overview of the literature

According to Polish law (Announcement, 2022), DHW installation should be designed and constructed in a way that allows the amount of thermal energy needed to prepare hot water to be kept at a reasonably low level. This is the necessity to analyse all stages, starting from heat generation, by its distribution and accumulation to regulation.

For years, energy was generated from fossil fuels, while in the last decade, various RESs have been used more frequently. Liu et al. (2023b) conducted a study of the effect of zero-carbon transformation of public kindergartens in Beijing. Liu et al. (2023b) focused their study on the kindergarten and concluded that the utilisation of renewable energy such as solar energy, wind energy, and geothermal energy, enhancing the awareness of green energy conservation and integration of the building with the environment were crucial to achieving sustainable development. Before the selection of the optimal energy source, a preliminary analysis should be conducted. As presented by Kolendo and Krawczyk (2018), the decision about the installation of solar flat or vacuum collectors on buildings' roofs should be predated by analysis of data on solar potential, exposure, slope, surface and roofs' shape. Achbab et al. (2022) used the precise recon-

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struction of the territory in a 3D urban model called digital surface model (DSM) in the analysis that included geographical location, shade, tilt, orientation, roof accessibility and topography to estimate the energy production of solar panels. Additionally, the profile of users should be taken into account, e.g., education buildings or offices have different week and day schedules than residential buildings. The usefulness of modern tools like GIS & T technology, multi-criteria decision support, and remote sensing techniques, including airborne laser scanning, etc., for analyses, was shown by Krawczyk and Kolendo (2017), Krawczyk et al. (2019), Liu et al. (2023a), Shono et al. (2023).

In existing kindergartens located in Bialystok, hot water is most often prepared in heat centres supplied by a combined heat and power plant (CHPP); thus, in this paper, various options to include RES in a heat production for DHW were analysed.

Research methods

The procedure of selecting of a reliable energy source supplying the DHW system in the kindergarten used in this article comprises several sequential stages, as illustrated in Figure 1.

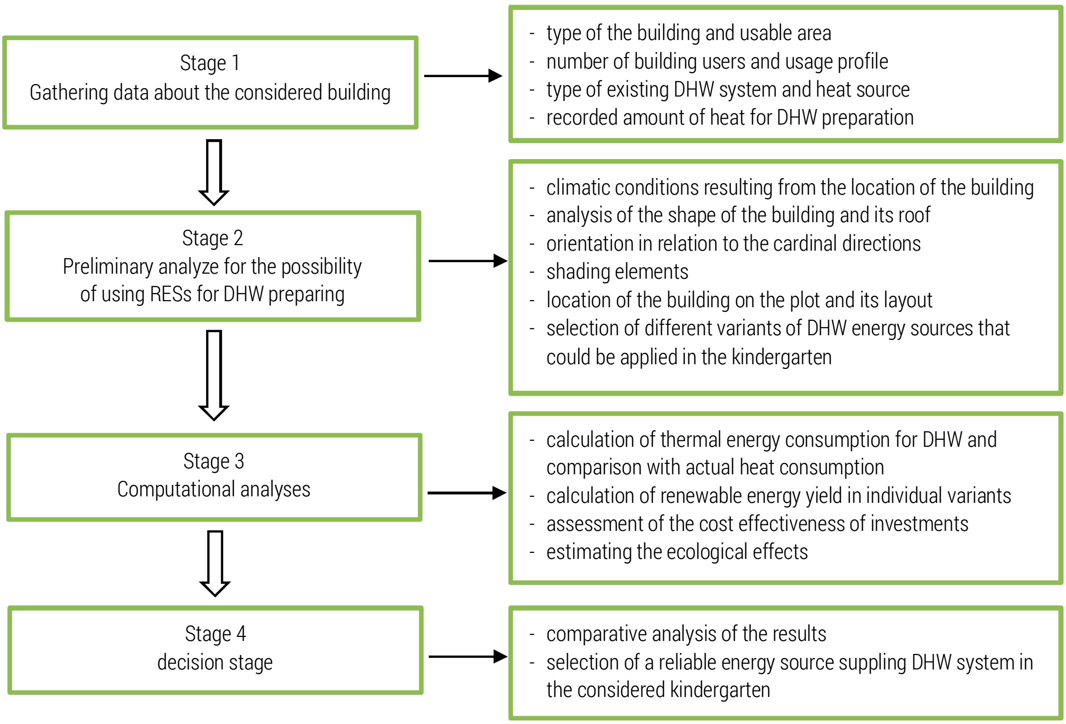

Figure 1. Research methods diagram

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The amount of energy needed to prepare domestic hot water Q_W can be determined from Equation 1.

$$Q_W = \frac{V_W \cdot c_W \cdot \rho_W \cdot (\Theta_W - \Theta_0) \cdot k_R \cdot t_R}{\eta_{W,tot}}, \quad (1)$$

where:
V_w – unit daily demand for domestic hot water [dm^3/(m^2·day)],
c_w – specific heat of water [J/kg·K],
ρ_w – water density [kg/m^3],
Θ_W – hot water temperature in a draw-off tap [K],
Θ_0 – temperature of cold water [K],
k_R – correction coefficient due to breaks in use of the domestic hot water system [-],
t_R – number of days in a year [-],
$\eta_{W,tot}$ – average seasonal total efficiency of the hot water preparation system [-], calculated based on the Formula 2:

$$\eta_{W,tot} = \eta_{W,g} \cdot \eta_{W,d} \cdot \eta_{W,e} \cdot \eta_{W,s}, \quad (2)$$

where:
$\eta_{(w,g)}$ – average seasonal efficiency of heat generation of the domestic hot water system [-],
$\eta_{w,d}$ – average seasonal efficiency of heat transfer of the domestic hot water system [-],
$\eta_{w,e}$ – average seasonal efficiency of the use of heat of the domestic hot water system [-],
$\eta_{w,s}$ – average seasonal efficiency of heat accumulation in the capacitive elements of the domestic hot water system [-].

In the Polish building certification system in force in 2008-2014 (Regulation, 2008), the annual consumption of thermal energy using the calculation method was determined based on the daily demand for DHW (V_W) related to number of people (dm^3/(person·day)). According to the current law (Regulation, 2015) it is determined based on a DWH consumption rate related to the usable area (dm^3/(m^2·day)). In practice, in the case of DHW systems, the usage profile in the context of daily, weekly and monthly needs is also very important. In part of kindergartens, there is a kitchen where dishes are prepared, and plates and pots are washed, which increases the hot water load significantly. In other preschools, lunches are delivered by an external catering company, which results in hot water needs just for washing hands. Therefore, to correctly estimate the amount of heat needed for preparing hot water, the calculated demand should be compared with the measured heat consumption. This is legally required in the Polish energy audit system (Nowakowski, 2012), but it is also extremely important when selecting new energy sources, including RESs. The hot water temperature is set at the level from 55 to 60°C, while cold water in the winter season is assumed to

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be 10°C (Announcement, 2022). Polish regulations (Regulation, 2002) and literature (Nowakowski, 2012) recommend estimating DHW consumption in kindergartens as 15-20 dm^3/(child) but do not take into account the usage profile of the institution.

In the absence of a separate measurement of heat for heating and hot water preparation in heating nodes powered by combined heat and power plants (CHPP) in the months of the heating season (from January to May and from September to December), the amount of heat for hot water preparation can be determined from Equation 3:

$$Q_{Wav:I-V,IX-XII} = \frac{\sum_{VI-VII}^{month} Q_W}{2}, \tag{3}$$

where:
$Q_{(Wav:I\text{-}V,IX\text{-}XII)}$ – computational monthly heat needs for DHW [GJ/month].

When calculating the average water consumption in months during the heating season, one of the summer months (August), with a different usage profile (during which children have a summer break and do not attend kindergarten), was omitted.

Energy yield from solar radiation can be determined from the Formula 4:

$$Q_{sol} = \sum_{I-XII}^{month} (A_{ac} \cdot I_i \cdot \eta_o), \tag{4}$$

where:
$A_{(ac)}$ – total active surface of solar collectors or photovoltaic panels [m^2],
$I_{(i)}$ – the sum of total solar radiation on a surface with a given orientation and the tilt angle [kWh/(m^2·month)],
$\eta_{(o)}$ – the average efficiency of solar collectors taking into account zero-loss efficiency, heat loss coefficient, temperature of absorber surface, temperature of second glazing and inlet temperature of the working fluid and incident solar radiation / photovoltaic panels conversion efficiency[-].

A simple payback time (SPBT) can be used for the economic assessment of the investment. The SPBT indicator, described by Formula 5, determines the time after which an investment begins to generate economic profit, taking into account the investment incurred.

$$SPBT = \frac{N_u}{\Delta O_{rU}}, \tag{5}$$

where:
$N_{(u)}$ – cost of system [PLN],
$\Delta_{O(rU)}$ – annual savings in energy costs resulting from the application of the improvement [PLN/year].

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In order to determine the reduction of CO_2 emissions (ΔEM) to the atmosphere resulting from the combustion of the fuel in the CHPP, the amount of pollutant emissions was calculated before and after replacing the heat source for DHW according to Formula 6:

$$\Delta EM = Q_{W0} \cdot w_0 - Q_{W1} \cdot w_1, \tag{6}$$

where:
$Q_{(0,1)}$ – the amount of energy needed to prepare DHW before and after replacing the heat source [GJ/year],
w_0 – CO_2 emission factor resulting from fuel combustion in the CHPP in Bialystok [kg/GJ],
w_1 – CO_2 emission factor after replacing the heat source [kg/GJ].

Characteristics of the considered building with preliminary analysis for the possibility of using RESs for preparing hot water

A kindergarten building, shown in Figure 1, located in the north-eastern part of Poland (in Bialystok), was selected for the research. The geographic coordinates of the case study are, respectively, longitude 23°10′E and latitude 53°06′N. The average monthly temperature for this location is given in Table 2.

Table 1. The average monthly temperature (Θ_W) in Bialystok

month	1	2	3	4	5	6	7	8	9	10	11	12	Total
(°C)	-4.9	-2.0	1.7	7.3	13.2	15.9	17.3	14.5	12.1	7.1	1.6	-1.3	6.9

Source: authors' work based on https://www.gov.pl/web/archiwum-inwestycje-rozwoj/dane-do-obliczen-energetycznych-budynkow [23-11-2023].

It is a two-storey building with a partial basement, put into use in 1985. The heated area is 946 m^2, while the volume is 4040 m^3.

The building was constructed on the basis of a typical project, using industrialized large-block technology. Thermal modernization was carried out in the building, and it was adapted to the needs of people with disabilities, which was achieved, among other things, by building a ramp at the main door.

The analysed kindergarten building is located on a plot with an area of over 4000 m^2, and the building development area is 484 m^2. The main façade is oriented towards the south-west. A large part of the kindergarten plot is covered with trees, which shade most of the surroundings and the building's facades. However, the trees are not high enough to shade the roof. The ventilated flat roof

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is shaded only by the roof elements and roof infrastructure, which does not prevent it from being used to place PV panels. In the plan, the building has a shape similar to a rectangle (Figure 3) with dimensions of approximately 15 m and 37 m.

The kindergarten building in question has a heat center supplied by a combined heat and power plant (CHPP). The actual heat consumption in 2022 is presented in Figure 4. Due to the lack of a separate measurement of heat consumption for water preparation, it was calculated based on formula 3.

Figure 2. The view of the kindergarten building under consideration

Figure 3. View of the location of the tested building with its layout on the plot
Source: authors' work based on Miejski System Informacji Przestrzennej (2023).

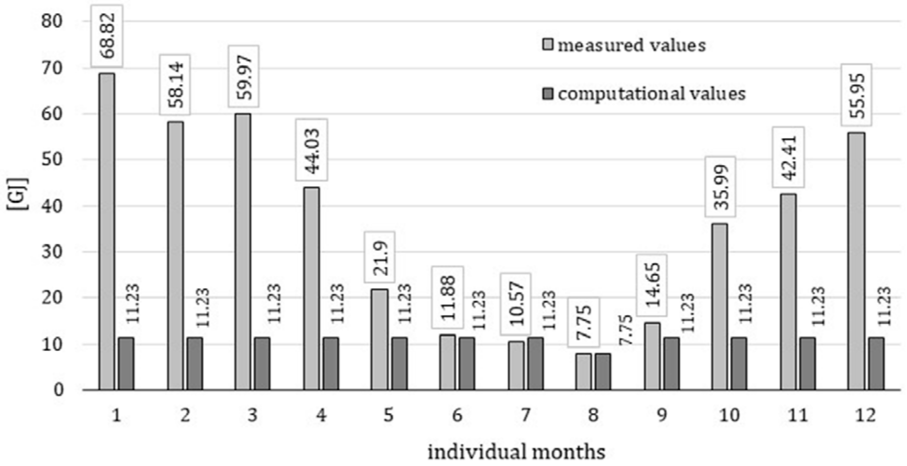

Figure 4. Measured total heat consumption in the kindergarten building in 2022 and computational needs for hot water preparation

The assumptions for the analysis and simulations

The computational annual heat needs for hot water preparation amounted to 131.23 GJ and was 29% lower than calculated in the energy audit (National Energy Conservation Agency, 2018). For further analyses, a value based on the measurement results was adopted.

In the case study, the following variants of energy sources could be applied for preparing hot water in place of the existing solution (DHS – Variant 0):

- Variant 1: Air heat pump (AHP) and existing energy sources (DHS),
- Variant 2: Air heat pump (AHP) and photovoltaic panels (PV),
- Variant 3: Solar collectors (SC) and existing energy sources (DHS).

The selection of the air heat pump was based on the thermal power of the domestic hot water system obtained from an energy audit (National Energy Conservation Agency, 2018). The installation of an air/water heat pump with a power of 21.7 kW was assumed.

Due to the orientation, shape and shading elements on the roof of the building (Figure 3), it was decided to install PV panels and solar collectors facing south-west. When determining the value of the tilt angle of these devices, the graph developed by Żukowski and Radzajewska (2015) was used. The optimal angle for the considered location of the building was 32°. Statistical climatic data for energy calculations of buildings in Poland were used to determine the yield from solar radiation energy (Ministerstwo Inwestycji i Rozwoju, 2008). The adopted values are shown in Table 2.

Table 2. The sum of total solar radiation in Bialystok on a surface with a SW orientation and the tilt angle qual 30°

month	1	2	3	4	5	6	7	8	9	10	11	12	Total
kWh/m^2	25.621	32.548	64.245	96.497	138.904	138.978	136.098	117.084	91.104	46.107	22.56	17.274	927.02

Source: authors' work based on https://www.gov.pl/web/archiwum-inwestycje-rozwoj/dane-do-obliczen-energetycznych-budynkow [06-10-2023].

Unit energy prices were based on data provided by their producers and distributors. In a case of combined heat and power plant (CHPP) in Bialystok (Enea, 2023; Optimal Energy, 2023) energy prices for a unit of supplied heat amounted to: 108.36 PLN/GJ and 23447.28 PLN/MW/month and for electricity: 1.779 PLN/kWh.

Results of the research and discussion

In each of the considered variants, the heat demand for hot water preparation was estimated, taking into account RESs. In Variants 1 and 2, Formulas 1 and 2 were used. In the variants in which photovoltaic panels (Variant 2) and solar collectors (Variant 3) were proposed, the heat yield from solar radiation energy was determined from Formula 4.

In Variant 1 (Table 3) the AHP will only operate up to a certain bivalent point, e.g. 5°C, and then it will be disconnected because the amount of electricity supplied for its operation (internal defrosting and heating) will make this work unprofitable and then the system will be switched to power supply from the existing DHS. According to the average monthly temperature data for Bialystok, assuming a bivalent point, in January, February and December, the entire hot water will be prepared from the heating station, while in March and November – for part (half) of the month. However, in the remaining months, the maximum yield from heat pumps was assumed.

Electricity consumption for the AHP in Variant 1 was estimated assuming 2 hours of work in March and November and 4 hours during 7 months (from April to October) and 30.5 (approximately) days per month. In Variant 2 the operation of the AHP throughout the entire year and the production of electricity for its needs from PV panels was assumed. The results of energy demand calculations in this variant are presented in Table 4.

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Table 3. Results of energy calculations in variant 1

month	1	2	3	4	5	6	7	8	9	10	11	12	Total
Heat demand for DHW													
Q_w kWh	3119.44	3119.44	3119.44	3119.44	3119.44	3119.44	3119.44	2138.89	3119.44	3119.44	3119.44	3119.44	**36452.80**
Energy demand supplying from the existing DHS and from AHP (total renewable and non-renewable energy													
From DHS	3119.44	3119.44	1559.72	0	0	0	0	0	0	1559.72	3119.44	3119.44	**15597.22**
From AHP	0	0	1559.72	3119.44	3119.44	3119.44	3119.44	2138.89	3119.44	1559.72	0	0	**20855.56**
degree of coverage %	0	0	50	100	100	100	100	100	100	50	100	100	**57.21**
Electricity consump-tion for the pump (5.34kWe) kWh	0	0	331.08	640.80	662.16	640.80	662.16	662.16	640.80	662.16	0	0	**5233.20**

* In August many children go for holidays that results in reduced energy consumption.

Table 4. Results of energy calculations in variant 2

month	1	2	3	4	5	6	7	8	9	10	11	12	Total
Heat demand for DHW													
Q_w kWh	3119.44	3119.44	3119.44	3119.44	3119.44	3119.44	3119.44	2138.89	3119.44	3119.44	3119.44	3119.44	**36452.80**
Energy demand supplying from AHP (total renewable and non-renewable energy													
Electricity consumption for the pump (5.34kWe) kWh	662.16	598.08	662.16	640.80	662.16	640.80	662.16	662.16	640.80	662.16	640.80	662.16	**7796.40**
Energy yield from 50 PV (50 photovoltaic panels with an active surface and PV conversion efficiency of 20.4%)													
kWh	512.13	650.59	1284.16	1928.83	2776.49	2777.97	2720.40	2340.34	1821.04	921.61	450.94	345.28	**18529.77**
degree of coverage %	77.34	108.78	193.94	301.00	419.31	433.52	410.84	353.44	284.18	139.18	70.37	52.14	**237.67**

month	1	2	3	4	5	6	7	8	9	10	11	12	Total
possibility of using solar energy for domestic hot water purposes kWh	512.13	598.08	662.16	640.80	662.16	640.80	662.16	662.16	640.80	662.16	450.94	345.28	**7139.63**
amount of electricity supplied from the power grid kWh	150.03	0	0	0	0	0	0	0	0	0	189.86	316.88	656.77

* In August many children go for holidays that results in reduced energy consumption.

Based on the data presented in Table 4, it can be seen that despite a significant overproduction of electricity from planned PV panels in summer, it was not possible to cover energy needs in the winter months (January, November and December). The missing amount of electricity must be supplied from the power grid.

Table 5 shows the results of energy calculations in Variant 3, where SC was proposed, supporting the heating of hot water by existing energy sources (DHS). The number of solar collectors has been selected in such a way that there is no excess production of thermal energy in the summer (except for August, when most children do not attend kindergarten and the excess hot water can be used for cleaning work in and around the building).

Table 5. Results of energy calculations in variant 3

month	1	2	3	4	5	6	7	8	9	10	11	12	Total
Heat demand for DHW													
Q_w kWh	3119.44	3119.44	3119.44	3119.44	3119.44	3119.44	3119.44	2138.89	3119.44	3119.44	3119.44	3119.44	**36452.80**
Energy yield from 12 SC (12 collectors with an active surface and an optical efficiency of 74%)													
From SC	546.03	693.66	1369.19	2056.54	2960.32	2961.90	2900.52	2495.29	1941.61	982.63	480.80	368.14	**19756.65**
degree of coverage %	17.50	22.24	43.89	65.93	94.90	94.95	92.98	116.66	62.24	31.50	15.41	11.80	**54.20**
Heat from DHS kWh	2573.41	2425.78	1750.26	1062.90	159.12	157.55	218.92	0.00	1177.84	2136.81	2638.65	2751.30	**16696.13**

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To indicate the reliable energy source supplying DHW system in the analyzed kindergarten building, an economic analysis was carried out. Maintenance costs were calculated for the existing state and the proposed 3 variants (1-3) of energy sources. In the next step, investment costs were estimated, based on detailed systems schemas and installation cost estimate. Total maintenance and investment costs were used to calculate the SPBT economic indicator. CO_2 emissions were also determined. The obtained results are summarized in Table 6.

Table 6. Results of the economic and ecology analysis

Evaluated indicator	Unit	Variant 0	Variant 1	Variant2	Variant 3
Heat from DHS	kWh/year	36452.80	15597.22	-	16696.13
	GJ/year	131.23	56.15	-	60.11
Prices for a unit of supplied heat	PLN/GJ	108.36			
Prices for a unit of thermal power	PLN/MW/month	23447.28			
Unit value of CO_2 emissions (for Heat from DHS) (KOBiZE, 2023a)	kg/GJ	49.73			
Energy from the power grid	kWh/year	-	5233.20	656.77	-
Unit value of CO_2 emissions (for electricity from power grid) (KOBiZE, 2023b)	kg/MWh	761			
Prices for a unit of supplied heat	PLN/kWh	1.799			
Maintenance costs (no charge for thermal power)	PLN/year	14220	15499	1182	6514
Maintenance costs (with charge for thermal power)	PLN/year	19150	20428	1182	11443
Investment costs	PLN	126122	135300	261422	115173
Saving of maintenance costs	PLN	-	-1279	17968	7707
SPBT	**years**	**-**	**-**	**14.55**	**14.94**
EM CO_2	t/year	6.526	6.775	0.500	2.989

Based on economic and ecological analysis, an air heat pump with PV panels turned out to be the reliable energy source supplying DHW system in the analyzed kindergarten building. Despite the highest investment cost, the investment will pay off the fastest (after 14.55 years) and has the lowest impact on the environment, assessed by the amount of CO_2 emissions.

A system with solar collectors supporting the heating of DHW from the DHS can be also recommended. The simple payback time in this case was 14.94 years and a decrease in CO_2 emissions was observed compared to the condition of the existing building.

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However, in Polish economic conditions and with the current mix of electricity produced in the network, it is not recommended to use heat pumps, which additionally in winter, must be supported by DHS, which does not allow waiving the payment for thermal power and makes the investment unprofitable and not bringing any environmental benefits. It is worth mentioning that subsidy programs for the purchase of heat sources that are periodically offered in Poland, as well as changes in electricity prices (in the analysis, government-guaranteed prices for 2023 were taken into account), may influence the results obtained.

Conclusions

- In order to correctly estimate the amount of heat needed for DHW in education buildings like kindergartens, when selecting new energy sources, it is advisable to compare the calculated heat demand with the measured heat consumption, as significant differences are observed.
- In Polish climatic conditions, it is difficult to ensure that the heat demand for DHW preparation in kindergartens is fully covered with RESs due to low energy yield in winter.
- The highest solar yields in summer do not correspond with high energy consumption as a result of holidays in educational institutions.
- Without conducting an economic efficiency analysis, it is not possible to indicate the reliable energy source supplying domestic hot water (DHW) systems in the buildings.
- Price volatility, varied availability of subsidy programs for the purchase of heat sources and short-term policy of government-guaranteed prices result in high uncertainty regarding the real payback time and may introduce variability in the optimal solution (especially in case of small differences in SPBT of analysed variants).

This paper presents the methodology for analysis that can be used for other climate conditions and national environmental, economic and social conditions.

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The contribution of the authors

Conceptualisation, D.A.K. and B.S.; literature review, D.A.K., B.S. and M.K.; methodology, D.A.K. and B.S.; formal analysis, D.A.K., B.S. and M.K.; writing, D.A.K. and B.S.; conclusions and discussion, D.A.K., B.S. and M.K.

The authors have read and agreed to the published version of the manuscript.

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TEMPO TRANSFORMACJI ENERGETYCZNEJ W KRAJACH EUROPEJSKICH W LATACH 2004-2021

STRESZCZENIE: Odnawialne źródła ciepła są coraz częściej wykorzystywane do zasilania systemów ogrzewania i przygotowania ciepłej wody użytkowej. Na ich efektywność energetyczną, a co za tym idzie także korzyści ekologiczne jakie niesie ich zastosowanie, wpływa jednak wiele czynników. Przed podjęciem decyzji, jaki rodzaj OZE jest w danym przypadku użyteczny i uzasadniony, należy przeprowadzić kompleksową analizę pod kątem uwarunkowań technicznych, finansowych i ekologicznych. W artykule omówiono różne warianty zastosowania OZE w budynku przedszkola. Za najbardziej odpowiednie pod względem ekonomicznym i środowiskowym uznano powierzchną pompę ciepła z panelami PV. Okres zwrotu tej inwestycji wynosi 14.55 lat. Rozwiązanie to skutkuje najniższą emisję CO_2. Można również polecić system z kolektorami słonecznymi wspomagającymi przygotowanie ciepłej wody w węźle cieplnym. Prosty czas zwrotu inwestycji w tym przypadku wyniósł 14.94 lat i zaobserwowano spadek emisji CO_2 w porównaniu do stanu istniejącego.

SŁOWA KLUCZOWE: przedszkole, pompa ciepła, energia słoneczna, SPBT, emisja CO_2

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