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Environmental Assessment of Energy System Upgrades in Public Buildings

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Abstract: The use of fossil fuel-based energy systems that provide heat and electricity to a building has adverse environmental impacts. These impacts can be mitigated, to a certain extent, through the incorporation of renewable energy sources (RES). The primary objective of this study was to conduct an environmental assessment of the performance of energy systems in existing public facilities located in Poland. Based on the findings, we proposed and implemented changes to these systems and validated the environmental impact of the RES systems used. SimaPro 8.1 software and the Ecoinvent 3.0 database were employed for the analysis, which entailed an environmental assessment of six public facilities located in Poland. The installation of RES resulted in an average 27% reduction in electricity consumption from the national electricity grid. This reduction was observed to be the least in the hospital and the most in the religious building. This was reflected in the environmental assessment of heating systems. The implementation of RES reduced the environmental impact of the religious building by an average of 20%. Concurrently, the CO_2 emissions decreased by 35%, SO_2 by 44%, and PM_{10} by 42%. Significant investments and the installation of advanced RES will not prevent the occurrence of unintentional environmental consequences unless the demand for electricity and thermal energy is reduced. The use of RES in the analyzed buildings and the associated avoided emissions do not entirely offset the negative emissions resulting from the utilization of other (conventional) energy sources in the analyzed energy systems of public buildings. Consequently, the analyzed facilities collectively exert a detrimental impact on the environment.

Keywords: life cycle assessment; eco-energy; renewable energy sources; electricity consumption

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1. Introduction

Suburbanization is a globally recognized process that involves the development of suburban zones. It manifests itself in the expansion of the administrative boundaries of cities and the construction of new housing developments and public infrastructure facilities, such as schools, hospitals, offices, and religious building. This phenomenon can be attributed to the growing global population, migration problems, and the increasing comfort of residents of developed countries. The construction of buildings, both private and public, is based on the latest technologies, which, on the one hand, improves the quality of life but, on the other hand, entails a greater demand for electricity and heat [1]. Energy consumption in Europe has increased by 5% over the past 20 years [2,3]. The energy economy of the EU countries is predominantly reliant on finite resources of conventional fuels, including hard coal, lignite, oil, and others. This has resulted in elevated levels of harmful gases and particulate matter (containing, among other substances, hydrocarbons, sulfur, heavy metals, etc.) being emitted into the atmosphere, exceeding global norms [4,5]. In order to reduce energy and fuel consumption and CO_2 emissions into the atmosphere, EU member states have set the following goals: to wean themselves off fossil fuels, to develop renewable energy, and to promote appropriate attitudes that will allow the implementation of a circular economy by 2030 [6,7].

A review of studies on energy and fuel consumption at different stages of the life cycle of an average 50-year-old construction facility reveals that the largest energy consumption is associated with the use phase. This phase accounts for approx. 84.2% of energy consumption, primarily due to its duration. In the phase of operation of a building, the demand for energy needed to ensure user comfort is variable, for example, due to the functional diversity of the building, the degree of equipment, with various types of installations and devices requiring a power supply. The operation phase also includes renovations, maintenance, and repairs, which also consume energy during their implementation. Moreover, it is the longest phase of the building life cycle. The manufacture of construction materials accounts for approx. 9.9%, repairs account for 4.3%, the construction process accounts for 0.8%, transportation for 0.5%, and the "end of life" phase for 0.5% [8,9]. The energy demand in each phase of the building life cycle is not constant. It depends on the equipment of the building, the construction materials used, and the area and volume of the building.

The negative impact of a building on the environment can be mitigated with relative ease, safety, and economic viability. Investment activities primarily concern alterations to electricity and heat supply systems. They are implemented in both private and public facilities through the installation of renewable energy systems, thermal upgrade of the building envelope, and the replacement of electrical power equipment with equipment of a higher energy class.

The advantage of using renewable energy systems is their potentially beneficial impact on the environment, including the reduction of atmospheric emissions and the consumption of conventional energy resources, and the possibility for the consumer to achieve energy independence [10–12]. Renewable energy sources (RES) are used to provide both heat and electricity. Solar collectors, biomass (pellet and briquette) boilers, and heat pumps (air and ground sources) are employed to provide central heating and hot water. In contrast, photovoltaic (PV) panels, domestic wind, and hydroelectric power plants are utilized to provide electricity [13–17]. Kania et al. [2] demonstrated that single-family residences powered by renewable energy systems exhibited a reduced environmental impact relative to buildings reliant on conventional energy sources.

The use of RES, despite the advantages, also has a negative environmental impact, which can be attributed to various factors [18]. These include the extraction of the necessary raw materials to manufacture RES equipment, as well as the damage to the ecosystem, which can take the form of the death of birds due to collisions with wind turbine blades [19–21]. Abbasi et al. [22] assessed the impact of wind turbine noise on the general condition of the personnel operating the Manjil wind farm in Iran. The closer the people were to the wind turbine, the more they felt the effects of low-frequency noise produced by the wind turbines, including headaches, sleep disturbances, excessive fatigue, and stress. Similar results were obtained by Krogh et al. [23], who studied the impact of wind turbines on people living near the wind farm. Wind farms also have a direct impact on the environment, including bird deaths and the migration of birds to other areas. Kumara et al. [24] showed that the annual animal mortality was 0.26 per year. In addition, species richness, abundance, and unique bird species were relatively higher in places where there were no wind farms. Tougaard et al. [25] analyzed offshore wind turbines in their study. Wind turbines during operation exhibit noise levels that are at least 10–20 dB lower than ship noise in the same frequency range. However, in the case of a large wind farm, the noise range and volume level may increase. Wind turbines will significantly affect the aquatic environment with low natural ambient noise and low ship traffic. PV systems do not produce sound, noise, or gases during their operation. However, during fires, PV modules generate chemical pollutants that are released into the atmosphere. In addition, PV farms occupy areas from several to several dozen hectares, transforming the landscape [26]. The negative effect of building hydropower plants was demonstrated by Sperling [27]. The main effects of a negative nature were changes in the water quality, human migration, changes in the structure of aquatic communities, loss of genetic heritage (flora and fauna), destabilization of slopes, and climate change, including those related to greenhouse gas emissions. The above-mentioned negative impacts of renewable energy sources are shared by the opinion of the residents of the Chojnice District, Poland [28].

In addition to utilizing RES, homeowners are investing in building renovation treatments with the objective of reducing the energy demand. Thermal upgrade activities include the use of modern insulation materials, which can result in energy savings of 33–60% [29,30]. Another option is domestic hot water (DHW) preparation using RES, which can result in energy savings of 50–80% [31]. High-end window and door frames can also be used, which can result in energy savings reaching up to 20% [3,31]. Finally, ventilation system upgrades can result in energy savings of 16–21% [3,32]. Hossain and Marsik [33] demonstrated that, despite the higher greenhouse gas emissions associated with the construction of low-energy buildings, energy-efficient houses can play an important role in combating climate change.

According to Polish law, public facilities are defined as buildings designed for purposes such as public administration, culture, religious worship, education, healthcare, services, and other buildings for similar functions [34]. The energy demand of public facilities varies from that of households, because their peak electrical and thermal demand occurs mainly during the brightest part of the day. This diverse use of facilities has a significant impact on how energy systems are selected. Owners of public facilities most often choose to use RES in their buildings. The use of RES in public facilities can help offset or reduce the negative environmental impact associated with reduced fossil fuel consumption. Nevertheless, the question remains as to whether this is feasible for all types of facilities. Can the utilization of RES systems to support the heating and electricity supply systems in existing public facilities discernibly reduce the negative environmental impact generated by the use of these energy systems throughout their life cycle?

In order to assess the environmental impact of investments, a variety of computer programs have been developed which operating principle is based on conducting a life cycle evaluation of a product or process. The most important software programs include SimaPro, GaBi, OneClickLCA, openLCA, CAALA, and Umberto [35]. These programs utilize specific models to forecast the environmental impact of a product or process, calculate emissions into the environment, and present the results using various indicators. SimaPro and GaBi are considered full-service life cycle assessment (LCA) tools, as they not only provide data but also allow for in-depth analysis. Some software programs, such as Umberto and SimaPro, require a high level of proficiency in LCA from the user, while others, like CAALA, can be used in a simpler mode by non-experts [35]. Abrahamsen et al. [36] employed SimaPro for an environmental analysis of the use of a zero-energy university facility in Norway. Hossain and Marsik [33] utilized SimaPro to contrast the environmental impact of a building in two design variants: constructed as an energy-efficient edifice and with traditional technology. The GaBi program was employed to assess the environmental performance of buildings on the campus of the University of Cantabria (Spain) in terms of electricity, natural gas, and water consumption, as well as the amount of paper sent for recycling [37]. Life cycle assessment programs are also being used to analyze the environmental impact of RES systems. Piotrowska et al. [38] analyzed a three-blade wind power plant and a 2 MW PV plant and demonstrated that a PV system, in comparison to other RES systems, has a reduced environmental impact throughout its life cycle. Gomaa et al. [39] assessed the environmental impact of wind farms (38 Vestas V112 wind turbines of 3 MW each) in Jordan. Constantino et al. [40] compared the environmental impact of

PV farms and coal-fired power plants as sources for meeting the energy needs of Brazilian households. John et al. [41] conducted a life cycle assessment of the use of RES systems in Malaysia with the objective of selecting the optimal solution for powering the Tatau rural area. The analysis revealed that the most environmentally sustainable option was the acquisition of energy from a mini-hydropower plant. Conversely, the PV farm exhibited the greatest environmental impact, with a 10-fold greater global warming factor and a 13-fold greater acidification factor compared to the mini-hydropower plant. Additionally, Mahmud et al. [42] compared the environmental impact of RES systems to determine which energy source has the lowest negative impact in the preparation of domestic hot water. A life cycle assessment of PV panels and vacuum tube solar collector, along with components that are responsible for the proper functioning of the entire off-grid PV system and solar collector, demonstrated that the PV system exerts a less detrimental impact on the environment than the solar system. The PV system has a less deleterious impact on human health, climate change, and the ecosystem than the solar installation.

Kania et al. [2] demonstrated that the installation of RES systems in residential buildings significantly reduces negative emissions. They carried out an analysis encompassing single-family residential buildings using the following scenarios: (1) coal and electricity from the grid, (2) coal with a 4 m^2 solar collector and electricity from the grid, (3) coal with a 4.46 kWp PV system, and (4) a 6 kW air-to-water heat pump with electricity from the grid. The research revealed that a single-family house powered by conventional energy sources generates 487% more CO_2 emissions compared to a building heated by a heat pump and 252% more compared to a building with a PV system.

Borkowski [43] conducted a comparative analysis of the environmental impact for residential buildings, including a traditional building, a wooden (Canadian-style) building, an ecological building, and a passive house. For the first three buildings, the thermal needs were met with a dual-function heating boiler, while the passive house utilized a recuperation system and solar collectors in conjunction with an electric heater. The results showed that the traditional building had the highest CO_2 emissions during operation, with the passive house exhibiting the lowest emissions (approximately 40% less). The other residential houses had higher CO_2 emissions compared to the passive house but lower than the traditional building. Despite the differences in materials and energy systems used, RES technologies reduced emissions in all cases.

Energy systems responsible for heating, domestic hot water, and electricity supply in public buildings in Poland primarily or exclusively utilize unconventional sources [6,8,44]. From a cognitive perspective, it is of significant interest to ascertain whether the utilization of RES equipment in public facilities and the related avoided emissions can offset the detrimental impact on the environment associated with the operation of energy systems based on non-renewable sources. The main goal of this study is to analyze the environmental impact of converting conventional energy sources to renewable energy systems in public buildings. As the literature review demonstrates, this specific research on public buildings has not yet been presented in the scientific literature. The key contribution of this research is the application of LCA to provide a comprehensive evaluation of the environmental effects of utilizing renewable energy systems in public facilities.

2. Materials and Methods

2.1. Characteristics of the Facilities under Study

The assessment encompassed 6 public buildings located in Lesser Poland Voivodeship (Figure 1). The analyzed facilities were situated in climatic zone III, in accordance with the division into climatic zones of the country [2,45]. The average annual temperature for this zone is approximately 7.6 °C [46], with an average annual irradiation of around 1120 $kWh \cdot m^{-2} \cdot year^{-1}$ [47]. The average amount of rainfall falls within the range of 610–620 mm, with 143 days of rainfall annually. The average wind speed ranges from 3.0 to 3.2 $m \cdot s^{-1}$, and there are approximately 22–24 days with snow [48].

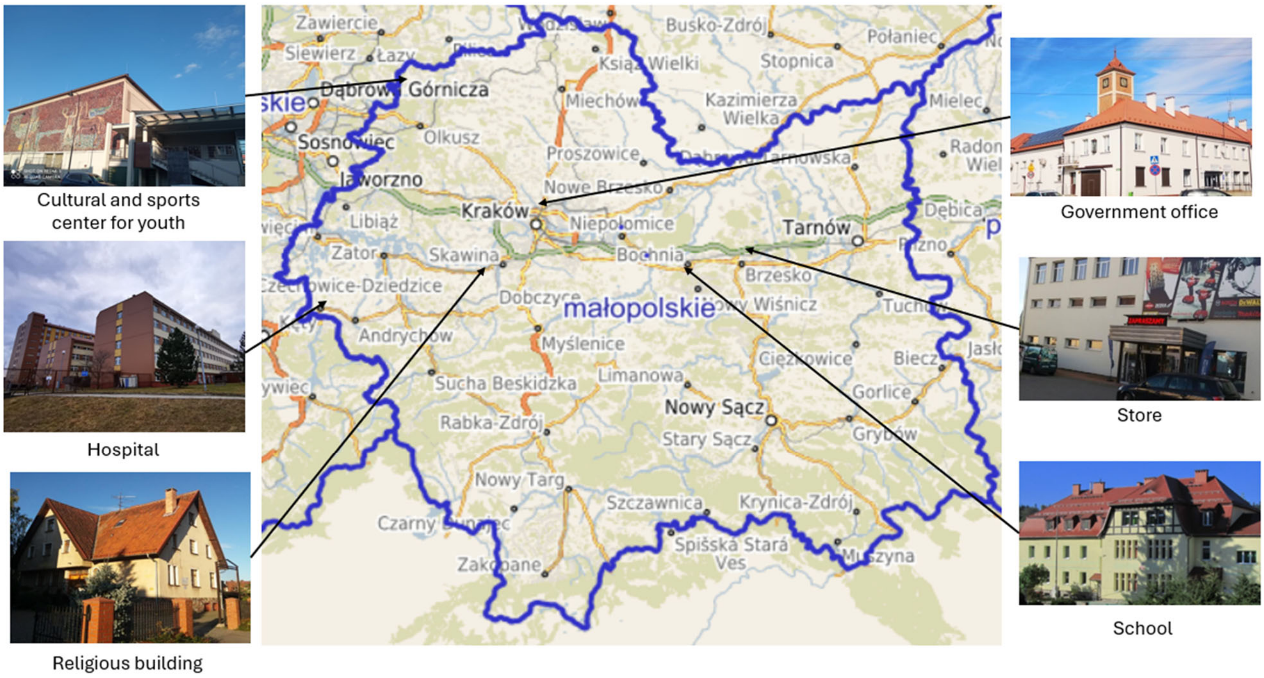

Figure 1. Location of the analyzed public utility facilities. Source: own work based on [49].

The following public facilities were selected for environmental analysis: cultural and sports center for youths, religious building, school, hospital, store, and government office. The facilities exhibited several common characteristics, including the year of the last thermal upgrade, the method of insulating the external walls and roof, and the use of the power grid to meet the demand for electricity (Table 1). However, they differed in several respects, including the heating source (e.g., gas or coal), area, number of floors, and employees, as well as the internal temperature (influenced by the function performed by the facility), which significantly affect the energy demand of the facility. The selection of these specific buildings for analysis provided us with the possibility to compare public buildings with different social functions yet with certain common characteristics, such as the timing of the last thermal upgrade and readiness to implement RES. Table 1 presents the average information from two years of operation of the facility (2019 and 2020).

Table 1. Characteristics of public buildings assessed.

	Cultural and Sports Center for Youths	**Religious Building**	**School**	**Hospital**	**Store**	**Government Office**
Year of construction	1960	1994	1900	2000	1966	1922
Year of last thermal upgrade	2000	2000	2000	2000	2000	2000
Source of thermal energy after investment	Coal	Gas	Gas	Coal	Coal	Gas
Construction material	Brick	Brick	Brick	Reinforced concrete	Aerated concrete	Brick

Table 1. *Cont.*

	Cultural and Sports Center for Youths	**Religious Building**	**School**	**Hospital**	**Store**	**Government Office**
Type of material and thickness of external wall insulation	Polystyrene foam—10 cm	Polystyrene foam—12 cm	Polystyrene foam—12 cm	Polystyrene foam—10 cm	Polystyrene foam—12 cm	Polystyrene foam—12 cm
Type of material and thickness of roof insulation	Mineral wool—20 cm	Mineral wool—20 cm	Mineral wool—20 cm	Mineral wool—20 cm	Mineral wool—20 cm	Mineral wool—20 cm
Usable area of the building [m^2]	1841	721	3105	40,000	2150	1355
Number of floors	2	4	4	10	3	3
Number of employees	32 employees	4 employees + 30 guests	27 employees + 200 students	1075 employees	35 employees	75 employees
Annual power consumption [$kWh \cdot year^{-1}$]	85,170	32,101	39,097	3,724,903	80,807	72,623
Annual consumption for thermal energy [$kWh \cdot year^{-1}$]	579,700	366,455	936,446	45,961,492	336,000	667,696

Source: own materials.

2.2. Experiment Description

The schematic diagram of the analysis performed is illustrated in Figure 2. The initial stage of the environmental assessment entailed the acquisition of data on buildings, including energy demand (heat and electricity), and the subsequent selection of new energy systems, with a primary focus on RES, for these buildings. For this purpose, PV*SOL Premium 2021 software (Valentin Software, Berlin, Germany) was employed to design a PV installation. This program is regularly validated by adding the latest devices and installations to the database. The subsequent stage of the experiment involved the proposal of selected new RES devices to investors. Importantly, the selection of equipment also took into account the results of the facility manager interviews and the available space on the roofs and around the buildings that could be used to implement RES solutions. The RES systems were unable to cover 100% of the electricity demand of the analyzed facilities.

The installation of the RES systems based on the presented guidelines was completed in 2021 (Figure 3). In 2022 and 2023, the managers of the analyzed facilities were interviewed once more to verify the electricity consumption of the analyzed buildings, as well as the electricity generated from the implemented RES systems (Table 2). During the years 2021–2023, no additional measures were taken in the assessed buildings to reduce the demand for heat and electricity. Moreover, the number of users of the facility and the daily behavior of using electricity and heat have remained unchanged since the installation of the RES system.

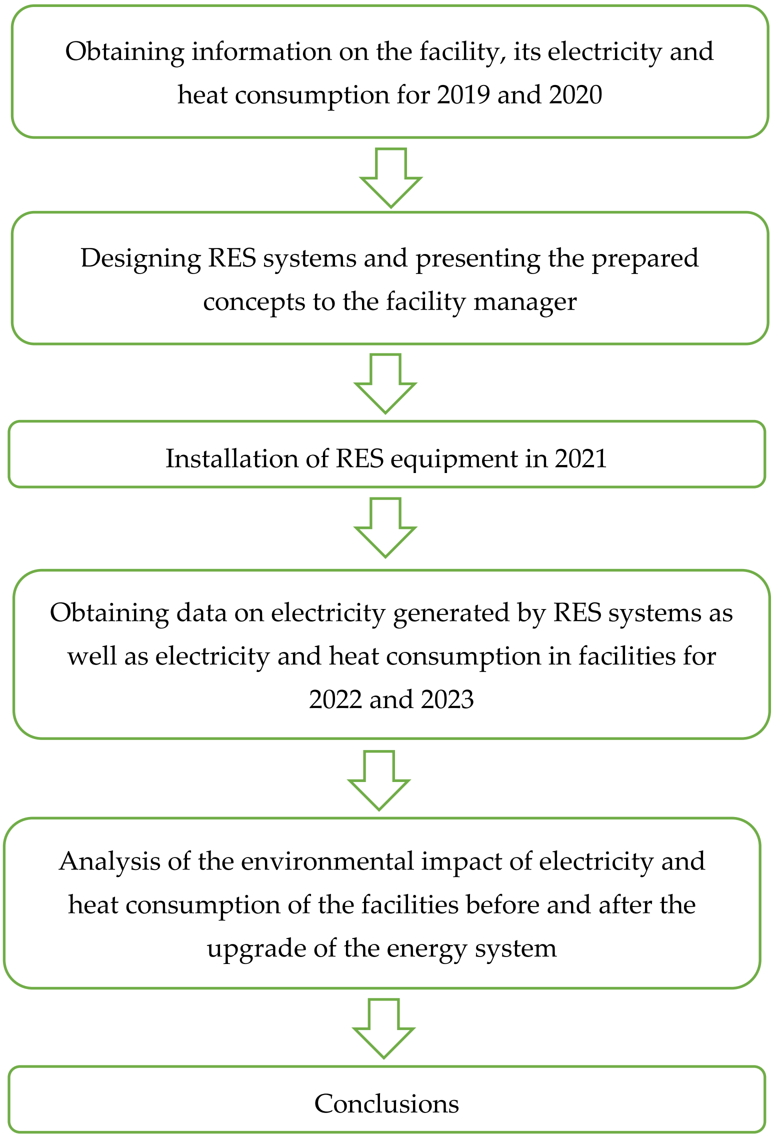

Figure 2. Experiment execution stages. Source: own materials.

Table 2. Characteristics of the designed RES installations for the analyzed public facilities.

Parameters	Cultural and Sports Center for Youths	Religious Building	School	Hospital	Store	Government Office
Power	40.12 kWp photovoltaic (polycrys-talline) system	22 kWp photovoltaic (monocrys-talline) system	16.43 kWp photovoltaic (monocrys-talline) system	400 kWp photovoltaic (monocrys-talline) system	25.11 kWp photovoltaic (monocrys-talline) system	11.69 kWp photovoltaic (monocrys-talline) system
Tilt angles [°]	35	30	35	40	30	45
Exposures	south	southwest	southwest and southeast	south	south	south
Location	roof	freestanding structure	roof	ground	roof	roof
Type of installation	on-grid	on-grid	on-grid	on-grid	on-grid	on-grid

Source: own materials.

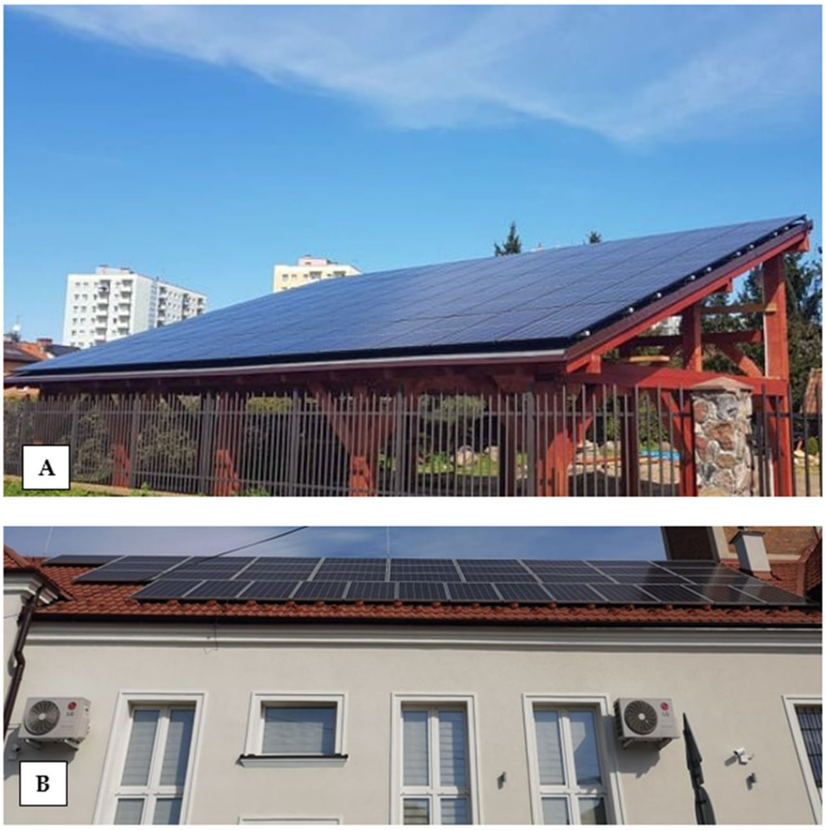

Figure 3. Example photos of the PV systems under study ((**A**) religious building, and (**B**) government office). Source: own materials.

2.3. Environmental Assessment

There is a range of tools available for assessing environmental impacts, including the Environmental Impact Assessment (EIA), LCA, Environmental Auditing, and Material Flow Analysis (MFA) [50]. These tools can be complementary and are not mutually exclusive [51]. However, the most widely applied method is LCA, which allows for a comprehensive assessment of the causal relationships between solutions employed to mitigate environmental impacts. Additionally, LCA can be used to calculate the carbon footprint according to ISO standards 14040 [52] and 14044 [53,54]. The LCA methodology permits the comprehensive tracing of a product's entire life cycle, a practice that has been employed since the 1990s. LCA serves as a pivotal component of numerous environmental management systems across the globe [55,56]. Life cycle assessment is a method of analyzing the environmental hazards and effects related to a specific product throughout its entire life cycle. This may be expressed as "from cradle to grave" or "from cradle to cradle", depending on the final use of the analyzed product. The product analyzed using the LCA technique may be a specific item, the entire production process, or a service [55–57]. In the construction industry, LCA enables the control and optimization of the environmental impact of construction materials, the building as a whole, or individual stages of the construction process. The impact on the environment is assessed using eco-indices in individual damage and impact categories [58,59].

The method enables users to recognize the impact of a facility on the environment, from the extraction of resources, production, construction, and operation phase to the decommissioning of a building or other product. LCA includes four main phases [60,61]: definition of purpose and scope, life cycle inventory, life cycle impact assessment, and interpretation of the results [62].

2.3.1. Goal and Scope, Functional Unit, and System Boundaries

The objective of this study is to analyze the environmental benefits of utilizing RES systems in public buildings and to assess the potential for offsetting the negative impact on the environment resulting from the operation of energy systems based on non-renewable sources.

The functional unit in LCA serves as a reference point for all calculations and allows for the comparison of different facilities. In this analysis, the reference point for all calculations regarding the assessment of the product's impact during the entire life cycle period is 1 $m^2 \cdot year^{-1}$.

The LCA methodology is founded upon the precise definition of the system boundaries, which allows for the identification of the basic input and output flows (energy, raw materials, etc.) in the subsequent phases of the process. The boundaries of the analyzed system do not include the environmental impact of the construction process, as well as the equipment of the building; waste from fuel extraction and the production of electricity and heat; the process of demolition of the building; and the elements of the energy system functioning in it (heat receivers, electrical sockets, etc.). Rather, the focus is on the environmental assessment of electricity consumption in the analyzed facilities. Following the upgrade of the facilities (installation of RES systems), the system boundaries were revised to encompass the devices utilized. The scope of data employed in the analysis is presented in Table 3.

Table 3. Comparative summary of the consumption and production of electric and thermal energy in public buildings before and after the use of RES systems.

		Cultural and Sports Center for Youths	Religious Building	School	Hospital	Store	Government Office
Electricity and heat consumption before using RES systems							
Electricity consumption	[$kWh \cdot year^{-1}$]	85,170	32,101	39,097	3,724,903	80,807	72,623
	[$kWh \cdot m^{-2} \cdot year^{-1}$]	46	45	13	93	38	54
Heat demand	[$kWh \cdot year^{-1}$]	161,028	101,793	260,124	12,767,081	93,333	185,471
	[$MJ \cdot m^{-2} \cdot year^{-1}$]	315	508	302	1149	156	493
Electricity and heat consumption after using RES systems and energy production by RES systems							
Electricity consumption	[$kWh \cdot year^{-1}$]	46,273	12,803	24,448	3,493,102	56,535	62,951
	[$kWh \cdot m^{-2} \cdot year^{-1}$]	25	18	8	87	26	46
Heat demand	[$kWh \cdot year^{-1}$]	158,922	94,172	241,079	13,000,422	90,337	172,121
	[$MJ \cdot m^{-2} \cdot year^{-1}$]	311	470	280	1170	151	458
Electricity generation	[$kWh \cdot year^{-1}$]	40,600	20,101	15,470	339,823	25,807	11,487
	[$kWh \cdot m^{-2} \cdot year^{-1}$]	22	28	5	8	12	8

Source: own materials.

2.3.2. Life Cycle Inventory

The life cycle inventory (LCI) employs the Ecoinvent 3.0 database and entails the delineation of quantifiable and accessible data, including the consumption of raw materials and energy within the system boundaries under analysis. The quantitative values used in the data sets were derived from an interview with managers of public facilities. The data on the quantity of electricity generated and consumed were expressed in kilowatt hours [kWh] and then entered into the SimaPro 8.1 program. The input values of the LCA model were adjusted to align with the national energy mix.

The data set for electricity from the medium-voltage public network in Poland (in the Ecoinvent database) considers the environmental impact of electricity generation and its transmission through the power grid (overhead lines and cables). The data set does not include electrical equipment such as transformers, fuses, and others, as well as waste from energy production. In the case of PV systems, the data set encompasses the production of

PV modules and components that collectively constitute a system for electricity production, as well as transport, assembly, and disposal. The data set excludes maintenance activities (renovations) and waste generated during these activities, such as the replacement of an inverter or a damaged PV module.

The data set on the generation of heat from a coal-fired boiler and a gas furnace encompasses the environmental impacts associated with the production and management of waste from these devices. However, it excludes maintenance activities. Additionally, it encompasses the production of hot water tanks, central heating, plumbing security systems, and pipes.

2.3.3. Life Cycle Impact Assessment Method

The analyses were conducted using SimaPro 8.1 software (PRé Sustainability B.V., Amersfoort, The Netherlands) and the Ecoinvent 3.0 database. This tool is compliant with the following standards: PN-EN ISO 14067 [63] and PN-EN ISO 14040. The ReCiPe model was employed for evaluation purposes. This model employs indices for an evaluation at two levels: the midpoint and endpoint. The ReCiPe model was developed in 2008 as a result of a collaborative effort between the RIVM, Radboud University Nijmegen, Leiden University, and PRé Consultants. This method combines the previously used Eco-Indicator 99, CML, and other methods and establishes their common boundaries by connecting midpoints with endpoints. The ReCiPe Midpoint (H) V1.12 method was used to assess the environmental impact with the midpoint method. In the midpoint method, the influence of previous cause-and-effect chains is analyzed before reaching the endpoint. The final section of this analysis focuses on the factors influencing the environment from the last cause-and-effect chain. Midpoint indices are indirect measures of environmental impact that reflect changes in the natural environment due to emissions or resource use and thus show where each impact category is characterized. ReCiPe encompasses three endpoints (human health, ecosystem, and resources) and eighteen impact categories [64–66].

In the ReCiPe method, the output unit is the so-called total environmental load point or eco-point (Pt). This unit is equivalent to a person, and thus, the term "person equivalent" (PE) is used. A unit of 1000 PE represents the annual environmental impact caused by all the activities of an average European [67].

3. Results

The average consumption of electricity obtained from the national power grid in the analyzed facilities before the implementation of the RES systems was 48 $kWh \cdot m^{-2} \cdot year^{-1}$. As a public facility, the analyzed hospital exhibited the highest demand for electricity per 1 m^2 (Table 3). In contrast, the school had the lowest electricity consumption (over seven times less than the hospital). The thermal energy consumption averaged 487 $MJ \cdot m^{-2} \cdot year^{-1}$. In this regard, the hospital also exhibited the highest energy consumption, while the store exhibited the lowest. This discrepancy can be attributed to the specific characteristics of each facility.

Following the introduction of RES devices to supply electricity, the demand for heat remained mostly consistent. There was a slight decrease in the heat demand of around 2.8% on average across all facilities compared to 2019–2020. This was primarily the result of shorter winter periods and higher average temperatures. As predicted, a significant change in the consumption of electricity from the grid was observed, with a reduction by 27% on average, to an average of 35 $kWh \cdot m^{-2} \cdot year^{-1}$. The remaining energy needed for operation was sourced from RES. The PV system for the hospital only fulfills less than 9% of electricity needs, suggesting challenges in achieving zero emissions. In contrast, the school relies on renewable energy for about 38% of its electricity demand, while the cultural and sports center covers approximately 46% from the PV installation. The highest percentage of electricity from the PV system was observed for the religious building, where more than half of the electricity demand was met.

The results of the environmental assessment of energy systems for the analyzed facilities prior to the use of RES systems are presented in Table 4. Based on the LCA, it can be concluded that the hospital has the greatest negative impact on the environment among all the analyzed facilities. The hospital achieved the highest indicator values in 17 out of 18 impact categories. This is due to the fact that the facility operates 24 h a day, which, in turn, is associated with a constant demand for electricity. The consumption of electricity and heat in the hospital significantly affects the following impact categories: 230.4 kg CO^2 eq, human toxicity: 101.1 kg 1,4-DB eq, and fossil depletion: 57.6 kg oil eq. In the case of the impact category "natural land transformation", the religious building and the government office recorded the greatest negative impact on the environment.

Table 4. Normalized environmental impact of analyzed existing energy systems in public facilities (without RES—theoretical calculations)—ReCiPe Midpoint method.

Sel	Impact Category	Unit	Cultural and Sports Center for Youths	Religious Building	School	Hospital	Store	Government Office
1	Climate change	kg CO_2 eq	87.155	92.716	39.024	230.379	60.974	102.066
2	Ozone depletion	kg CFC-11 eq	2.38×10^{-6}	5.29×10^{-6}	2.96×10^{-6}	7.69×10^{-6}	1.38×10^{-6}	5.27×10^{-6}
3	Terrestrial acidification	kg SO_2 eq	0.501	0.348	0.122	1.371	0.341	0.401
4	Freshwater eutrophication	kg P eq	0.059	0.059	0.018	0.120	0.048	0.071
5	Marine eutrophication	kg N eq	0.019	0.017	0.005	0.043	0.015	0.020
6	Human toxicity	kg 1,4-DB eq	45.256	41.118	12.673	101.060	35.440	48.745
7	Photochemical oxidant formation	kg NMVOC	0.215	0.167	0.065	0.594	0.145	0.189
8	Particulate matter formation	kg PM_{10} eq	0.136	0.104	0.037	0.361	0.095	0.119
9	Terrestrial ecotoxicity	kg 1,4-DB eq	0.002	0.002	0.001	0.007	0.002	0.002
10	Freshwater ecotoxicity	kg 1,4-DB eq	1.785	1.800	0.560	3.734	1.449	2.130
11	Marine ecotoxicity	kg 1,4-DB eq	1.642	1.639	0.506	3.445	1.331	1.941
12	Ionizing radiation	kBq U^{235} eq	3.529	2.545	1.070	10.462	2.238	2.802
13	Agricultural land occupation	m^2a	1.896	1.985	0.613	3.832	1.566	2.352
14	Urban land occupation	m^2a	0.241	0.278	0.093	0.488	0.199	0.324
15	Natural land transformation	m^2	0.002	0.008	0.004	0.004	0.002	0.008
16	Water depletion	m^3	0.181	0.132	0.048	0.494	0.124	0.151
17	Metal depletion	kg Fe eq	0.867	1.292	0.541	1.927	0.681	1.424
18	Fossil depletion	kg oil eq	22.124	27.903	12.338	57.587	15.660	30.271

CFC—the characterization factor for ozone layer depletion accounts for the destruction of the stratospheric ozone layer by anthropogenic emissions of ozone depleting substances, 1,4-DB—the characterization factor of human toxicity and ecotoxicity accounts for the environmental persistence (fate) and accumulation in the human food chain (exposure) and toxicity (effect) of a chemical, NMVOC—the unit of human health ozone formation potential; the characterization factor is determined from the change in intake rate of ozone due to change in emission of precursors, and kBq U^{235}—the characterization factor of ionizing radiation accounts for the level of exposure for the global population [68]. Source: own research.

The school exhibited the lowest environmental impact (in 16 out of 18 impact categories) compared to the other facilities under study. CO_2 emissions (related to climate change) amounted to only 39 kg CO_2 eq, human toxicity: 12.7 kg 1,4-DB eq, and fossil depletion: 12.3 kg oil eq. In contrast, the store had the smallest impacts in the following categories: ozone depletion (1.38×10^{-6} kg CFC-11 eq) and natural land transformation (0.002 m^2).

The impact of the last cause-and-effect chain on the environment (ReCiPe Endpoint model) of (conventional) energy systems used in public facilities is illustrated in Figure 4. The hospital obtained 20.85 Pt (eco-points), with the resources category accounting for 45% of the eco-points, human health for 35%, and ecosystems for 20%. The second-most negatively impacted energy system (9.96 Pt) was the one installed in the government office. The energy system installed at the school recorded the lowest indicator (3.82 Pt).

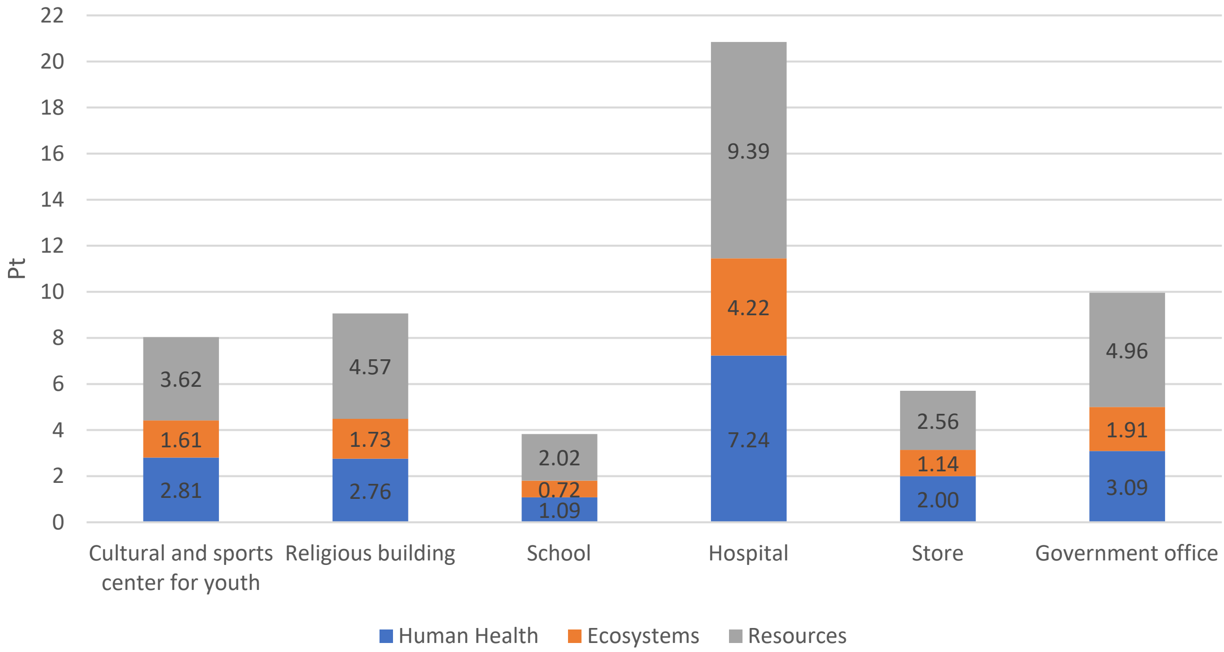

Figure 4. Comparison of the environmental impact of energy systems used in public facilities powered only by conventional energy sources (without the use of RES)—ReCiPe Endpoint method. Source: own research.

The analysis of electricity consumption in public facilities based on data obtained for the period 2022–2023, i.e., after the implementation of the proposed RES installations (Table 5), revealed that the smallest emission reduction was achieved in the hospital and the government office. Conversely, the greatest reduction in the negative impact on the environment was observed in the religious building. This phenomenon can be attributed to the fact that this facility exhibited the highest rate of electricity generated from RES per usable area of the building. The implementation of RES systems in the religious building reduced the impact on freshwater eutrophication and agricultural land occupation. A reduction in the impact indices was also observed for the remaining criteria, with the exception of terrestrial ecotoxicity, water depletion, and metal depletion, for which the negative impact increased by 147.9%, 13.9%, and 29.4%, respectively. The observed increase can be attributed to the release of chemical fumes during the production of PV panels, as well as possible leaks containing harmful chemicals such as cadmium, lead, tin, copper, and aluminum. These chemical elements may be washed out and released into the environment as a result of damage to the device or after its operation as waste [69,70]. Each facility recorded an increase in values for the following impact categories: terrestrial ecotoxicity, water depletion, and metal depletion. Moreover, the values of the indices: ozone depletion and ionizing radiation increased only in the hospital.

Table 5. Normalized environmental impact of analyzed energy systems in public facilities with consideration of avoided emissions (resulting from RES systems)—ReCiPe Midpoint.

Sel	Impact Category	Unit	Cultural and Sports Center for Youths	Religious Building	School	Hospital	Store	Government Office
1	Climate change	kg CO_2 eq	63.776	60.520	31.867	226.264	47.429	90.472
2	Ozone depletion	kg CFC-11 eq	2.36×10^{-6}	4.49×10^{-6}	2.76×10^{-6}	7.83×10^{-6}	1.35×10^{-6}	4.92×10^{-6}
3	Terrestrial acidification	kg SO_2 eq	0.382	0.194	0.092	1.353	0.272	0.351
4	Freshwater eutrophication	kg P eq	0.034	0.027	0.012	0.113	0.034	0.061
5	Marine eutrophication	kg N eq	0.012	0.009	0.004	0.042	0.011	0.018
6	Human toxicity	kg 1,4-DB eq	29.732	21.062	8.861	97.245	26.467	42.636
7	Photochemical oxidant formation	kg NMVOC	0.167	0.105	0.051	0.589	0.117	0.167
8	Particulate matter formation	kg PM_{10} eq	0.102	0.060	0.028	0.355	0.075	0.105
9	Terrestrial ecotoxicity	kg 1,4-DB eq	0.005	0.005	0.001	0.007	0.003	0.003
10	Freshwater ecotoxicity	kg 1,4-DB eq	1.332	1.205	0.443	3.635	1.180	1.943
11	Marine ecotoxicity	kg 1,4-DB eq	1.221	1.086	0.398	3.353	1.082	1.768
12	Ionizing radiation	kBq U^{235} eq	3.067	1.948	0.925	10.507	1.971	2.566
13	Agricultural land occupation	m^2a	1.118	0.976	0.422	3.617	1.120	2.045
14	Urban land occupation	m^2a	0.149	0.158	0.069	0.463	0.147	0.286
15	Natural land transformation	m^2	0.001	0.007	0.004	0.004	0.001	0.008
16	Water depletion	m^3	0.190	0.151	0.050	0.509	0.131	0.154
17	Metal depletion	kg Fe eq	1.208	1.672	0.589	2.083	0.852	1.500
18	Fossil depletion	kg oil eq	15.973	19.157	10.302	56.444	12.102	26.964

Descriptions the same as for Table 4. Source: own research.

In the cultural and sports center for youths, the environmental impact was reduced by an average of 15%. The largest decrease in negative impact was determined in the following categories: freshwater eutrophication (42.9%) and agricultural land occupation (41%). Although the hospital had the largest RES installation, it exhibited the smallest reduction in the negative impact on the environment compared to the other examined facilities. The hospital recorded the largest declines in impact categories such as freshwater eutrophication (5.9%) and agricultural land occupation (5.6%).

Figure 5 demonstrates that the installed RES systems contributed to a decrease in the negative impact on the environment. The largest decrease was recorded for the religious building (by 34.4%).

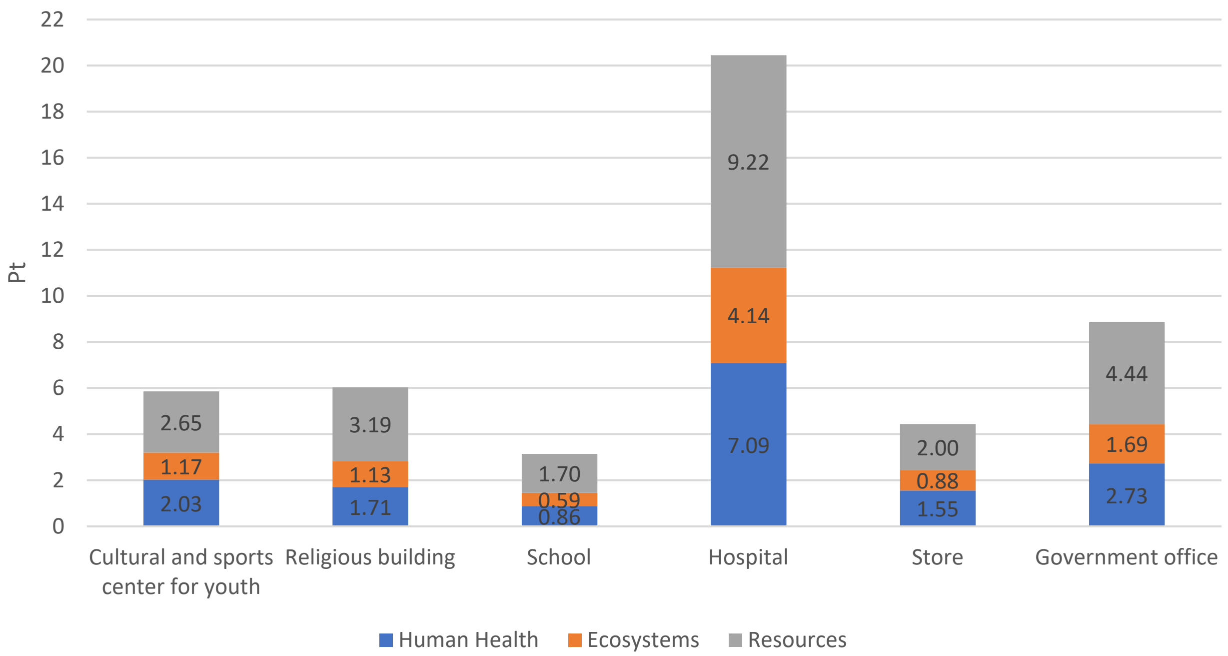

Figure 5. Comparison of the environmental impact of energy systems used in public facilities powered only by conventional energy sources (using RES)—ReCiPe Endpoint method. Source: own research.

4. Discussion

The assessment of the environmental impact of public facilities is a developing field, and as a consequence, the results of detailed studies conducted for these facilities are not widely available in the scientific literature. This is in contrast to analyses of residential homes (e.g., single-family houses), which are relatively straightforward to compare among themselves due to their similar function. The life cycle assessment of residential houses is primarily concerned with emissions generated during the construction phase, the transportation of construction materials, the operation of the building, its demolition, and the analysis of the potential environmental impact of thermal upgrading. The present paper undertakes an assessment of the environmental impact of energy systems installed in selected public facilities. In contrast to residential houses, public buildings exhibit considerable variations in energy and heat consumption due to the distinct functions performed by these facilities. This directly translates into variations in the environmental impact. The primary determinant of the environmental impact is the consumption of heat and electricity, as well as the capacity of the RES system installed.

In the case of the religious building under study, the proposed PV installation led to a reduction of over 30% in unwanted environmental emissions. In comparison, other public facilities saw reductions ranging from 2% (hospital) to 27% (culture and sports center). These reductions were solely due to changes in the electricity system delivery and were lower than reductions in emissions for residential buildings estimated by Kania et al. [2] or Borkowski [43], which were described in the Introduction section. A comparison of the environmental impact on climate change for the studied facilities before and after implementing RES, as well as for the single-family residential buildings, is presented in Figure 6.

It is important to consider that the introduction of a PV system may not always have a positive impact on the environment. The emissions from other sources providing electricity must also be taken into account. For example, a study by Abrahamsen et al. [36] found that the PV modules installed at a university had a higher emission factor compared to electricity from a power plant. The reason for this finding is that Norway has a higher share of RES in the energy system, especially hydroelectricity, which accounts for more than one-third of the country's energy system [71].

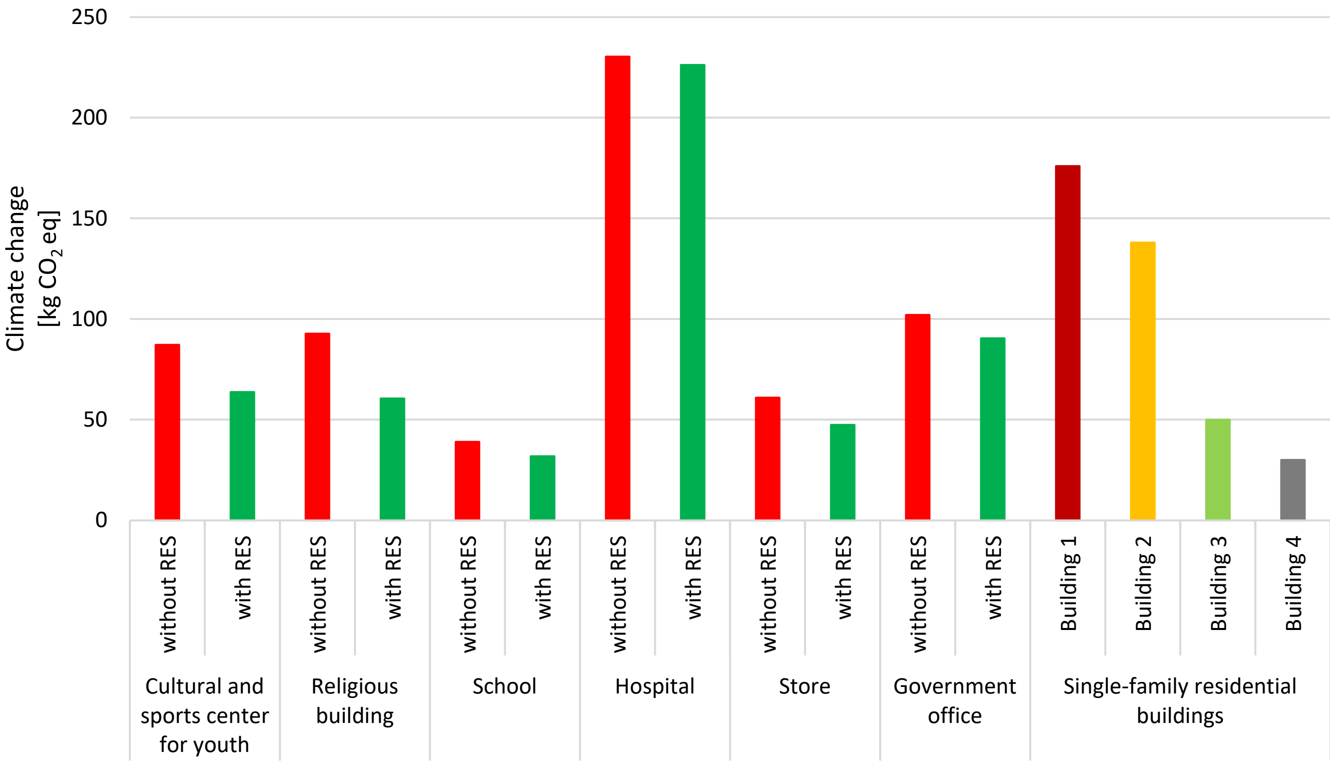

Figure 6. Environmental impact on climate change of public facilities with and without RES systems, and single-family residential buildings with different energy supply systems [2]: Building 1—coal and electricity from the grid; Building 2—coal, solar collectors, and electricity from the grid; Building 3—coal and PV system; and Building 4—heat pump and electricity from the grid. Source: own research and [2].

Given the fact that some elements of the energy balance of a facility, such as the recovery of energy from thermal radiation emitted by users and equipment, were not included in this study, further analyses will be conducted to address these elements. It would also be interesting from a cognitive point of view to conduct a life cycle environmental assessment of other public buildings with similar thermal characteristics. In future research, the environmental assessment methods presented in this paper could be applied together with energy management methods, such as an active distribution network in the case of office buildings [72]. Other possible research could encompass applying environmental assessment methods for multi-agent energy systems that integrate, for instance, solar power plants, wind power plants, and buildings [73].

5. Conclusions

The replacement of conventional energy sources with RES systems reduces the negative environmental impacts of facilities during their operation. The reduction in negative impacts varies and is mainly dependent on energy consumption. The smallest positive impact on the environment of the installed RES system was recorded for the hospital, while the greatest was for the religious building with a low energy demand. This proves that the application of RES in public facilities with relatively low energy demands represents an effective strategy. The use of RES in the buildings and the associated avoided emissions do not entirely offset the negative emissions resulting from the utilization of other (conventional) energy sources in the analyzed energy systems of public buildings. Consequently, the analyzed facilities collectively exert a detrimental impact on the environment.

In the future, it is advisable to prioritize the eco-design of RES equipment in terms of their construction, operation, and the materials used. It is of paramount importance that green energy is not only environmentally friendly in terms of its production but also throughout its entire life cycle. Eco-design can play a pivotal role in minimizing the negative environmental consequences associated with the production and operation of green resources.

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