INTERNATIONAL JOURNAL OF RENEWABLE ENERGY RESEARCH
B. A. Aljashaami et al. ,Vol.13, No. 2, June, 2023

Analysis of Technical Efficiency, Economic Feasibility, and Environmental Impacts of using Solar Heating Installations for Buildings

Baseem A. Aljashaami[*], Sajjad A. Salih[*], Naseer T. Alwan [**‡], Mohammed A. Qasim[*], Milia H. Majeed[*], Ahmed H. Mola[*], Vladimir I. Velkin[*], Sergey E. Shcheklein[*], Lech Lobocki[***]

[*]*Department of Nuclear and Renewable Energy, Ural Federal University, Yekaterinburg 620002, Russia*

[**]*Technical Engineering College of Kirkuk, Northern Technical University, Kirkuk 36001, Iraq*

[***]*Warsaw University of Technology, Pl. Politechniki 1, 00-653 Warszawa, Poland*

‡ Corresponding Author; Naseer T. Alwan, *Department of Nuclear and Renewable Energy, Ural Federal University, Yekaterinburg 620002, Russia, and, Technical Engineering College of Kirkuk, Northern Technical University, Kirkuk 36001, Iraq*, Tel: +964-77111487263, nassir.towfeek79@gmail.com

Received: 22.12.2022 Accepted:22.03.2023

Abstract- This study aims to provide a clear vision of the potential of solar heating installations currently available in the market as a successful alternative to traditional methods, economic feasibility, and contribution to reducing greenhouse gas emissions. The study involves using solar energy to provide the energy needed to heat a house in Warsaw. The solar installations were tested, and their performance was simulated and compared based on production quantity with cost and suitability for the climatic conditions of the study area. In addition to determining the best way to install solar panels by calculating optimal tilt and azimuth angles. The work methodology for designing a suitable solar system went in two directions; the first is using a solar thermal collector in direct heat generation, while the second is using photovoltaic panels to generate electricity to heat water by a water heater. All results were obtained through simulation work in RETScreen and PVGIS software. The results showed that solar thermal collectors and photovoltaic panels contributed to the annual energy demand by 40% and 43%, and the financial returns in case the conventional energy is electricity or natural gas are 715 and 252 EUR (for STC) and 765 and 269 EUR (for PV), respectively. It also reduced annual emissions by 2.36 and 2.53 tCO_2.

Keywords- Solar heating installations, Solar thermal collectors (STC), Photovoltaic panels (PV)

1. Introduction

Population increases and industry advances have increased the energy demand, leading to the cost of raw materials used in energy production and the depletion of its natural reserves [1]. According to statistics, global energy production in 2019 amounted to (606411168 TJ) (In Figure 1. the growth of energy supply in the world can be seen) [2]. Fossil fuels are considered one of the most important energy sources in the world today, but their use results in greenhouse gas emissions, which pose a real threat to the global climate. Therefore, the trend toward using alternative energy such as solar, wind, and biomass has recently begun [3, 4, 5].

Several reasons are pushing toward a shift to alternative energy, such as solar energy, including technical, economic, political, and environmental. There are other reasons related to traditional methods of energy production, which will lead to problems in the future if the world continues the same path without switching to alternative energy. Fossil fuels (natural gas, oil, and coal) are a finite energy source, so the world's reserves are on the way to depletion, especially with excessive consumption over the past hundred years [6]. With declining fossil fuel stocks, the cost of extraction goes up, and the quality goes down, as it requires access to great depths and complex technologies [7]. The differing whereabouts of fossil fuels in the world make countries either an exporter or an importer and thus make the global energy market affected by politics and wars. The supply and demand factor affects price fluctuations significantly and complicates future expectations, which makes it difficult to establish a stable economy [8]. Although fossil fuels are characterized by their high energy and the possibility of storing them in large quantities, their combustion emits large amounts of GHG, one of the main elements of global warming and climate change, as well as its impact on public health [9].

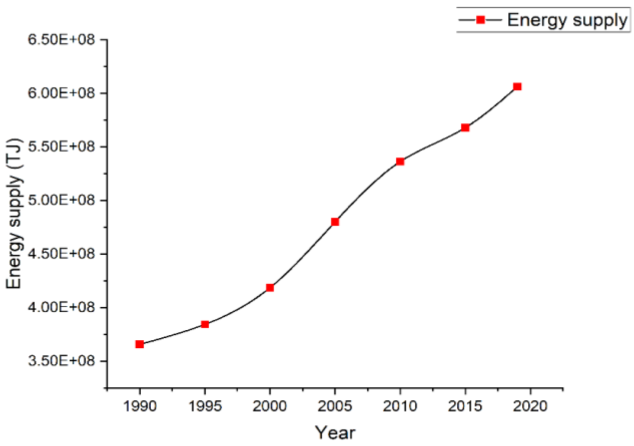

Fig. 1. Energy supply growth in the world [2].

The buildings sector is one of three main sectors (the industrial sector, the transport sector, and the buildings sector) in energy consumption, as it consumes 40% in the European Union, according to statistics [10]. Building heating constitutes the most significant part of energy consumption [11]. There are several forms of building heating, including the use of the district heating system, if available, or the use of local installation, such as the use of thermal boilers that depend on different types of fuel (as shown in Figure 2. the energy used in area heating and cooling in European Union and Poland according to the record in 2015 classified by energy source) [12]. Neutralizing this sector by partially or wholly relying on solar energy will significantly reduce greenhouse gas emissions, and there will be greater flexibility in the security of energy supplies.

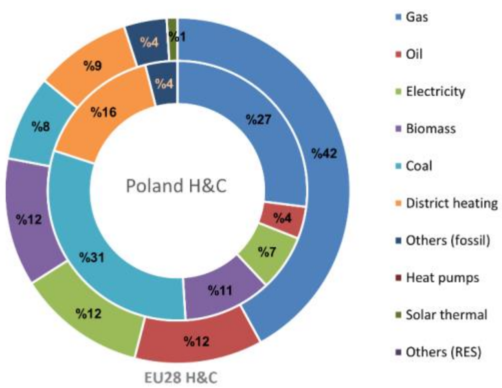

Fig. 2. Heating and cooling energy in the European Union and Poland by source [12].

A literature review conducted in recent years shows three main objectives that studies seek to verify: technical efficiency, economic feasibility, and environmental impacts (contributing to emissions reduction). The studies included several places worldwide and followed different methodologies to reach their goals. Pokhrel et al. [13] investigated the possibility of replacing natural gas used in heating and water heating for two multi-level buildings with renewable energy sources using solar borehole thermal energy storage and heat recovery from wastewater, then identified the efficiency, economic feasibility, and environmental impact of this transformation. Also, the study [14] presented a practical experience to improve the performance of flat plate collectors for heating air and water for buildings and the extent of their economic and environmental contribution. In the study [15], the author claimed that the performance of evacuated tube collectors is better than flat plate collectors in their role in heating domestic water instead of using fossil fuels, and thus a more significant contribution to reducing carbon dioxide emissions after conducting simulations in 21 cities in South Africa. [16] The author put forward the idea of gas-solar hybrid systems whose purpose is to reduce energy consumption, which reflects positively on the environment by using solar energy in heating an administrative building. The research methodology was based on a genetic algorithm and software simulation to reach the best-proposed solutions. The study [17] presented a performance analysis of a group of solar energy collectors used to reduce energy consumption in buildings, where the study was based on a dynamic simulation and verification of the results after installing the system and testing it practically and determining the possibility of solar installations in achieving the planned goals. In a study presented by Cannon et al. [18], a solar heating system consisting of 10 flat plate collectors and two storage tanks. Built for the purpose of heating a hall in a building in Erbil, northern Iraq. The results showed a reduction in energy consumption to 8% in December and 14% in January and February. Moreover, the system reduced CO_2 emissions by up to 86.4% in January, with an estimated payback period of 4.65 years. Some studies tended to experiment with hybrid solar systems. Elmnifi et al. [19] presented a feasibility study for a hybrid photovoltaic solar thermal collector designed to provide electricity and heat for a residential house in northern Libya. Nine solar collectors with an annual production of 4,733 kWh/year were used to cover the average annual household consumption of about 10,529 kWh. The authors claimed annual savings per house of 1,895 dollars, with CO_2 emissions reductions for light oil, heavy oil, and gas of 252, 195, and 15,447 kg, respectively.

Recent studies have focused on finding ways to improve solar energy installations [20]. The studies sought to achieve the optimum utilization of the available solar energy and providing an energy supply at night is the most important goal. One of the essential methods is using phase change materials, which can store heat [21, 22]. Habib et al. [23] increased the thermal storage of a solar air collector used to heat a room in a building in Iraq using phase change materials. By adding single-walled carbon nanotubes to paraffin wax. The results showed a clear improvement in the stored thermal energy. In the same context, Jawad et al. [24] used an aluminum wafer, and tubes filled with nanoscale silicon carbide (SiC) were added to paraffin wax in a solar air heater to improve the physical and thermal properties. The results showed an improvement in the performance of the solar heater and the acceleration of air heating, in addition to the heating continuing for 3 hours after sunset.

Solar heating installations are one of the available solutions for converting solar radiation into energy that can be used in residential heating buildings [25, 26]. However, it is considered a complex system, and several factors affect its performance [27]. And to reach high-reliability results (technical efficiency, economic feasibility, and environmental impact), the work must be comprehensive and not neglect any element that may impact the results. Despite the abundance of literature available in this field, there is a lack of research papers that shed light on the production of solar heating installations and compare them with demand throughout the year.

To bridge gap, this work will follow a methodology that deals with the subject in detail. We will compare between types of solar heating installations (solar thermal collectors (STC) and photovoltaic panels (PV) each separately) currently available in the market in terms of efficiency versus cost and choose the best, and then determine the appropriate installation method and determine the optimal angles (azimuth and slope). We will also calculate the amount of heat load for a whole year for the building to be heated using the average daily temperature of the study area, then simulate two types of solar heating installations: solar thermal collectors (STC) and photovoltaic panels (PV). This work is keen to provide a comprehensive view of the ability of solar energy installations of both types (STC, PV) available in the market to provide heating for a building under cold weather conditions, as well as the system's flexibility to respond to changes in energy demand.

2. Solar Heating Installations Available on the Markets

Several types are currently available in the market from the installations that utilize solar energy produced by many manufacturers across the world, competing to develop and improve the performance of these installations [28]. These species can be classified into two main categories, solar thermal collectors and photovoltaic panels [29, 30].

2.1. System Solar Thermal Collector

These installations produce heat directly by converting solar radiation into heat. Solar thermal systems are usually used for water or space heating but can also be used for other purposes [31]. Currently, many installations are available from them that differ in design and work mechanism [32]. The most common types used in buildings are flat plates and evacuated tubes, which use water as a heat transfer medium [33, 34, 35], which will be the focus of this work.

2.2. Photovoltaic Panels

Transforms sunlight into electricity; it's not installations that produce heat directly but can be used to produce heat through other appliances such as water heaters, air conditioners, and electric heaters [36, 37].

All photovoltaic cells consist of two or more layers of semiconducting material, the most commonly silicone. Solar cells generate a direct current (DC) when exposed to the sun. The amount of energy produced depends on the intensity of the radiation and the time of the sun's brightness, as well as the efficiency of the photovoltaic cell to convert solar radiation into electricity [38].

These solar cells can give a large amount of power if these cells are connected, respectively, the energy produced in lead acid batteries can also be stored or alkaline made of nickel and cadmium, and the DC can be converted to AC by inverters for use and management of household electrical appliances. Therefore, it can use electricity produced to generate heat for residential or water heating [39].

Many types of photovoltaic cells differ in how they are manufactured, the materials used in their industry and their ability to generate electricity, and their price. The most common types available in the market and the most used are monocrystalline silicon (mono-Si) and polycrystalline silicon (poly-Si) [40, 41].

3. Comparison Between Solar Installations

To compare solar structures, we must divide them into two main categories: Solar thermal collectors and Photovoltaic panels and perform the comparison process separately for each class because they differ in their composition, work mechanism, and outputs. Identify two types for each category for comparison; for Solar thermal collectors, we will choose Flat plate and Evacuated tube, and for Photovoltaic panels, we will select Monocrystalline silicon and Polycrystalline silicon, which are the most common. The RETScreen database will be relied upon as the use of the program for data analysis and to get results [42]. This analysis considered the climatic conditions of the study area. Therefore, the results cannot be applied to all regions because climatic conditions are an essential factor in influencing solar installation performance. Manufacturers produce many different models, so we will select a group of models and subject them to analysis and comparison.

3.1. Comparison of Solar Thermal Collectors' Installations

For solar thermal collectors, efficiency and cost will be essential factors in the comparison, where we will calculate efficiency as follows:

$$\text{Efficiency} = \text{Solar fraction} / \text{Aperture area per solar collector} \tag{1}$$

Where the efficiency is the ratio of the solar fraction per one square meter of installation, the greater the value, the greater the efficiency of the installation. The smaller the value, the lower the efficiency of the installation.

To get the best cost, we calculate it as follows:

$$\text{Energy cost } (€/\text{kWh}) = \text{Energy produced } / \text{Cost for one solar collector} \tag{2}$$

The energy produced: is the energy produced by the solar collector for twenty years under the climatic conditions of the study area, which is the project's lifespan. Cost for one solar collector: this is the cost of purchasing the system, including the price of the solar collector, the tank, the necessary connections, and the installation. Energy cost: is the cost of producing one kilowatt of energy; whenever it is the cost of producing a kilowatt lower, the system is better.

The solar installations we will address in this work are solar water collectors because they are the most common, in addition to the possibility of storing the heat using water tanks insulated thermally to be used this heat at night.

Table 1. RETScreen energy model input parameters

No.	Input Parameter	Value
1	Solar tracking mode	Fixed
2	Slope	40º
3	Azimuth	0º
4	Storage capacity	75 l/m²
5	Miscellaneous losses	15%
6	Types of flat plate collectors	30
7	Types of evacuated tube collectors	18

3.2. Comparison of Photovoltaic panels

There are a lot of manufacturers worldwide and a lot of models which are somewhat similar in technical specifications, so we headed towards opting for PV panels that have high efficiency; we will choose the most appropriate through comparison between them based on the cost of one-kilowatt production.

To get the best cost, we calculate it as follows:

$$\text{Energy cost } (€/\text{kWh}) = \text{Energy produced } / \text{Cost for one PV panel} \tag{3}$$

The energy produced: is the energy produced by the PV panel for twenty years under the climatic conditions of the study area, which is the project's lifespan. Cost for one PV panel: this is the cost of purchasing the system, including the price of the PV panel, inverter, batteries, change control, the necessary connections, and installation. Energy cost: is the cost of producing one kilowatt of energy; whenever it is the cost of producing a kilowatt lower, the system is better. PV panels that we will address in this work are Monocrystalline silicon and Polycrystalline silicon because it is the most types of photoelectric panels available in the markets, have high efficiency, and are suitable for installation on the roofs of houses or separately, as well as are easy to install and maintain.

Table 2. RETScreen energy model input parameters

No.	Input Parameter	Value
PV panel		
1	Solar tracking mode	Fixed
2	Slope	40º
3	Azimuth	0º
4	Number of units	1
5	Nominal operating cell temperature	45 ºC
6	Miscellaneous losses	14%
7	Types of monocrystalline silicon PV panels (mono-Si)	20
8	Types of polycrystalline silicon PV panels (poly-Si)	20
Inverter		
9	Efficiency	90%
10	Miscellaneous losses	10%
11	Capacity factor	8.5%

4. Install Solar Panels

What is the method of installing solar panels? This question is important because the orientation of solar panels affects the solar radiation received during daylight hours. The optimal angle of the solar panels must be calculated to get the maximum amount of solar radiation.

It is known that the sun changes its position in the sky from hour to hour, from day to day, and from month to month. It must follow the movement of the sun to get the most energy. The solar tracker can be installed to do this, but there will be an increase in cost. Additionally, the power consumed by the solar tracker eliminates many of its benefits and its ongoing need for maintenance [43, 44].

There are several options for installing solar panels in residential buildings, as they can install on the buildings' roofs, this method saves space, but the shape of the top of the building can affect the flexibility of directing solar panels. Still, this method exposes workers to potential risks during installation or maintenance, resulting from the shape and slope of the roof and its stability, especially if the building is old [45]. Solar panels can also install on the walls of the building, and this method is less affected by weather conditions such as wind, dust, and snow accumulation. Still, the disadvantages are that they are often installed vertically and, thus, a loss in the amount of solar radiation received. There is a way to install solar panels on a structure independent of the building if space is available. In this case, the user has great flexibility in directing solar panels. Still, this method requires a large surface area.

Suppose the solar panels will be in a fixed position throughout the year, or the angle can be adjusted twice a year in summer and winter or four times a year in spring and autumn. All these options make the most of the solar system, so we must find the optimal angles (slope and azimuth).

4.1. The Angle of Azimuth and Slope

Three types of solar radiation are exposed to every surface on Earth: direct, diffuse, and reflected. Direct radiation comes directly from the sun without being absorbed or scattered. Diffuse radiation is the proportion of solar radiation reflected by the atmosphere in all directions and can be up to 15% when the sun is high and up to 40% when the sun is low in the sky. Reflected radiation results from the reflection of solar radiation from the Earth's surface and objects on the surface [46]. The azimuth angle changes every hour of the day, so the direction of the solar panel cannot be changed. The location of the study is in the northern hemisphere, so the orientation of the solar panels will be toward the south. To calculate the optimal slope angle of the solar panels, whether it is along the year or for the seasons. The idea is to choose ten solar panels (same space and specifications) and install them on a different slope angle, where the first panel will be installed on a slope angle of 0º (the horizontal plane). The second panel is on a slope angle 10º from the horizontal plane, and so on, until we reach the angle that is perpendicular to the horizontal level, i.e., 90º. Energy3D software analyzes and gets the average energy produced by each panel. Figure 3. shows the monthly performance of solar panels installed at different slope angles.

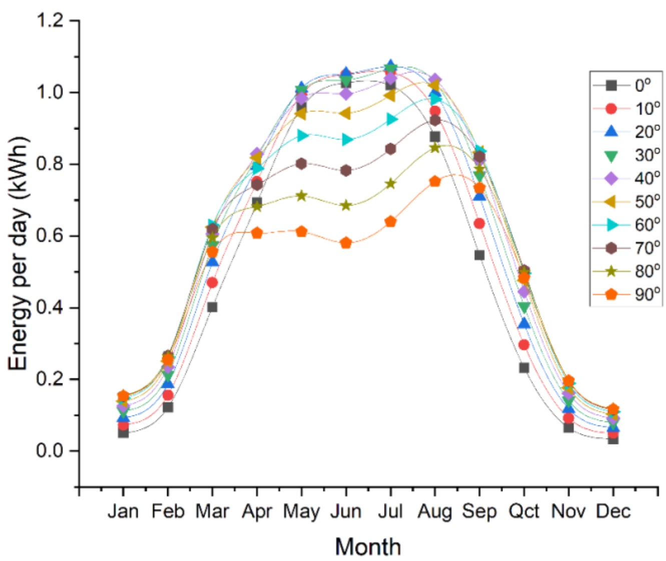

Fig. 3. the monthly performance of solar panels installed at different slope angles.

5. Amount of Heat Required for Heating.

When calculating the heating installation volume for a particular building, it is necessary to know the heat load, which is the quantity of heat required to maintain the constant temperature of that building based on the external and internal temperature of the building design. In our case, the building is a house located in Warsaw. The home of a family of four. An area of (100) square meters and dimensions (10*10) m^2, consists of one floor with a cellar, as shown in Figure 4. Several factors affect the heat load, including exterior walls, doors, windows, floor, and ceiling. Therefore, calculations will be based on Polish standards PN-EN 12831: 2006 standard, which is a translation of the European standard EN 12831: 2003 (Heating systems in buildings - method for calculation of the design heat load) and instructions published in the Journal of Laws of the Republic of Poland (Dziennik Ustaw 2013 poz. 926) for amending the regulation on technical conditions to be met by buildings and their location [47].

Design heat loss

$$\Phi_i = \Phi_{T,i} + \Phi_{V,i} \quad (4)$$

$$\Phi_{HL,i} = \Phi_{T,i} + \Phi_{V,i} + \Phi_{RH,i} \quad (5)$$

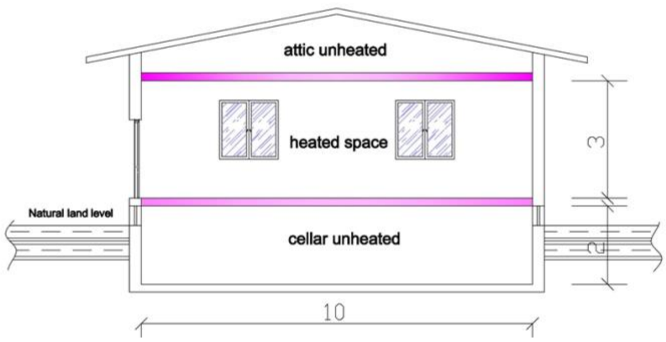

Fig. 4. The form and dimensions of the house (units are in a meter).

The design heat load for a building

$$\Phi_{HL} = \sum \Phi_{T,i} + \sum \Phi_{V,i} + \sum \Phi_{RH,i} \quad (6)$$

$\sum \boldsymbol{\Phi_{T,i}}$: sum of transmission heat losses of all heated spaces excluding the heat transferred inside the building entity or the building, W.

$\sum \boldsymbol{\Phi_{V,i}}$: ventilation heat losses of all heated spaces excluding the heat transferred inside the building entity or the building, W.

$\sum \boldsymbol{\Phi_{RH,i}}$: sum of heating-up capacities of all heated spaces required to compensate for the effects of intermittent heating, W.

Design transmission heat loss:

- Transmission of heat loss through exterior walls:

Thermal bridges: in a simplified method, using correction coefficient, which values are given in the national annex to PN–EN 12831.

- Thermal transmittance

$$U_{kc} = U_k + \Delta U_{tb}, \ \frac{w}{m^2k} \tag{7}$$

$U_k = 0.23 \frac{W}{m^2K}$ (Dziennik Ustaw 2013 poz. 926)

$\Delta U_{tb} = 0.2 \frac{W}{m^2K}$ correction factor ΔU_{tb} (the horizontal elements of the building) (Dziennik Ustaw 2013 poz. 926)

- Heat loss

$$H_{T,i} = A_k \cdot U_{kc} \quad \frac{W}{K} \tag{8}$$

$H_{T,i}$: heat loss from external walls ($\frac{W}{K}$)

A_k : Area of external walls (m^2)

$$\Phi_{T,i} = H_{T,i} \cdot (\theta_{int,i} - \theta_e) \quad W \tag{9}$$

$\theta_{int,i}$ (Internal temperature): Internal temperature 16°C or higher, so considered internal temperature equal 18 °C. (Dziennik Ustaw 2013 poz. 926), θ_e (External temperature)

- Transmission of heat loss through ceiling: Heat losses through unheated space

The thickness of the ceiling is 20 cm and there is an unheated attic above it, so we can calculate the transmission of heat loss as follows:

$$H_{T,iue} = \sum_k A_k \cdot U_{ke} \cdot b_u \quad \frac{W}{K} \tag{10}$$

b_u : The temperature reduction factor. In this case:

$b_u = 0.7$ (Dziennik Ustaw 2013 poz. 926)

$$U_{kc} = U_k + \Delta U_{tb} \quad \frac{W}{m^2K} \tag{11}$$

$U_k = 0.18 \frac{W}{m^2K}$ (PN-EN 12831), *(*floor under attic)

$\Delta U_{tb} = 0$ (Dziennik Ustaw 2013 poz. 926), *(*Vertical building elements)

$$\Phi_{T,i} = H_{T,i} \cdot (\theta_{int,i} - \theta_e) \quad W \tag{12}$$

- Transmission of heat loss through flooring:

Assume that there is an unheated cellar under the floors.

$$H_{T,iue} = \sum_k A_k \cdot U_{ke} \cdot b_u \quad \frac{W}{K} \tag{13}$$

b_u : The temperature reduction factor. In this case:

$b_u = 0.8$ (PN-EN 12831)

$$U_{kc} = U_k + \Delta U_{tb} \quad \frac{W}{m^2K} \tag{14}$$

$U_k = 0.25 \frac{W}{m^2K}$ (Dziennik Ustaw 2013 poz. 926), (floor over unheated cellar)

$\Delta U_{tb} = 0$ (PN-EN 12831), (vertical building elements)

$$\Phi_{T,i} = H_{T,i} \cdot (\theta_{int,i} - \theta_e) \quad W \tag{15}$$

- Transmission of heat loss through windows: Assume that the building has six windows, four on the sides of the building and two in front. All windows conform to Polish standards. Calculate the area of the windows as follows:

The sides: (1.5*1.5) *4 = 9 m^2

Front: (1.5*1) *2 = 3 m^2

The total area of windows: 12 m^2

$$H_{T,i} = \sum_k A_k \cdot U_{ke} \quad \frac{W}{K} \tag{16}$$

$U_{ke} = 1.1 \frac{W}{m^2K}$ (Dziennik Ustaw 2013 poz. 926), (The maximal U-values for residential buildings in Poland at 2017)

$$\Phi_{T,i} = H_{T,i} \cdot (\theta_{int,i} - \theta_e) \quad W \tag{17}$$

- Transmission of heat loss through doors:

Assume that the building has one door in front only. Calculate the area of the door as follows:

Area = 1*2 = 2 m^2

$$H_{T,i} = \sum_k A_k \cdot U_{ke} \quad \frac{W}{K} \tag{18}$$

$U_{ke} = 1.5 \frac{W}{m^2K}$ (Dziennik Ustaw 2013 poz. 926), (the maximal U-values for residential buildings in Poland at 2017)

$$\Phi_{T,i} = H_{T,i} \cdot (\theta_{int,i} - \theta_e) \quad W \tag{19}$$

Design ventilation heat loss

Design ventilation heat loss, $\Phi_{V,i}$ heated space (i) is calculated as follows:

$$\Phi_{V,i} = H_{V,i} \cdot (\theta_{int,i} - \theta_e) \quad W \tag{20}$$

$H_{V,i}$: design of the ventilation heat loss in watts per Kelvin (W/K).

$\theta_{int,i}$: The design temperature inside the heated space (i) in degrees Celsius (°C).

θ_e: Design external temperature in degrees Celsius (°C).

$H_{V,i}$ heated space (i) is calculated as follows:

$$H_{V,i} = 0.34 \cdot \dot{V}_i \quad \frac{W}{K} \tag{21}$$

$\dot{V}_i$: volume flow of ventilation air heated space (s) in cubic meters per hour (m^3/h).

As the value of the airflow area heated (i) which is used to calculate the design of the ventilation heat losses adopts the maximum value of subscript required infiltration $\dot{V}_{inf,i}$, the airflow directed through the slots and connections in the housing building or minimum ventilation airflow, $\dot{V}_{min,i}$ required for hygienic reasons:

$$\dot{V}_i = max(\dot{V}_{inf,i}\ ,\ \dot{V}_{min,i}) \quad \frac{m^3}{h} \tag{22}$$

Calculation of infiltration ($\dot{V}_{inf,i}$):

$$\dot{V}_{inf,i} = 2 \cdot V_i \cdot n_{50} \cdot e_i \cdot \varepsilon_i \quad \frac{m^3}{h} \tag{23}$$

V_i: volume of heated space, m^3.

n_{50}: air exchange rate per hour, resulting from a pressure difference of 50 Pa between the inside and the outside of the building, h^{-1}.

e_i: shielding coefficient.

ε_i: height correction factor.

$V_i = (10 * 10) * 3.2 = 320\ m^3$

Where: $n_{50} < 4\ h^{-1}$ (PN-EN 12831), (*single family dwellings, high (high quality seal windows and doors)*).

$e_i = 0.03$ (PN-EN 12831), *(Moderate shielding (buildings in the country with trees or other buildings around them, suburbs), Heated space with more than one exposed opening).*

$\varepsilon_i = 1.0$ (PN-EN 12831), *(Height of heated space above ground-level (Centre of room height to ground level) choose 0 – 10 m).*

$\dot{V}_{inf,i} = 2 * 320 * 3.5 * 0.03 * 1 = 67.2 \quad m^3/h$

- Calculation minimum air flow rate required for hygienic reasons ($\dot{V}_{min,i}$):

$$\dot{V}_{min,i} = n_{min} \cdot V_i \quad \frac{m^3}{h} \tag{24}$$

n_{min}: minimum external air exchange rate, h^{-1}.

In this case $n_{min} = 0.5\ h^{-1}$ (PN-EN 12831), *(Habitable room (default)).*

$V_i = 320\ m^3$ volume of heated space

$\dot{V}_{min,i} = 0.5 * 320 = 160 \quad m^3/h$

Now we can see that the minimum air flow rate required for hygienic reasons $\dot{V}_{min,i}$, greater than infiltration $\dot{V}_{inf,i}$ so we choose the biggest.

$$\dot{V}_i = max(\dot{V}_{inf,i}\ ,\ \dot{V}_{min,i}) = 160 \quad m^3/h$$

Calculation of capacity heating up (to compensate for the effects of intermittent heating):

$$\Phi_{RH,i} = A_i \cdot f_{RH} \quad W \tag{25}$$

A_i: internal floor area of heated space m^2.

f_{RH} : coefficient of heating.

$A_i = 10 * 10 = 100\ m^2$

Assume:

Building mass: high (PN-EN 12831)

Probable reduction in temperature during the night weakening: 2 K (PN-EN 12831)

Reheat time: 2 hours (PN-EN 12831)

So, f_{RH}=11 (PN-EN 12831)

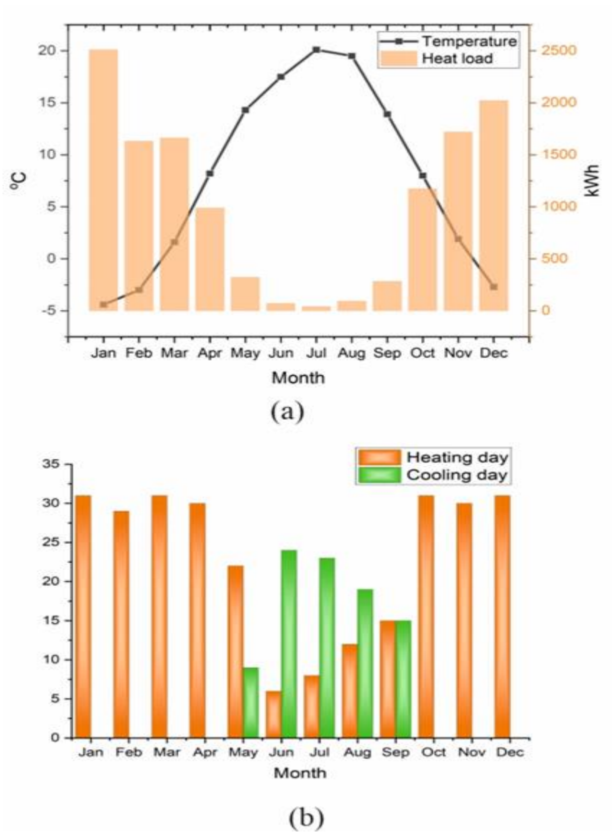

Fig. 5. (a) monthly heat distribution required for heating and (b) number of days of heating and cooling for each month.

6. Design of Solar Heating Installations

In this part of the research, we will design an appropriate solar heating installation for residential use, which is relied upon to supply heating demand for an entire year (12530.8 kWh). The aim is to determine the efficiency of these installations, the financial returns generated from saving annual fees for traditional energy consumption, and the amount of emission reduction resulting from converting to clean energy [48].

Several factors affect the results. For solar technology, there are two options: a solar thermal collector and photovoltaic panels, these installations are not solar panels only, but a system made up of different parts, as each piece has an impact on the performance and productivity of this system, which we will take them into account [49].

As for economic and environmental effects, there is a role for the type of traditional energy used in heating, as the fees for the consumption of this energy vary from one type to another [50]; for example, electricity consumption charges in Poland are 0.142 €/kWh, while the natural gas consumption of 0.05 €/kWh [51]. Either emission reduction is also different depending on the energy type used and the energy amount.

The search tools are RETScreen and PVGIS software through the application of two scenarios based on the conventional energy used in residential heating (natural gas, electricity), as shown in Table 3.

Table 3. Research trends scenario

scenario	Type of traditional energy	Solar tracking mode
The first scenario	Natural gas	Fixed, (Slope 42, Azimuth 0 toward south)
The second scenario	Electricity	Fixed, (Slope 42, Azimuth 0 toward south)

7. Results

This section summarizes the main findings of this work. The results showed that the optimal inclination angle is 42° and azimuth towards the south if the solar panels are constant throughout the year. However, it is preferable to adjust the angle of inclination four times per year since each season in the year has an optimal angle of inclination that makes the solar system more efficient. Where winter 78° (on 21 December), spring 47° (on 21 March), summer 25° (on 21 June), and autumn 62° (on 21 September). as shown in Figure 6.

The annual energy needed to heat 12530.8 kWh was calculated based on the average daily temperature. The number of heating days was 276 days, while the number of cooling days was 90. The results also showed that the energy saved from the solar thermal collectors (STC) does not exceed 40% of (5,037 kWh) of the system's design capacity of (12,530 kWh). as shown in Figures (7 (a), 8).

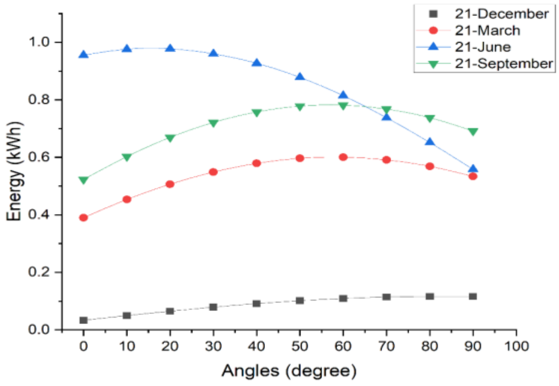

Fig. 6. Performance of solar panels for different slope angles on four dates in a year.

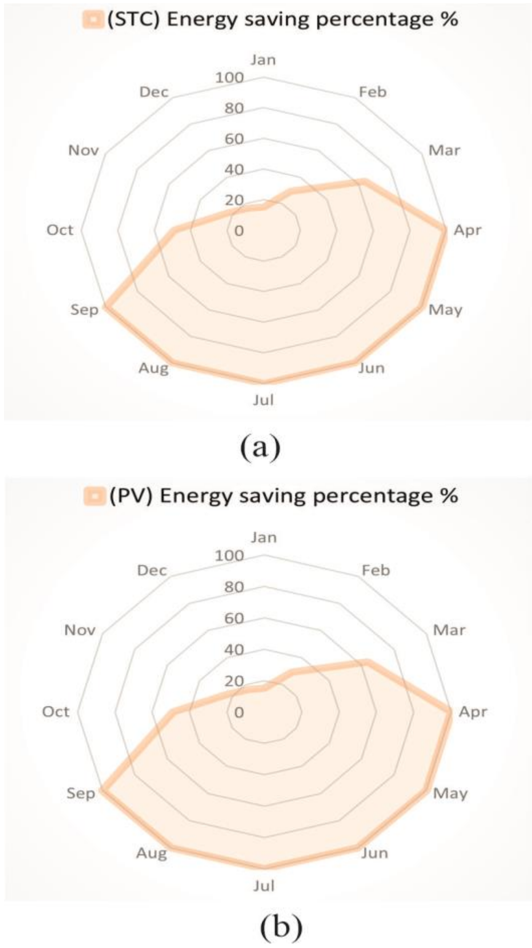

Fig. 7. (a) The efficiency of solar thermal collectors in producing energy and providing the heat needed for heating and (b) the efficiency of photovoltaic panels in producing energy and providing the heat needed for heating.

On the other hand, the photovoltaic panels (PV) showed efficiency in energy production that did not exceed 43%, amounting to (5387 kWh). At the same time, the design capacity of the system was (12,530 kWh) under the climate conditions of the study area. as shown in Figures (7 (b),9).

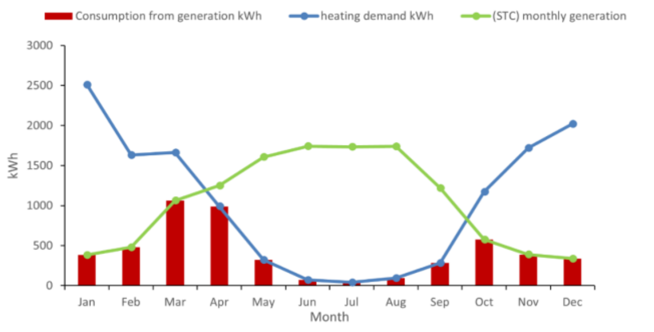

Fig. 8. The amount of energy produced from solar thermal collectors, the required energy, and the actual energy used.

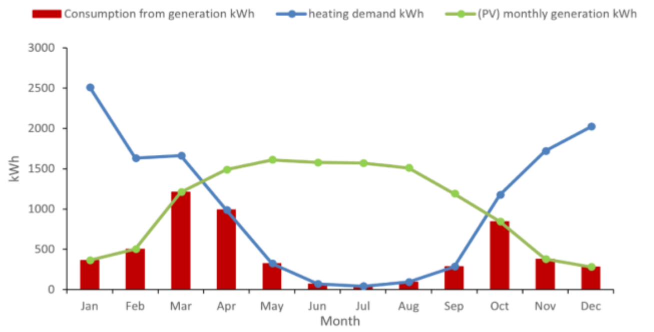

Fig. 9. The amount of energy produced from photovoltaic panels, the required energy, and the actual energy used.

The financial returns result from saving the annual fees and costs for heating the building using conventional energy. The results showed that the annual costs saved when using solar thermal collectors (STC) are 715 EUR if electricity is the conventional energy used for heating in the base case, and 252 EUR if natural gas is the conventional energy used for heating. as shown in Figure 10.

While the annual costs saved when using photovoltaic panels (PV) were 765 EUR if electricity is the conventional energy used for heating in the base case, and 269 EUR if natural gas is the conventional energy used for heating. as shown in Figure 11.

The annual reduction in greenhouse gas (GHG) emissions when using solar thermal collectors (STC) is 2.36 tCO2, out of the total emissions of 5.93 tCO2 in the base case before using clean energy. as shown in Figure 12.

While the annual reduction in greenhouse gas (GHG) emissions when using photovoltaic panels (PV) is 2.53 tCO_2, out of the total emissions of 5.93 tCO_2 in the base case before using clean energy. as shown in Figure 13.

Table 4. compares the results obtained in this study and the results of previous studies.

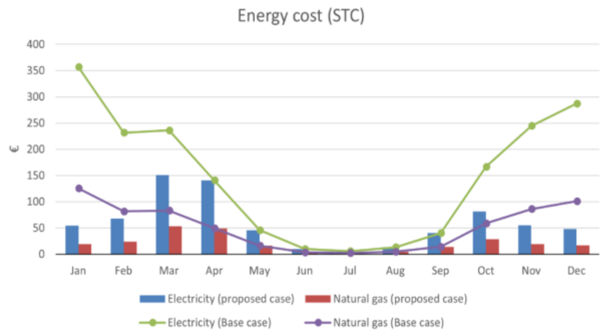

Fig. 10. The annual energy cost for the base case and saving energy costs for the proposed case.

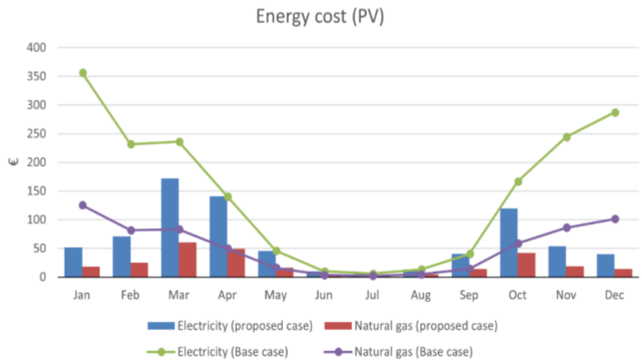

Fig. 11. The annual energy cost for the base case and saving energy costs for the proposed case.

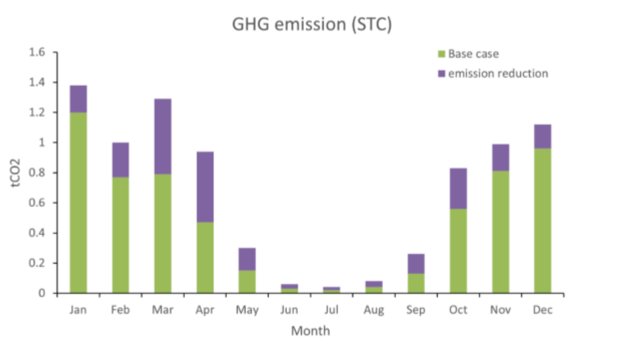

Fig. 12. Greenhouse gas (GHG) emissions reduction.

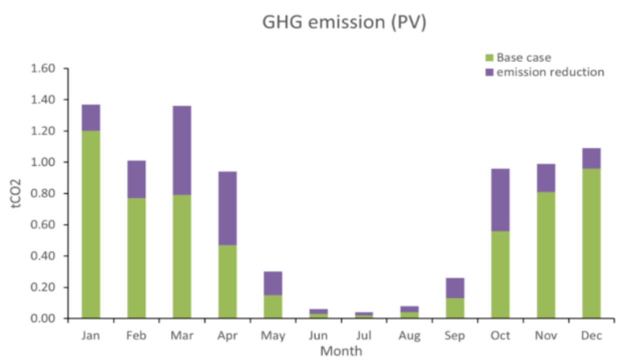

Fig. 13. Greenhouse gas (GHG) emissions reduction.

Table 4. Comparison of other studies with results of the current study

No.	Ref.	Mechanism used	Efficiency	Economic feasibility		Environmental feasibility
1	[18]	photovoltaic solar thermal collector	4,733 kWh/year	1,895 dollars/year		consumption reductions for light oil, heavy oil, and gas of 252, 195, and 15,447 kg, respectively
2	[19]	flat plate collectors	a reduction in energy consumption to 8% in December and 14% in January and February	payback period of 4.65 years		reduced CO_2 emissions by up to 86.4%
3	[48]	Evacuated tube	60% of solar fractions	payback period is between 7 and 10 years		739 tCO_2 per 25 years For 7 sites
4	[52]	Evacuated solar collector	-	131.14 USD/year		3.767 tCO_2 per year
5	[53]	Photovoltaic-thermal (PVT) air collectors coupled to a water-to-air heat exchanger	15.30 kWh/day	-		11.4 kg CO_2 per day
6	The current study	Solar thermal collectors	40%	715 EUR/year	252 EUR/year	2.36 tCO_2 per year
		Photovoltaic panels	43%	765 EUR/year	269 EUR/year	2.53 tCO_2 per year

8. Conclusions

The most significant energy production from solar thermal collectors and photovoltaic panels is in the summer when energy demand energy is at its lowest levels, in return to the lowest level of energy production is in the winter when the energy demand is at its highest levels, thus leading to the lack of full use of the output of the solar systems, for the solar system to be more efficient, the possibility of selling redundant electricity to the grid should be available to cover the cost of purchasing energy from the grid at another time of the year. Or use the electricity produced to cover the consumption of other household equipment. Thus, the solar system becomes economically viable.

Financial returns are low if conventional heating fuels cheap, such as coal, but in return, emission reductions are significant. Here, the goal of using solar energy will be environmental more than economic. Of course, this is not a priority of individuals since the financial aspect is more important than the other at the level of individuals. To implement this project, there must be funding from institutions in the form of soft loans to help individuals to bear the initial costs of setting up the expensive solar system.

It cannot be claimed that these results can be applied to all world regions. Still, the methodology can be used in most cold climates, such as northern Europe, Russia, the northern USA, and Canada. Also, this technology is expected to be more efficient when used in regions with hot climates with more significant solar radiation and longer daylight hours.

Despite the design of a solar energy system with an annual capacity that is supposed to cover the total demand, we note that the results showed that it could not cover half. In some months, it's up to 15 percent of what's required for processing. Therefore, we recommend that future studies be towards hybrid systems, such as integrating both technologies or using other renewable energy that has stable performance throughout the year, such as geothermal or wind energy, in addition to improving the performance of solar systems and reducing energy losses resulting from several factors such as temperature, dust, solar tracking, shade, and others.

Acknowledgments

Funding from the Ministry of Science and Higher Education of the Russian Federation (Ural Federal University Program of Development within the Priority-2030 Program) is gratefully acknowledged: Grant Number FEUZ-2022-0031.

Nomenclature

Φ_{HL}	Total heat load (W)
Φ_T	Transmission heat loss (W)
Φ_V	Ventilation heat loss (W)
Φ_{RH}	Heating-up capacity (to compensate for the effects of intermittent heating) (W)
U-values	Thermal transmittance (W m^{-2} k)
ΔU_{tb}	Correction coefficient (W m^{-2} k)
bu	The temperature reduction factor
V	Volume heated space (m^3)
n_{50}	Air exchange rate per hour (h^{-1})
e	Shielding coefficient
ε	Height correction factor

n_{min}	Minimum external air exchange rate (h^{-1})
V_{inf}	Infiltration air rate ($m^3 h^{-1}$)
V_{min}	The minimum air flow rate required for hygienic reasons ($m^3 h^{-1}$)
f_{RH}	Coefficient of heating
STC	Solar thermal collectors
PV	Photovoltaic panels
TJ	Terajoule

References

[1] F. Ayadi, I. Colak, I. Garip, and H. I. BULBUL, "Targets of countries in renewable energy," in 2020 9th International Conference on Renewable Energy Research and Application (ICRERA), 2020, pp. 394–398.

[2] "Energy Statistics Data Browser – Data Tools - IEA." https://www.iea.org/data-and-statistics/ (accessed Jan. 31, 2023).

[3] S. Kumar Pathak, V. v. Tyagi, K. Chopra, and R. Kumar Sharma, "Recent development in thermal performance of solar water heating (SWH) systems," Mater Today Proc, vol. 63, pp. 778–785, Jan. 2022, doi: 10.1016/j.matpr.2022.05.502.

[4] A. Alkholidi, H. Hamam, R. Andon, and Z. Cajupi, "Solar energy potentials in Southeastern European countries: A case study," International Journal of Smart Grid-ijSmartGrid, vol. 3, no. 2, pp. 108–119, 2019.

[5] M. A. Qasim and V. I. Velkin, "Maximum power point tracking techniques for micro-grid hybrid wind and solar energy systems-A review," International Journal on Energy Conversion, vol. 8, no. 6, pp. 223–234, 2020.

[6] M. Umar, S. Farid, and M. A. Naeem, "Time-frequency connectedness among clean-energy stocks and fossil fuel markets: Comparison between financial, oil and pandemic crisis," Energy, vol. 240, Feb. 2022, doi: 10.1016/j.energy.2021.122702.

[7] N. Abas, A. Kalair, and N. Khan, "Review of fossil fuels and future energy technologies," Futures, vol. 69, pp. 31–49, May 2015, doi: 10.1016/J.FUTURES.2015.03.003.

[8] D. K. Manley, V. A. Hines, M. W. Jordan, and R. E. Stoltz, "A survey of energy policy priorities in the United States: Energy supply security, economics, and the environment," Energy Policy, vol. 60, pp. 687–696, Sep. 2013, doi: 10.1016/J.ENPOL.2013.04.061.

[9] Q. Zhao, P. Yu, R. Mahendran, W. Huang, Y. Gao, Z. Yang, T. Ye, B. Wen, Y. Wu, S. Li, and Y. Guo, "Global climate change and human health: Pathways and possible solutions," Eco-Environment & Health, vol. 1, no. 2, pp. 53–62, Jun. 2022, doi: 10.1016/J.EEHL.2022.04.004.

[10] X. Cao, X. Dai, and J. Liu, "Building energy-consumption status worldwide and the state-of-the-art technologies for zero-energy buildings during the past decade," Energy Build, vol. 128, pp. 198–213, Sep. 2016, doi: 10.1016/j.enbuild.2016.06.089.

[11] S. Zhang, P. Ocłoń, J. J. Klemeš, P. Michorczyk, K. Pielichowska, and K. Pielichowski, "Renewable energy systems for building heating, cooling and electricity production with thermal energy storage," Renewable and Sustainable Energy Reviews, vol. 165, p. 112560, Sep. 2022, doi: 10.1016/J.RSER.2022.112560.

[12] "Heating and Cooling Energy Demands – Heat Roadmap Europe." https://heatroadmap.eu/heating-and-cooling-energy-demand-profiles/ (accessed Jan. 31, 2023).

[13] S. Pokhrel, L. Amiri, S. Poncet, A. P. Sasmito, and S. A. Ghoreishi-Madiseh, "Renewable heating solutions for buildings; a techno-economic comparative study of sewage heat recovery and Solar Borehole Thermal Energy Storage System," Energy Build, vol. 259, Mar. 2022, doi: 10.1016/j.enbuild.2022.111892.

[14] E. Vengadesan, D. Bharathwaj, B. S. Kumar, and R. Senthil, "Experimental study on heat storage integrated flat plate solar collector for combined water and air heating in buildings," Appl Therm Eng, vol. 216, Nov. 2022, doi: 10.1016/j.applthermaleng.2022.119105.

[15] A. Tang, F. H. Alsultany, V. Borisov, A. Mohebihafshejani, A. Goli, A. Mostafaeipour, and R. Riahi, "Technical, environmental and ranking analysis of using solar heating: A case study in South Africa," Sustainable Energy Technologies and Assessments, vol. 52, Aug. 2022, doi: 10.1016/j.seta.2022.102299.

[16] M. D. Sarmouk, A. Smaili, H. Fellouah, and A. Merabtine, "Energy and economic assessment of a hybrid solar/gas heating system using a combined statistical-based multi-objective optimization method," Journal of Building Engineering, vol. 59, Nov. 2022, doi: 10.1016/j.jobe.2022.105095.

[17] D. García-Menéndez, J. C. Ríos-Fernández, A. M. Blanco-Marigorta, and M. J. Suárez-López, "Dynamic simulation and exergetic analysis of a solar thermal collector installation," Alexandria Engineering Journal, vol. 61, no. 2, pp. 1665–1677, Feb. 2022, doi: 10.1016/j.aej.2021.06.075.

[18] R. O. Cannon, N. F. Antwan, and B. N. Yaqob, "Investigation of Solar Water Heating System in Erbil City: An Experimental and Numerical Study," International Journal of Renewable Energy Research, vol. 12, no. 3, pp. 1225–1233, Sep. 2022, doi: 10.20508/IJRER.V12I3.13071.G8507.

[19] M. Elmnifi, H. Moria, A. M. Elbreki, and O. D. H. Abdulrazig, "Possibilities Study of Using Hybrid Solar Collectors in Northeastern Libya Residential Home," International Journal of Renewable Energy Research, vol. 11, no. 2, pp. 654–661, Jun. 2021, doi: 10.20508/IJRER.V11I2.11938.G8186.

[20] M. A. Qasim, V. I. Velkin, and S. E. Shcheklein, "The Experimental Investigation of a New Panel Design for Thermoelectric Power Generation to Maximize Output Power Using Solar Radiation," Energies (Basel), vol. 15, no. 9, p. 3124, 2022.

[21] X. Qiao, X. Kong, and M. Fan, “Phase change material applied in solar heating for buildings: A review,” J Energy Storage, vol. 55, p. 105826, Nov. 2022, doi: 10.1016/J.EST.2022.105826.

[22] S. Kyaligonza and E. Cetkin, “Photovoltaic System Efficiency Enhancement with Thermal Management: Phase Changing Materials (PCM) with High Conductivity Inserts,” Int. J. Smart grid, vol. 5, no. 4, pp. 138–148, 2021.

[23] N. A. Habib, A. J. Ali, M. T. Chaichan, and M. Kareem, “Carbon nanotubes/paraffin wax nanocomposite for improving the performance of a solar air heating system,” Thermal Science and Engineering Progress, vol. 23, p. 100877, Jun. 2021, doi: 10.1016/J.TSEP.2021.100877.

[24] Q. A. Jawad, A. M. J. Mahdy, A. H. Khuder, and M. T. Chaichan, “Improve the performance of a solar air heater by adding aluminum chip, paraffin wax, and nano-SiC,” Case Studies in Thermal Engineering, vol. 19, p. 100622, Jun. 2020, doi: 10.1016/J.CSITE.2020.100622.

[25] Y. Chen, H. Hua, J. Xu, J. Wang, P. D. Lund, Y. Han, and T. Cheng, “Energy, environmental-based cost, and solar share comparisons of a solar driven cooling and heating system with different types of building,” Appl Therm Eng, vol. 211, Jul. 2022, doi: 10.1016/j.applthermaleng.2022.118435.

[26] S. M. H. Zanjani, H. Shahinzadeh, A. B. Oskui, W. Yaïci, M. Longo, and S. M. Zanjani, “Performance Assessment of Heat Pump and Solar Thermal Heating with Seasonal Storage Systems for Smart Microgrid Research Center Building at IAUN,” in 2022 10th International Conference on Smart Grid (icSmartGrid), 2022, pp. 345–350.

[27] Q. Chen and Y. Wang, “Research Status and Development Trend of Concentrating Solar Power,” in 2020 9th International Conference on Renewable Energy Research and Application (ICRERA), 2020, pp. 390–393.

[28] J. Wang, Z. Han, and Z. Guan, “Hybrid solar-assisted combined cooling, heating, and power systems: A review,” Renewable and Sustainable Energy Reviews, vol. 133. Elsevier Ltd, Nov. 01, 2020. doi: 10.1016/j.rser.2020.110256.

[29] S. A. Kalogirou, “Solar thermal collectors and applications,” Progress in Energy and Combustion Science, vol. 30, no. 3. pp. 231–295, 2004. doi: 10.1016/j.pecs.2004.02.001.

[30] L. Brottier and R. Bennacer, “Thermal performance analysis of 28 PVT solar domestic hot water installations in Western Europe,” Renew Energy, vol. 160, pp. 196–210, Nov. 2020, doi: 10.1016/j.renene.2020.06.072.

[31] C. Maurer, C. Cappel, and T. E. Kuhn, “Progress in building-integrated solar thermal systems,” Solar Energy, vol. 154, pp. 158–186, 2017, doi: 10.1016/j.solener.2017.05.065.

[32] L. Evangelisti, R. de Lieto Vollaro, and F. Asdrubali, “Latest advances on solar thermal collectors: A comprehensive review,” Renewable and Sustainable Energy Reviews, vol. 114. Elsevier Ltd, Oct. 01, 2019. doi: 10.1016/j.rser.2019.109318.

[33] Y. Selikhov, J. J. Klemeš, P. Kapustenko, and O. Arsenyeva, “The study of flat plate solar collector with absorbing elements from a polymer material,” Energy, vol. 256, Oct. 2022, doi: 10.1016/j.energy.2022.124677.

[34] S. M. Tabarhoseini, M. Sheikholeslami, and Z. Said, “Recent advances on the evacuated tube solar collector scrutinizing latest innovations in thermal performance improvement involving economic and environmental analysis,” Solar Energy Materials and Solar Cells, vol. 241. Elsevier B.V., Jul. 01, 2022. doi: 10.1016/j.solmat.2022.111733.

[35] M. B. Elsheniti, A. Kotb, and O. Elsamni, “Thermal performance of a heat-pipe evacuated-tube solar collector at high inlet temperatures,” Appl Therm Eng, vol. 154, pp. 315–325, May 2019, doi: 10.1016/j.applthermaleng.2019.03.106.

[36] A. del Amo, A. Martínez-Gracia, T. Pintanel, A. A. Bayod-Rújula, and S. Torné, “Analysis and optimization of a heat pump system coupled to an installation of PVT panels and a seasonal storage tank on an educational building,” Energy Build, vol. 226, Nov. 2020, doi: 10.1016/j.enbuild.2020.110373.

[37] M. A. Qasim, V. I. Velkin, S. E. Shcheklein, S. A. Salih, B. A. Aljashaami, and A. A. Sammour, “Conversion of Heat Generated During Normal PV Panel Operation into Useful Energy via a Hybrid PV-TEG Connection,” International journal of renewable energy research, Vol.12, No.4, December 2022.

[38] D. Sharma, R. Mehra, and B. Raj, “Comparative analysis of photovoltaic technologies for high efficiency solar cell design,” Superlattices and Microstructures, vol. 153. Academic Press, May 01, 2021. doi: 10.1016/j.spmi.2021.106861.

[39] A. A. Belsky, D. Y. Glukhanich, M. J. Carrizosa, and V. v. Starshaia, “Analysis of specifications of solar photovoltaic panels,” Renewable and Sustainable Energy Reviews, vol. 159. Elsevier Ltd, May 01, 2022. doi: 10.1016/j.rser.2022.112239.

[40] I. Sari-Ali, K. Rahmoun, B. Chikh-Bled, B. Benyoucef, Y. Menni, M. Ghazvini, H. Ameur, and M. H. Ahmadi, “Mono-crystalline silicon photovoltaic cells under different solar irradiation levels,” Optik (Stuttg), vol. 223, Dec. 2020, doi: 10.1016/j.ijleo.2020.165653.

[41] A. Elamim, B. Hartiti, A. Haibaoui, A. Lfakir, and P. Thevenin, “Analysis and comparison of different PV technologies for determining the optimal PV panels- A case study in Mohammedia , Morocco.,” IOSR Journal of Electrical and Electronics Engineering, vol. 12, no. 01, pp. 37–45, Jan. 2017, doi: 10.9790/1676-1201013745.

[42] “RETScreen.” https://www.nrcan.gc.ca/maps-tools-and-publications/tools/modelling-tools/retscreen/7465 (accessed Jan. 31, 2023).

[43] Z. Jin, K. Xu, Y. Zhang, X. Xiao, J. Zhou, and E. Long, "Installation Optimization on the Tilt and Azimuth Angles of the Solar Heating Collectors for High Altitude Towns in Western Sichuan," in Procedia Engineering, 2017, vol. 205, pp. 2995–3002. doi: 10.1016/j.proeng.2017.10.225.

[44] H. Tchakounté, C. B. N. Fapi, M. Kamta, and P. Woafo, "Performance comparison of an automatic Smart Sun tracking system versus a manual Sun tracking," in 2020 8th International Conference on Smart Grid (icSmartGrid), 2020, pp. 127–132.

[45] C. Ho, H. W. Lee, and J. A. Gambatese, "Application of Prevention through Design (PtD) to improve the safety of solar installations on small buildings," Saf Sci, vol. 125, May 2020, doi: 10.1016/j.ssci.2020.104633.

[46] S. A. Kalogirou, "Environmental Characteristics," Solar Energy Engineering, pp. 51–123, Jan. 2014, doi: 10.1016/B978-0-12-397270-5.00002-9.

[47] M. Strzeszewski and P. Wereszczyński, "Norma PN–EN 12831. Nowa metoda obliczania projektowego obciążenia cieplnego." [Online]. Available: www.purmo.pl (accessed Jan. 31, 2023).

[48] S. Singh, A. Anand, A. Shukla, and A. Sharma, "Environmental, technical and financial feasibility study of domestic solar water heating system in India," Sustainable Energy Technologies and Assessments, vol. 43, Feb. 2021, doi: 10.1016/j.seta.2020.100965.

[49] M. A. ben Taher, Z. Benseddik, A. Afass, S. Smouh, M. Ahachad, and M. Mahdaoui, "Energy life cycle cost analysis of various solar water heating systems under Middle East and North Africa region," Case Studies in Thermal Engineering, vol. 27, Oct. 2021, doi: 10.1016/j.csite.2021.101262.

[50] T. Kiso, H. R. Chan, and Y. Arino, "Contrasting effects of electricity prices on retrofit and new-build installations of solar PV: Fukushima as a natural experiment," J Environ Econ Manage, vol. 115, Sep. 2022, doi: 10.1016/j.jeem.2022.102685.

[51] "Database,Eurostat."https://ec.europa.eu/eurostat/web/main/data/database (accessed Feb. 01, 2023).

[52] I. Singh and S. Vardhan, "Energy, exergy, environmental and economic (4E) analysis of evacuated tube solar collector with helical coils," Journal of Mechanical Science and Technology, vol. 36, no. 11, pp. 5801–5808, Nov. 2022, doi: 10.1007/S12206-022-1041-6/METRICS.

[53] O. Hachchadi, M. Bououd, and A. Mechaqrane, "Performance analysis of photovoltaic-thermal air collectors combined with a water to air heat exchanger for renewed air conditioning in building," Environmental Science and Pollution Research, vol. 28, pp. 18953–18962, 2021.