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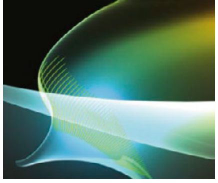

ORIGINAL RESEARCH

The potentials of thermal energy storage using domestic electric water heater technology with PV systems in the EU countries

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ABSTRACT

1. ***The recent extraordinary increase in installed photovoltaic (PV) capacity cannot be successful without integrating it with energy storage (ES) to store generated surplus power to be consumed later.***
2. ***Technological developments and the trend of falling PV module and inverter prices makes it possible to apply economical solutions for hot water production for domestic hot water use and/or assisting space heating, based on the use of solar energy.***
3. ***The combination of modern inverter technology, PV and domestic electric water heating systems provides a storage solution for PV energy with considerable cost saving potentials in the countries of the EU.***
4. ***Many factors influence the ideal and economical size of such combined systems and their components, which need careful consideration and calculation.***
5. ***For a better utilization of the potentials offered by this new solution more complex analyses and the investigation of the ways of linking thermal energy storage (TES) and PV systems and possibly other technologies is necessary.***

Recently, there has been a considerable decrease in photovoltaic technology prices (i.e. modules and inverters), creating a suitable environment for the deployment of PV power in a novel economical way to heat water for residential use. Although the technology of TES can contribute to balancing energy supply and demand, only a few studies have investigated its potentials. These days, TES technology can play a significant role in mitigating the negative network effects resulting from higher proportions of electricity generated by PV systems. The presented research examined the possibility of applying a new technological direction in connection with PV utilization in the European Union (EU), with a view to promoting the spread of cost-effective energy storage and increase energy independence. The purpose of this study was to examine the deployment of combined TES and PV systems in the EU countries by the example of a special 3.5 kW inverter and a 200-l domestic electric water heating system. The innovative significance of the research is that it explores this practical solution, by determining the seasonal energy saving potentials of the application of this sensible heat storage method in the context of all the EU countries.

Keywords photovoltaic · energy generation · energy storage · specific heat · sustainability · circular economy

Discussion

(1) How can the efforts to decrease the household consumption of energy used for heating water and space heating connected to the issue of integrating variable renewable energy sources into energy systems?
(2) How can currently commercially available technology be used for storing electrical energy generated by photovoltaic systems in the form of heat energy?
(3) What determines the potential energy and costs savings achieved by a combined system of a small photovoltaic power plant and a home electric water heating system for the households in the various countries of the European Union?
(4) What are the potentials of the suggested system in terms of energy and costs savings in the context of households in the EU countries?

Introduction

The energy sector faces numerous challenges these days, such as the all-encompassing issue of sustainability,[1] and the ever-increasing demand coupled with the looming exhaustion of energy resources, leading to shortages.[2,3] At present, humanity's insatiable hunger for energy is still covered by fossil fuels mainly. However, due to the severe negative effects of fossil fuel-based energy generation, renewable energy sources (RES) have been ascribed more and more importance to, although the technologies utilizing these are not without sustainability issues either.[4] As a considerable drop in the costs of renewable energy technologies (RETs) has cleared the way for their higher penetrations, countries have increased their efforts to promote new ways in both energy production and consumption.[5] More and more governments worldwide seem to agree that without sustainable and reliable energy there is no socioeconomic well-being for any nation.[5,6]

Wind and solar energy are commonly regarded as great alternatives to conventional fossil fuels thanks to their practical infinity and clean power production technologies. On the downside, however, due to the variable nature and geographically and climatically determined availability of RES, it is indispensable to make electricity networks more flexible and dynamic than traditional ones, characterized by centralized and vertically integrated structures, if a high share of RES is to be attained in the power supply. As a result, concepts for decentralized power production (e.g. stand-alone power systems, micro-grids and smart grids) have emerged to accommodate a high share of RES.[7–9]

The above-mentioned intermittency of solar energy and the frequent discrepancies between demand and supply make the effective and/or continuous use of solar energy difficult in such solar-assisted uses as the heating of buildings.[4] In the EU, it is buildings that consume 40% of the total energy consumption and emit 36% of all greenhouse gases.[10,11] Since they primarily deploy traditional sources of energy, they constitute an obvious sector where energy efficiency measures and RES technologies could produce conspicuous changes.[12] An apparent solution would be storing the solar energy when it is plentiful and utilize it for the sustainable operation of various applications when it is needed. Thermal energy storage (TES) systems could play a considerable role in the sustainable utilization of RES,[4] as TES applications could offer vital solutions to ensure the sustainability of PV energy.[13,14] Designing suitable TES systems and integrating them with energy systems can be conducive to their continued efficiency, sustainability and environmentally friendly operation.[15]

At the beginning of this decade, in 2020, households were responsible for almost one third, 27.0%, of the final energy consumption in the European Union. Most of this came from natural gas (31.7%) and electric energy (24.8%), followed by renewables at 20.3%, and oil and petroleum products at 12.3%, and derived heat at 8.2%. A relatively small percentage, 2.7%, came from coal and associated solid fuel products. The heating of homes requires the most energy in EU households, with 62.8% of the final energy use in total. Adding water heating to this, the combined percentage of space and water heating comes to 77.9%.[16,17] This hot water is most commonly produced by burning gas or biomass, or using electricity.[18] The heating season lasts seven months in most of the EU, typically from October till the end of April. What proportion of a nation's primary energy demand this corresponds to depends on the actual energy mix of the given country.

With a view to decreasing the deployment of fossil fuels and protecting the environment, the European Parliament and the Council of the European Union have passed numerous directives and regulations that oblige the member states to promote energy efficiency and the deployment of renewable sources of energy in their economies. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings [19] has had a great impact on national energy policies in terms of decreasing the energy consumption of buildings.[16]

The heating of water for household use is not only an elemental need in every home, but it is also responsible for about 15.1% of the total residential energy consumption in the EU,[17,20,21] as it is a very energy intensive process.[18] In a vast number of households worldwide, it is domestic electric water heating systems (DEWH) that supply hot water for people.[21] The majority of these are based on the use of immersive resistive heaters, as they are a cost-effective solution, but air-to water heat pumps also represent a viable alternative due to their better energy efficiency characteristics.[22] The water storage tanks of DEWHs essentially comprise a large thermal storage capacity, where the energy of hot water can be kept for a relatively long time for later use. Due to this considerable storage capacity coupled with the high penetration of this technology all around the world and the high energy requirement of heating water, DEWH has become one of the most popular applications utilized for the purposes of demand side management for network operators.[23]

Increasing efficiency and falling equipment prices have made PV one of the most cost-effective technologies of electricity generation that is available to residential electricity consumers, resulting in increasing installation rates, which are expected to continue in the future.[24–26] Using PV systems, households produce electric power within their premises (behind the meter), with the combined benefits of utilizing more renewable energy and achieving financial savings by reducing the amount of electricity purchased from the network. Nevertheless, it also needs to be noted that the growing levels of distributed electricity production by PV modules may cause difficulties for power networks, as they were essentially made to accommodate only unidirectional energy flows.[27]

A source of great potential challenges resulting from the integration of increasing levels of distributed PV energy generation is keeping the voltage within safe limits in network areas with high PV penetration.[27] One way of coping with this problem is controlling and curtailing PV power generation, while a more reasonable strategy would be to increase the households' PV self-consumption rates, which would not only reduce the quantity of electricity fed into the grid but also greatly reduce CO2 emissions.[28] One of the methods to achieve this would be to deploy ES behind the meter, but as scientific studies [29,30] have also pointed out lately, people still do not find residential battery ES systems attractive, for economic reasons. A potential solution could be the utilization of DEWH storage tanks to store the surplus energy from PV power production in the form of the energy of hot water. This solution could achieve two goals at once: decreasing the quantity of electricity purchased from the network for heating water, and increasing the proportion of PV energy self-consumption. Due to the fact that DEWHs are extremely common appliances in many parts of the world and their inexpensiveness relative to battery ES systems, DEWHs can play a big role in facilitating the integration of PV systems and distributed electricity generation into the grid, by providing a certain amount of flexibility necessary for the integration of variable renewable energy, as PV systems become increasingly common.[26] It needs, however, to be noted here that domestic hot water (DHW) consumption habits and patterns are rather complex and vary greatly depending on a number of factors, such as geography, climatic and weather conditions, social aspects (e.g. number of people in a household), people's habits, lifestyles, economic status, etc.[31]

The use of photovoltaic systems in buildings is increasing quickly due to the demand for environmentally-friendly energy sources and the need to reduce carbon emissions from buildings. However, there is a growing emphasis on improving PV self-consumption through energy storage systems (ESS) to make PV plants more profitable and minimize reliance on the power grid. This has made it necessary to analyze the self-consumption of PV energy with various ES configurations, which is not only of great relevance and importance in building energy modelling, but is also a complex and time-consuming process, especially when trying to optimize ESS designs with multiple objectives in mind.[32] The combination of TES and PV systems has the potential to provide an ideal solution to the current energy challenges in the EU, as today's technological advancements effectively facilitate the direct use of electricity generated by PV systems for water heating. Furthermore, information on the seasonal energy saving potentials of these devices in the territory of the EU is currently very scarce. This study examines the joint application of TES and PV systems in the context of the EU countries, using a special 3.5 kW inverter and a 200-L domestic electric water heating system to determine the seasonal energy saving potential. The structure of this paper is as follows: Sect. 2 introduces the methods related to the research, Sect. 3 contains the description of the results and the related discussion, while Sect. 4 presents the conclusions.

Methodology

Reasons for researching water-based sensible heat storage

The aim of the following part is to provide an overview of the physical and technical aspects of the researched field as well as the significance of water-based heat storage and its residential solutions, as the relationships and information connected to these comprise the basis of the various methodological approaches used in the research.

TES has become an increasingly significant area that has received a lot of attention from scientists over the past few decades.[33] A significant amount of literature has been published on the advantages of utilizing TES in renewable energy systems and their integration.[34–37] While PV installations typically use batteries to store electrical energy in the form of chemical energy,[35] there is a growing interest in storing PV energy in the form of thermal energy.[26] Thermal energy storage is typically classified in the literature as sensible and latent heat storage, with the current research focusing on sensible heat storage, while the latent heat TES (LHTES) technology, which is based on the use of phase change materials, is outside the scope of the present research. On the other hand, sensible heat TES (SHTES) is a well-established and economically viable technique that has more practical applications than LHTES. SHTES systems store thermal energy through changes in temperature, and they require a significant amount of storage medium and great variations in temperature to store great quantities of thermal energy.[4] Materials used for sensible heat thermal energy storage have the ability to store heat energy through their specific heat capacity (Cp). Thermal energy stored by using SHTES is expressed as $Q = m \cdot Cp \cdot \Delta T$, where m means the mass (kg), Cp refers to the specific heat capacity (kJ kg−1 K−1) and ΔT is the temperature rise during the process of charging. While absorbing heat energy, the materials go through an increase in temperature without undergoing any phase change. The quantity of heat that can be thusly stored is directly related to the storage material's density, volume, specific heat, and the degree of temperature variation.[35] The following are the most common sensible heat storage materials:

- liquid storage media: water,[37,38] mineral oil,[35] molten salts,[35,39] liquid metals and alloys[38];
- solid storage media: rocks,[40] concrete [35,41,42], sand,[35,43], bricks.[35,38,44]

The present research focused on water-based sensible heat storage in relation to space heating and hot water supply, so the most important relationships related to this are described herein. In the case of sensible heat storage, it is necessary to take into account the daily heat loss from the tank to the environment.[18] For low temperature storage applications, water is one of the best materials. The temperature of operation for a system based on water is between 25 and 90 °C, and it has several advantages, such as high specific heat, affordability, easy accessibility, and non-toxicity. However, it has some disadvantages too, including high vapor pressure and corrosivity. Water is an ideal choice for applications such as space heating and hot water supply in households. Water storage tanks are manufactured from a wide of range materials, including steel, aluminium, reinforced concrete, and fiberglass, and can be insulated with materials like polyurethane, glass wool or mineral wool. Tank sizes may vary greatly, from as small as a couple of hundred liters up to several thousand cubic meters. To preserve the thermal performance and lifespan of a solar heating plant, technologies must be able to ensure water tightness, to minimize heat loss by steam diffusion through the walls, and to optimize stratification of the water inside the tank. Large-scale seasonal heat energy storage can also be achieved by using water in underground aquifers mixed with sand and gravel, which can be a cost-effective alternative to constructing expensive water tanks.[37,38]

In Europe, water tanks are frequently used connected to solar collectors to produce warm water for space heating and/or hot tap water, with the primary application being in smaller plants for single-family homes. However, there are also large water tanks utilized for seasonal or even buffer storage. Since seasonal storage requires large amounts of water, tanks are typically placed in the ground or near the ground surface. To produce hot tap water, auxiliary heat sources like biomass, gas or electricity are often necessary. Heat pumps are also commonly used to assist with heating and/or cooling, regarding the low storage temperatures in the case of seasonal thermal storage.[45] Determining the right size for a storage tank is a significant challenge,[46] and all water storage tanks exhibit some level of stratification, which is influenced by such factors as the volume, geometry, water flow rates, and circulation conditions of the given storage system. Studies have shown that temperature stratification within the TES unit of a solar heating system can greatly enhance the system performance.[37,45,46] Several factors determine the optimal size of the storage tank for a solar system in terms of its economy and operation, including the intended purpose of the energy system, the collector area, the prevailing meteorological conditions, and the operational features of the system. The cost-effectiveness of the system is determined by the cost percentage, and the proportion of the total operational energy consumed by the solar collectors in meeting the load.[37] In connection with this issue, it should be noted that nowadays there are economical [47,48] devices with the help of which hot water can be produced using the electricity generated by PV systems, for the purposes of assisting with the heating and/or the domestic hot water supply. This research explores this particular application.

Using PV systems for producing hot water and the related modelling aspects of the research

The present research investigated the application potentials of a technology developed by AZO Digital Sp. z o.o., through the combined use of PV systems and household electric water heating systems of a given size. The technology developed by the company is a new, effective solution in the European market. By using the inverter presented in this chapter, households can store large amounts of solar energy in the form of heat in the most cost-effective way available currently, thereby reducing their fossil-based energy demand. The study presented herein determined the average daily energy saving capacity of a household electric water heating system of a given volume when heated with the help of a PV system during the 12 months of the year. The modelling did not take specific consumer habits for hot water into account. The main goal of the simulation was to determine the amount of average daily water temperature increase (ΔT) for each month of the year.

The inverters developed by the above-mentioned company have a rated power of 3.5 kW or 4.5 kW. This paper focuses on the application possibilities of the 3.5 kW inverter, technical and economic parameters of which are shown in Table 1. The device was designed to supply power to heating appliances, e.g. boilers, heaters and heating mats directly with electricity generated by PV modules. Therefore, an energy storage system of this type can provide a more cost-effective solution compared to, for example, a traditional off-grid PV system, where the current costs of batteries are rather high. A feature of this technological solution is that if the PV system is installed with this type of inverter, the PV energy can only be used for heating devices, i.e. it can not be used for other energy-consuming systems. The system consists of 4–9 PV modules connected in series, with the sum of open circuit voltages (Voc) ranging from 120 to 350 V, where the total power of the connected modules must not exceed 5 kW. Heaters with a power of 200–3500 W can be connected to the inverter. The casing has two primary outputs that enable the connection of two heating devices. One of these is always heated first, while the second one is only heated once the thermostat of the first device stops receiving power from the inverter. This mechanism guarantees that energy from the PV modules is not wasted when either of the heating units reaches a predetermined temperature. The device incorporates an algorithm for maximum power point tracking (MPPT), which maximizes the amount of power that can be obtained from the PV modules and automatically adjusts the heater power. According to the manufacturer's recommendations, for optimal operation in Europe, systems should comprise 4–7 PV modules and boilers with a capacity of 50–200 l.[48] This research calculated with the larger storage capacity, i.e. 200 l. The inverter can be used for conventional heating devices with no electronics (e.g. electric boiler). The reason for this is that the electronic control of a heater may be disturbed by the modified sine wave of the inverter. With the help of the inverter, conventional electric boilers are able to operate with reduced power too; it is not necessary to provide the constant, factory-specified heating power, thanks to their resistance heating operation. Therefore, the water heating system selected for the research, which is easily available in the EU[49] was the Hajdu Z200S ErP,[50] the technical characteristics of which are shown in Table 2.

In general, domestic electric water heating systems with a storage capacity of 200 l have a heating power of 2400 W, so the research scaled the rated power of the PV system to this power magnitude. However, during periods when the power of the PV system exceeds 2400 W, the available surplus PV power is not utilized and is lost, since the heating power of the water heating system limits the PV power that can be used. The goal was to maximize the daily and annual energy production potential of the PV system. PV systems in Europe typically deliver 75–80% of their rated output in summer during ideal, cloud-free, sunny periods.[51–53] To ensure that the PV system has the highest probability of reaching the 2400 W heating capacity of the electric water heating system in the months with high irradiation, and

Table 1. The technical and economic parameters of the 3.5 kW inverter suitable for domestic electric water heating systems.

The minimum and maximum values of the open circuit voltage range for PV modules in series connection (V_{DC})	120–350
Waveform, output type	Modified sine wave (quasi-sine)
MPPT	Yes, included
PV array connection	Serial and serial-parallel
Maximum power (kW)	3.5
Gross price, 3rd quarter 2023 (€)	400
Efficiency (%)	96
Output VAC, 1	Priority
Output VAC, 2	Dependent
Thermal protection	Yes, included
High and low voltage protection	Yes, included
Over current protection	Yes, included
Energy meter	Yes, included
Power meter	Yes, included
Cooling	Active intelligent fan
Housing	Aluminum
Dimensions (mm)	320 × 272 × 96
Weight (kg)	4.1

to maximize the annual energy generation potential of the PV system, the modelled PV system size was 3200 W.

A PV system can heat the water in a water heater as long as the PV modules are exposed to the rays of the sun. The extent of this as well as the power output of the PV modules–consequently–are not constant throughout the day, as they vary following a daily power curve, which is also subject to seasonal changes. It follows from this that if a PV system is used for power supply, the factory-specified heating time for the water heating device increases. This means that during the period when the PV system produces less power than the 2400 W heating power of the water heating system studied in the research, the electric boiler will operate at reduced power. For domestic electric water heating systems of a given capacity, it is generally accepted by manufacturers to take into account the same amount of energy requirement for heating water by 1 °C at ΔT 35 °C, ΔT at 45 °C and also ΔT at 50 °C (Table 2). During this research, the approach used by manufacturers in their calculations was applied in the modelling.[50,54] The model took into account the proportional amount of factory-specified energy loss (Table 2) at standby energy consumption during 24 h, for the period the water was heated with power from the PV system.

Table 2. The technical parameters of the Hajdu Z200S ErP water heating system.

Volume (l)	200
Nominal working pressure (Mpa)	0.6
Heating power (kW)	2.4
Heating time, manufacturer's data, ΔT 50 °C (h)	5.3
Average energy demand for heating by 1 °C (kWh)	0.25
Standby energy consumption, manufacturer's data (kWh/24 h)	1.45

Currently, in the second quarter of 2023, a number of PV module power sizes ranging from 365 to 600W, with open circuit voltages (Voc) typically between 37 and 50 V, are already available to investors in Europe.[55–57] For the purposes of the research a type of PV module that can be easily connected in series to achieve a rated power of 3200 W was selected. Thus, the research used 8 JA Solar JAM54S30 400/MR type [58] (Table 3) half-cell, monofacial, monocrystalline PV modules with a nominal power of 400 W and an open circuit voltage (Voc) of 37.07 V, for the simulations.[56] As a result, the total power of the PV modules corresponded to the power value recommended by the inverter manufacturer, which is less than 5 kW. Figure 1 is a schematic diagram of the examined system, comprising domestic electric water heater technology and a PV system.

Radiation, power generation, PV module orientation and economic data of the examined EU countries, modelling aspects

In order to determine the annual electricity production of the PV system under consideration, it is essential to know the local climatic characteristics, including solar radiation, temperature and other weather factors. Although some of the countries in the study occupy vast areas with very diverse geographical and climatic conditions, for the purposes of the present research the investigations focused only on the capital cities. This decision was justified by their economic role and the size of their populations as well as their general significance in the life of the respective countries. Data from the Global Solar Atlas (GSA) [59] were used for the majority of the countries, but due to data gaps, in the case of Finland the information was obtained from the Photovoltaic Geographical Information System (PVGIS).[60] As for the climatic data, the GSA database works with a 22-year-old (1999–2021),[61] while the PVGIS database with a 15-year-old real weather data series (2005–2020).[62] The results of the research were based on this input information. The two databases also propose optimal slope and azimuth values for PV system installations, based on the radiation conditions of the given capitals, on which the research is based (Table 4).

The data on the average daily number of hours suitable for heating water with electric power from the PV systems in the different months were compiled from the GSA for all the countries examined, except for Finland, whose data were collected from the PVGIS, as mentioned earlier.[59,60] From the data, it was possible to determine the PV operating hours for the given capitals. In addition, with the help of the two platforms, a database of average daily energy production for the particular months was also developed for the PV capacities and the countries examined. The purpose of this was to estimate the average daily energy saving potential of a household electric water heating system with a capacity of 200 L for the particular months, using the PV capacity examined, which is shown by the magnitude of water temperature increase (ΔT) in the research.

The research also evaluated the results from an economic point of view, using the electricity prices for EU household customers, i.e. the European Union Country Household Electricity Prices (EUCHEP), based on the information in the Eurostat's database [63] for each member state. The research used the electricity prices for the second half of 2022 for the annual consumption range between 2500 and 4999 kWh, in Euros, including all taxes and levies [63] (Fig. 2). For the economic calculations, the following methodology was used for each country:

$$Costsaving = E_{pvsystem} \times EUCHEP \tag{1}$$

Figure 2 shows that there are significant differences in electricity prices for household consumers in the EU countries. Denmark stands out with the highest price at 58.71 EUR cents/kWh, followed by Belgium (44.89 EUR cents/kWh), the Czech Republic (38.44 EUR cents/kWh), Italy (36.41 EUR cents/kWh) and Romania (34.11 EUR cents/kWh). Hungary is one of the EU countries with the lowest electricity prices, with an average price of only 10.84 EUR cents per kWh, and it is followed by Bulgaria (11.47 EUR cents/kWh), Malta (12.77 EUR cents/kWh), the Netherlands (13.5 EUR cents/kWh) and Croatia (14.79 EUR cents/kWh).

Table 3. JA Solar JAM54S30 400/MR type PV module standard test conditions technical parameters (STC) (STC: irradiance 1000 W/m^2, cell temperature 25 °C, AM1.5).

Rated maximum power (Pmax) (W)	400
Open circuit voltage (Voc) (V)	37.07
Maximum power voltage (Vmp) (V)	31.01
Short circuit current (Isc) (A)	13.79
Maximum power current (Imp) (A)	12.90
Module efficiency (%)	20.5
Temperature coefficient of Isc (%/°C)	+0.045
Temperature coefficient of Voc (%/°C)	– 0.275
Temperature coefficient of Pmax (%/°C)	– 0.350

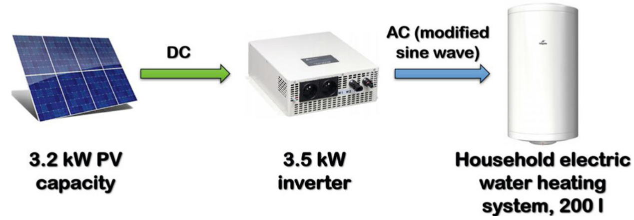

Figure 1. The schematic diagram of the examined system: domestic electric water heating system, inverter, PV modules.

Summary of the modelling aspects

This section summarizes the modelling aspects described in previous sections for easier comprehension in Table 5.

The values of the average daily PV system operating hours suitable for powering water heating appliances in each month ($PV_{\text{ave. operating hours}}$) and those of average daily electricity generation of a 3.2 kWp PV system in each month ($E_{\text{ave. PV}}$) were determined on the basis of the results of the GSA and the PVGIS simulations. It was these results that provided the basis for the further energy calculations. As a result, it became possible to determine energy metrics that could not be calculated with the help of modeling programs, but are essential for the modeling used in research. The estimated daily energy loss in the electric water heating system during the period of water heating powered by the PV system ($E_{\text{ave. loss, heating period by PV}}$) was calculated as follows:

$$E_{ave.\,loss,\,heating\,period\,by\,PV} = E_{ave.\,loss} \times PV_{ave.\,operating\,hours} \quad (2)$$

Knowing the values of $E_{\text{ave. PV}}$ and $E_{\text{ave. loss, heating period by PV}}$ is necessary, because this allows the determination of the amount of stored energy in the water heating system that remains at the end of the heating period powered by PV after the heat losses, on the average ($E_{\text{rem.}}$):

$$E_{ave.\,rem.} = E_{ave.\,PV} - E_{ave.\,loss,\,heating\,period\,by\,PV} \quad (3)$$

The $E_{\text{rem.}}$ figures are not specifically given in the Results and Discussion section, since they logically follow from the $E_{\text{ave. PV}}$ and the $E_{\text{ave. loss, heating period by PV}}$ data.

The potential rate of the average daily increase in the water temperature (ΔT) over the PV heating period can be determined by the following formula:

$$\Delta T = \frac{E_{ave.\,rem.}}{E_{ave.\,energy\,demand|,for\,water\,heating}} \quad (4)$$

Results

The daily PV system operating hours in the countries of the EU

The research determined the average daily PV system operating hours in the capitals of the EU countries, during which PV systems can be used for powering water heating equipment, for each month (Table 6). It can be said that in the capital cities examined there are significant differences in the seasonal operating time of PV systems. According to the results shown in Table 6, the length of the period during which a water heating appliance can be powered by a PV system is significantly influenced by the geographical location and the climatic factors. During the coldest and darkest winter months (e.g. December) the operating time in the capitals of the northern countries is typically 5–6 h (e.g. Helsinki in Finland, Stockholm in Sweden), while in the south, for example in Nicosia (Cyprus), Rome (Italy) or Valetta (Malta) it reaches 10 h. In contrast, due to seasonal changes, this value is significantly longer in the summer months, even up to 11–12 h longer than

Table 4. The average radiation, energy generation and PV module orientation data of the capitals of the examined countries.

Country (city)	Yearly global horizontal irradiation, average (kWh/m^2)	Yearly global tilted irradiation at optimum angle, average (kWh/m^2)	Yearly specific PV system output at optimal tilt angle and orientationwith system loss, average (kWh/kWp)	3.2 kWp PV system annual energy output at optimal tilt angle and orientation with system loss, average ($E_{PV\ system}$) (kWh)	Optimal tilt angle (slope) of PV modules (°)	Optimal orientation (azimuth) (°)
Austria (Vienna)	1207	1417	1186	3795	36	180
Belgium (Brussels)	1073	1255	1060	3392	36	180
Bulgaria (Sofia)	1416	1637	1352	4326	34	180
Croatia (Zagreb)	1295	1504	1247	3990	35	180
Cyprus (Nicosia)	1927	2179	1723	5514	31	180
Czech Republic (Prague)	1122	1313	1108	3546	36	180
Denmark (Copenhagen)	1028	1238	1055	3376	39	180
Estonia (Tallinn)	999	1228	1051	3363	41	180
Finland (Helsinki)	964	1189	1018	3258	42	180
France (Paris)	1158	1355	1134	3629	36	180
Germany (Berlin)	1065	1261	1065	3408	37	180
Greece (Athens)	1752	1988	1596	5107	32	180
Hungary (Budapest)	1272	1502	1252	4006	36	180
Ireland (Dublin)	956	1123	961	3075	37	180

Table 4. (continued)

Country (city)	Yearly global horizontal irradiation, average (kWh/m^2)	Yearly global tilted irradiation at optimum angle, average (kWh/m^2)	Yearly specific PV system output at optimal tilt angle and orientationwith system loss, average (kWh/kWp)	3.2 kWp PV system annual energy output at optimal tilt angle and orientation with system loss, average ($E_{\text{PV system}}$) (kWh)	Optimal tilt angle (slope) of PV modules (°)	Optimal orientation (azimuth) (°)
Italy (Rome)	1594	1843	1522	4870	34	180
Latvia (Riga)	1026	1239	1055	3376	39	180
Lithuania (Vilnius)	1019	1200	1017	3254	38	180
Luxembourg (Luxembourg)	1117	1296	1086	3475	36	180
Malta (Valetta)	1817	2017	1648	5274	29	180
Netherlands (Amsterdam)	1044	1225	910	2912	37	180
Poland (Warsaw)	1087	1283	1083	3466	37	180
Portugal (Lisbon)	1730	1982	1626	5203	32	180
Romania (Bucharest)	1374	1593	1316	4211	34	180
Slovak Republic (Bratislava)	1238	1451	1210	3872	36	180
Slovenia (Ljubljana)	1283	1485	1232	3942	35	180
Spain (Madrid)	1742	2048	1654	5293	35	180
Sweden (Stockholm)	1013	1231	1027	3286	42	180

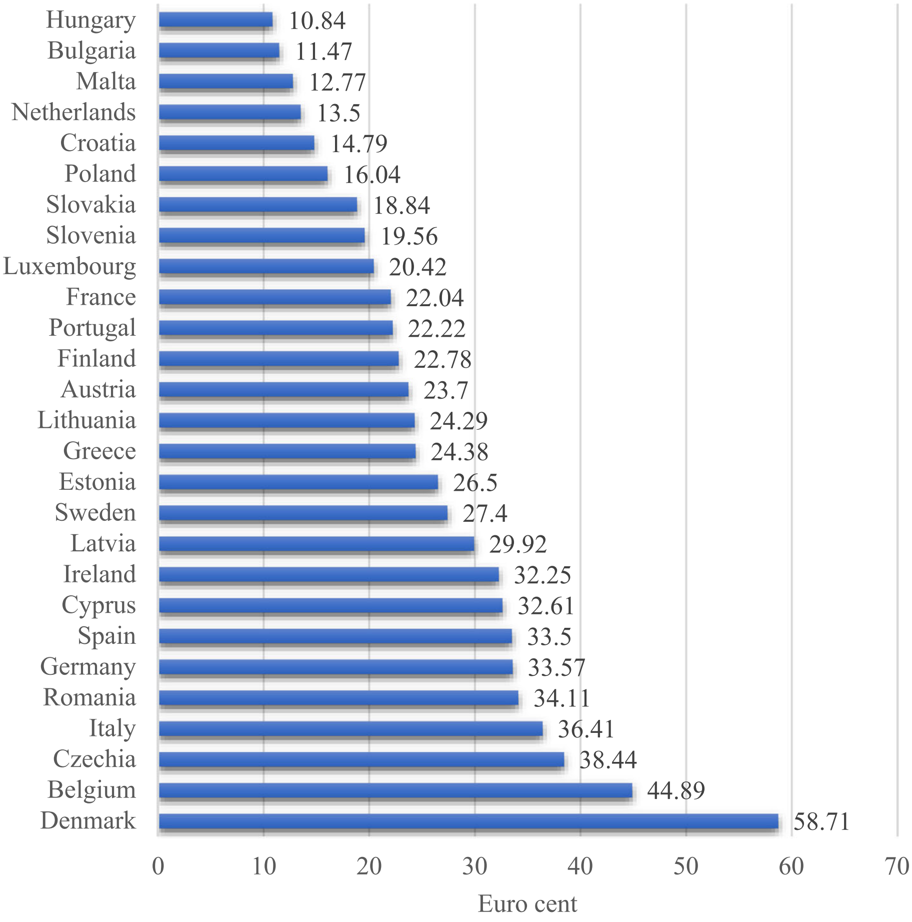

Figure 2. The electricity prices for household consumers in the EU countries in the second half of 2022, inclusive of all taxes and levies.

in the winter (e.g. Helsinki in Finland, Tallinn in Estonia). The number of PV system operating hours varies between 14 and 18 h during the summer period (e.g. June).

The different shades of red in Table 6 help interpret the data. The lighter the red color of the cell is, fading into white, the more the hours of PV system operation suitable for powering water heating devices decrease. The value represented by the brightest shade of red, 18 h, was recorded in Stockholm, Sweden, in June, while the lowest value, which was a mere 5 h, was recorded in Helsinki, Finland, in December.

Average daily electricity production, thermal energy loss and the average daily energy saving potentials during the PV system operating hours which are suitable for powering water heating appliances in each month

The specific information on the average daily electricity production of PV systems in each month allows the planning of the energy saving potentials of the combined use of PV and domestic electric water heating systems. The PV system modeled in the research had a capacity of 3200 W. Table 7 shows how the average daily electricity production of a PV system of this capacity changes in each month in the capitals examined. The determination of these values is crucial because these amounts of energy are stored in the form of heat. Table 7 shows that there are significant differences between countries concerning the quantities of electricity that can be generated by PV systems, due to geographical location, climatic factors and irradiation. In general, it can be stated that PV systems are less efficient in terms of energy production in winter than in summer. However, the differences between the months vary significantly in the countries examined. In the case of the Nordic countries, the average daily electricity production in January ranges between 2.1 and 2.6 kWh, while in the case of the southern ones it may even exceed 10 kWh, for the PV capacity examined. In contrast, during the summer period, e.g. in June, these values range from 11.8 to 17.6 kWh in all the countries. It is worth noting that in the case of the Nordic countries, the summer period can be considered favorable for PV system electricity generation, since during this period 12.0–14.5 kWh can be produced in Stockholm, Sweden, or 13.3–15.7 kWh in Helsinki, Finland for example. However, in Belgium, for instance, which is farther south than the two countries above, these values are lower, ranging from 11.6 to 12.8 kWh. The colors in Table 7 are used for easier interpretation. The brightest red represents Valetta’s (Malta) 18.1 kWh, which was typical in July, while the lowest figure is seen for Estonia (Tallinn), which is 1.2 kWh in December.

Table 5. The main aspects of the modeling.

Aspect applied in the modelling process	Value
Examined inverter technology: maximum output power (kW)	3.5
Examined water heating system: maximum heating power (kW)	2.4
Examined water heating system: heating time at max. heating power, ΔT 50 °C (h)	5.3
Examined water heating system: average energy demand for heating by 1 °C ($E_{\text{ave. energy demand for water heating}}$) (kWh)	0.25
Examined water heating system: standby energy consumption, manufacturer's data (Wh/24 h)	1450
Examined water heating system: average energy loss over a 1-h period ($E_{\text{ave. loss}}$) (Wh)	60.4
Examined PV module: rated maximum power, STC (Pmax) (W)	400
Examined PV modules: power, connected in series, STC (W)	3200
Does the PV system feed into the grid?	No
Does the PV system only produce hot water?	Yes
Average daily information on radiation, power generation, PV system operation, PV-based heating hours of water heating systems; orientation	Authors' own results based on aggregation of GSA and PVGIS simulation results
Examined locations	Capitals of EU member states
Does the modelling take specific hot water usage patterns into account?	No
Does the modelling determine the potential magnitude of the average daily PV-based water temperature increase (ΔT) on a monthly basis for the whole year?	Yes

The power output of PV modules varies throughout the day along a daily power curve. For this reason, if a PV system is used for powering a water heating appliance, the factory-specified heating time increases, so the proportional amount of thermal energy loss during the factory-specified standby energy use was taken into account for the period of heating with power from the PV system (Sect. 2.2). The estimated energy loss in the electric water heating systems varied between 0.3 and 1.1 kWh in the particular months in the EU capitals during the heating periods with power from the PV systems. It can be seen that heat loss is higher in the summer months because the PV system heats up the electric boiler more than in winter. In the period from March to September, heat loss is typically 0.7–1.1 kWh, while in winter it is between 0.3 and 0.7 kWh. The colors in Table 8 are also used for ease of interpretation. The highest (brightest red) value was recorded in Sweden, Stockholm at 1.1 kWh, which was typical in June, while the lowest (faintest red) was recorded in Finland, Helsinki, at 0.3 kWh, which was recorded in December.

The estimation of the heat loss in the domestic electric water heating system was necessary to determine the average increase in water temperature (ΔT) during the period of heating powered by the PV system for each month of the year. The results in Table 9 show that local climatic conditions, including irradiation to the PV system, have a significant influence on the average daily temperature increase (ΔT) of the water during the period of heating powered by the PV system. In general, regarding the capital cities studied, the value of ΔT shows significant differences during the year, ranging between

Table 6. The average daily PV system operating hours which are suitable for powering water heating appliances in each month.

Country (city)	$PV_{\text{ave. operating hours}}$ (h)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Austria (Vienna)	9	10	12	14	15	16	16	14	13	11	9	8
Belgium (Brussels)	8	10	12	14	15	16	16	14	13	11	9	8
Bulgaria (Sofia)	9	11	13	13	15	15	15	14	13	11	10	9
Croatia (Zagreb)	10	10	12	14	15	16	16	14	13	11	9	9
Cyprus (Nicosia)	10	12	12	13	14	14	14	14	12	11	11	10
Czech Republic (Prague)	8	10	12	14	16	16	15	14	12	10	9	8
Denmark (Copenhagen)	7	9	11	14	16	17	16	15	12	10	8	7
Estonia (Tallinn)	7	9	11	15	17	17	17	15	13	10	8	6
Finland (Helsinki)	7	9	11	14	17	17	17	15	13	10	8	5
France (Paris)	8	10	12	14	15	16	16	14	13	11	9	8
Germany (Berlin)	8	9	12	14	16	16	16	14	12	10	8	8
Greece (Athens)	10	11	13	13	14	15	15	13	12	11	10	9
Hungary (Budapest)	9	10	12	14	15	16	15	14	13	11	9	9
Ireland (Dublin)	7	10	12	13	15	16	15	15	13	11	8	7
Italy (Rome)	9	11	12	14	14	15	15	14	12	11	10	10
Latvia (Riga)	7	9	11	15	15	17	17	15	13	10	7	7
Lithuania (Vilnius)	7	9	11	14	15	17	16	15	13	10	8	7
Luxembourg (Luxembourg)	9	11	13	14	15	16	16	15	13	11	9	9
Malta (Valetta)	10	11	12	14	14	14	14	14	12	11	10	10
Netherlands (Amsterdam)	8	10	12	14	15	16	16	14	13	11	9	8
Poland (Warsaw)	8	10	12	14	15	16	16	14	13	11	9	8
Portugal (Lisbon)	10	11	12	13	15	15	15	13	13	11	10	9
Romania (Bucharest)	9	11	12	14	14	15	15	14	12	12	10	9
Slovak Republic (Bratislava)	8	10	12	14	15	16	16	14	13	11	9	8
Slovenia (Ljubljana)	9	10	12	14	15	16	16	14	12	11	9	8
Spain (Madrid)	10	11	12	14	14	15	15	14	12	12	10	10
Sweden (Stockholm)	6	9	12	14	16	18	16	15	12	10	7	6

Table 7. The average daily electricity generation of a 3.2 kWp PV system in each month.

Country (city)	$E_{\text{ave. PV}}$ (kWh)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Austria (Vienna)	5.0	8.1	10.6	13.3	13.4	13.9	13.9	13.4	11.1	8.1	4.9	4.2
Belgium (Brussels)	4.0	6.3	9.3	12.1	12.7	12.8	12.4	11.6	10.1	7.2	4.5	3.3
Bulgaria (Sofia)	7.2	9.9	11.7	12.4	13.3	14.4	15.1	14.9	12.6	10.6	7.8	6.0
Croatia (Zagreb)	6.0	8.7	11.0	12.4	13.6	14.4	14.7	14.2	11.4	9.0	5.7	5.0
Cyprus (Nicosia)	10.6	12.6	14.8	15.5	16.3	17.1	17.3	17.1	16.4	14.2	12.2	10.2
Czech Republic (Prague)	4.3	7.1	9.6	12.6	13.0	13.3	12.9	12.5	10.3	7.4	4.3	3.6
Denmark (Copenhagen)	3.1	5.4	9.6	13.1	14.0	13.9	13.4	12.1	9.7	6.2	3.3	2.1
Estonia (Tallinn)	2.1	5.2	10.1	13.6	15.5	15.0	14.4	12.5	9.0	5.3	2.0	1.2
Finland (Helsinki)	2.2	5.2	10.2	14.3	16.3	15.7	15.3	13.3	9.6	5.8	2.1	1.2
France (Paris)	4.6	7.1	10.1	12.6	13.0	13.5	13.4	12.7	11.1	7.9	5.2	4.1
Germany (Berlin)	3.7	6.4	9.1	12.5	13.3	13.3	12.9	12.2	10.1	7.0	4.1	3.0
Greece (Athens)	9.4	11.5	13.6	15.0	15.9	16.8	17.2	16.9	14.9	12.2	9.7	8.2
Hungary (Budapest)	5.5	8.4	11.2	13.1	13.8	14.1	14.3	13.9	11.4	9.2	5.6	4.4
Ireland (Dublin)	3.6	6.1	8.5	10.9	12.3	11.8	10.9	9.9	8.6	6.4	4.4	3.1
Italy (Rome)	8.7	11.1	13.1	14.2	15.5	16.5	17.2	16.4	13.8	11.5	8.6	8.0
Latvia (Riga)	2.6	5.7	9.8	13.2	14.8	14.6	14.0	12.4	9.6	6.0	2.5	1.5
Lithuania (Vilnius)	3.0	5.6	9.4	12.3	13.5	13.7	13.0	12.2	9.6	6.0	2.5	1.9
Luxembourg (Luxembourg)	3.9	6.6	10.0	12.7	12.9	13.6	13.3	12.3	10.7	7.2	4.0	3.2
Malta (Valetta)	9.7	12.2	14.3	15.7	17.2	17.6	18.1	17.2	14.5	12.0	9.8	9.0
Netherlands (Amsterdam)	3.8	6.2	9.1	12.3	13.2	13.0	12.7	11.5	9.5	6.7	3.9	3.0
Poland (Warsaw)	3.7	5.9	9.4	12.4	13.6	13.7	13.2	12.8	10.2	7.0	3.6	2.7
Portugal (Lisbon)	9.3	11.6	13.9	15.1	16.0	16.8	17.4	17.5	15.5	12.1	9.7	8.5
Romania (Bucharest)	6.0	8.9	11.6	13.1	14.2	14.7	15.2	14.9	12.6	9.7	6.5	5.3
Slovak Republic (Bratislava)	4.8	7.9	10.7	13.5	13.9	14.4	14.2	13.7	11.3	8.4	5.0	3.9
Slovenia (Ljubljana)	5.2	8.5	11.3	12.4	13.4	14.3	14.8	13.9	11.4	8.1	4.6	3.9
Spain (Madrid)	10.2	12.7	14.7	15.2	15.6	16.8	17.5	17.1	15.4	12.7	10.3	9.4
Sweden (Stockholm)	2.6	5.7	10.1	13.4	14.5	14.5	13.8	12.0	9.5	5.9	2.7	1.7

Table 8. Estimated daily energy loss in the electric water heating system during the period of water heating powered by the PV system.

Country (city)	$\mathbf{E_{ave.\ loss,\ heating\ period\ by\ PV}}$ **(kWh)**											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Austria (Vienna)	0.5	0.6	0.7	0.8	0.9	1.0	1.0	0.8	0.8	0.7	0.5	0.5
Belgium (Brussels)	0.5	0.6	0.7	0.8	0.9	1.0	1.0	0.8	0.8	0.7	0.5	0.5
Bulgaria (Sofia)	0.5	0.7	0.8	0.8	0.9	0.9	0.9	0.8	0.8	0.7	0.6	0.5
Croatia (Zagreb)	0.6	0.6	0.7	0.8	0.9	1.0	1.0	0.8	0.8	0.7	0.5	0.5
Cyprus (Nicosia)	0.6	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.7	0.6
Czech Republic (Prague)	0.5	0.6	0.7	0.8	1.0	1.0	0.9	0.8	0.7	0.6	0.5	0.5
Denmark (Copenhagen)	0.4	0.5	0.7	0.8	1.0	1.0	1.0	0.9	0.7	0.6	0.5	0.4
Estonia (Tallinn)	0.4	0.5	0.7	0.9	1.0	1.0	1.0	0.9	0.8	0.6	0.5	0.4
Finland (Helsinki)	0.4	0.5	0.7	0.8	1.0	1.0	1.0	0.9	0.8	0.6	0.5	0.3
France (Paris)	0.5	0.6	0.7	0.8	0.9	1.0	1.0	0.8	0.8	0.7	0.5	0.5
Germany (Berlin)	0.5	0.5	0.7	0.8	1.0	1.0	1.0	0.8	0.7	0.6	0.5	0.5
Greece (Athens)	0.6	0.7	0.8	0.8	0.8	0.9	0.9	0.8	0.7	0.7	0.6	0.5
Hungary (Budapest)	0.5	0.6	0.7	0.8	0.9	1.0	0.9	0.8	0.8	0.7	0.5	0.5
Ireland (Dublin)	0.4	0.6	0.7	0.8	0.9	1.0	0.9	0.9	0.8	0.7	0.5	0.4
Italy (Rome)	0.5	0.7	0.7	0.8	0.8	0.9	0.9	0.8	0.7	0.7	0.6	0.6
Latvia (Riga)	0.4	0.5	0.7	0.9	0.9	1.0	1.0	0.9	0.8	0.6	0.4	0.4
Lithuania (Vilnius)	0.4	0.5	0.7	0.8	0.9	1.0	1.0	0.9	0.8	0.6	0.5	0.4
Luxembourg (Luxembourg)	0.5	0.7	0.8	0.8	0.9	1.0	1.0	0.9	0.8	0.7	0.5	0.5
Malta (Valetta)	0.6	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.7	0.7	0.6	0.6
Netherlands (Amsterdam)	0.5	0.6	0.7	0.8	0.9	1.0	1.0	0.8	0.8	0.7	0.5	0.5
Poland (Warsaw)	0.5	0.6	0.7	0.8	0.9	1.0	1.0	0.8	0.8	0.7	0.5	0.5
Portugal (Lisbon)	0.6	0.7	0.7	0.8	0.9	0.9	0.9	0.8	0.8	0.7	0.6	0.5
Romania (Bucharest)	0.5	0.7	0.7	0.8	0.8	0.9	0.9	0.8	0.7	0.7	0.6	0.5
Slovak Republic (Bratislava)	0.5	0.6	0.7	0.8	0.9	1.0	1.0	0.8	0.8	0.7	0.5	0.5
Slovenia (Ljubljana)	0.5	0.6	0.7	0.8	0.9	1.0	1.0	0.8	0.7	0.7	0.5	0.5
Spain (Madrid)	0.6	0.7	0.7	0.8	0.8	0.9	0.9	0.8	0.7	0.7	0.6	0.6
Sweden (Stockholm)	0.4	0.5	0.7	0.8	1.0	1.1	1.0	0.9	0.7	0.6	0.4	0.4

3 and 68 °C. This value was above 30 °C in every country in the period from March to September. In summer, this figure varied between 35 and 68 °C. The lowest ΔT value during summer was observed in Dublin, Ireland (35°), while the highest was recorded in Valetta, Malta. In the case of the Scandinavian countries, e.g. Stockholm, Sweden, these temperatures were between 44 and 53 °C during this period, while in the case of Helsinki, Finland, slightly higher values were observed between 49 and 58 °C. In the countries with higher irradiation, the ΔT values exceeded 60 °C during the summer period, e.g. in Cyprus (Nicosia), Greece (Athens), Italy (Rome), Malta (Valetta), Portugal (Lisbon) and Spain (Madrid). It is worth noting that the maximum hot water temperature value for electric water heating systems varies between 65 and 95 °C,[50] so a storage tank with the appropriate technical parameters should always be chosen for the efficient and economical storage of thermal energy.

The magnitude of ΔT in winter deteriorates significantly compared to summer. From the point of view of the system under consideration, the month of December is the most unfavorable. ΔT values below 10 °C were observed in 8 countries, namely Denmark (Copenhagen), Estonia (Tallinn), Finland (Helsinki), Latvia (Riga), Lithuania (Vilnius), Netherlands (Amsterdam), Poland (Warsaw) and Sweden (Stockholm). During this period, the worst situation can be seen in the Scandinavian countries, where the ΔT is between 3 and 5 °C.

The colors in Table 9 were added for ease of interpretation. Malta (Valetta) had the brightest red color with 68 °C, which was recorded in July, while Estonia (Tallinn) had the lightest color with 3 °C, which was observed in December.

The potentials of using home electric water heating technology in energy storage

It should be noted that the dynamic spread of so-called on-grid PV systems, which are capable of feeding into the grid, for example, the currently unused electricity of a household, is increasingly causing technical problems in the EU's macroenergy systems. This mainly causes reverse power flows in local power grids, resulting in the inverter disconnecting from the grid for safety reasons, in which case it is not possible to feed into it. For this reason, off-grid or hybrid PV systems are more and more often installed in the EU. An off-grid PV system does not feed into the grid, it only charges a battery to facilitate the use of the generated electricity. In contrast, in the case of a hybrid system, a hybrid inverter not only enables feeding power into the grid, but also allows the charging of batteries, as in the case of an off-grid system. The disadvantage of both systems is the use of batteries, which requires a significant investment. With regard to hybrid PV systems, it is worth noting that an earlier research determined [64] the proportion of household electricity consumption that can be saved in certain European countries by directly using PV energy when deploying PV capacities between 0.5 and 5 kW coupled with lithium-ion energy storage equipment with usable energy capacities of 0–20 kWh.

Table 9. Average daily water temperature increase (ΔT) during the period of water heating powered by the PV system.

Country (city)	Average daily water temperature increase (ΔT) during the period of water heating powered by the PV system											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Austria (Vienna)	18	29	39	49	49	51	51	49	40	29	17	15
Belgium (Brussels)	14	22	34	44	46	47	45	42	37	26	16	11
Bulgaria (Sofia)	26	36	43	46	49	53	56	55	46	39	28	21
Croatia (Zagreb)	21	32	40	45	50	53	54	52	42	33	20	18
Cyprus (Nicosia)	39	47	55	58	61	64	65	64	62	53	45	38
Czech Republic (Prague)	15	26	35	46	47	48	47	46	38	27	15	12
Denmark (Copenhagen)	11	19	35	48	51	51	49	44	35	22	11	7
Estonia (Tallinn)	7	18	37	50	57	55	53	46	32	18	6	3
Finland (Helsinki)	7	18	37	53	60	58	56	49	35	20	6	3
France (Paris)	16	25	37	46	47	49	49	46	41	29	18	14
Germany (Berlin)	13	23	33	46	48	49	47	45	37	25	14	10
Greece (Athens)	35	43	50	56	59	63	64	63	56	45	36	30
Hungary (Budapest)	20	30	41	48	51	52	53	51	42	33	20	15
Ireland (Dublin)	12	22	31	40	45	42	39	35	31	23	16	11
Italy (Rome)	32	41	49	52	58	61	64	61	52	42	31	29
Latvia (Riga)	9	20	36	48	55	53	51	45	35	21	8	4
Lithuania (Vilnius)	10	20	34	45	50	50	47	44	35	21	8	6
Luxembourg (Luxembourg)	13	23	36	46	47	50	48	45	39	26	14	10
Malta (Valetta)	36	45	53	58	64	66	68	64	54	45	36	33
Netherlands (Amsterdam)	13	22	33	45	48	47	46	42	34	24	13	10
Poland (Warsaw)	13	21	34	45	50	50	48	47	37	25	12	9
Portugal (Lisbon)	34	43	52	56	59	62	65	66	58	45	36	31
Romania (Bucharest)	21	32	43	48	53	54	56	55	47	35	23	19
Slovak Republic (Bratislava)	17	29	39	50	51	53	52	51	41	30	17	14
Slovenia (Ljubljana)	18	31	42	45	49	52	54	51	42	29	16	13
Spain (Madrid)	38	47	55	57	58	63	65	64	58	47	38	35
Sweden (Stockholm)	9	20	37	49	53	53	50	44	34	21	9	5

Furthermore, the potentials for the direct use of PV energy compared to the annual energy production of such hybrid PV systems were also determined. The findings showed that by raising the energy capacity of the energy storage systems the electricity saving efficiency of residential hybrid PV systems per capita is increased up to a level when it reaches 100%. The hybrid PV system capacities that correspond to this point, however, need to be established for each country separately, which is impossible without taking into account the country-specific conditions and the relationships of the relevant factors. Also, the investigations revealed that beyond a given size, higher energy storage system energy capacities do not result in any or only slight improvements in the yearly direct PV energy consumption.

When designing off-grid and hybrid PV systems it is worth considering the energy storage method presented in this study. It is necessary to think about what the potentially generated PV energy that would be stored in the batteries would be used for. If part of it would be used for heating water, it is worth considering designing part of the PV capacity exclusively for hot water production. This is mostly justified by the fact that this could reduce the required battery energy capacity, which could create a more favorable situation from an investment point of view, and on the other hand, energy storage in an electric water heating system is a much more economical and cost-effective solution. Moreover, a battery used in a PV system undergoes frequent charge–discharge cycles, as a result of which it suffers constant technical deterioration.

It needs to be noted here that the gross consumer price of the LiFePO4 batteries used in off-grid or hybrid systems was around EUR 400/kWh in the EU in the third quarter of 2023.[65] This means that the price of a larger LiFePO4 battery with a nominal energy capacity of 15.3 kWh exceeded EUR 6000. The advantage of choosing such an option is that the stored energy can not only be used as electricity, but can also be converted into thermal energy. On the other hand, the disadvantage of the domestic electric water heater technology combined with PV system presented in this research is that the energy can only be stored in the form of heat. However, based on the rate of the average daily water temperature increase (ΔT), it was apparent that even ΔT 65 could be achieved with the help of the system studied in the research during the PV heating period. This means that in summer, a domestic electric water heating system with a storage capacity of 200 l can store more than 16 kWh of energy in the form of heat on average per day. In addition, the gross retail price of a 200 l water heating system over the same period was around EUR 1000,[49] which is much more favorable compared to that of the LiFePO4 battery. Therefore, in this type of investments, it is worth carefully considering whether it would be more economical to use the technology and method presented in this research in the production of domestic hot water or in aiding heating. This could help reduce the investment costs associated with the battery system by optimizing the nominal energy capacity. Related to this, it should also be taken into account that the

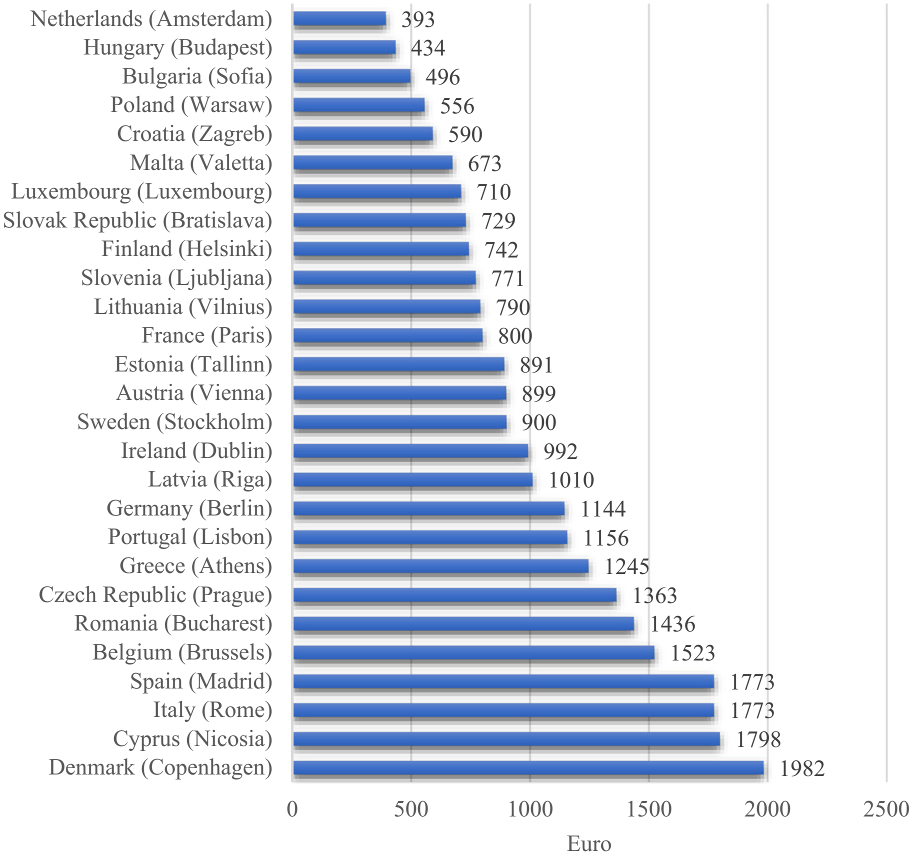

Figure 3. Cost saving potentials for households in the EU based on the electricity prices prevailing in the second half of 2022 (inclusive of taxes and levies) by the use of the combination of domestic electric water heating technology and a 3.2 kWp PV system examined in the research.

total system efficiency (system loss, inverter, battery) of off-grid and hybrid PV systems varies typically between 72 and 86%, depending on the battery type. However, in the case of the electric water heating system tested in the research, heated to 65 °C, 89% of the stored thermal energy is still available after 24 h.

The annual cost-saving potential of the combined system of domestic electric water heater technology and PV studied in the research

The results (Fig. 3) show that, taking into account the electricity prices inclusive of taxes and levies prevailing in the second half of 2022, the use of a combination of domestic electric water heating technology and PV system examined in the research has significant cost-saving potentials for EU households. Combining these technologies will allow for efficient, more sustainable water heating, while also facilitating solar self-sufficiency. At the top of the list are countries such as Denmark, Cyprus, Italy and Spain, which offer outstanding savings opportunities to energy consumers, helping to promote sustainable energy use in the EU. These results underline the importance of energy efficiency measures and contribute to achieving the goals of the Energy Strategy for Europe. The high cost savings are mainly due to high electricity prices in some countries, so high energy prices can be an incentive for consumers to reduce energy consumption and adopt energy-efficient systems. Thus, the results highlight that electricity prices greatly influence the choice of energy sources used and the possibilities of the spread of alternative energy technologies.

Conclusions

The past ten years have seen a great rise in on-grid PV power generation capacities in many countries of the world. This rapid spread has involved large commercial utility-size power plants as well as small, household PV systems, and all sectors. However, the use of intermittent renewable energies also entails some limitations, due to their high variability and availability limited by various factors, such as geography, climate and weather. Consequently, energy production from variable sources needs to be combined with efficient ES options, so that power can be stored to be used later when the energy source is not available.

Among variable renewable energies, solar PV has experienced an unprecedented hike lately, and this growth is forecasted to accelerate more in years to come. Because of the absence of solar radiation at night and the great variability and difficult predictability of solar power in the daytime, the successful deployment of PV energy relies on ES technologies to a high degree. Thanks to the fact that energy can be stored in different forms such as electrical, mechanical and thermal energy, there are many practical and potential methods for storing it. Although the most common ES option in the case of PV power generation is the use of batteries, solutions based on thermal energy are also gaining more and more popularity. Thermal energy storage can also be achieved in different ways: latent heat, sensible heat and thermochemical ES, or even by a combination of these.

Reducing the demand for energy based on fossil fuel is of paramount importance in the European Union. The present research offers a novel technological solution, which is already available in the market, to achieve this goal. The new type of PV system discussed herein will be of increasing importance in the European market nowadays, as with the help of the presented inverter, the population can store large amounts of solar energy in the most cost-effective way currently possible, thusly reducing the fossil-based energy demand of households.

The research presented herein focused on water-based sensible heat storage in relation to space heating and household hot water supply, as nowadays there is an increasing interest in storing generated PV power in the form of thermal energy. The work explored the application possibilities of the 3.5 kW inverter technology developed by AZO Digital Sp. z o.o. using a 3.2 kWp PV system together with a 200-l capacity domestic electric water heating system. The results of the research showed that the local climatic characteristics and irradiation to the PV system significantly influenced the amount of average daily increase in water temperature (ΔT) during the examined period of water heating powered by the PV system. For the capitals of the EU countries studied, the value of ΔT varied significantly during the year, ranging from 3 to 68 °C. This value was always above 30 °C from March to September, ranging from 35 to 68 °C in summer and from 1.2 to 12.7 °C in winter. In six countries with high irradiation figures during the year, the ΔT value exceeded 60 °C during the summer months, of which Malta (Valetta) stood out. However, the applicability of the system examined is limited during the winter, especially in the Nordic countries. In these countries, December is the most unfavorable month, when the ΔT is between 3 and 5 °C. In contrast, the estimated value of the ΔT during this period is 38 °C in Cyprus (Nicosia), 35 °C in Spain (Madrid) and 29 °C in Italy (Rome), as these countries are characterized by warm summers and mild winters.

The aim of the research was to present a possible alternative of using TES and PV systems combined, under the conditions prevailing in the countries of the EU, through the deployment of a special inverter and a household electric water heating system of a relatively large capacity. The seasonal energy-saving potentials of a water-based sensible heat storage method, which represents an up-to-date practical possibility of connecting TES and PV systems, were determined for each capital city in the EU. The objectives of related future research include more complex analyses of other ways of linking TES and PV systems, e.g. also considering the domestic hot water usage patterns of households, or in relation to assisting space heating in homes, combined with heat pumps.

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Author contributions

HZS: Conceptualization. HZS, NHB: Methodology. HZS: Software. HZS, NHB: Validation. HZS, NHB, AV: formal analysis. HZS, NHB, VA: writing–original draft preparation. HZS, NHB, GP, AV: writing–review and editing. HZS, NHB, GP, AV: Supervision. HZS: Project administration. HZS: funding acquisitio. All authors have read and agreed to the published version of the manuscript.

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Data availability

All data are included in the supplementary material.

Code availability

No code was written or used.

Declarations

Conflict of interest

The authors declare that they have no confict of interest.

Ethical approval

We follow the ethical code of conduct by the MRS.

Consent for publication

All authors gave their consent for publication in the journal MRS Energy and Sustainability.

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