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Integration of Thermal Energy Storage and Photovoltaic Systems by Using Domestic Electric Water Heaters

A Case Study of Austria and Hungary

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Abstract

Lately, the prices of photovoltaic (PV) technology, including modules and inverters, have significantly dropped, making it more economically feasible to use PV power for heating water in homes. Although thermal energy storage (TES) has the potential to balance energy supply and demand, it remains largely underexplored. TES solutions may have a key role in dealing with the adverse effects of the dynamically growing share of electricity generated by photovoltaic (PV) systems on electricity networks. This research explored the potential of implementing a novel technological approach in conjunction with PV usage in Austria and Hungary, aiming to encourage the adoption of economical energy storage solutions and lessen energy dependence. This study aimed to investigate the joint use of TES and PV systems in Austria and Hungary, specifically using a 3.5 kW quasi-sine inverter and an electric water heating appliance for households with a capacity of 200 liters, as examples. According to the results of the research, the tested 200-liter domestic electric water heating system can store an average of more than 16 kWh of heat energy per day during the summer months, with a maximum water temperature increase (ΔT) of up to 53 °C during this period. The research is innovative and practical, as it explores the application of this solution to assess the seasonal energy-saving potential of this method of sensible heat storage in the contexts of Austria and Hungary.

Keywords

photovoltaic (PV) technology, electric energy generation, energy storage, specific heat, sustainability, circular economy

1 Introduction

Our world is undergoing a process of energy transition unprecedented in human history. Now we are at a phase when much of our energy need is still satisfied by deploying fossil fuels, but renewable energy sources (RES) have already come to the fore and gained significance in a global attempt to curb the harmful effects of using traditional energy carriers [1]. Among RES, wind and solar energy appear to be two of the top candidates to replace fossil fuels, as virtually inexhaustible and green alternatives. Both being variable sources of energy, however, means that they are not always and everywhere accessible, and their intermittency requires more flexibility and dynamism of power systems. This means fundamental changes, as today's networks are predominantly centralized and vertically integrated. In an effort to address this issue and make systems suitable to handle bigger percentages of RES, new solutions for decentralizing electric energy production have emerged, such as micro-grids, smart grids stand-alone power systems [2–4].

As in the countries of the European Union, it is buildings that account for 40% of all energy consumption and more than one third (36%) of total greenhouse gas emissions [5, 6], it seems to be logical that the traditional sources of energy used in this sector need to be replaced by RES—coupled with higher energy efficiency—in order to reach a significant achievement in the energy transition process [7]. Unfortunately, the variability of solar energy, referred to earlier, results in divergences between demand and supply, thusly making it difficult to rely on solar power for the

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heating of homes and other buildings [1]. What seems to be a logical approach is storing the energy from the Sun for later use to bridge the gap between supply and demand. One method of this is storing heat, i.e. thermal energy storage (TES), which has the potential to enhance the utilization of RES [1], for example, in various sustainable applications based on PV energy [8, 9]. The deployment of appropriate integrated TES systems could greatly facilitate the sustainable, environmentally friendly and economical operation of PV systems in terms of energy use in buildings [10].

In the homes of the European Union, where in most countries there is a heating season of seven months starting in October and ending around the end of April, it is heating that consumes the most energy, reaching 62.8% of the total final energy consumption. Furthermore, adding the heating of water for household use, which is mostly done by gas or biomass burning solutions or electric power [11], raises this percentage to 77.9% [12, 13]. Thus, household water heating, which is not only necessary for everyone but also requires a lot of energy [11], takes up 15.1% of the total energy consumption of homes in the EU [13–15] A very common solution for producing hot water for the household around the world is using some kind of domestic electric water heating system (DEWH) [15]. Most of these systems operate with an immersive resistive heater, which is an economical solution, however air-to-water heat pumps offer even higher economic efficiency, and thus represent an option too [16]. The other main component of these devices, the water storage tank is basically a substantial capacity for thermal energy storage, suitable for storing the heat of the water for later use. Utilizing the significant storage capacity and the popularity of this relatively simple technology worldwide, DEWH is currently one of the most common applications that network operators use for demand side management [17].

The swift uptake of PV systems in buildings is fueled by the rising demand for renewable energy and the pressing necessity of carbon emission reduction. There is also an increasing focus on enhancing PV self-consumption via energy storage systems (ESS), aiming to boost the profitability of PV installations and reduce dependence on the electric energy network. This necessity demands a thorough analysis of PV energy self-consumption across different ES configurations from researchers. This task is crucial for building energy modeling; however, it is also very complex and laborious, particularly when optimizing ESS designs to meet multiple objectives [18]. Integrating TES with PV systems could offer an optimal solution to part of the EU's current energy challenges, as modern technology enables the efficient use of PV-generated electricity for water heating. Given the current scarcity of data on the seasonal energy savings potential of such systems in the Member States of the European Union, studies like this one help to address and bridge that gap. The present paper investigates the combined use of TES and PV systems in Austria and Hungary, employing a specialized 3.5 kW inverter together with a 200-liter domestic electric water heater to assess the potential for seasonal energy savings in the two countries.

2 The aspects examined in the study

2.1 Why to investigate water-based sensible heat storage?

This study examined the potential of water-based sensible heat storage for heating spaces and water for hot water supply, detailing the key related dynamics. It is generally agreed that water is one of the most suitable media for heat storage at low temperature applications for a number of reasons. First of all, it is easily available, cheap and non-toxic with a high specific heat. Furthermore, the temperature at which a water-based system can operate ranges from 25 to 90 °C. In spite of its drawbacks, e.g. corrosivity and high vapor pressure, it is still an ideal solution in applications in space heating and domestic hot water supply. As for storing the water itself, water tanks with various capacities from a few hundred liters to thousands of cubic meters are made of a large variety of easily accessible materials (e.g. aluminum, concrete, fiberglass, steel, etc.) and are insulated with similarly common products (e.g. glass wool or mineral wool, polyurethane, etc.). For optimal thermal performance and service life, equipment must be watertight and well insulated to decrease heat loss through the walls as much as possible, and it must be ensured that the water stratification inside the tank is optimal too. There are even large-scale seasonal solutions that utilize underground aquifers with water mixed with sand and gravel, offering an economical option compared to building water tanks of similar dimensions [19, 20].

It is common practice in the countries of the European Union, and elsewhere too, to use solar collectors—a technology becoming less preferred due to its higher investment and maintenance costs—with relatively small water tanks to heat water for heating buildings and/or supply household hot water, mostly for private homes. (On the other hand, there are also seasonal or even buffer storage water tanks with large quantities of water, which are mostly installed under the ground.) Water heating in such systems often requires supplementary sources of energy too, such as biomass, electric power or gas, while heat pumps are frequently a technology of choice to help with heating and cooling [21]. The optimal storage tank size is a crucial question for every system [22], and it is further complicated by the issue of stratification, which occurs in every water storage tank to a certain extent, depending on a number of variables, such as volume, circulation conditions, geometry and water flow rates. Other factors determining optimal size are related to economy, the purpose and operation of the energy system, location and weather conditions, etc. The economic efficiency of the system depends on the following main factors: the investment and maintenance costs, and the own energy consumption of the solar collector [20]. It is in this context, i.e. the economic considerations, that it should be pointed out that the recent technologies this study is meant to investigate are promising to become an alternative to solar collectors due to their drawbacks mentioned at the beginning of this paragraph [23, 24]. In these new solutions water is heated by electric power directly from PV systems in order to help with space heating and/or providing homes with hot water.

2.2 Heating water by PV systems and the aspects of modelling used in the present study

For the purposes of the study herein, a specific technology, a new and effective solution by AZO Digital Sp. z o.o. was used. Taking it as an example, the potential of deploying a PV system coupled with a domestic electric water heating system of a certain capacity was examined. The inverter introduced herein makes it possible to store great volumes of PV-generated power in heat form in the presently most economical way, which has the benefit of decreasing fossil fuel use. The set of equations developed for the purpose of examining a household electric water heating system of a given capacity powered by a PV system made it possible to establish the daily average capacity for saving energy. This method, however, did not consider the different hot water consuming habits in the examined countries. The principal objective of the calculations was to reveal the average daily water temperature increase (ΔT) attainable in the particular months.

AZO Digital's inverters are available with a rated power of 3.5 kW or 4.5 kW. Of the two, the current study concentrates on the 3.5 kW inverter, whose technical specifications and economic characteristics are presented in Table 1. The primary purpose of this product is to power various heating devices (including boilers and heaters) connected to PV systems. Compared to conventional off-grid PV systems equipped with batteries, this is a much more economical energy storage solution [25, 26]. It needs to be noted here that this configuration, i.e. deploying this type of inverter with a PV system, is only suitable to power heating devices, so the PV power generated cannot be utilized for any other purpose. A system like this is comprised of PV modules (typically 4–9, connected in series) with a total open circuit voltage (Voc) between 120 and 350 V, and a total power with less than 5 kW, and a 200–3500 W boiler/heater. The casing of the inverter features two main outputs, so two heating devices can be linked to it. Their power supply is managed in a way that the second heater only starts operating when the thermostat of heater number one switches off the device, which ensures the optimal utilization of the electricity generated by the PV modules. The inverter comes with a maximum power point tracking (MPPT) algorithm to optimize the use of the electric energy available from the PV system. AZO Digital claims that for the best results under European conditions, the use of 4–7 PV modules with heaters/boilers of volumes of 50–200 l are advisable [24]. For the purposes of this study, a 200-liter storage capacity was selected. As for the compatible boilers/heating devices, the inverter works with traditional non-electronic heating equipment (i.e. simple electric boilers), because the modified sine wave of the inverter might disturb the electronic control. This inverter technology allows conventional electric boilers to operate at lower power levels too, eliminating

Table 1 The technical specifications and economic characteristics of the 3.5 kW inverter according to [24]

Open circuit voltage range (min. – max.) for PV modules connected in series (V_{DC})	120–350
Waveform (output type)	modified sine wave (quasi-sine)
MPPT	included
Connection of PV array	serial and serial-parallel
Maximum power (kW)	3.5
Gross price, 2nd quarter 2024 (€)	400
Efficiency (%)	96
Output VAC, 1	priority
Output VAC, 2	dependent
Energy meter, power meter, thermal protection, high and low voltage protection, overcurrent protection	included
Type of cooling	active intelligent fan
Housing	aluminum
Dimensions (mm)	320 × 272 × 96
Weight (kg)	4.1

the need to continuously maintain the factory-defined heating power. So, the water heating device selected to be used in this study was the Hajdu Z200S ErP [27], a very common and easily available appliance in the European Union [25] with the following technical specifications:

- Capacity (l): 200
- Nominal working pressure (Mpa): 0.6
- Heating power (kW): 2.4
- Heating time, ΔT 50 °C (h): 5.3
- Average energy needed for raising temperature by 1 °C (kWh): 0.25
- Energy consumption in standby mode (kWh/24h): 1.45 [27]

200-liter residential electric water heating systems usually come with a 2400 W heating power, therefore the rated power of the PV system considered for the purposes of this research was scaled to this value. If the PV system generated more electricity than 2400 W, the surplus energy could not be utilized by the water heating system, and it would be lost. On the other hand, it is also important to maximize the electric energy production potential of the photovoltaic system. Under optimal summer conditions, PV systems generally perform at 75–80% of their rated output in Europe [28–30]. Considering the above, the PV system in the calculations had a rated power of 3200 W to allow the electric water heating system to reach its 2400 W maximum heating capacity during the periods with the highest irradiation and to utilize as much of its annual energy production potential as possible. This means that the PV system power does not exceed the maximum heating power of the electric water heating system of 2400 W, even during the summer period, thus the PV energy produced is fully utilized and there is no energy loss.

Since the power supply from the PV system depends on exposure to the Sun, the heating time needed for the water heating device to heat a given amount of water to a certain temperature may be longer than what is given in the manufacturer's technical specifications. During the periods with less than the 2400-W power output by the PV system, the envisaged boiler operates at lower power levels. It is a common practice among manufacturers of domestic electric water heating systems that they calculate with the same energy need for raising the water temperature in a water heater of a given capacity by 1 °C, at ΔT 35 °C, ΔT at 45 °C and ΔT at 50 °C. This method was also adopted for the purposes of this study [27, 31]. As for energy loss, the energy loss on standby in a 24-hour period given in the manufacturer's specifications was taken as a basis, then it was calculated for the period of electricity supply by the PV system.

As of the second quarter of 2024, a variety of PV modules with power capacities ranging from 365 W to 600 W and open circuit voltages (Voc) generally between 37 V and 50 V are readily available in the countries of the European Union [32–34]. For the simulations in the research, it was important to use a PV module that is easy to connect in series and able to reach a rated power of 3200 W. So, a half-cell, monocrystalline, monofacial PV module with a rated power of 400 W and an open circuit voltage (Voc) of 37.07 V [33] the 8 JA Solar JAM54S30 400/MR was chosen [35]. Thus, the inverter manufacturer's recommendations to keep the total power of the modules below 5 kW were also observed.

2.3 Country-specific data on solar radiation, electric power generation and photovoltaic module orientation regarding Austria and Hungary – aspects of the calculations

To establish the yearly electricity output of the photovoltaic system in question, understanding the local climate, such as temperature, solar radiation, and other weather conditions, is crucial. This study focused exclusively on the two capital cities, Vienna and Budapest, due to their economic significance, population size, and overall importance. The Global Solar Atlas (GSA) provided the necessary data [36], based on a comprehensive 22-year series (1999–2021) of actual weather records [37]. The research findings were derived from this data. Additionally, the GSA database also contains recommended values for slope and azimuth for the installation of PV systems based on the radiation characteristics in the selected locations, which formed the basis of the research (Table 2).

The data regarding the average number of hours per day suitable for heating water with electricity from PV power generation across different months were sourced from the GSA for the two cities [36, 38]. This data allowed the determination of PV operating hours. Furthermore, utilizing the information, a database was created for the average daily PV power generation for each month, for the studied PV capacities and locations. This was aimed at estimating the average energy savings potential per day of a 200-liter domestic electric water heating system for each month. The potential energy savings were measured by the rise in the temperature of the water (ΔT) observed in the research.

Table 2 The average solar radiation, electric energy generation and PV module orientation data of the Austrian and the Hungarian capital, based on [39]

Country (city)	Austria (Vienna)	Hungary (Budapest)
Average annual global horizontal irradiation (kWh/m^2)	1207	1272
Average annual global tilted irradiation at optimum angle (kWh/m^2)	1417	1502
Average annual specific PV system output at optimal orientation and tilt angle with system loss (kWh/kWp)	1186	1252
3.2 kWp PV system yearly energy output at optimal orientation and tilt angle with system loss, average ($E_{ave. PV}$) (kWh)	3795	4006
Optimal tilt angle of PV module (slope) (°)	36	36
Optimal orientation (azimuth) (°)	180	180

2.4 The summary of the parameters used for the calculations

Here below, in Table 3, the summary of the aspects of the modelling can be seen.

The results of the GSA simulations provided the basis for the determination of the average number of hours of the operation of the PV system per day capable of supplying power for water heating equipment for each month ($PV_{ave. operating hours}$) and the average daily electric power production of a 3.2 kWp PV for each month ($E_{ave. PV}$). These results formed the foundation for subsequent energy calculations. Consequently, it became possible to determine crucial energy metrics that could not be calculated solely through modeling programs but were indispensable for the research. The quantity of energy lost daily in the electric water heating system during the time it is powered by the PV system ($E_{ave. loss, heating period by PV}$) was established using the following calculation [39]:

$$E_{\text{ave. loss, heating period by PV}} = E_{\text{ave. loss}} \times PV_{\text{ave. operating hours}} \quad (1)$$

It is essential to be aware of the values of $E_{ave. PV}$ and $E_{ave. loss, heating period by PV}$, since this information enables the calculation of the remaining energy stored by the water heating system at the end of the PV-powered heating period, after accounting for heat losses, on average ($E_{rem.}$):

$$E_{\text{ave. rem.}} = E_{\text{ave. PV}} - E_{\text{ave. loss, heating period by PV}} \quad (2)$$

As the $E_{rem.}$ data are logically derivable from the $E_{ave. PV}$ and the $E_{ave. loss, heating period by PV}$ figures, they are not specifically presented in the Results and Discussion part.

Table 3 The most important parameters used in the research, based on [39]

Aspect considered in the investigation	Value
Maximum of the output power of the inverter: (kW)	3.5
Maximum heating power of the water heating system: (kW)	2.4
Heating time at maximum heating power, ΔT 50 °C of the water heating system: (h)	5.3
Average energy need for raising temperature by 1 °C by the 200-liter water heating system: ($E_{ave. energy demand for water heating}$) (kWh/°C)	0.25
Standby energy consumption of the water heating system according to manufacturer's specifications: (Wh/24h)	1450
Average energy loss over a one-hour period of the water heating system based on standby energy consumption: ($E_{ave. loss}$) (Wh)	60.4
Rated maximum power, STC of the PV module: (Pmax) (W)	400
Analyzed PV system power (STC)	3200
Feeding into the grid by the PV system?	No
Is the PV system only used for heating water?	Yes
Data on average daily radiation, PV system operation, power generation, PV-based operating hours of water heating systems; orientation	Authors' own results based on aggregation of GSA simulation results
Examined locations	Capitals of Austria and Hungary
Considering specific hot water usage patterns?	No
Assessing the potential average daily rise in water temperature (ΔT) resulting from PV system use, on a monthly basis throughout the year?	Yes

The potential rate of the average daily rise of the temperature of the water (ΔT) during the period of heating with PV-generated electric energy is calculated using the formula below:

$$\Delta T = \frac{E_{\text{ave. rem.}}}{E_{\text{ave. energy demand for water heating}}} \quad (3)$$

3 Result and discussion

3.1 PV system operating hours per day in the examined locations

The average number of hours of heating time by the water heating system powered by the PV system was determined in a monthly resolution for the capitals of Austria and Hungary (Fig. 1). It can be observed that there is no

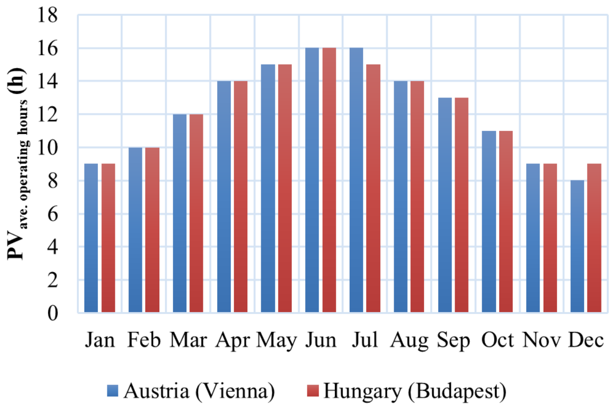

Fig. 1 Average PV system operating hours per day that can supply power for water heating devices over one year

significant difference in the seasonal time of operation of PV systems in the capital cities studied. According to the results in Fig. 1, the operating time of the water heating device with the PV power supply is determined by geographical and climatic factors. In the coldest months, such as December, the operating time is typically 8–9 hours, while the number of hours of water heating in the summer months is significantly longer, by up to 6–8 hours, than in the winter months. As a result, the number of operating hours, e.g. in June, ranges between 14–16 hours.

3.2 Average electric energy generation per day, thermal energy loss and the average daily energy saving potential during the hours of PV energy production suitable for supplying power to water heating equipment, in each month

Specific knowledge of the average electric energy generation per day by the PV system in each month is necessary to plan the amount of energy saving potential of PV and the application of a household electric water heating system. The photovoltaic system analyzed in the study was of a capacity of 3200 W. Fig. 2 shows the average daily electricity generation for each month for a PV system of the given capacity in the two capitals under investigation. Determining this is significant because this amount of energy is stored in heat form. Fig. 2 shows that there exist differences between the two locations in terms of the electric power that can be produced by PV systems determined by geographical location, irradiation and other climatic factors. Overall, photovoltaic systems generate less energy during winter compared to summer. Furthermore, the differences between months do not vary significantly between the countries examined. The average daily electricity production is expected to be between 4.2 kWh and 4.4 kWh

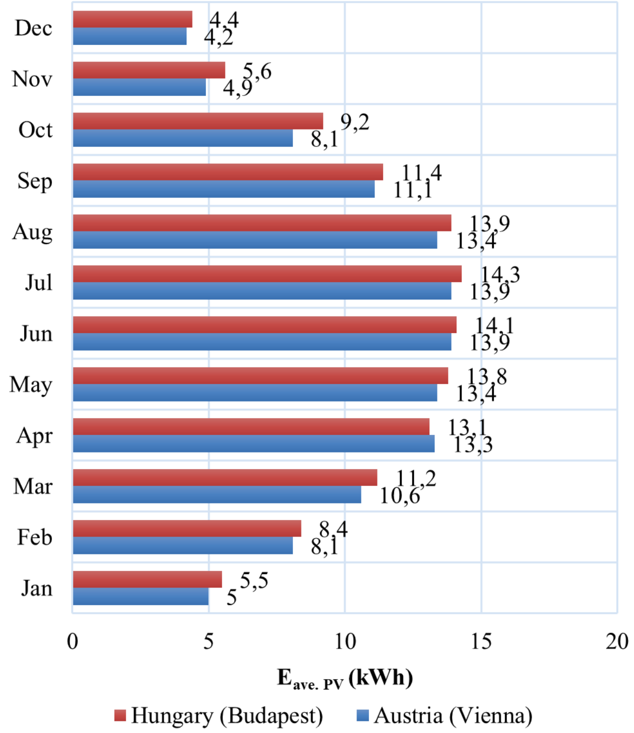

Fig. 2 Average daily electric energy production by a 3.2 kWp PV system over one year

in December for the PV capacity investigated herein. However, during the summer period, these characteristics range from 13.9 kWh to 14.3 kWh in July, for example.

The energy output of photovoltaic modules changes over the course of the day, following a daily power curve. Consequently, when using a photovoltaic system to supply electricity, the heating time given by the manufacturer for the water heating equipment will increase, so during the heating period with the PV system, the proportional amount of thermal energy loss during the factory-specified standby energy consumption has been considered. The estimated amount of energy lost in the electric water heating system was between 0.5 kWh and 1 kWh in the course of a year in the capital cities examined during the heating period with the PV system (Fig. 3). Between March and September, heat loss usually ranges from 0.7 kWh to 1 kWh, whereas in the winter months, it falls between 0.5 kWh and 0.6 kWh. (Fig. 3).

The reason why it is necessary to assess the loss of heat in the domestic electric water heating system is to determine the rate of increase in average water temperature (ΔT) over the PV-powered heating period on a monthly basis for the whole year. The results in Fig. 4 indicate that local climatic characteristics, including solar irradiation, substantially influence the rate of average daily water temperature rise (ΔT) over the heating period. Generally

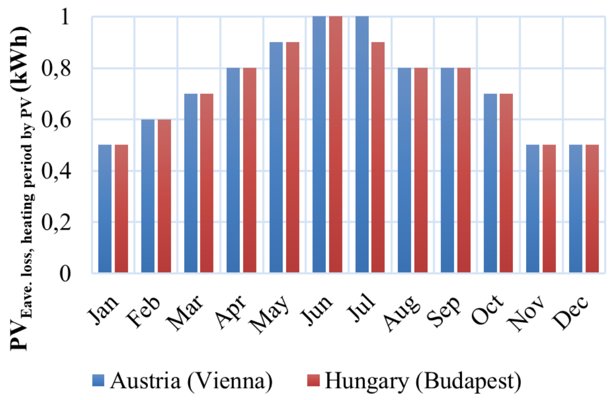

Fig. 3 Daily loss of energy in the electric water heating system during the period when water is heated by photovoltaic power

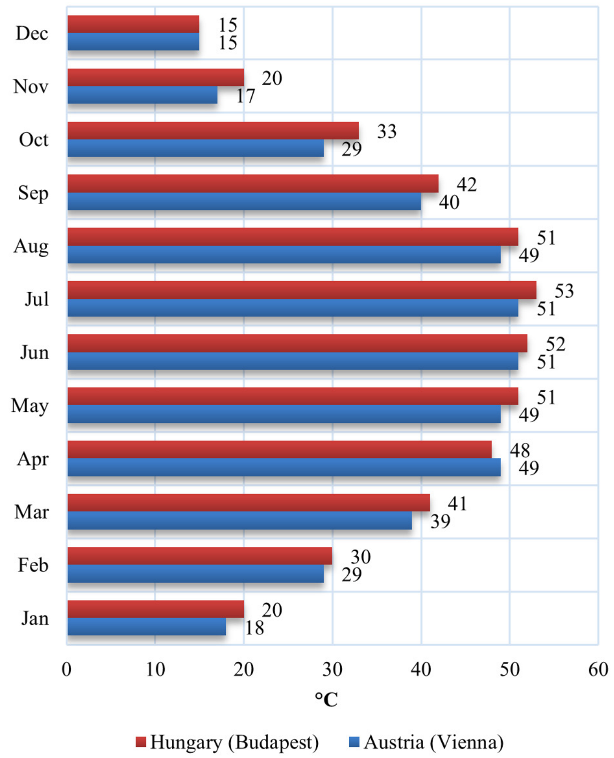

Fig. 4 Average water temperature rise per day (ΔT) during the period of PV-powered water heating

speaking, in terms of the capitals studied, the values of ΔT show considerable differences over the year, varying between 15 °C and 53 °C. From March to September, this value was above 38 °C. In the summer season, this value varied between 49 °C and 51 °C (Fig. 4). It is important to mention that the highest water temperature for electric water heating systems typically falls within the range of 65 to 95 °C [27]. Thus, a storage tank with the suitable technical features must always be selected to enhance the efficiency and economy of the thermal energy storage. The extent of ΔT in winter declines considerably compared to summer. In terms of the system examined herein, December is the most unfavorable month.

4 Conclusion

The research aimed to explore a potential method for integrating TES and PV systems in two EU countries by using a specialized inverter and a high-capacity household electric water heating system. The study assessed the potential for seasonal energy-saving by deploying a water-based sensible heat storage method, a practical approach for connecting TES and PV systems, in the capital cities of Austria (Vienna) and Hungary (Budapest).

In designing hybrid and off-grid PV systems, it is beneficial to take into account the energy storage method discussed herein. It is essential to determine the intended use of the PV-generated electric energy that would be stored in the batteries. If a portion of this energy is to be used for water heating, it might be advantageous to allocate part of the PV capacity specifically for heating water. This approach is substantiated by two main reasons: it could reduce the necessary battery capacity, thereby lowering investment costs, and storing energy in an electric water heating system is generally more efficient and economical. Additionally, batteries linked to PV systems endure frequent charge-discharge cycles, which leads to ongoing technical deterioration.

The aspects of costs and efficiency need to be highlighted. Compared to battery storage, using a domestic electric water heater linked to a PV system for power supply has the drawback that the energy is only stored as thermal energy. However, in terms of water temperature increase (ΔT), even values as high as ΔT 53 are attainable with the system studied while powered by PV. During the summer months, a 200-liter domestic electric water heating system is capable of storing an average of more than 14 kWh thermal energy daily. As for the costs in the above-mentioned period, a 200-liter water heating system costs investors only approximately EUR 1000.

All things considered, when planning domestic off-grid or hybrid PV system projects, it is advisable to take into account the option of producing hot water and/or assisting heating in the household by deploying the technology explored herein, from an economic point of view. By doing so, and thus optimizing the nominal energy capacity, the investment costs related to the battery system can be decreased. It is also an important aspect to highlight that, while the total system efficiency (also taking system loss, inverter, and battery into account) normally ranges between 72% and 86% in hybrid and off-grid PV systems, water heated to 65 °C in the investigated electric water heating system retains 89% of its stored thermal energy even after 24 hours.

Future research objectives include conducting more complex analyses of alternative ways to link TES and PV systems, such as considering patterns in residential hot water usage or combining TES and PV systems with heat pumps to assist residential space heating.

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