Assessment of Different Energy Management Strategies for the Operation of Hybrid Hot-Water Installations in Hotels

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Abstract—With the adoption of the Energy market in Bulgaria, large fluctuations in the price of electrical energy have been occurring, which is a challenge for businesses in the different sectors of the economy. This study is aimed at evaluating the energy and financial performance of three energy management strategies for operating hybrid hot water installations in hotels: the first one is one assumes the water is heated only by an evacuated solar tube system; the second one assumes electrical energy is used whenever the water's temperature falls below a certain threshold; and the third one uses preliminary pre-heating of the water during the off-peak hours when electrical energy is cheaper. A simulation model has been developed based on well-known physical and empirical dependencies, allowing for the necessary evaluations. A hot water installation operation has been investigated for a hotel with a capacity of 80 guests on a sunny summer day. The results showed that the first strategy does not allow for maintaining the temperature of the water in the tank above the required threshold. The second strategy ensured the requirements towards the water temperature are met with minimal application of electrical energy, leading to daily expenses between 3.4 EUR and 62 EUR. The third strategy increased the grid energy usage, but the daily expenses were limited to 18.5 EUR. The obtained results indicate that hotel owners could significantly reduce their hot water expenses with the help of a hybrid hot-water installation and an appropriate energy management strategy.

Keywords—Energy management; energy market; evacuated tube collectors; hot water consumption; strategies

I. INTRODUCTION

With the development of modern technologies, many new problem-solving opportunities were created based on energy storage and renewable energy sources. One of these solutions is the application of solar energy for heating water. The application of hot water in the domestic and utility sectors is one of the major reasons for the peaks in the energy consumption in the morning and evening hours of the day [1]. According to [2], solar water heating systems could play a key role in ensuring the heating and hot water needs in the domestic sector and have a major impact on the energy efficiency and sustainable development. Hybrid installations are widely used for heating water for domestic purposes and for supporting the energy resource for producing hot water in hotels, guesthouses, and industrial facilities [3, 4]. They are based on the simultaneous application of a wide range of renewable and conventional energy sources, such as thermal collectors, photovoltaic panels, photovoltaic thermal collectors (PVT), grid energy, etc. [5,6], as well as appropriate control systems [7]. Furthermore, according to [8], the application of solar thermal collectors in hot water production systems ensures relatively low operational and maintenance expenses.

Numerous studies offered different hybrid solutions for ensuring electrical and/or thermal needs. In [9], a thermal performance analysis was conducted of 28 PVT solar domestic hot water installations in Western Europe. It was concluded that they provide twice as much energy as PV-only modules. In another study [10], the technical and economic aspects of PVT systems were investigated when used to ensure the electrical energy and hot water needs of a house with four inhabitants in Belfast, UK. The obtained results showed that a 16.3 m2 system could cover 30% of the electrical energy and 80% of the hot water demand of the household.

In [11], an investigation of the energetic and ecological performance of a PVT hybrid system for hot water was performed. The system achieved 9.77% conversion efficiency for the weather conditions in Algeria and 3.61 W improvement in the produced energy compared to a PV module. Other authors [12] evaluated the potential of a hybrid hot water system of a Spanish household with an integrated Organic Rankine Cycle (ORC) for electricity production. A positive internal rate of return (IRR) of 8.61% was reported if the ORC is operated 15% of the year. In [13], a technical and economic assessment of a hybrid PV system was performed, with the excess energy being used to drive a hot and cold-water storage system. The results of the study showed a very short payback time of 2.87 years.

In [14], the optimal scenarios for ensuring the electrical energy consumption, cooling, and hot water of a building in Tehran (Iran) with the use of a hybrid energy system were assessed, based on water and solar energy. The calculations were made using MATLAB, TRNSYS, and Carrier HAP software. In [15] and [16], a TRNSYS18-based numerical model of an intermittent solar hot water production system was developed, which supplies a veal calf farm with hot water two times a day. It consists of 16 evacuated tube solar water heaters connected with an unpressurized tank. The obtained results indicate that the installation contributed with 60% to the energy demand.

In [17], a hybrid system was investigated consisting of thermal solar collectors, gas tube heaters' exhaust, and a gas

boiler. The performed energy analysis showed that the system was able to cover 80% of the energy requirements. In another study [18], an energy, exergy, ecological, technical, and economic analysis of a hybrid energy system for the production of 60° hot water was performed. It relies on energy from biomass pellets and three types of solar thermal systems (evacuated tube, flat plate, and parabolic trough collectors). The performed TRNSYS simulation showed that the price of thermal energy could get as low as 0.0642 $/kWh with a payback period for the installation of 4.9 years. A TRNSYS-based model was also used in [19] to size the water tank of a hybrid solar-biomass system.

Other studies have used renewable and conventional resources for producing hot water. In [20], a techno-economic and environmental analysis was performed of a hybrid hot water system for heating buildings in a subtropical climate. It consists of a flat plate and evacuated tube collectors, coupled with panel heaters. The obtained results showed that the life cycle cost of such a system is 62% less than that of an equivalent capacity electric heater. Furthermore, the study reported that evacuated tube collectors are 72% more energy efficient compared to flat plate collectors. In another study [21], a theoretical and experimental investigation of a hybrid residential hot-water system with solar and gas was conducted. The analysis showed that the hybrid approach has better economic efficiency compared to a gas-only water heater.

In [22], the impact of different hot-water profiles on the techno-economic aspects of a hybrid solar hot-water heating system was studied. The obtained results showed that it is very important to properly size the hot water tank to ensure both technical and economic performance. The study concluded that with the liberation of the energy price, it is economically viable to produce 80-90% of the daily hot water (DHW) by solar systems. On the other hand, the results of a study about the Australian solar hot water system users [23] showed that they still struggle to integrate them and are generally dissatisfied.

The authors of [24] and [25] support the opinion that even though renewable energy sources have their advantages, their periodicity and uncertainty increase the interest towards hybrid energy systems, capable of significantly reducing the energy shortages. However, a major problem with hybrid hot water systems is deciding when to use conventional energy to provide the additional energy required for heating water. The optimization of this process allows minimizing the financial and heat losses to the environment; however, such optimization requires accounting for the hourly hot water consumption, as well as the hourly changes in the price of energy on the energy market.

Other studies have investigated different hot water management strategies, specifically in hotels. In [26], the temperature profiles of the heated water with and without auxiliary heating were evaluated. The study also investigated the usage of backup heaters for stabilizing the hot water temperature; however, the source of energy used was not electrical energy but LPG. In another study [27], a fuzzy-based approach for energy management of DHW systems in hotels was proposed.

It is applicable for electrical energy-heated water and shows a good response to hot water instant demand. However, none of the above studies considers the influence of the liberated energy market, i.e., the presented results do not allow for optimizing the combined energy-financial process with respect to the price fluctuations of electrical energy.

The performed analysis shows that even though numerous studies have shown the viability of solar hot-water systems, numerous problems still exist. Users struggle to optimize their systems, and with the integration of renewable and conventional energies, appropriate strategies are required for optimizing the process in both energetic and economic aspects. On the other hand, with the adoption of the Energy market in Bulgaria and many EU countries, the price has been varying significantly during the different hours of the day, which additionally complicates the decision-making process for consumers. The performed analysis also shows that the energy management of hot water installations under such conditions (liberated energy market) remains poorly investigated. Furthermore, to the best of our knowledge, no such studies exist that are specifically focused on hotels, which is an obvious research gap.

This study aims to evaluate the performance of different energy management strategies for operating hybrid hot water installations in a hotel under the liberated energy market conditions. The obtained results should provide a better understanding of the pros and cons of different strategies and allow the identification of clear directions for optimizing hotels' expenditures.

The remaining sections of the study are structured as follows: Section II presents the object of the study, the methodology and algorithm for its analysis, as well as the strategies considered; Section III presents the main simulation results, demonstrating the energy and financial performance of the different strategies; Finally, in Section IV, conclusions are made about the obtained results.

II. Materials and Methods

A. Object of the Study

The object of the investigation is a hybrid hot water installation, which uses solar and electrical energy to ensure the hot water requirements of a hotel (see Fig. 1). The system includes evacuated tube collectors, a water tank, a heat exchanger, an electric heater, and pipes. The water in the primary loop is circulated between the evacuated tube collector and the heat exchanger with a water pump. Normally, the pump is not operating continuously but only when the temperature of the fluid at the solar collectors is high enough.

If the available solar power is not enough to reach the necessary water temperature in the tank, additional energy is provided by an electric heater. Finally, if the water tank temperature is higher than required, it is mixed with cold water via a mixing valve to meet the temperature requirements. The electric heater could be replaced with another source of conventional energy, but in this study, we assume electrical energy only.
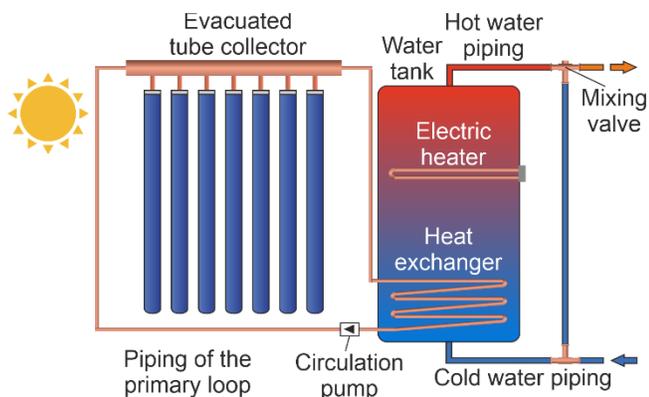
Fig. 1. A general scheme of a hybrid hot water installation with evacuated tube collectors and electrical energy.

B. Background of the Hot Water Consumption and the Energy Price

The application of conventional energy for additional heating of the water in a hybrid installation leads to financial expenses that depend on the price of electrical energy and the thermal losses to the environment. On the other hand, with the adoption of the Energy market in Bulgaria, the electrical energy price is changing on an hourly basis and since the autumn of 2025 on a 15-minute basis. Following this, the industrial consumers need to plan their energy consumption and could buy energy one day ahead. Therefore, in order to optimize the financial losses for additional water heating, it is necessary to account for the forecasted hot water consumption and the energy price for the next day. Based on these factors, an appropriate strategy for hot water pre-heating could be implemented, allowing the necessary water temperature to be maintained while minimizing financial expenses.

In this study, we are using the hotel hot water consumption profile presented in [28], where it is assumed that the DHW is approximately 80-100 liters per guest (Fig. 2). It is characterized by two peaks of the consumption: one in the morning hours around 8:00 reaching up to 7 l/h and a second one in the evening hours around 19:00, reaching almost 10 l/h. During the night, when the guests are sleeping, the hot water consumption is near zero, and in the noon and afternoon hours, it is 2-4 l/h.
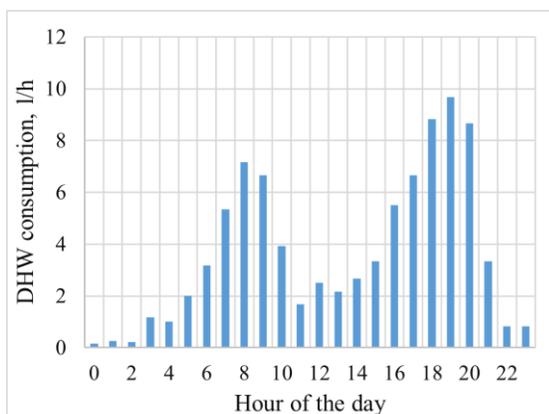

Fig. 2. Average DHW consumption of the hotel in l/h per guest according to [28].

Similar is the pattern of the electrical energy price in Bulgaria. For example, Fig. 3 shows the average hourly price of electricity in May 2024 [29]. It is also commonly characterized by one peak in the morning hours, when people wake up and prepare for work, and a second peak in the evening around 21:00, when people have dinner and spend their time at home. In May, the lowest energy price occurs around 13:00-14:00, which can be explained by the energy produced from photovoltaic installations. It should be noted that this is an average curve, though on some of the days, the noon energy could reach zero or even a negative number. During the night, the average May price falls to approximately 80 EUR/MWh. While the general curve is maintained during all months of the year, there are some differences in the prices, which could be quite significant. For example, in July and August, the evening energy price peak could reach up to 500 EUR/MWh, which is caused by the high environmental temperatures and the mass application of air conditioners.
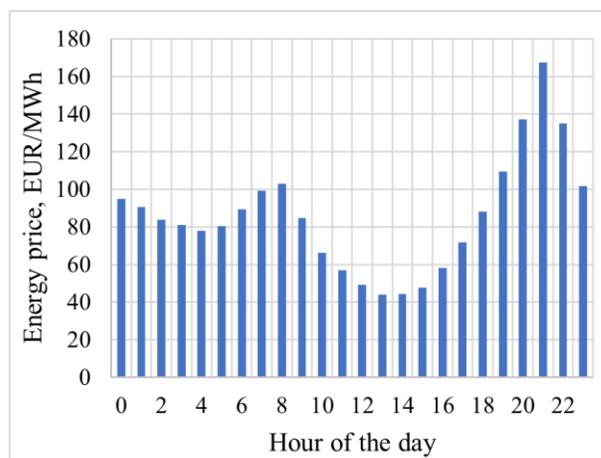

Fig. 3. Average hourly price of the electrical energy in EUR/MWh for May 2024 in Bulgaria.

C. Energy Management Strategies for Operation of Hybrid Hot Water Systems in Hotels

Considering the object of the investigation, it is assumed that there is a basic energy input coming from the evacuated tube collectors that depends on the meteorological conditions and time of day. Thereafter, additional energy could be provided by the electric heater, depending on the adopted strategy. In this study, we are investigating the performance of a hotel's hybrid hot water system with the following strategies:

- Strategy 1 – the water is heated only with solar energy. This is a basic strategy that is feasible when the hot water consumption profile is similar to that of solar energy, or when the evacuated tube collectors and the water tank are oversized.

- Strategy 2 – additional energy is supplied by an electric heater when the water tank temperature falls under a certain threshold. This strategy could be used to ensure electrical energy is only used when necessary and to minimize its consumption. In the current study, it is assumed that the heater turns on and off when the water temperature gets below or

above the threshold, though in practical situations, a hysteresis cycle could be adopted.

- Strategy 3 – preliminary heating of the water is applied before the morning and evening peaks in the price of electrical energy. This strategy is aimed at optimizing financial expenditures, though it could lead to increased energy consumption due to increased energy losses.

D. Algorithm for Modeling the Energy and Financial Flows in the Installation

To assess the performance of the defined strategies, a model for the simulation of the energy and financial flows in a hotel's hot water installation is developed. It is based on the Finite difference method, and its algorithm is summarized in Fig. 4. In block 1, the initial conditions for the simulation are set, such as:

- The parameters of the installation (volume and diameter of the water tank; length of pipes in the first and second contour; number of vacuum collectors; geographic location; azimuth and tilt angles; power of the electric heaters; temperature of the cold water; required temperature of the hot water; etc.);

- Number of guests in the hotel during the next 24 hours;

- Forecasted energy prices for the next 24 hours.

Next, in block 2, the initial values of the model variables are set, such as the time of day, the sun's angle, the initial water temperature, etc. In block 3, the energy management strategy to be used in the simulation is chosen.
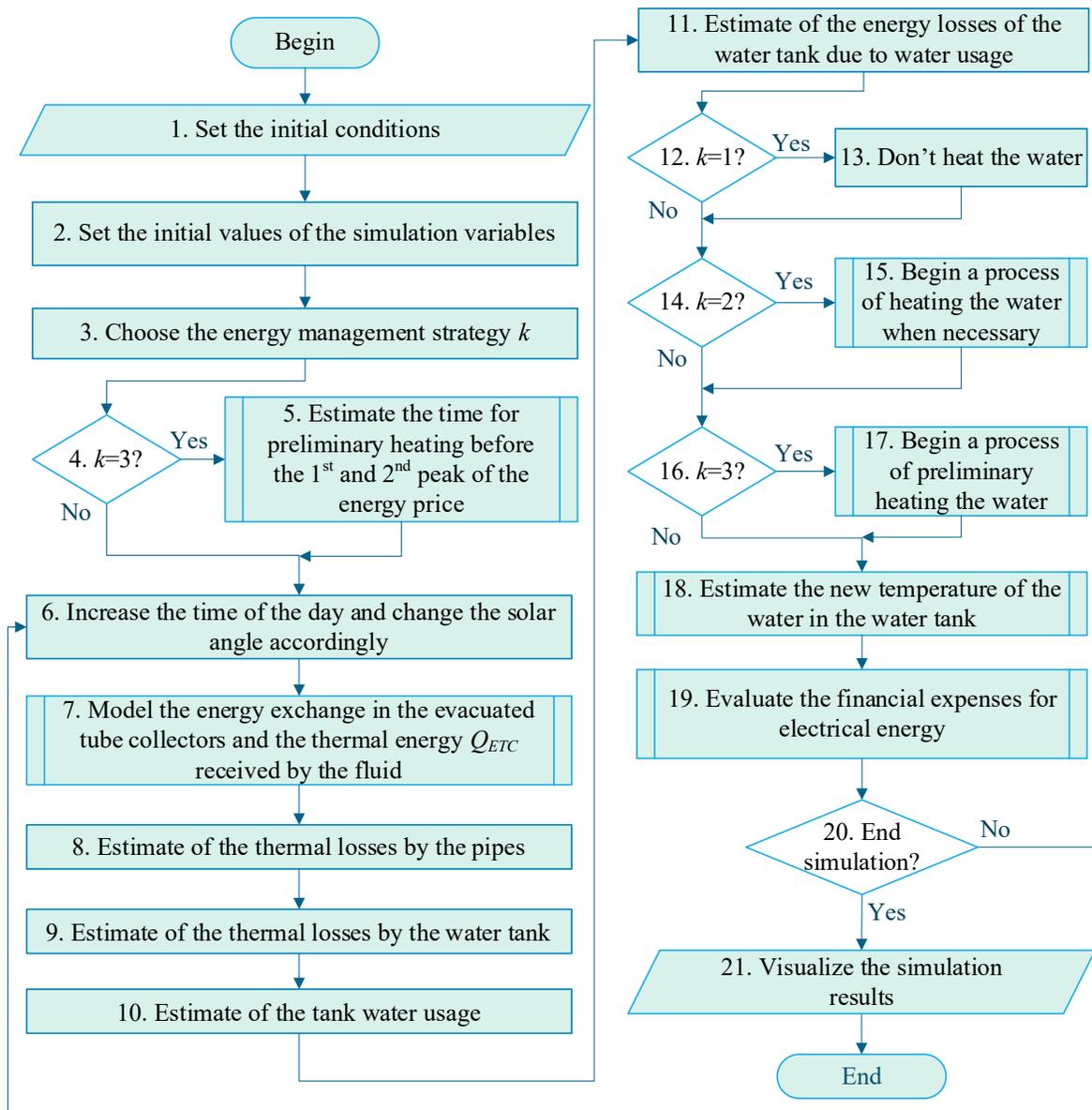

Fig. 4. Algorithm for modelling the energy and financial flows in a hybrid hot water installation with evacuated tube collectors.

In block 4 is verified whether strategy 3 was chosen, and in such a case, the duration and optimal starting time of the preliminary heating are evaluated using the day-ahead forecasted hourly prices of the energy (block 5). The energy required for preliminary heating of the water in the water tank is estimated according to Eq. (1) and Eq. (2). First, the volume of water consumption $Q_{W.CONS}$ that will be used starting from the current hour of the day t_1 until the end of the peak energy price t_2 is obtained with:

$$Q_{W.CONS} = \sum_{t=t_1}^{t_2} G[t].t \, , m^3 \qquad (1)$$

where, $G[t]$ is the expected water consumption during the tth hour of the day, $m^3.h^{-1}$.

Thereafter, the required electrical energy for additional heating of the water in the tank is estimated according to [30]:

$$E_{ADD.HEAT} = Q_{W.CONS}.\rho_W.C_W.(T_{W.REQ} - T_{W.COLD}), J, \qquad (2)$$

where, ρ_W is the density of water in $kg.m^{-3}$, C_W is the specific heat capacity of water in $J.kg^{-1}.K^{-1}$, $T_{W.REQ}$ is the required temperature of the hot water in $°C$, and $T_{W.COLD}$ is the temperature of the cold water in $°C$.

The time $\Delta t_{ADD.HEAT}$ required for the heater to operate is estimated with Eq. (3):

$$\Delta t_{ADD.HEAT} = \frac{E_{ADD.HEAT}}{P_{EH}}, s, \qquad (3)$$

where, P_{EH} is the power of the heater in W. Depending on the duration, the optimal start time for heating is determined based on the forecasted energy price.

The increase in the temperature of the water in the tank can be approximated using a calorimetric equation, as in Eq. (4) [30]:

$$T_{W.TANK}(t + \Delta t) = T_{W.TANK}(t) + \frac{P_{EH}}{V_{W.TANK} \times \rho_W \times C_W} \Delta t, °C \qquad (4)$$

where, $V_{W.TANK}$ is the volume of the water tank in m^3.

In block 6, the current moment of time is increased, and the Sun angle is changed accordingly. Thereafter, in block 7, the energy acquired by the evacuated tube collectors Q_{ETC} is obtained according to a model presented in [31]. In block 8, the thermal losses by the pipes of the system are estimated according to Eq. (5) [30]:

$$P_{PIPES.LOSS} = k_{PIPE}.l_{PIPE}.(T_{FL} - T_{ENV}), W, \qquad (5)$$

where, l_{PIPE} is the length of the pipes in m, T_{FL} is the temperature of the fluid in $°C$, T_{ENV} is the temperature of the environment in $°C$, and k_{PIPE} is the heat transfer coefficient in $W.m^{-1}.K^{-1}$. The latter can be estimated with Eq. (6) [30]:

$$k_{PIPE} = \frac{1}{\frac{1}{2.\pi\lambda_{ins}} \times ln\frac{d_{OUT}}{d_{IN}} + \frac{1}{\alpha_{air}.\pi.d_{OUT}}}, W.m^{-1}.K^{-1}, \qquad (6)$$

where, d_{IN} and d_{OUT} are respectively the internal and external diameters of the pipe insulation in m, λ_{INS} is the coefficient of thermal conductivity in $W.m^{-1}.K^{-1}$, and α_{AIR} is the convective heat transfer coefficient between the water pipe's insulation and the surrounding environment in $W.m^{-2}.K^{-1}$.

Similarly, in block 9, the power losses from the water tank are estimated with Eq. (7):

$$P_{TANK.LOSS} = A_{W.TANK}.k_{W.TANK}.(T_{W.TANK} - T_{ENV}), W, \qquad (7)$$

where, $A_{W.TANK}$ is the area of the surface of the water tank in m^2 and $k_{W.TANK}$ is its coefficient of heat transfer in $W.m^{-2}.K^{-1}$. It can be approximated according to Eq. (8) [30]:

$$k_{W.TANK} = \frac{1}{\frac{d_{INS}}{\lambda_{INS}} + \frac{1}{\alpha_{AIR}}}, W.m^{-2}.K^{-1}, \qquad (8)$$

where, d_{INS} is the width of the insulation layer of the tank in m.

Next, in block 10, the water consumption for the current moment of time is estimated according to the expected consumption profile, and in block 11, the energy losses due to water consumption are estimated similarly to Eq. (2) [see Eq. (9)]:

$$P_{W.LOSS} = m_{TANK.CONS} \times C_W \times (T_{W.TANK} - T_{W.COLD}), W, \qquad (9)$$

where, the tank's water consumption mass debit $m_{TANK.CONS}$ is estimated using the total water output of the system $m_{W.CONS}$ and the cold-water consumption $m_{CW.CONS}$, both in $kg.s^{-1}$ [see Eq. (10)]:

$$m_{TANK.CONS} = m_{W.CONS} - m_{CW.CONS}, kg.s^{-1}, \qquad (10)$$

If the first strategy is selected (block 12), no additional heating should be used, i.e., in block 13, the electrical heating is turned off. If the second strategy is selected (block 14), a process begins in which the heater is turned on automatically whenever the tank temperature falls below the required output temperature (block 15). Otherwise, if the third strategy is selected (block 16), a process begins in which the heater is turned on for preliminary water heating before the morning and evening peaks in the price of electrical energy (block 17).

Next, in block 18, the new temperature of the water in the tank is estimated after a period of time Δt [see Eq. (11)]:

$$T_{W.TANK}(t + \Delta t) = T_{W.TANK}(t) + \frac{(Q_{ETC} + Q_{ADD} - P_{PIPES.LOSS} - P_{TANK.LOSS} - P_{W.LOSS})\Delta t}{m_W \times C_W}, °C, \qquad (11)$$

where, m_W is the mass of the water in the tank, kg. Finally, in block 19, the financial results for the current time interval are estimated using the actual data for the hourly energy prices. In block 20, it is verified whether the simulation should end. In such a case, the results of the simulation are visualized in graphical form (block 21); otherwise, the algorithm goes back to block 6.

E. Means and Parameters of the Simulation

The developed algorithm was implemented in a specialized software tool developed in Microsoft Visual Studio 2019. In the current study, we investigate the hybrid hot water installation of a hypothetical hotel with a total capacity of 80 guests. Its latitude is assumed to be 43.85°, which corresponds to the geographic location of the city of Ruse, Bulgaria. The volume of the water tank is 2 700 *l*, and the evacuated solar collectors consist of 15 modules with 12 tubes each. The daily hot water consumption profile is according to the one presented

in Fig. 2. The simulations are performed using the meteorological and energy data for 19 August 2025, some of which can be observed in Fig. 5.

The other important parameters of the simulation are summarized in Table I. It is assumed that polyurethane is used as an insulation material for both the water tank and the water pipes.
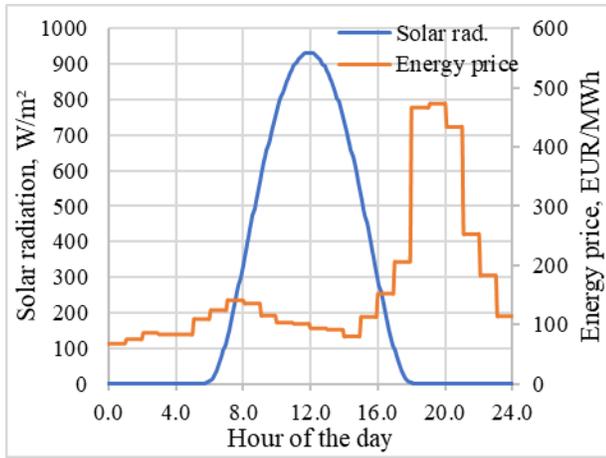

Fig. 5. Solar radiation (blue line) in Ruse (Bulgaria) and hourly energy price (orange line) in Bulgaria on 19 August 2025.

TABLE I. GENERAL PARAMETERS OF THE SIMULATION

Parameter name	Value
ETC parameters	
Azimuth	0° (South)
Tilt angle	60°
Number of the ETC modules	15
Number of tubes in one module	12
Diameter of the tube	58 mm
Length of the tube	1.8 m
Distance between the tubes	17 mm
Water installation parameters	
Volume of the water tank	2700 l
Diameter of the water tank	1 m
Length of the pipes in the first loop	10 m
The temperature of cold water	20 °C
Temperature requirements for the hot water	55 °C
Power of the water heaters	200 kW
Water tank insulation parameters	
Width	5 cm
Coefficient of thermal conductivity	0.037 W.m^{-1}.K^{-1}
Pipes insulation parameters	
Width	2 cm
Coefficient of thermal conductivity	0.037 W.m^{-1}.K^{-1}
Other parameters	
Latitude (the city of Ruse, Bulgaria)	43.85°

Temperature of the environment	25 °C
Hourly energy price	Acc. to Fig. 5
Hot water consumption profile per 1 guest	Acc. to Fig. 2
Forecasted cloudiness	0%
Step of discretization	30 s
Duration of the simulation	24 h

To assess the influence of the number of customers in the hotel on the system performance, four scenarios are investigated:

- 25% occupancy, corresponding to 20 guests;

- 50% occupancy, corresponding to 40 guests;

- 75% occupancy, corresponding to 60 guests;

- 100% occupancy, corresponding to 80 guests.

III. RESULTS AND DISCUSSION

The results for the abovementioned scenarios under the three different management strategies are presented below.

Strategy 1. No additional heating is used.

The simulation results for Strategy 1 are summarized in Fig. 6 and Fig. 7. Fig. 6 shows that with the increase in the number of guests of the hotel, the utilized energy also increases. This can be explained by the reduced water tank and pipe system losses due to the lower temperature of the water.
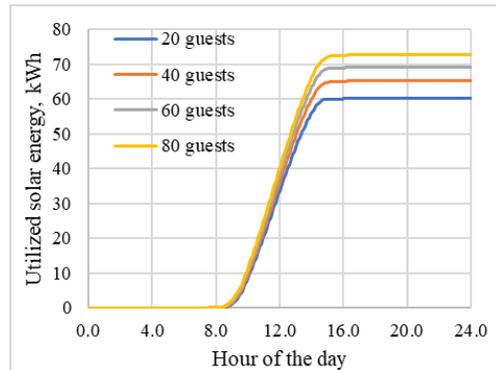

Fig. 6. Utilized solar energy in the form of heat by the evacuated tube collectors with 20, 40, 60, and 80 guests in the hotel.
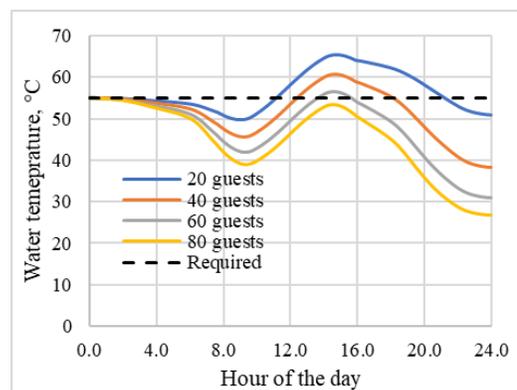

Fig. 7. Water temperature during the day with 20, 40, 60, and 80 guests in the hotel with Strategy 1.

In Fig. 7, the influence of the hotel's occupancy on the temperature of the water in the tank is visualized. It can be observed that for the parameters of the current case study, the system is not able to maintain the necessary water temperature of 55 °C during most of the day. This means that Strategy 1 is only feasible in long sunny days, but still requires a significant increase in the installed ETC power. Nevertheless, the obtained data provides some basic understanding of the energy processes taking place in the installation.

Strategy 2. Additional heating of the water is used when necessary.

The second strategy, in which additional heating is provided with electrical energy when the water temperature falls below the required threshold (in the current study, it is 55°C), is investigated next. Fig. 8 shows the integrated electrical energy used by the heaters during the day for the four scenarios. It can be observed that electrical energy is required during the morning hours from 7:00 to 9:00 and during the evening hours after 17:00. Furthermore, the amount of energy used strongly depends on the number of guests. If the hotel is 25% occupied (20 guests), the energy expenses reach up to 33 kWh, while if the hotel is 100% occupied (80 guests), the daily energy expenses could surpass 230 kWh on a sunny day. Understandably, the energy expenses will further increase on cloudy days.
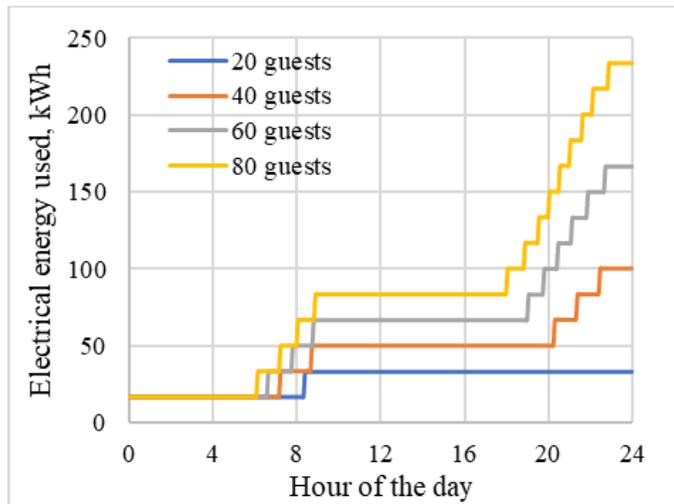
Fig. 8. Required additional electrical energy for ensuring the water temperature with Strategy 2.

In Fig. 9, the variation of the water temperature in the water tank over the simulated day is presented. It can be observed that this scenario ensures the water does not fall below the required threshold of 55 °C. The electric heaters increase the water temperature during the morning and evening hours, while the available solar radiation is enough to maintain the system's operation during the day. Naturally, when the hotel occupancy is higher, the heaters have to turn on more often. On the other hand, if the hotel has 25% occupancy, the heaters are turned on only once in the morning.
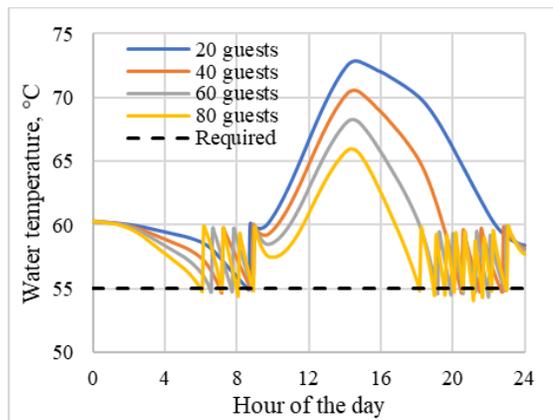
Fig. 9. Water temperature during the day with 20, 40, 60, and 80 guests in the hotel with Strategy 2.

The resulting financial expenditures are summarized in Fig. 10. It can be seen that with 20 guests, the daily financial losses are approximately 3.4 EUR, while for 40, 60, and 80 guests they could reach up to 20 EUR, 42 EUR, and 62 EUR, respectively.
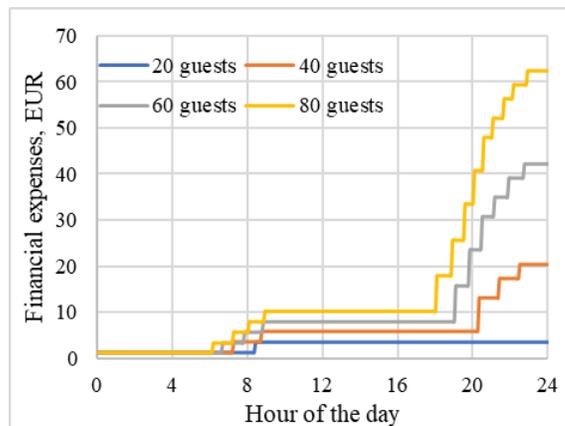
Strategy 3. Preliminary heating of the water is used.

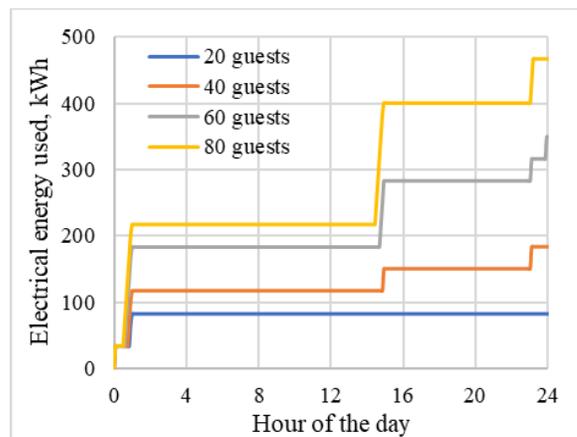Fig. 10. Financial expenditures for buying electrical energy with Strategy 2.

Fig. 11. Required additional electrical energy for ensuring the water temperature with Strategy 3.

The third strategy also assumes the application of electrical energy for additional heating; however, this process occurs during the low-peak hours of the energy price. Fig. 11 presents the electrical energy used by the system for preliminary heating of water. With 20 guests, water heating is used only once after midnight, when the energy price is the cheapest. On the other hand, with the increase in occupancy, the heaters are also used in the afternoon. It can be seen that with this scenario, the energy consumption for 20, 40, 60, and 80 guests reaches up to 80 kWh, 183 kWh, 350 kWh, and 466 kWh, respectively, which is a significant increase compared to Strategy 2.

The temperature of the water with Strategy 3 is presented in Fig. 12. It can be seen that there are two peaks, which follow the grid energy consumption – one shortly after midnight and another one around 15:00. Furthermore, it can be observed that in most cases the simulated system can cover the temperature requirements for the water. The only exception is the scenario with a fully occupied hotel, in which the temperature of the water falls to 45 °C later in the evening. In this case, further pre-heating of the water in the tank is not possible because it has reached 95 °C. In such a situation, two options exist for maintaining the temperature of the water within the necessary limits:

- To increase the volume of the water tank;

- To make a combination between Strategy 2 and 3, i.e., to provide additional heating of the water when its temperature falls below the minimum threshold.
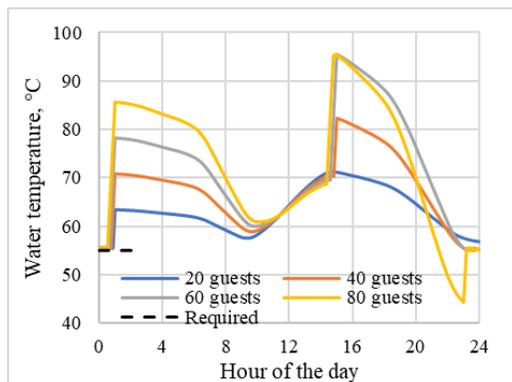

Fig. 12. Water temperature during the day with 20, 40, 60, and 80 guests in the hotel with Strategy 3.
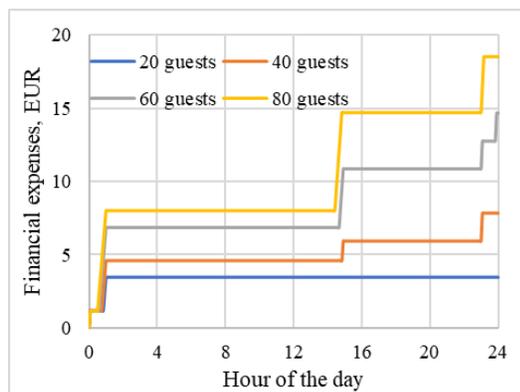

Fig. 13. Financial expenditures for buying electrical energy, used to heat the water in the tank.

Finally, the expenditures for water heating are summarized in Fig. 13. It can be seen that the daily expenditures for additionally heating the hot water with grid energy under a sunny summer day for 20, 40, 60, and 80 guests are 3.4 EUR, 7.8 EUR, 14.7 EUR, and 18.5 EUR, respectively. This shows that using Strategy 3, the hotel's daily hot water expenditures could be significantly decreased.
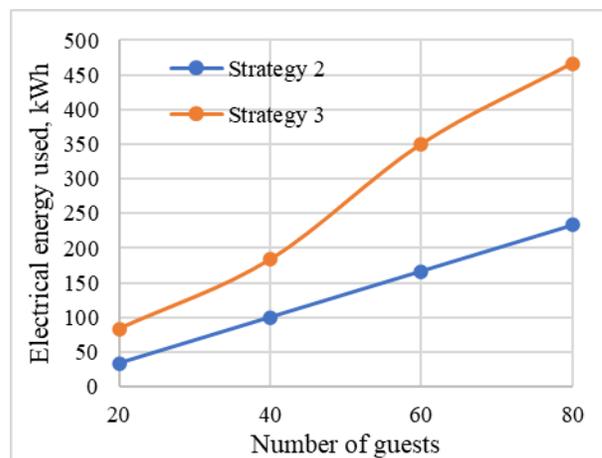

Fig. 14. Comparison of the consumed grid energy between Strategy 2 and Strategy 3 with different hotel occupancy.

To better understand the differences between Strategy 2 and Strategy 3, their results are compared in graphical form. Fig. 14 shows that the amount of additional electrical energy used has a linear dependency on the number of guests with Strategy 2. On the other hand, the amount of energy used with Strategy 3 increases non-linearly with the increase in the number of guests. In fact, the Strategy 3 result with 80 guests should be higher because the water temperature requirement was not met during the evening hours. In general, it can be seen that the energy consumption with Strategy 3 is approximately twice as high as that of Strategy 2. This can be explained by the increased thermal losses of the water tank due to the higher water temperature.
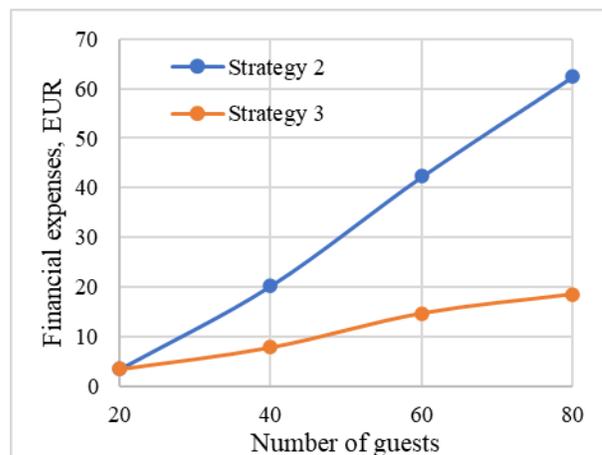

Fig. 15. Comparison of the daily financial expenses for grid energy between Strategy 2 and Strategy 3 with different hotel occupancy.

The situation with the financial expenses, however, is exactly the opposite (Fig. 15). The number of guests in the

hotel have more or less linear influence on the financial expenses; however, with the increase in occupancy, the financial expenses with Strategy 3 become significantly lower. With 40, 60, and 80 guests, Strategy 3 becomes 2.6, 2.9, and 3.4 times cheaper, respectively. Of course, the ratio for 80 guests should be slightly lower because, as mentioned earlier, the temperature of the water was below the necessary threshold in the evening, i.e., additional heating is required.

These results were obtained for a typical summer day, when the evening peak price of electrical energy could reach higher levels due to the hot weather. For the other seasons, Strategy 3 would still provide better profit compared to Strategy 2; however, the difference might not be that high. It is also important to consider the hot water consumption profile, which could differ significantly depending on the scope of the hotel. For example, the hot water consumption profile could depend on the season, especially for seaside hotels. On the other hand, SPA hotels could have a similar profile all year round.

The obtained results indicate there is a significant controversy between energy efficiency and financial efficiency. The fact that the hotel owners could reduce their expenditures by increasing their energy consumption is somewhat disturbing. This could be explained by the current legislation in the European Union and the hourly changes in the energy price. One solution that might have a positive impact on both energy and financial efficiency could be the integration of a photovoltaic installation with battery storage. This way, the hotel owner might become significantly less dependent on the price of electrical energy; however, the current prices of batteries and their life expectancy do not allow for giving a straightforward answer about the financial efficiency of such a solution and require deeper analysis.

It should be mentioned that this study has several limitations. While the obtained results provide a general understanding of the differences between the investigated energy management strategies and their performance under the conditions of a liberated energy market, they do not account for the required investments and maintenance costs, as this was not a goal of this study. Furthermore, the performance of these strategies was investigated only for the summer season, when the impact of such installation is the strongest. Future studies could extend these results by performing a whole year-round simulation; however, this would require different DHW profiles for the different seasons of the year. Furthermore, the financial gains strongly depend on the proper sizing of the solar hot water installation. And this can only be done when the object of the investigation is a specific hotel for which data about its seasonal hot water consumption is available.

IV. Conclusion

With the adoption of the Energy market in Bulgaria, the price of electrical energy has been estimated on an hourly basis. This has led to large fluctuations in the energy price depending on the hour of the day and is a significant problem for business owners in the different sectors of the economy. This study is aimed at evaluating the energy and financial performance of different energy management strategies for operating hybrid hot water installations in hotels, thus providing their owners with basic guidelines for the reduction of financial expenditures.

Three strategies are evaluated: the first one assumes the water is heated only by an evacuated solar tube system; the second one assumes electrical energy is used whenever the water temperature falls below a certain threshold; and the third one uses preliminary heating of the water during the off-peak hours of the electrical energy price. For the aims of the study, a simulation model has been developed, which is based on well-known physical and empirical dependencies.

A case study was performed on a hot summer day for a hotel with a capacity of 80 guests with 25%, 50%, 75%, and 100% occupancy. The results show that with the first strategy, it is not possible to maintain the temperature of the water in the tank above the required threshold in most cases. The second strategy ensures the requirements towards the water temperature are met with minimal application of electrical energy, leading to daily expenses between 3.4 EUR and 62 EUR. The third strategy increases the energy usage significantly, especially for higher occupancy of the hotel. However, the daily expenses for purchasing grid energy are significantly reduced and vary between 3.4 EUR and 18.5 EUR.

The obtained results indicate that with an appropriate energy management strategy, hotel owners could significantly reduce their hot water expenses. However, the improved financial results are at the expense of increased energy consumption. A potential solution for increasing both financial and energy efficiency is the integration of a photovoltaic installation with battery storage. Such an approach offers many opportunities but also increases the initial investment and related risks; therefore, further analysis is required, which is an objective for future studies. Another object for further investigation is the assessment of the energy management strategies' performance under different seasons and with different hot water consumption profiles.

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