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Article

# Optimal micro-pump-storage system for the average Greek hotel with PV generation

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**Abstract:** In this paper, a modern micro-scale pumped hydro storage system that is specifically designed to operate in coordination with photovoltaics installed at the roof of an average Greek hotel is presented. The fictitious hotel chosen as a case study, displays the energy profile of an average sea-side hotel around the Mediterranean Sea, while photovoltaics' energy generation is assumed to follow the typical production profile of such sites. Pumped hydro storage and photovoltaic generation, size and cost have been appropriately modeled so that they realistically simulate their operational scheme, while also considering the spatial and technical characteristics and limitations of such projects. Results derived from the implementation of such a scheme into the Average Greek hotel demonstrated significant monetary benefits, accompanied with a substantial net annual profit and low payback period of the investment.

**Keywords:** pumped storage hydropower; pump as turbine; photovoltaics; renewable energy sources; average Greek hotel; levelized cost of energy; payback period

## 1. Introduction

Significant steps have already been taken in the last decades in the direction of developing RES as a replacement for energy production from fossil fuels. Even though fossil fuels are responsible for air pollution and greenhouse gas emissions, a substantial part of the total production still relies on them. This is because RES, such as wind power and photovoltaics, depend on the prevailing weather conditions, the time of the day and the season of the year. These elements render RES highly associated with uncertainty and unpredictability. These two major disadvantages of RES for the generation of electricity could be mitigated with storage, working as a buffer for generation-load imbalances: excess RES generation could be stored for consumption at a later time when demand is higher than generation. However, storage is still quite expensive [1], making conventional power plants still necessary for power balancing and for ensuring stability and reliability in the grid.

The necessity of energy storage is imperative in order to increase the level of independence of power systems from fossil fuels through the higher penetration of RES. The global pumped storage hydropower capacity increased by more than 30% in roughly a decade, from some 100 gigawatts in 2010 to more than 139.9 gigawatts in 2023, accounting for 90% of total electrical energy storage capacity. Pure pumped storage hydropower capacity worldwide from 2010 to 2023 [2,3]. These systems aim to overcome the problems deriving from the further penetration of RES to the power system, as effectively as possible. However, small-scale energy storage is dominated by batteries. Their modularity allows them to reach significant capacity (in the order of tens of MWh) at a lower total initial cost, mainly because PHS systems of the same scale still face spatial limitations and immense civil-work costs. However, even if the development of battery storage has made significant steps, their cost per kWh is at least 3 times greater than PHS [4]. Indeed, according to Li et al. [5], the LCOS of batteries typically ranges between 30 and 40 US$/kWh, while Smallbone et al. [6] reports that LCOS for PHS is estimated between 10 and 15 US$/kWh. Furthermore, there is still an ongoing debate whether batteries are environmentally safe or really recyclable at a reasonable cost [7,8]. Additionally, unlike batteries, the number of cycles of charging and discharging for PHS, does not shorten its operational lifespan of the system or impact its efficiency [9]. Finally, there are concerns regarding the future availability of raw materials that are used during the manufacturing of batteries and the impact of rising prices on battery production costs [8].

The most common turbine technology employed in pico-hydro projects is the pump used as turbine (PAT), mainly due to its low purchase cost resulting from the wide commercial availability of pumps (wide variety between 1.7 kW and 160 kW range). According to Bideris Davos and Vovos [10], the purchase cost of PATs is on average 5 times lower than conventional turbines, and only tends to become comparable (2 times lower) for outputs greater than 40 kW. However, PAT technology is not as well documented as turbines, the determination of their BEP when operating as turbines still presents a major challenge.

PATs are effective mainly when used in locations with controllable water flow variation [11] since they do not possess an adjustable guide vane mechanism and thus their adaptability in fluctuating flow rates and head is rather limited. In practice, in order to improve their operational flexibility the combined employment of hydraulic and electrical regulation is required [12]. Pérez-Sánchez et al. [13] performed a thorough review regarding the various empirical methods employed to predict the BEP of a PAT and proposed an improved approach to both BEP prediction and the construction of the characteristic curves. A numerical model to predict the BEP of PATs when the actual pump characteristics from catalogues are available is established in Barbarelli et al. [14]. The results demonstrated high accuracy when the detailed geometrical parameters of the pumps were provided. In the study of Venturini et al. [15], a physics-based simulation model was developed that utilizes the performance curve of pumps in order to predict the performance curves of PATs. In Pugliese and Giugni [12], an operative framework is developed under which the preliminary selection of PATs from a manufacturer’s database is optimized in terms of energy production and payback periods. Fecarotta and McNabola [16] and Nguyen et al. [17] aim at the optimal location of PATs. However, they simulate them as simple head losses rather than real machines and disregard their feasible region by assuming constant efficiency. Finally, they ignore the rotational speed variations that fluctuating operating conditions create on the runner.

Very few micro-scale PHS systems have been implemented. They can be found in commercial and residential buildings. In combination with a renewable energy source, they are used to store the excess of generated electrical energy and return it back to the consumption later, when the RES cannot cover the demand.

The first completed micro-scale PHS system was constructed in the Goudemand apartment building complex in the Arras region of France, counting 240 apartments and housing approximately 700 people. At one of the buildings, 2.16 kWp of PV panels, 2 small vertical-axis wind turbines with a total power of 1000 W and a hybrid storage system consisting of a PHS system and a stack of lead-acid batteries have been installed [18]. When the electrical energy production from RES exceeds the energy demand, the excess energy charges the batteries. When the batteries are fully charged, pumping of water starts. Conversely, when the energy demand exceeds the production, batteries start providing energy to the building and when fully discharged, energy production from the PHS unit begins. The PHS system uses the 30-meter height of the building to store water in the appropriately sealed 60 $m^3$ upper reservoir placed on the roof. The lower reservoir is located in the building's basement consisting of 5 rectangular plastic tanks, 10 $m^3$ each. To pump water from the lower to the upper reservoir, a multistage 1.5 kW pump is installed, while for the energy production a Pelton 450 W turbine is used. The water flow supplying the turbine is regulated by an electric valve. The battery system operating in parallel with the PHS system, consists of 12 lead-acid battery cells with a total capacity of 2400 Ah. Although the useful energy capacity of 3.5 kWh for the hydroelectric system is considered small compared to the battery capacity (24 kWh), it is essential because it extends the batteries' lifespan by 1000 cycles.

Another completed micro-scale PHS system was implemented at the Negundo innovation center in the Froyennes area of Belgium. The energy supply to this facility is provided by PV panels with a total capacity of 110.2 kWp power and 4 wind turbines with a capacity of 2.4 kWp each. The installed PHS system uses an existing artificial 1500 $m^3$ basin, for collecting run-off water from roofs and roads, as the upper reservoir. An underground tank with a capacity of 650 $m^3$, located near the buildings is used as the lower reservoir. These 2 reservoirs are connected through a piping system with a total length of 80 m and an internal diameter of 335 mm. Between the upper and the lower reservoir, a pump with a variable frequency drive is installed, which also functions as a turbine (PAT) and is able to generate a maximum of 7 kW of power [19].

Other implementations of micro-scale PHS systems can be found in some remote areas and villages, which are not connected to the main grid. In such cases, the primary energy sources are PV parks or small wind turbines. Their possible excess energy is stored by the PHS system and returned to the consumers when power demand exceeds production. An example of such as system is described below.

A micro-scale PHS system, combined with PVs and batteries, has been constructed in the isolated village of Mersina on Donoussa Island, Greece. This remote village is not connected to the grid which supplies the rest of the island. The main purpose of this system is to provide uninterrupted power supply to the 13 houses of the village, covering the basic electricity needs of the residents: lighting, TVs and refrigerators. The system is powered by 18 kWp of PV panels. Two identical 150 $m^3$ water tanks are used as upper and lower reservoirs with an elevation difference of 100 m. The micro-hydraulic system consists of a 6 kVA water pump and a turbine connected to a 7.5 kW DC generator. During the day, the electrical load of the village is totally covered by PVs through an inverter, and the excess electrical energy pumps water to the upper tank. At night, the stored water is directed to the lower reservoir, rotating the turbine and providing electric power to the village. The entire system is also accompanied by a 100 Ah battery array, to cover peak demand that exceeds the 7.5 kW of the hydro-generator, for a short period of time [20].

The constructed micro-scale PHS systems, presented above, suffer from certain disadvantages. Their small-sized reservoirs and their low-power pumps and turbines, provide a reduced energy storage capacity, compared with the PV generation. To overcome this reduced capacity, the installation of a battery system was more than necessary, rendering the whole installation unsustainable. Additionally, in Goudemand and Donoussa PHS systems, separate pumps and turbines were used, which increased further the initial cost of the installation. Furthermore, in all the aforementioned examples, the PHS system was constructed several years ago when the development of such micro-scale systems was still in its early stages. As a result, their efficiency remained low and their cost quite high. These disadvantages hindered the further implementation of micro-scale PHS systems.

In this paper, a micro-scale hybrid PHS and PV system freed from most of the issues of similar systems mentioned above, specifically sized and configured for the AGH, is proposed. Even if the AGH is a fictitious installation, it roughly describes a very common demand profile for a great number of hotels around the mediterranean sea. Therefore, the conclusions drawn from this work can be expanded to a great number of sea-side hotels or installations of similar size. Specifically, first the system is dimensioned and the estimation of the total cost of the project is carried out. Existing literature and data from the market have been combined and verified in order to create up-to-date cost models. The economic viability of the project is assessed by the most popular indexes for similar hydro-power projects: PP and LCOE. These 2 indexes, especially when used in conjunction with one another, provide useful insights for assessing the investment profitability and success.

The main contributions and results of the paper are summarized below:

- Results indicate that the combined operation of micro-PHS systems and PVs provide an economically sustainable option, with payback periods that range below 6 years.
- The PAT system performance map is evaluated for both nominal and part load operation for both pump and turbine modes.
- Results also indicate that the LCOE value for the selected PAT is calculated 0.08202 €/kWh and is much lower than other energy storage systems [21].

Furthermore, it is demonstrated that micro-PHS can be a financially viable small-scale storage solution when the location and characteristics of the installation permits significant cost cuts in civil works. The case study in this paper concerns the AGH, mainly, due to its location, which is close to both a hill for placing the upper reservoir and the sea for using it as a lower reservoir. Generation performance is quite high, too, since the Mediterranean weather in Greece boosts PV generation (days are sunny for most of the year) and the hotel's roof can accommodate significant PV capacity. We have also examined the possibility of higher exploitation of PHS by taking advantage of the cheaper electricity rates during the night to store energy, in order to cover part of the demand during the more expensive time-of-use during the day.

All effort has been given, so that the analysis contains realistic data for most operating and financial factors: civil work costs, PV installation costs, pump storage costs, energy production, tariffs for energy purchase from the utility and a precise PAT model that estimates the varying efficiency of PHS under part-load conditions. It has to be noted that this last factor is usually ignored in most studies. The purpose of this paper is to demonstrate that, under some typical conditions, a micro-scale PHS system may be viable solution that can coexist in the so-defined AGH.

The structure of the paper is as follows. Section 2 contains the methodology used to simulate the average Greek hotel, as an energy consumer, PV generation throughout the year, pump-storage system efficiency and operation under full and partial load conditions. Section 3 contains the mathematical model used to calculate PV excess generation or deficiency with respect to the varying load and the amount of water pumped or used for power generation at the PAT and the conditions that this is happening with respect to different strategies and financial incentives. Section 4 contains the cost models and assumptions made to estimate the cost of the system, as well as the compensation scheme of the generated power from the PV or the PAT during operation as a turbine. In the same section the financial indexes used to assess the financial viability of such a project are described. In Section 5, the results from the operational and financial assessment are presented. Conclusions, as well as suggestions for future work, are contained in the last section.

## 2. Methodology

### 2.1. The average Greek hotel

In this paper, the AGH was chosen as a case study for analyzing and implementing a modern micro-scale PHS system. First, the dimensions of the AGH must be defined so that its energy profile can then be constructed precisely. We assume that a PHS system could be implemented either at a 4-star or 5-star hotel due to its significant capital cost. We opted for the 4-star hotel, because there is a limited number of 5-star hotels in Greece. Since the majority of hotels in Greece are at seaside, it is assumed that the AGH is located at such a location, near the city of Kalamata. Consulting the "Hellenic Chamber of hotels" [22], an average newly built 4-star hotel consists of 70 rooms. By utilizing data from governmental regulations regarding the individual areas of hotel spaces [23], an average area for the hotel of 2600 $m^2$ was obtained. This area can be reasonably divided as follows: 1st and 2nd floor will occupy an area of 700 $m^2$ each, the ground floor 810 $m^2$ (assuming a lobby, a reception and administrative rooms) and the basement of the building 400 $m^2$.

Having estimated the dimensions of the AGH, its energy profile will be illustrated. Greek regulations classify buildings according to their energy consumption and performance into the following scale categories: A, B, C, D, E, F, G [24]. Class "A" characterizes an energy efficient building, while class "G" indicates an energy inefficient building. The criteria considered for categorizing buildings according to this scale, include the thermal insulation characteristics of the building's external surfaces and its design, the active and passive heating, cooling and ventilation systems, the method of hot water production, the quality of natural ventilation and air conditioning. Obviously, the AGH occupied with the PHS system, should belong to energy classes A or B, as it would make no sense to have a highly sophisticated and expensive storage system and have abundance of energy wasted, as it is the case in a lower class. Since most of the 4-star Greek hotels belong to "B" energy class, this class is also assumed for the AGH. According to the Energy Inspections of buildings for the year 2021 by the Ministry of Environment and Energy, and the "Building energy efficiency regulation" in Greece Hellenic [24], an annual electricity consumption of 223 kWh/m$^2$ is expected from the AGH. This consumption includes only electrical energy, since all thermal needs are solely covered by heat pumps. By multiplying the total area of the AGH with the energy consumption per m$^2$, the total annual energy consumption for the building is obtained, which equals 580 MWh.

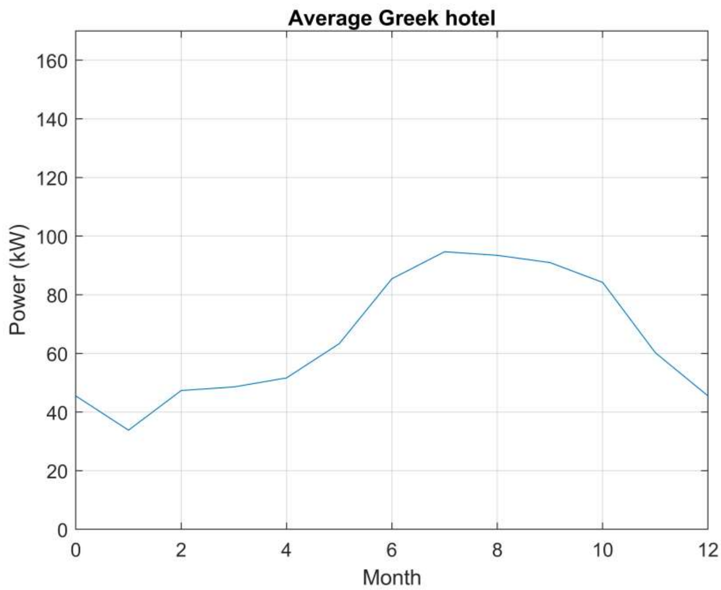



**Figure 1.** Average monthly power demand of the AVG with respect to the month of the year. It is assumed that the average daily demand is constant throughout each month of the year.

To complete the energy profile of the AGH, since pumping depends on the difference between PV generation and demand, its daily and annual load curves must be constructed. Due to the lack of data for specific 4-star seaside Greek hotels, we had to use data from other Mediterranean hotels found in literature, which fitted the profile of the AGH well: four stars, seaside, similar climate, volume and demand. First, we used the mean daily power demand of a hotel in Malta. The power demand was provided as an average value for all days of the same month [25]. In order to get the estimate for AGH's mean demand (**Figure 1**), we had to scale up those values, in order to make sure that the total aggregate (i.e., annual demand) equals that of the AGH (580 MWh). Similarly, the estimated variation of demand throughout the day has been based on an Italian hotel [26]. The demand curve was provided per square meter (**Figure 2**), so it had to be scaled up, so that its average value is equal to the daily averages provided for each month in **Figure 1**. It is assumed that during a month, the daily demand curves calculated with the above procedure, do not change (**Figure 3**).

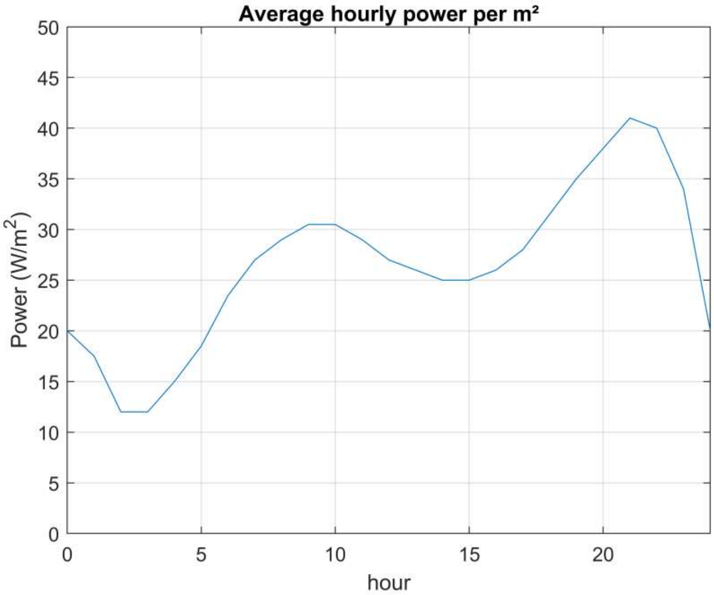



**Figure 2.** Daily demand curve of AGH (adjusted from hotel with similar profile in Provenzano [26]).

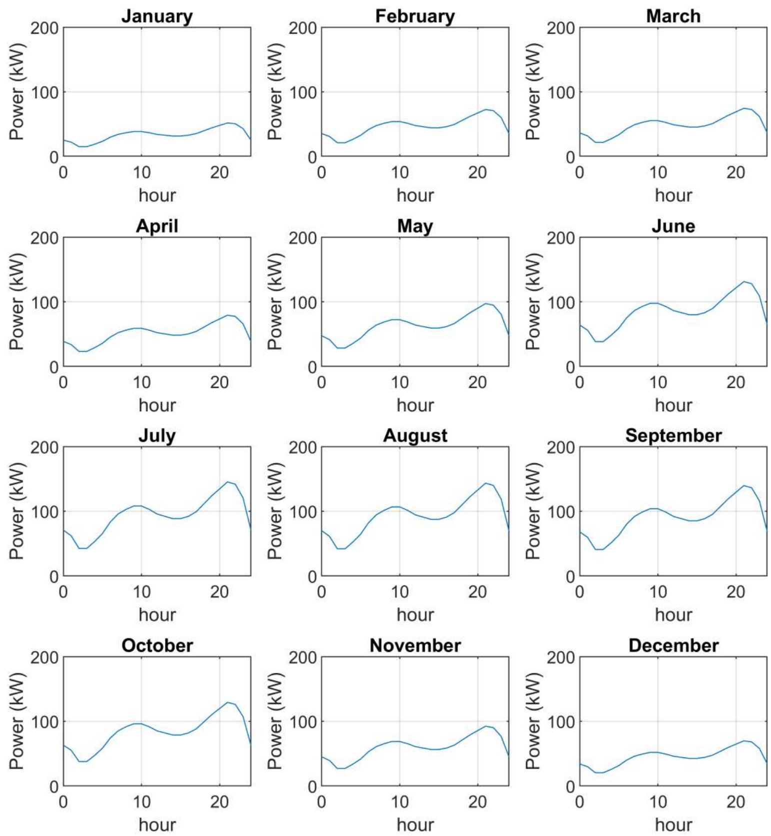



**Figure 3.** Daily demand curves for each month of the year for AGH.

## 2.2. PV generation

It is assumed that the RES which provides electrical energy to the AGH is PVs. This energy source is preferred among others (such as wind turbines) mainly because of its low installation and maintenance cost for a micro-scale project. PVs are also a RES that does not have an aesthetic impact to the hotel, as the panels cover the roof of the building.

To obtain the energy production curves from PV panels, some basic data for the AGH and the PV technology need to be determined first. The panels cover the entire surface area of the 700 $m^2$ roof, tilted at the optimal angle of 35 degrees and having the optimal orientation towards the south, for maximum yearly yield. The irradiation curves for the region of Kalamata were retrieved from the European platform PVGIS European Commission [27].

Choosing the appropriate PV technology for the system plays a pivotal role in the final production curves of PVs. Solar panels from monocrystalline silicon have been chosen, because they are the recommended solution for limited spaces (such as the hotel roof top) due to their higher efficiency among other commercially widespread technologies, at a reasonable cost. If further increase of PV's energy production is sought, sun tracking bases are suggested. However, this technology, displays a much higher installation and maintenance cost, which would probably not be bearable for the average Greek hotel. For the above reasons, constant bases have been selected. Simulation results presented in Section 5 demonstrate that they are sufficient to cover the AGH's energy needs, considering the high number of sunny days in Greece.

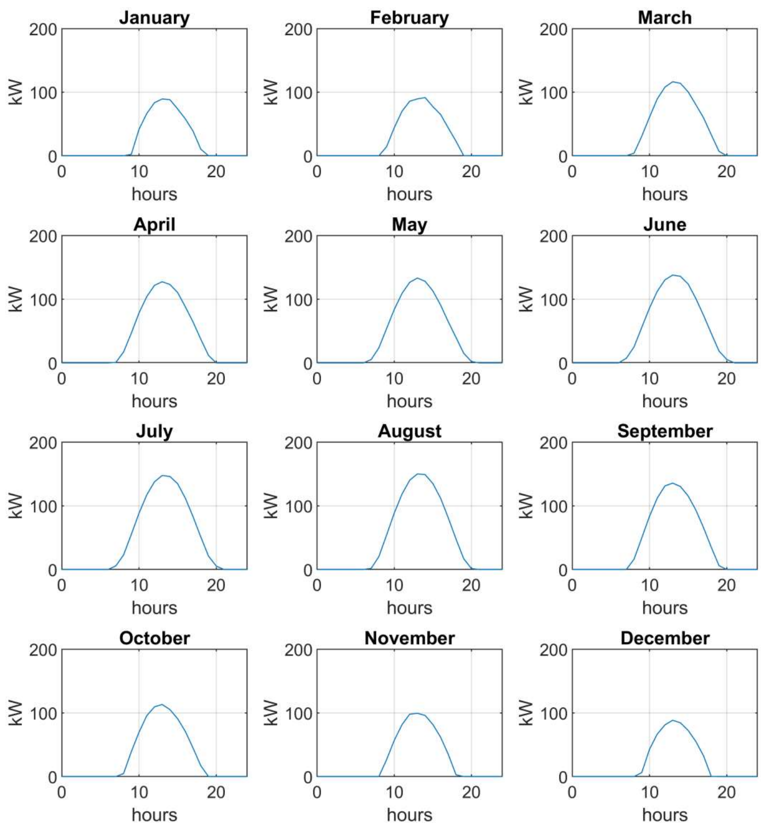



**Figure 4.** Daily PV energy production curves for each month of the year.

The PV daily production curves have been calculated by applying the daily irradiance curves obtained from the PVGIS platform on the array of panels, assumed to be covering the whole rooftop of AGH and then by assuming an average efficiency factor of 22% for monocrystalline silicon solar panels (**Figure 4**).

## 2.3. Pump storage

PAT is one of the most common turbine technologies used for pico/micro scale projects, mainly due to its low purchase cost resulting from the wide commercial availability of pumps. Moreover, they are proven robust and require little maintenance, with a lifespan typically greater than 20 years Le Marre et al. [28]. The power output of the PAT in turbine mode is given by Equation (1) [29]:

$$P_T(W) = \gamma \cdot Q_T \cdot H_T \cdot n_h \cdot n_g \tag{1}$$

where $\gamma$ is the specific weight of water (9810 $\mathrm{N/m^3}$), where $Q_T$ is the volumetric flow rate ($\mathrm{m^3/s}$) through the turbine, $H_T$ is the turbine's working head (m), while $n_h$ and $n_g$ is the turbine's hydraulic efficiency and generator's efficiency, respectively.

However, despite being highly sufficient in pump mode, their performance prediction in turbine mode is still based on empirical relations and prediction methods, since the characteristic curves in turbine mode are not typically provided by the manufacturers [30]. Among the various analytic models available in literature, the equations of Yang et al. [31] are widely applied because they provide the best accuracy for both flow rate and head ratio estimation, according to Pugliese et al. [32]. Moreover, unlike other models, they correlate PAT performance in turbine mode with PAT performance in pump mode. The latter is always provided by the manufacturer, and thus, their implementation becomes simple and straightforward. The estimation of the BEP in turbine mode when the BEP in pump mode is available, can be determined according to the expressions presented in **Table 1**. PAT performance in turbine mode and operating away from the BEP is calculated by Equation (2) [33]. Among the other expressions available in the literature, this model was selected because the values obtained by CFD analysis and by the model forecasts accurately the PATs' performance in off-design operating conditions that are close to the BEP (with max discrepancy 3%), while a slight mismatch is shown when operating far from it (max discrepancy 10%), as it is explained in the study of Novara and McNabola [34].

$$\frac{H_T}{H_{T,BEP}} = 0.2394 \cdot \left(\frac{Q_T}{Q_{T,BEP}}\right)^2 + 0.769 \cdot \frac{Q_T}{Q_{T,BEP}} \tag{2}$$

**Table 1.** Correlation of BEP in turbine mode with BEP in pump mode. Subscripts T and P refer to turbine and pump mode.

| $\boldsymbol{Q_{T,BEP}}$ [31] | $\boldsymbol{H_{T,BEP}}$ [31] | $\boldsymbol{n_{T,BEP}}$ [34] |
|---|---|---|
| $\frac{1.2\ Q_{P,BEP}}{(n_{P,BEP})^{0.55}}$ | $\frac{1.2\ H_{P,BEP}}{(n_{P,BEP})^{1.1}}$ | $0.89 - \left(\frac{0.024}{Q_{T,BEP}^{0.41}}\right) - 0.076\left[0.22 + \ln\left(\frac{N_{st}}{52.993}\right)\right]^2$ |

where $N_{st} = \frac{N_t\sqrt{Q_t}}{H_t{}^{0.75}}$ is the specific speed of the turbine.

## 3. PHS operation schemes

In this section, the mathematical model of the PHS system, which estimates the energy stored (pumping) or recovered (generating) from it is presented.

### 3.1. Pumping

Pumping is the process of storing energy in a PHS system by pumping water from a lower tank to a higher tank. In our case this is happening under two possible schemes of operation: a) pumping only during excess PV generation and b) pumping during excess PV generation and during lower prices for purchased electricity from the grid, in a time of use billing system, such as the Greek. Both of them are detailed below.

#### 3.1.1. Pumping only during excess PV generation

The energy production curve of PVs during daytime follows a pattern as shown in **Figure 4**. PVs start producing electrical energy in the morning and stop producing around sunset, so the duration depends on the time of the year. The peak production is observed at midday hours and its magnitude also depends on the time of the year and the clarity of the sky of that day. During peak production and depending on the demand of the AGH at that time of the year, PV generation exceeds demand, and this excess energy can be stored at the PHS system. Practically, this is done by a control system that continuously checks the hotel's hourly power demand and the hourly power production from the PV panels. The hours of the day, which generation exceeds consumption, their difference is calculated, and the possibility of pumping is examined, according to the following algorithm.

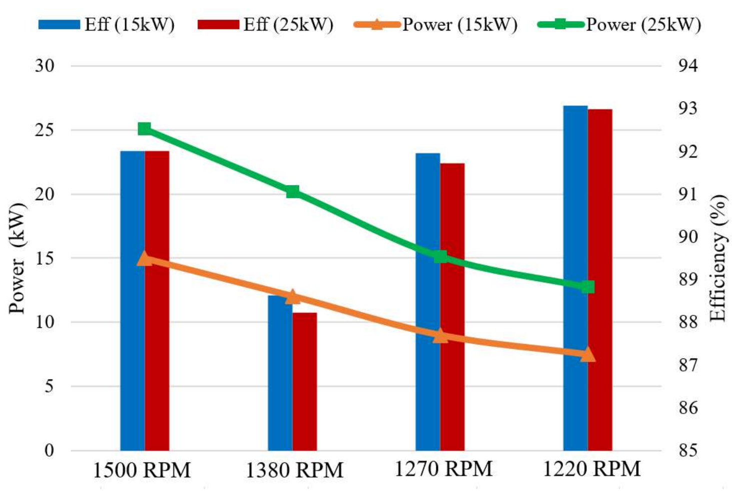
**Table 2.** BEP of the PAT system in pump mode.

| $P_{P,BEP}$ (kW) | $Q_{P,BEP}$ (m$^3$/h) | $H_{P,BEP}$ (m) | $n_{P,BEP}$ (%) |
|---|---|---|---|
| 15 | 275 | 20 | 92 |
| 25 | 460 | 20 | 92 |
| 35 | 645 | 20 | 92.5 |
| 45 | 830 | 20 | 92.5 |
| 55 | 1000 | 20 | 92.5 |
| 65 | 1200 | 20 | 93 |
| 75 | 1380 | 20 | 93 |
| 85 | 1560 | 20 | 93.5 |

Each PAT has its own nominal power consumption and a corresponding water supply when operating as a pump (**Table 2**). According to this nominal power consumption and the difference between generation and demand, the algorithm allows pumping or not and calculates the amount of water in the tank every hour of the day. First, the hours needed for the upper reservoir to be filled if the PAT operates continuously at its nominal power are determined. Two cases are then examined:

- If the difference between generation and demand is greater than the nominal power of the PAT, then the PAT is assumed to be pumping water with nominal flow by consuming nominal power. If during this mode of PAT's operation, we calculate that enough water has been pumped to fill in the upper tank, then we assume that pumping stops, and the tank is full. After this point in time, PV generation is assumed capped to the amount equal to demand, until demand becomes higher than generation again, which means that PV generation does not need to be capped longer.

- If these hours are fewer than those during which the excess power from the PV exceeds the power demand by an amount greater than the consumption of the PAT, the hours when the difference is the greatest are selected. In this case the PAT operates in its nominal power.
- If the difference between generation and demand is lower than 50% of the nominal power of the PAT, then the PAT is not pumping any water. This is because, we have assumed that operating the PAT as a pump in lower than half load would cause unacceptably high wear, cavitation effect and generally losses, significantly reducing its lifetime and increasing maintenance costs. During this time the PV generation is capped to an amount equal to demand, until the demand surpasses possible PV generation again.
- If the difference between generation and demand is between 50% and 100% of the nominal power of the PAT, then the PAT is pumping water, but with a flow and efficiency lower than nominal. In this range of operation, the height remains constant, but the pumping efficiency, the rotational speed of the PAT and the water supply are changing. From the simulation of the PAT based on its operating model, the power values and the corresponding efficiencies for water flow rates of 0.8, 0.6 and 0.5 of the nominal values were obtained. It was observed that the correlation between the PAT's power and the water flow is almost linear. Thus, the water flow as a function of surplus PV power can be obtained. The BEP and performance of the PAT system in pump mode for different flow rates and power outputs is displayed in **Figure 5**. By calculating these subnominal flow rates for each hour of the day, the amount of water pumped to the upper tank, thus the total amount of water in the tank, can be calculated. If the tank becomes full, pumping stops. After this point in time, PV generation is assumed capped to the amount equal to demand, until demand becomes higher than generation again, which means that PV generation does not need to be capped longer.




**(a)**

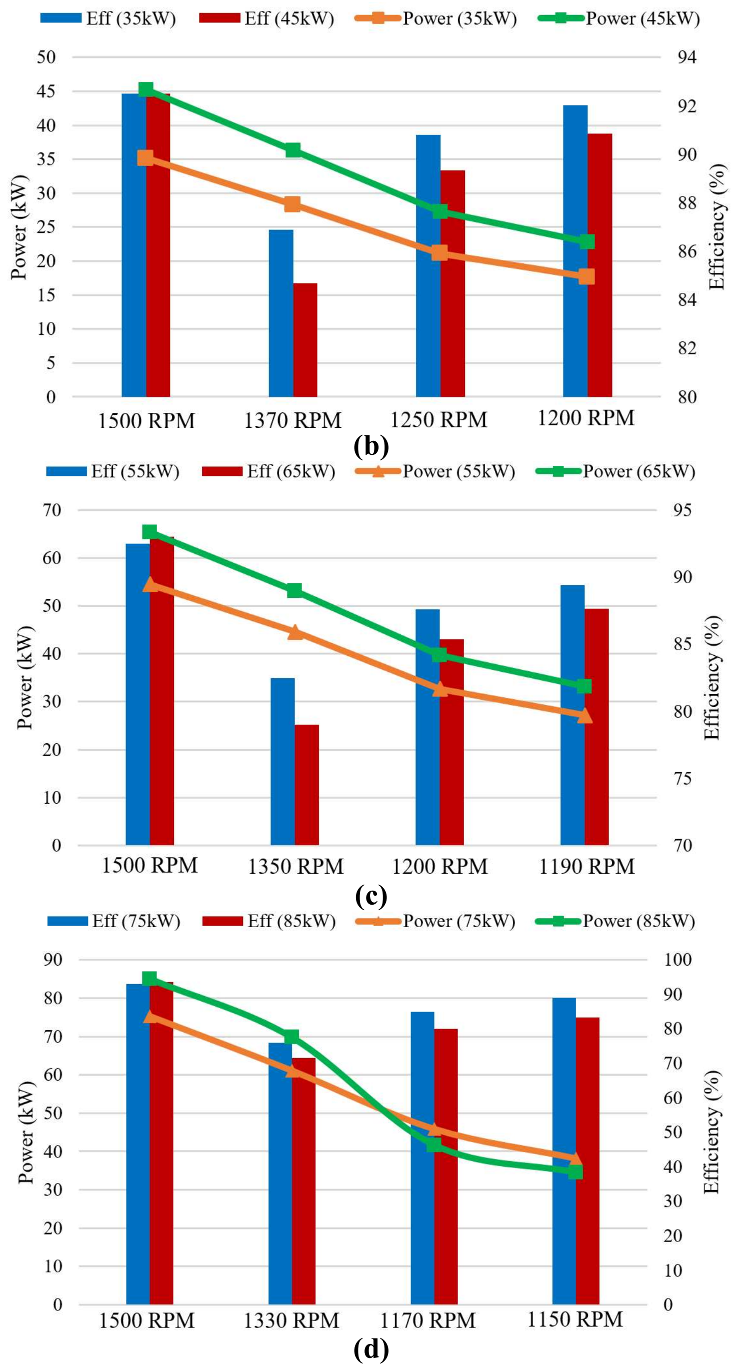



**Figure 5.** PAT performance in pump mode for different flow rates for **(a)** 15 and 25 kW; **(b)** 35 and 45 kW; **(c)** 55 and 65 kW; **(d)** 75 and 85 kW.

In any case, the amount of water pumped in the upper tank is automatically subtracted from the lower tank.

### 3.1.2. Pumping during excess PV generation and cheaper tariff

In subsection 3.1.1 the operation of the pumping system is limited to time periods that PV generation is greater than demand. This practically means that it operates only during the day. In this subsection, an analysis is conducted concerning the extension of the operation of the PHS system in a second daily cycle, during the night, using the cheaper tariff provided by the electrical utility during that time.

In Greece, some of the electricity suppliers provide a time-of-use billing option, giving a cheaper tariff for electrical energy consumed during 8 specific hours of the day. This reduced tariff takes place from 23:00 to 07:00 between 1 May and 1 November and from 02:00 to 08:00 and 15:00 to 17:00 for the rest of the year. In the present analysis, for simplicity of calculations, it was assumed that the cheaper tariff begins from 02:00 and ends at 07:00 throughout the year. It will be demonstrated from the simulation results in Section 5, that keeping only the night part of the cheaper tariff throughout the year, did not affect the pumping pattern. During winter afternoons, even if PV generation is reduced when compared with the summer, the much lower demand keeps PV excess power at a sufficient level to make the cheaper tariff useless.

The prices for daytime and nighttime electricity tariffs from the most popular supplier in Greece (PPC) for every month of the year 2023 are presented in **Table 3** [35]. It has to be noted that the tariff prices presented in this table, must be considered only as indicative, as they may vary significantly from supplier to supplier, from year to year and from country to country. Therefore, in order for such a pumping scheme to make sense, a basic principle must be met: the ratio of the night electricity tariff over the daytime tariff should be less than the cycle efficiency of the PHS system, which is calculated by multiplying the individual efficiencies of pumping and generating. Otherwise, there is no reason for night pumping, since the cost of the consumed energy by the PAT is certainly more than the financial gain derived from the morning generation.

**Table 3.** Daytime and nighttime electricity tariffs.

| | **Daytime tariff (€/kWh)** | **Nighttime tariff (€/kWh)** | **Ratio nighttime/daytime** |
|---|---|---|---|
| January | 0.404 | 0.314 | 0.777 |
| February | 0.218 | 0.138 | 0.633 |
| March | 0.238 | 0.154 | 0.647 |
| April | 0.214 | 0.124 | 0.579 |
| May | 0.208 | 0.118 | 0.567 |
| June | 0.204 | 0.114 | 0.559 |
| July | 0.204 | 0.114 | 0.559 |
| August | 0.204 | 0.114 | 0.559 |
| September | 0.204 | 0.114 | 0.559 |
| October | 0.217 | 0.114 | 0.525 |
| November | 0.256 | 0.129 | 0.504 |
| December | 0.256 | 0.129 | 0.504 |

The pumping process during the night is much simpler than the corresponding procedure during the noon (excess of PV generation). For the precise definition of the pumping hours at night, the system needs to predict the power demand during the next morning's hours from the end of the nighttime tariff until the time when the entire AGH's load is covered by PVs. Since such a precise prediction is quite difficult to make, the estimation of the next day's consumption is the consumption of the previous day. This can be easily assumed because it was considered in subsection 2.1 that during a month, the daily load curve of the AGH remains practically constant.

In the case of pumping at night, the algorithm followed for pumping water to the upper reservoir is easier than the corresponding procedure of pumping at noon. At night, there is no point in operating the pump below its rated power and maximum efficiency. The required pumping hours to fill the upper tank are calculated according to the nominal water flow at the PAT's nominal power. It should also be checked if the 7 h of cheaper electricity are sufficient for the pump to fill the upper tank, according to its nominal power and flow. If the upper tank becomes full, the pumping operation stops. In the case of operating the PHS system in two daily cycles, the midday pumping due to excess PV generation is completely independent of the nighttime pumping with cheaper electricity tariff, which greatly simplifies the calculations.

### 3.2. Generation

Generation is the process in PHS systems during which energy is recovered from the upper water tank by letting water flow to the lower tank through the hydro generator. In our case, both pumping and generation is performed by the same device, PAT. Generation is performed when demand surpasses PV generation, no matter what scheme is followed during pumping (see Section 3.1).

The decision process when the generation takes place is simpler than the pumping process for both pumping schemes, analyzed in subsections 3.1.1 and 3.1.2. In the first scheme (pumping occurs only at midday from PV excess energy), the stored energy is recovered in order to cover part of the demand of the hotel during the afternoon or evening. Due to the high demand during these hours, it is considered that all the PATs studied in this paper are operating in their nominal power. Even for the PAT with the highest nominal power (85 kW), the maximum power the generator can provide to the hotel is quite lower from the demand during the evening. Thus, the calculations are simplified, and the PAT is operating at its BEP.

Once the pumping process is completed at midday, the PHS control system calculates the time required for the PAT to operate, in order to empty the upper reservoir and recover energy to the hotel. Then, based on the load data from the previous day (since the prediction for the next day is uncertain and inaccurate), the hours during which the peak load is observed, are identified. Finally, prioritizing the hour with the highest peak load and in descending order to the hour with the lowest power demand, energy is recovered from the PHS system. When the upper reservoir is emptied, the PAT stops generating.

Similarly, once the nighttime pumping is completed, according to subsection 3.1.2, the energy recovered from the AGH in the morning is calculated, based on the stored water quantity in the tank and the nominal water flow of the PAT. The PAT is chosen to operate at its nominal power during production, so that maximum efficiency is achieved. Thus, the PAT operating at its BEP can provide the maximum energy and financial gain to the AGH.

The BEP of the PAT system in turbine mode, as calculated by Equation (2) and **Table 1** is displayed in **Table 4**. However, for all cases, turbine cannot operate at its nominal head $H_{T,BEP}$, as it exceeds the total elevation of the upper reservoir $H$ = 20 m, and therefore, it would have to operate at a lower $H_T$. PAT performance in turbine mode and operating away from the BEP is calculated by Equation (2) [33], while the results for all cases are displayed in **Table 5**.

**Table 4.** BEP of the PAT system in turbine mode.

| $P_{T,BEP}$ (kW) | $Q_{T,BEP}$ (m$^3$/h) | $H_{T,BEP}$ (m) | $n_{T,BEP}$ (%) |
|---|---|---|---|
| 24 | 345 | 26.3 | 82.6 |
| 41 | 577 | 26.3 | 83.5 |
| 57 | 807 | 26.1 | 83.9 |
| 74 | 1039 | 26.1 | 84 |
| 89 | 1252 | 26.1 | 84.2 |
| 106 | 1498 | 25.9 | 84.2 |
| 122 | 1723 | 25.9 | 84.2 |
| 136 | 1942 | 25.8 | 84.1 |

**Table 5.** PAT performance for turbine mode for $H_T$ =15 m and $N$ = 1500 RPM.

| $P_T$ (kW) | $Q_T$ (m$^3$/h) | $H_T$ (m) | $n_T$ (%) |
|---|---|---|---|
| 8.77 | 214 | 15 | 75 |
| 14.6 | 359 | 15 | 75 |
| 20.62 | 504 | 15 | 75 |
| 26.54 | 649 | 15 | 75 |
| 31.97 | 782 | 15 | 75 |
| 38.45 | 940 | 15 | 75 |
| 44.22 | 1081 | 15 | 75 |
| 50.09 | 1225 | 15 | 75 |

### 3.3. Daily cycle

The process of pumping and generation described in Sections 3.1 and 3.2, respectively, should be automated in a real-world system. The flowchart below (**Figure 6**) describes the algorithmic process that should be followed by any automation equipment aiming at maximizing the performance of the PHS system. The flowchart is divided in two parts: daily and night operation. In daily operation, the energy production is compared with the AGH's demand. When PV production exceeds demand, the PHS system can pump water to the upper reservoir until either the upper tank becomes full or the available excess energy is reduced to zero. In these situations the PAT can operate as a pump only when the difference between generation and demand is greater than the half of the PAT's nominal power. Otherwise, pumping stops or never begins. In night operation, the ratio between daytime and nighttime energy tariffs is compared with the PHS system's overall efficiency. If the ratio is lower than system's efficiency, the PHS system starts pumping water at night. Pumping procedure stops either when the necessary volume of water has been pumped to the upper reservoir or the nighttime tariff has ended. In both situations, when the nighttime reduced billing stops, the PHS system begin generation. The required equipment that could implement this automation logic is described in subsection 4.2.2.


**Figure 6.** Flowchart describing the automatic logic followed by PHS system for optimal performance.

A daily cycle of the suggested PHS schemes is explained below, so that the reader has a clearer view of the combined operation of pumping and generation. In **Figure 7**, the difference between daily demand and PV generation during a typical day of a month of June, is presented with the blue curve. It can be noticed that there is excess generation during noon (negative values) that without the PHS system would have to be fully capped. The operation of the PHS system with a 25 kW PAT, increases demand during pumping and covers part of the demand during generation (red curve). This exchange of energy from and to the PHS can be noticed as the difference between the two curves. Area "D" is the excess PV energy diverted to pumping according to the scheme presented in subsection 3.1.1. Obviously, much less PV power has to be capped during that period (area "C"). Additional energy can be stored (area "A") using the cheaper time-of-use night tariff, according to subection 3.1.2. That stored energy is supplied to the AGH when the more expensive time-of-use tariff starts at 7 am (area "B"). The energy stored during excess PV generation is supplied to AGH when demand is greater than PV generation again in the evening (area "E").

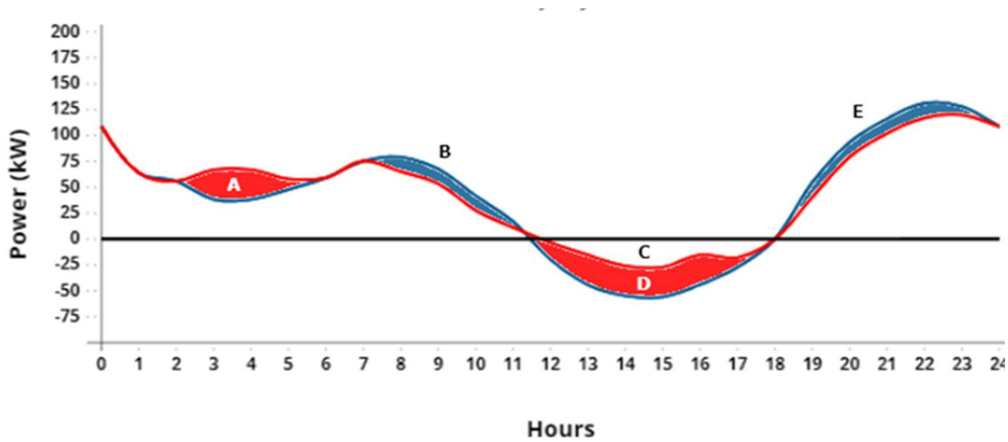
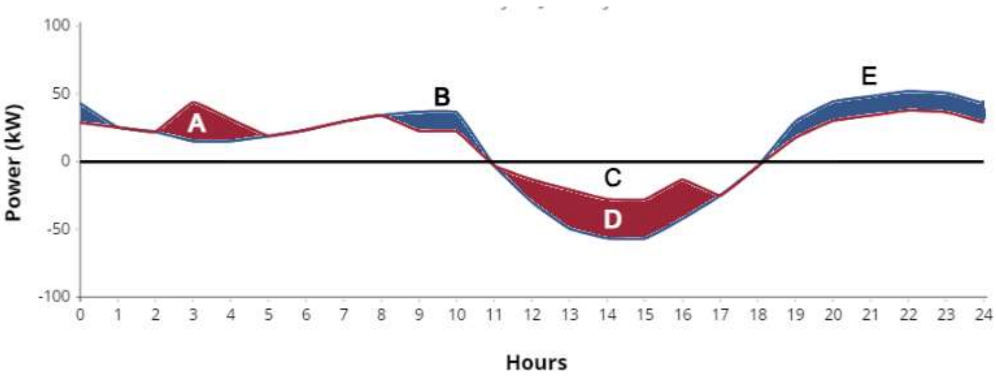
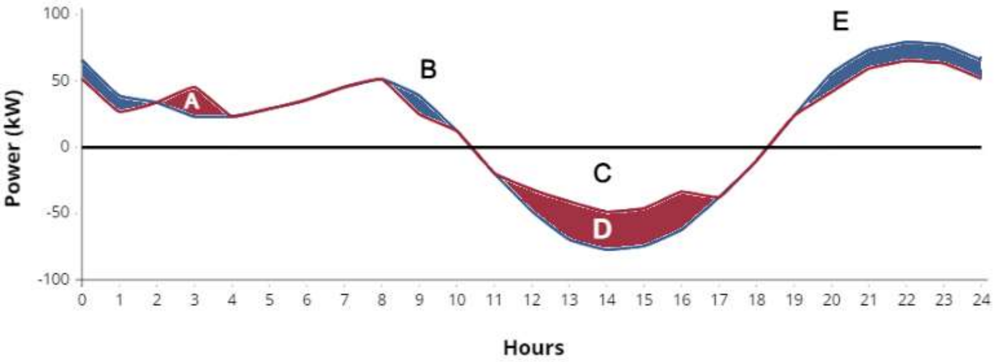



**Figure 7.** Impact of PHS system on demand of the AGH with PV generation.

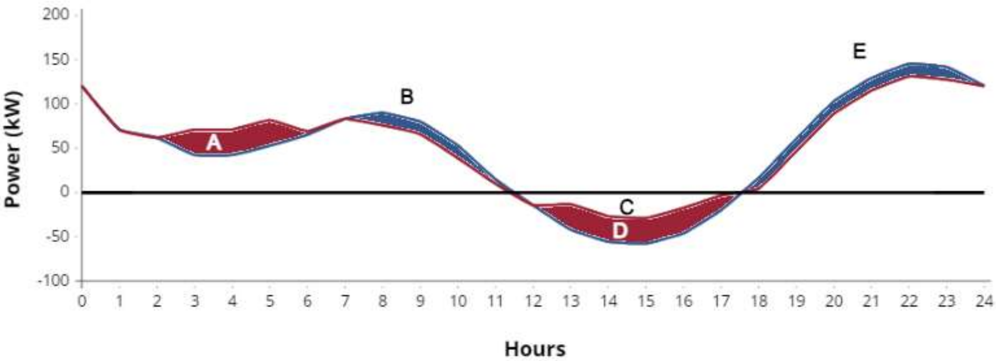
**Table 6** summarizes the different energy amounts that are exchanged between the PV (generation), PHS (storage) and AGH (demand). During July and October, two months of the year that the AGH operates close to its capacity (high touristic season, thus high demand) pumping during the night increases ("A" in **Figure 8c,d**), so that the savings from the difference of day and night tariffs are maximized ("B" in **Figure 8c,d**). April, a month that AGH has a rather low demand (low touristic season), but the PV generation is rather efficient (long sunny days, but low ambient temperatures) a great amount of PV energy is capped ("C" in **Figure 8b**). On the contrary, during October, the storage capacity of the PHS is underused during the day ("D" in **Figure 8d**), due to the relevantly high demand (high touristic season) but relevantly low PV generation (see October in **Figure 4**), Obviously, the under-usage of PHS during the evening leads to much less energy recovered as well ("E" in **Figure 8d**). For the rest of the cases, storage capacity is better used during the day ("D" in **Figure 8a–c**), plus much more energy is recovered during the evening ("E" in **Figure 8a–c**).



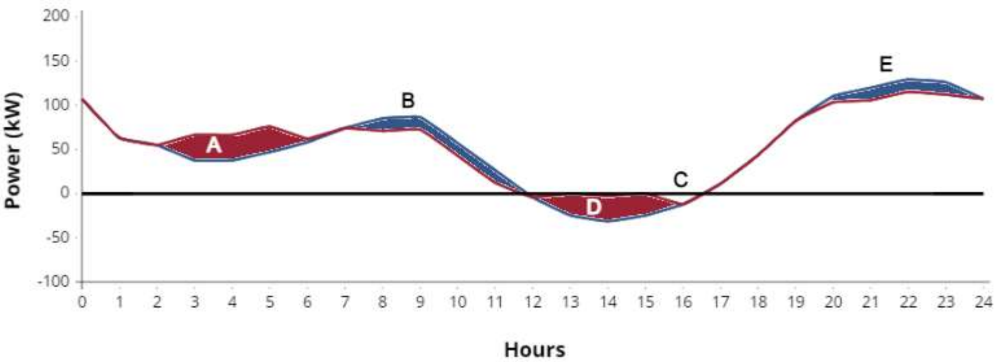

**(a)**




**(b)**




**(c)**




**(d)**

**Figure 8.** 25 kW PHS system daily performance under different demand and generation conditions: **(a)** January; **(b)** April; **(c)** July; **(d)** October.

**Table 6.** Energy amounts exchanged between the PV (generation), PHS (storage) and AGH (demand).

| | A | B | C | D | E |
|---|---|---|---|---|---|
| January | 44.62 | 27.9 | 134.6 | 130.7 | 81.61 |
| April | 22.31 | 13.95 | 268.0 | 130.7 | 81.61 |
| July | 89.57 | 55.8 | 103.8 | 130.7 | 81.61 |
| October | 89.57 | 55.8 | 18.8 | 79.4 | 48.83 |

## 4. Cost models

In this section, the indexes used to assess the financial viability of the simulated project are described. Furthermore, the cost models and assumptions made to estimate the overall cost of the system to be installed and maintained will be explained. Finally, the compensation scheme of the generated power from the PV or PAT will be described. The implementation of the PHS achieves attractive payback periods (5 years on average), which are in accordance with those of micro hydroelectric projects employing PATs, that typically range between 2 and 5 years, according to Pugliese and Giugni [12], Laghari et al. [36], the fact that the renewable energy overproduction is not wasted due to storage leads to low LCOE values (approximately 0.09 €/kWh) that are in compliance with other RES technologies with storage.

### 4.1. Financial indexes

For the evaluation of the investment and for proving that a micro-scale PHS system is feasible and economically viable, two separate financial indexes are presented and calculated in this subsection: LCOE and PP.

The LCOE is a method by which the price per energy unit that balances out the total cost of the project is obtained. The calculation of the LCOE can be performed either over a one-year period or over the lifetime of the project, with the latter method providing greater accuracy [37]. The mathematically calculation of the LCOE is given by Equation (3) [38]:

$$\mathrm{LCOE} = \frac{\sum_t^n \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_t^n \frac{E_t}{(1+r)^t}} \tag{3}$$

where $I_t$ represents the investment cost in year $t$ (€), $M_t$ in the operation and maintenance cost in year $t$ (€), $F_t$ stands for the fuel cost in year $t$ (€), $E_t$ is the generated electrical energy from the power unit in year $t$ (€), $r$ is the discount rate and n represents the lifetime of the installation.

In our case, the energy production unit is the PVs in combination with the PHS system. The lifetime of the entire system is limited to 25 years due to the PVs panel's lifetime. Additionally, a zero-discount rate and a zero-fuel cost (as PVs are a RES) are considered. The investment cost in year $t$, is fully depreciated in the first year of construction. Thus, Equation (3) is simplified as follows:

$$\mathrm{LCOE} = \frac{I_0 + n \cdot M_t}{n \cdot E_t} \tag{4}$$

The denominator of Equation (4) includes the total generated electrical energy for the AGH over its operating years and consists of three components. The first one is the total energy generated from the PVs and received directly by the hotel ($E_{pv}$). The second one refers to the total energy generated by the PHS system during the evening ($E_{ev}$) and the third one refers to the total energy generated by the PHS system during the morning ($E_{m}$). Thus, Equation (4) can be described as follows:

$$\mathrm{LCOE} = \frac{I_0 + n \cdot M_t}{n \cdot (E_{\mathrm{pv}} + E_{\mathrm{ev}} + E_{\mathrm{m}})} \tag{5}$$

On the other hand, PP is one simpler financial index than LCOE, for evaluating the investment and is referred to the time needed for an investment to recover its initial outlay, in terms of profits or savings. The calculation of PP is given by Equation (6):

$$\mathrm{PP} = \frac{I_0}{G_{\mathrm{an}}} \tag{6}$$

where $I_0$ represents the total investment cost, and $G_{an}$ stands for the annual energy gain by the operation of the system.

## 4.2. System costs

### 4.2.1. PVs

The total cost of the photovoltaic installation consists of the individual costs of the panels, inverters, constant mounting bases, electrical equipment and the installation works.

Starting with the panels, for a total installation capacity of 150 kWp, 273 monocrystalline silicon panels are required, each costing €190. Thus, the total cost amounts to €51,870. To convert the DC current generated by the PVs into AC, to can be connected to the AGH's electrical system, three 3-phase DC/AC inverters without transformers, with 50 kW nominal power and €3300 cost each, are required. For supervising and monitoring the PV installation, a communication unit is selected, costing €100. The mounting system of the 273 PV panels on the flat floor of the AGH will be carried out using fixed mounting brackets with a total cost of €19,040. For the proper operation and control of the PVs and for their connection with the AGH, electrical panel boards, energy meters, suitable solar cables, circuit brakers and relays are required. The cost of this electrical equipment is estimated at €14,800. Finally, the labor cost for the panels' installation amounts to €24,000 and includes the transportation of the equipment to the hotel and their installation.

Thus, the total investment expenses for the PVs amount to €148,440 (including taxes). If this is divided by the installed capacity, the cost per installed kWp is €990. This cost is derived from an offer obtained from a company in Greece [39] and involves material prices for the year 2023. Indeed, the cost per installed kWp (€990) is very close to the cost determined theoretically by Tzouras [37] in his study (€975) for the installation of monocrystalline silicon PV panels with fixed bases on a roof. The annual maintenance expenditures for the PVs have been calculated at €2019 and cover panel maintenance, cleaning and insurance.

### 4.2.2. PHS

*Reservoirs*

The Goudemand example, mentioned in the introductory Section of this work, has placed the upper reservoir on the roof of the building. However, such a construction requires the structural reinforcement of the building's roof to support the tank, as well the reinforcement of the adjacent floors, in order to overcome the limitations regarding the stability. This problem escalates as the volume of the upper tank increases. In our case, where the upper reservoir has a volume of 2100 $m^3$, the indicative cost of reinforcing the building amounts to €1,274,350, according to a study by a civil engineer [40], rendering the entire system unsustainable and uneconomical. Therefore, the construction of an artificial hill in the hotel's vicinity for the placement of the upper tank could be a more sustainable solution. In this case, according to a study by a civil engineer [40], the cost of constructing an embankment hill amounts to €128,000, much lower than the cost of building's reinforcement. The expenditures for the upper reservoir could be minimized by using an existing hill close to the hotel, for placing the upper tank. This assumption has been handled in this paper. Therefore, the only expense related to the reservoirs is the construction cost of the upper tank, which according to a civil engineer's study, amounts to €268,140.

Reservoir costs are the main force of ambiguity about the total cost and implementation of the suggested system to a hotel. Indeed, the suggested system cannot be implemented in all existing hotels. In order for the cost of the tanks to be bearable from the hotel owners, a nearby hill is required to provide the required elevation. In this work, we have assumed that this elevation is provided by the surrounding landscape within the hotel property and only the reservoir will have to be constructed on top of it. Otherwise, this elevation will have to be created with appropriate civil work, which, as already mentioned, will cost approximately €128,000 in Greece. Of course, the exact cost is hard to define, as it heavily depends on location of the hotel and the cost of the required workforce and expertise: different costs apply to a small island, seaside town etc. Furthermore, most Greek hotels may be near the sea that could be used as the lower "tank" but access to the sea may not always be possible at a reasonable cost, due to geomorphological, legal or practical reasons. Of course, that cost also varies greatly, depending on the level of hydraulic works required to connect the system to the sea, as well as the cost of purchasing or hiring land in between or even acquiring appropriate permits from the authorities. Finally, even if there is a natural elevation for the upper reservoir within the property and the sea shore is accessible for use as a lower reservoir, energy savings from PHS operation may not always adequate to compensate for the loss of revenue from using the occupied space otherwise, e.g., building a garden, kiosk or even another hotel wing.

*PATs*

In this paper, the analysis included the study of 8 different PATs with power ranging from 15 to 85 kW. The estimation of the electro-mechanical equipment cost for the PAT $C_{EM}$ system is provided by the most recent expressions available in the literature Alzohbi [41], Novara et al. [42], Saidur et al. [43], which are presented in **Table 7**. PAT estimation is usually correlated as a function of power ($P_{BEP}$), head ($H_{BEP}$) and flow rate ($Q_{BEP}$) at design point. In the same table, the individual cost of the PAT-generator set $C_{PAT+GEN}$ [42] and the inverter required by PATs for the regulation of their shaft speed $C_{inv}$ [43], is provided. In this case, total cost $C_{EM}$ is given by the sum of these two individual costs, contrary to the expression found in Alzohbi et al. [41], which directly calculates $C_{EM}$. Implementing the equations, shown in **Table 7**, for the PAT cost, based on cost models found in the literature mentioned above, the $C_{EM}$ per analyzed PAT is calculated and presented in **Figure 9**. It is observed that, the deviation between the final costs calculated by the two approaches is insignificant. For the evaluation of the LCOE and payback period, the annual operation and maintenance cost $C_{O\&M}$ of the PAT were considered 15% of $C_{EM}$, as it is suggested from various studies by Marini et al. [44], De Marchis et al. [45], Hammond et al. [46].

**Table 7.** Calculation of $C_{\mathrm{EM}}$, based on cost models found in the literature.

| Expression | Related Cost | References |
|---|---|---|
| $1355.6 \times P_{\mathrm{BEP}}{}^{0.8296} \times H_{\mathrm{BEP}}{}^{-0.1035}$ (€) | PAT + gen + inverter | Alzohbi [41] |
| $11{,}913.91 \times Q_{\mathrm{BEP}} \times H_{\mathrm{BEP}}{}^{0.5} + 1289.92$ (€) | PAT + gen | Novara et al. [42] |
| $1239.9 + 165.72 \times P$(€) | Inverter | Saidur et al. [43] |

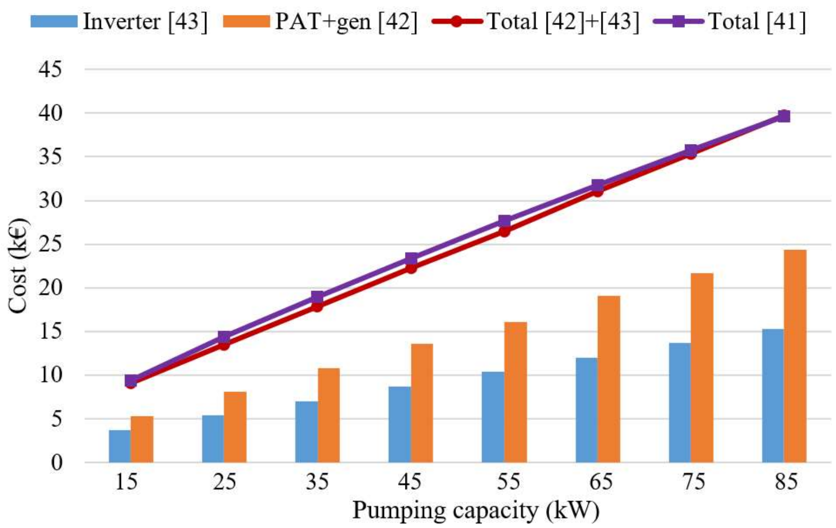



**Figure 9.** Total electro-mechanical equipment cost ($C_{EM}$), PAT-generator set cost ($C_{PAT+GEN}$) and inverter cost ($C_{inv}$) estimation with respect to different pumping capacities.

Sometimes due to unexpected leakages of the tanks, the upper reservoir can be emptied earlier than calculated and the PAT can be operating with almost zero water pressure. This can cause serious damage to the PAT, such as wear and cavitation. To overcome this unexpected situation, pressure gauges are installed within the tanks, which, once the water level exceeds a minimum threshold, stop the generation.

*Piping system and electro-valves*

For transferring water from the upper to the lower reservoir and vice versa, flexible PVC, 16-bar pipes are the most appropriate. Their connection with the reservoirs and with the inlet and outlet of the pump is achieved through a flange and a neck, while the sealing of the connection is ensured using electrofusion. For the entire piping installation, the following are required: 20 meters of flexible PVC pipe, 4 metal flanges, 4 necks and 4 electrofusions. Their cost ranges according to the internal and external diameter of each PAT as shown in **Table 8**.

For regulating water flow during generation, electro-valves with pneumatic actuator are selected. Their size depends on the external diameter of the PAT and hence their cost, which is also shown in **Table 8**, varies for each PAT studied.

**Table 8.** Total costs for PATs, piping system and electro-valves.

| PAT nominal power (kW) | PAT cost (€) | Piping system cost (€) | Electro-valve cost (€) |
|---|---|---|---|
| 15 | 9085.66 | 971.16 | 651.76 |
| 25 | 13,480.90 | 1571.76 | 808.84 |
| 35 | 17,876.13 | 1571.76 | 808.84 |
| 45 | 22,271.36 | 2485.96 | 1193.33 |
| 55 | 26,444.59 | 4021.24 | 1670.00 |
| 65 | 31,061.83 | 4021.24 | 1670.00 |
| 75 | 35,383.06 | 5602.00 | 3439.70 |
| 85 | 39,704.29 | 5602.00 | 3439.70 |

*Automation system*

An automation system is needed by PHS to operate according to the operating schemes explained in Section 3. This system consists mainly of a PLC. The PLC receives data from pressure meters, placed inside the reservoirs, and from the energy analyzer, and acts through a SCADA software on the electro-valve to control production. For connecting and disconnecting the PAT during the power generation, PLC acts on automations and relays in the low voltage electric panel board. The individual cost of these systems is presented in **Table 9** and is constant, regardless of the nominal power of each PAT.

**Table 9.** Total costs for the components of automation system.

| Automation | COST (€) |
|---|---|
| Programmable Logic Controller (PLC) | 520.00 |
| Energy analyzer | 360.00 |
| 2 pressure meters | 480.00 |
| SCADA software | 1200.00 |
| Electrical equipment | 1500.00 |

### 4.3. Total system cost

In the following **Table 10**, the total cost of the system for the different configurations is provided. As the reservoir and the automation system remains the same, indifferent of the PAT size, the total cost becomes a function of PAT size, since PAT size also determines the rest of the costs (piping system and electro-valves).

**Table 10.** Total system cost with respect to PAT size.

| PAT nominal power (kW) | Total system cost (€) |
|---|---|
| 15 | 431,349.6 |
| 25 | 436,501.5 |
| 35 | 440,896.7 |
| 45 | 446,590.7 |
| 55 | 452,775.8 |
| 65 | 457,393.1 |
| 75 | 465,064.8 |
| 85 | 469,386.0 |

### 4.4. Compensation scheme

It is considered that in a zero feed-in system, PV generation cannot be injected to the grid or cannot be compensated. In zero-feed grids, the transmission system is overly stretched, and no more permits can be given for net-metered or by-all-sell-all systems [47]. This is not an unusual situation already for many grids with high penetration of RES, such as the Greek system. Net metering started in Greece in 2013 and is about to end in 2024. With a net-metering system, consumers who have installed PVs on the roof of their homes, can inject the excess energy into the grid and be paid about that by the reduction of their energy bills. Now, such a system is replaced by a net-billing system. Similar results should be expected, though, if the system was simulated as a net-billing system [47], as this compensation scheme also incentivizes self-consumption of RES generation, such as the one provided by the PHS. Thus, consumers who have already installed a PV system at their homes, or are about to make such an installation, should find other ways to store the excess energy. From now on, in Greece, the only way the electricity to be reduced is by storing the excess generation through a PHS system and by covering parts of the peak demand with that energy.

The comparison between the reduced electricity bills and the electricity bills the AGH would pay without PVs and PHS, is the measurable compensation received by the operation of combined PVs and PHS. Separate analysis will follow: a) one that will calculate the cost of electricity for the AGH without PVs, which will be used as a base case, b) one with PVs but no PHS and c) one with both PVs and PHS in place. This way, the part of the compensation received purely by the operation of PHS will also be calculated, as a difference between the results of analysis b) and c).

## 5. Operational and financial assessment

In this Section, the methodology described in Section 2 is used to simulate the demand of the AGH, PV generation and PHS operation. The PHS system is assumed to take advantage of all the special properties of the AGH and is appropriately dimensioned for it (see subsection 4.1.1). The operation of the overall system is simulated and analyzed. The output of this analysis becomes the input for the financial assessment of the project. An AGH without the PHS is first considered as a benchmark case. Then its performance and financial attributes are compared with the same system, but with a PHS installed. The impact of both pumping schemes is considered (see subsections 3.1.1 and 3.1.2). The common system properties between all cases are the energy profile of the AGH, presented in Section 2.1, and the PV generation estimated in Section 2.2.

## 5.1. PV generation only

From the electricity tariffs presented in subsection 3.1.2 and the demand curves provided in Section 2.1, the annual energy cost for the AGH without PVs and PHS can be calculated. This cost amounts to 192,432 €/year.

With the PVs installed at the rooftop, covering part of the demand during daytime and having all excess generation during noon capped, the energy expenditures are reduced by 76,876 €/year to 115,556 €/year.

## 5.2. PVs and storage of excess generation at PHS

In this case, the PHS system pumps water only once per daily cycle, during excess PV generation, according to the scheme detailed in subsection 3.1.1. The results deriving from this analysis for different sizes of PATs (first column) are presented in **Table 11**. The new annual energy costs for each PAT size in order to cover AGH's demand are listed in the second column. By subtracting those costs from the annual energy cost of operating the system without PHS (Section 5.1), the profit from PHS operation can be calculated (third column). Using the annual costs and profits, the LCOE and the PP are also calculated according to Section 4.3, and listed in columns four and five, respectively.

**Table 11.** Annual energy cost and profits for the operation of the PHS system according to the scheme presented in subsection 3.1.1.

| PAT (kW) | Energy cost (€) | Profit from PHS operation (€) | LCOE (€/kWh) | PP (yr) |
|---|---|---|---|---|
| 15 | 107,070.83 | 8485.30 | 0.08512 | 5.05 |
| 25 | 104,781.04 | 10,775.09 | 0.08655 | 4.98 |
| 35 | 104,651.25 | 10,904.88 | 0.08978 | 5.02 |
| 45 | 105,253.73 | 10,302.40 | 0.09036 | 5.12 |
| 55 | 105,554.79 | 10,001.34 | 0.09780 | 5.21 |
| 65 | 106,863.69 | 8692.44 | 0.10282 | 5.34 |
| 75 | 108,212.44 | 7343.69 | 0.10833 | 5.52 |
| 85 | 107,286.81 | 8269.32 | 0.11063 | 5.51 |

## 5.3. Storage of excess PV generation and energy from the grid during lower tariff at PHS

The last case concerns the operation of the PHS system twice per daily cycle: a) when PV generation is greater than AGH's demand, and b) during the night, using the lower energy tariff provided by the grid. From the analysis conducted in this case (**Table 12**), even if more energy was purchased from the grid, the total energy cost has been reduced further from nighttime pumping (third column). In the same table, the LCOE and the PP for this case are also calculated according to Section 4.3.

**Table 12.** Annual energy cost and profits for the operation of the PHS system according to the scheme presented in subsection 3.1.2.

| PAT (kW) | Energy cost (€) | Profit from PHS operation (€) | LCOE (€/kWh) | PP (yr) |
|---|---|---|---|---|
| 15 | 106,844.22 | 226.61 | 0.08268 | 5.04 |
| 25 | 104,370.69 | 410.35 | 0.08202 | 4.96 |
| 35 | 104,056.37 | 594.88 | 0.08354 | 4.99 |
| 45 | 104,560.43 | 693.30 | 0.08661 | 5.08 |
| 55 | 104,847.64 | 707.15 | 0.08926 | 5.17 |
| 65 | 105,397.13 | 1466.56 | 0.09334 | 5.20 |
| 75 | 107,343.96 | 869.22 | 0.09902 | 5.47 |
| 85 | 106,356.96 | 929.85 | 0.10230 | 5.45 |

## 5.4. Comparison of results between cases

**Figure 10** presents a comparison of the economic indexes calculated for the AGH for various PAT sized for the same PHS system under the two different pumping schemes: pumping water once in a daily cycle (Section 5.2) and pumping twice in a daily cycle (Section 5.3). It can be easily noticed that PPs and LCOEs are comparable to other RES technologies with storage.

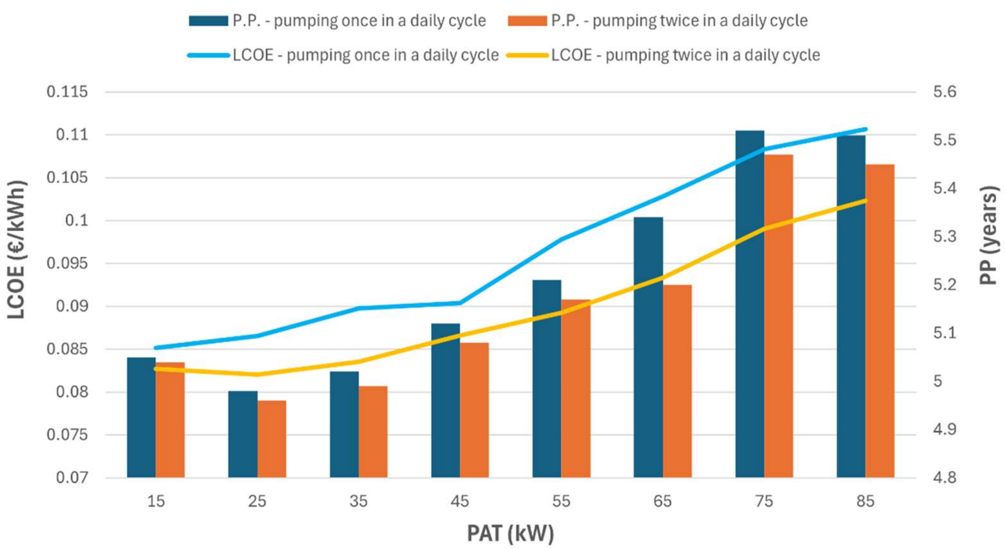



**Figure 10.** LCOE and PP of PHS system pumping either once or twice in a daily cycle.

First, if pumping takes place only when there is excess PV generation (i.e., once in a daily cycle) then the bigger the PAT becomes the more the LCOE increases. There is an optimal size of 25 kW, though, that fits AGHs demand and generation profile, providing the minimum PP. Furthermore, if the profits from PHS operation with respect to different PAT sizes are compared, then the 35 kW PAT is the optimal choice offering 10,904.88 €/year.

Interestingly, the same PAT size of 25 kW is considered as optimal, if the LCOE and PP are chosen as the economic assessment indexes for a PHS system that pumps water also during the cheaper energy tariff (pumping twice in a daily cycle). The results presented so far indicate that the construction of a micro-scale PHS system in buildings with a profile close to that of the AGH is feasible and economically viable. Obviously, if investment decisions are based on PP or LCOE they may be different from those derived from profit comparison: 25 kW PAT in the first case and 35 kW PAT in the second case. That happens because when comparing profits, the total costs of the installation are not taken into consideration.

The average LCOE from all PAT cases considered, is approximately 0.09 €/kWh. This value is in the range of 0.05 and 0.18 €/kWh, for PHS large-scale systems found in the literature by Zakeri and Syri [21], Mohsen Ibrahim Abd El-Rahman [48]. Considering now the PPs presented in Sections 5.2 and 5.3 for all PAT cases, we can observe that the system needs approximately 5 years to recoup the total investment. An average PP of 5 years for such a system is quite short, especially when compared to its lifespan of 25 years. This is explained by the fact that the annual profit provided by the system is quite high and when combined with the initial installation cost, a very short PP is achieved. Concluding, LCOE and PP indexes show that a micro-scale PHS system in combination with a PV installation, can provide electricity at a quite low total cost per kWh, compared with other methods of storage, such as batteries etc. [6,21].

## 6. Conclusions

In this work, a micro-scale PHS system has been suggested as energy storage for the AGH with PVs installed at its roof. Appropriate modelling of PV generation and demand throughout the year, allowed a good estimation of the excess generation available for storage. Since time-of-use tariffs exists in Greece, the extension of the pumping operation during the cheaper tariff was also investigated. PAT operation for PATs with different nominal power has been modelled for part load, both in pumping and generating mode. Such modeling of PATs in the economic assessment of PHS systems has not been previously presented. The simulation results of the overall system provided solid evidence that a micro-scale PHS system is a viable investment, if attention is paid in taking advantage of special properties of the installation in order to reduce installation costs (using the sea as the lower tank for PHS, covering the roof with PV etc.). The size of the PAT also plays pivotal role. Depending on the financial index used during decision, a different PAT size may qualify as the best choice. In the case of the AGH, it was proven that a 25 kW PAT is sufficient when LCOE or PP is considered, and 35 kW PAT is better if the profit is the decisive factor.

For the PHS system of the AGH, described in this paper, it was assumed an average upper reservoir volume of 2100 w.m. By increasing this volume, the PHS system's capacity is also increased and therefore, more water can be pumped and exploited through the day. A preliminary expansion of the system's capacity is possible, since a large amount of PV generation remains unexploited with the use of the 2100 q.m. tank. An alternative way to reduce the unexploited energy from PVs, after energy has already been stored through the PHS system, is the shift of hotel's energy-intensive processes (such as laundry, kitchens or water heating) to those hours during the day when this excess energy is available. Long-term, the collection of the rainwater to the upper reservoir would certainly improve PHS system's total energy efficiency. Greece is predominantly a rainy country, with big amounts of rainfalls throughout the year. The collection of this water would decrease the daily required water for fulfilling the upper tank and consequently the energy needed from the pump. The above-mentioned possible solutions of increasing the dimensions of the PHS system and exploiting the rainfall waters, in conjunction with the better dimensioning of the PV's installation and selection of the required equipment, will lead to a much better and more sustainable energy storage system for the AGH.

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## Abbreviations

| | |
|---|---|
| AGH | Average Greek Hotel |
| BEP | Best Efficiency Point |
| RES | Renewable Energy Sources |
| LCOE | Levelized Cost of Energy |
| LCOS | Levelized Cost of Storage |
| PP | Payback Period |
| PV | Photovoltaic |
| PVGIS | Photovoltaic Geographical Information System |
| PLC | Programmable Logic Controller |
| PAT | Pump As Turbine |
| PHS | Pumped Hydro Storage |

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