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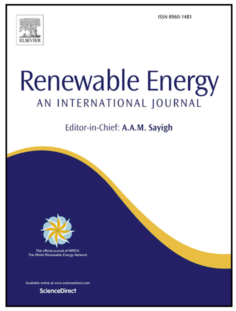

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PII: S0960-1481(25)02265-7

DOI: https://doi.org/10.1016/j.renene.2025.124601

Reference: RENE 124601

To appear in: *Renewable Energy*

Received Date: 24 June 2025

Revised Date: 11 October 2025

Accepted Date: 11 October 2025

Small Hydropower Plant enhanced with minimal storage capacity: Investigation of its techno-economic feasibility with intra-day regulation

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Highlights:

- Water tank addition to run-of-river small hydropower plant for low inflow operation
- New operational rule for storage-enhanced run-of-river production
- Techno-economic assessment to determine the appropriate concrete water tank volume
- Sensitivity analysis vs electricity price, lifespan, discount rate, investment cost

Abstract: In recent years, the penetration of Renewable Energy Sources (RESs) into the EU energy market has become increasingly significant. The perpetual availability of RESs, has given them the leverage of enabling rapid and growing implementation. Propelled by the above, this research examines how one of the most well-known and widely adopted renewable energy sources, namely run-of river hydropower plants, can be optimized to reduce their uncertainty and thus facilitate their integration into the grid. In particular, it is assessed how a Small Hydropower Plant (SHPP), operating as a typical run-of river scheme, can benefit from the addition of a small storage tank. In this vein, a novel operation rule of the SHPP with storage tank is proposed on a daily basis with hourly step, to ensure the best exploitation of the passing inflows. To evaluate the possible augmentation of the SHPP's efficiency, different scenarios are investigated regarding the size of the storage tank based on a percentage of the mean daily water supply. The results are rated after conducting a techno-economic assessment for each scenario, also considering their construction costs and the surplus from energy production due to storage. Key Performance Indicators are the Net Present Value (NPV), the Internal Rate of Return (IRR) and the Benefit-Cost ratio (B/C). Additionally, a sensitivity analysis is performed regarding the electricity sales prices, total investment cost, economic lifespan and discount rate. From the results for the small hydropower plant of nominal power 6.9 MW, net head 300 m, maximum inflow 2.40 m^3/s, at the Argyri area of river Platanias, Greece, which is being studied, it is found that tanks with a capacity of up to 5% of the mean daily water supply are technically and economically viable. The optimal result is achieved for a capacity corresponding to 1% of the mean daily water supply, with an active volume of 620 m^3, basic cost of 120 k€, with a Net Present Value equal to 436 k€, Internal Rate of Return equal to 40.83% and Benefit-Cost ratio equal to 3.99, for an economic lifespan of 20 years and a discount rate of 6%.

Keywords: small hydropower plant, run-of-river plant, energy storage system, daily regulation, feasibility study

1. Introduction

1.1. Motivation

Throughout the last two decades the EU has paved the way towards a more sustainable future by setting and establishing an ensemble of policies and targets. The latest policy is the European Green Deal (January 2020) whose implementation aims at climate neutrality by 2050. In addition, an intermediate goal of reducing Greenhouse Gas (GHG) emissions by at least 55% until 2030 has been also proposed and set into action by EU member states. Renewable energy sources entail a plethora of advantages and possibilities, the most important of which being the generation of abundant, distributed, low-cost and clean energy, in compliance with the global goal of decarbonization across all human activities (e.g. in residential, industry, transportation, commercial and agriculture sectors). Additionally, RESs, can provide autonomy at the national level, by taking into advantage the climatic and geographical conditions of each country. On the other hand, renewable sources are directly linked to natural phenomena that are related to hydroclimatic processes, such as precipitation, wind velocity and solar radiation, and local atmospheric conditions (e.g., cloud cover). All the above processes are subject to stochasticity, and thus uncertainty across all scales, and therefore, the use of RESs alone, cannot provide stability to the grid [1]. As a result, it is important to improve these technologies and provide further flexibility and reliability during their operation. In this context, many demand side management methods have been proposed, starting from the level of the interconnected power system of a country [2] and moving to smaller levels (in the sense of size) of energy communities, in the form of microgrids [3], in the form of large building complexes [4], in the form of small buildings [5] and in the form of small devices controlled by the Internet of Things (IoT) [6]. Technologically, they are combined with various types of energy storage systems (ESS), such as electrical [6] thermal energy [7], ice-thermal energy storage [8], natural gas/hydrogen storage [9], even reaching the configuration of virtual devices via IoT [5]. Batteries of various technologies are utilized, such as vanadium redox ESS with high capacity [2], electric vehicles batteries [4], battery integrated roof top solar panel [6], taking into account different utilization strategies, competitive or cooperative [10]. The corresponding results are improved when combined with heating, ventilation and air-condition loading management [10], with cogeneration [7] or even virtual production units [11]. On the contrary, a smaller number of studies have been conducted around the overall design of electrical power systems, whether autonomous, general-purpose [8] or specialized applications, or for an interconnected system [12].

Especially in the case of small run-of-river hydropower plants (SHPP), stochasticity is due to the variability of streamflow, which is the overall input process. However, if excluding flood events, this process exhibits minor only fluctuations on a daily basis, compared to the corresponding processes that drive wind and photovoltaic energy. A key characteristic of SHPPs is that, due to technical limitations of the hydro turbines, combined with the lack of regulation capacity, the exploitable water supply is restricted to a range between a technical minimum and maximum limit. Below this minimum, the turbine does not operate and the entire supply overflows, while above the technical maximum, the excess water overflows. Consequently, the energy exploitation degree of SHPPs is limited. In contrast, large hydroelectric reservoirs, although relying on the same technology, due to their storage capacity, can utilize a significant part of their hydropower potential, eventually offering reliable and predictable electricity.

At the design context, the problem of lack of regulation across run-of-river SHPPs is partially addressed through a suitable mixing of turbines, preferably a large and a smaller one, which allows to extend the range of exploitable flows [13]. Another option, which is the motivation of this research, is the incorporation of a small, and thus low-cost, storage element. For, the addition of a small tank/reservoir can improve the utilization of water at the intraday scale, especially during periods of water supply lower than the technical minimum, by re-adjusting it for short periods of time, of about one hour. In this vein, the question of the techno-economic viability of such a solution is raised, which is the focus of this paper.

1.2. Literature Review

Different approaches have been put into action to mitigate the deficiencies of run-of-river SHPPs with lack of storage and improve their capacity factor. Past studies have established that it is possible to reduce the uncertainty of those plants by using well-calibrated forecasting models and thus better predicting energy production in short-term [14]. Another solution, involving the design of the system, comes from the formation of a turbine mixing of different sizes (in terms of power capacity) and/or types, instead of one turbine or a twin-system. The above can be more challenging, leading sometimes to unsustainable investments, whilst -in some cases- promising more flexibility to the system and higher profit [15]. A more promising SHPP regulation rule, involving the change of priority among the large and the small turbines across different ranges of flow values, is proposed in [13], where the results show that the use of two turbines of different sizes, can lead to additional energy production (when compared to existing methodologies), thus maximizing the profitability of SHPPs.

Further improvement in the sector of RESs can be achieved via the integration of Energy Storage Systems (ESSs). Energy storage systems can mitigate the greatest weakness of RESs, meaning their inability to always align production with demand, thus causing curtailment and grid imbalance issues. Furthermore, by storing and exploiting the energy surplus produced during periods of peak production with respect to low demand, multiple benefits can be obtained; namely, the replacement of conventional energy sources as well as the opportunity for greater profit on behalf of the RESs Operators, through higher energy market prices.

Among the common renewable sources, solar and wind systems combined with ESSs seem to draw the interest of the research community so far, as compared to hydropower [16]. Apart from Pumped Storage Hydropower Plants (PSHP) and their combined operation with photovoltaic and/or wind parks [17], run-of-river hydropower plants have not yet managed to attract similar interest in the field of ESS. The optimized operation of this type of renewable energy has been focused mostly on the improvement of its technical characteristics. These include nominal capacity, turbine type and runner blade configuration [18]; the design of specialized turbines such as waterwheels for low water inflow [19]; analysis of inlet conditions and hydraulic losses across trash racks [20]; sizing of the settling basin [21]; evaluation of the surge tank with respect to head losses [22] and stability analysis [23]; optimization of the placement of core components (surge tank, power house, intake) using an automated mesh-sweeping approach driven by geographic information systems [24]; and dimensioning of electromechanical equipment (turbine, generator, penstock) based on levelized cost of energy [25]. Usually, the SHPPs are combined with batteries, implementing the appropriate energy management systems [26], optimal day-ahead scheduling for power production [27], studying transient analysis [28], solving stability [29] and frequency control issues [30], simulating a virtual power plant [31]. Rather rarely, they are combined with flywheels for very short-term energy storage, in the case of strongly fluctuating loads [32] or with the use of two tanks and compressed air storage [33].

1.3. Objective and contributions of the paper

In response to the above, in this paper the operation of a real-world run-of-river SHPP with a storage tank is examined, as opposed to [34], which examines the energy utilization of stored water, in settling basin, forebay tank and upper part of penstock during periods of low water inflow. By including a small-scale storage facility in the current infrastructure, the load of the incoming flows that would otherwise be lost, can be stored, and be exploited later, in an efficient way, following a proposed operation rule. Main goal of this study is the techno-economical evaluation of the profitability of such configuration, with the implementation of a novel operation rule for energy production optimization. The proposed operation rule is examined in eleven scenarios, with different tank sizes based on a percentage of the mean daily water supply. For each scenario, the techno-economic variables are calculated, considering construction costs and surplus of energy production due to storage. In this vein, the most profitable scenario is investigated, where the best possible equilibrium is achieved, between the income from energy production surplus and expenses (mainly, investment cost). Key Performance Indicators (KPIs), of the study, used to evaluate the most sustainable investment, are the Net Present Value (NPV), the Internal Rate of Return (IRR) and the Benefit- Cost ratio (B/C). These indices or related metrics have been taken into consideration, to define the financial viability of SHPPs in numerous studies [35]. In addition, a sensitivity analysis is performed in regard to electricity selling prices to the power system, total investment cost, economic lifespan and discount rate.

In summary, the innovative points of the suggested approach are the following:

- Combination of a small run-of-river power plant with a small tank for the utilization of water discarded during periods of inflows lower than the turbine technical minimum;
- Size selection of reinforced concrete tank, where capacity is correlated to a percentage of the mean daily water supply of the river;
- Establishment of a novel operation rule for the tank-turbine system, for the optimization of power production and the exploitation of small river inflows, which in ordinary SHPP remain unexploited;
- Techno-economical assessment of the storage-enhanced system;
- Sensitivity analysis for different, stable, electricity selling prices to the power system, total investment cost of tank, economic lifespan and discount rate of the investment plan, so as to assess the economic sustainability of the proposed solution.

1.4. Organization of the paper

In Section 2, the basic steps of the problem formulation are presented, including a description of the operational characteristics of the SHPP, the effects of the existence of a storage tank on the operation of the SHPP and the proposal of its operating rule along with the tank. In section 3, a brief analysis of the technical characteristics of different tanks and a cost analysis for its proposed type to be utilized are carried out. In section 4, the SHPP case study is analyzed in terms of hydrological and technical characteristics, as well as the design of the tanks under consideration. Section 5, presents the results of the application of the methodology, the sensitivity analysis and the relevant discussion. Finally, in section 6, the conclusions are summarized.

2. Problem Formulation

2.1. SHPP operation characteristics

Environmental flow to be released downstream of the intake is the first step of the hydrological analysis of a hydropower plant. Its proper estimation is fundamental in order to secure sustainable conditions of fauna and flora of the downstream ecosystem [36].

According to Greek legislation for SHPPs, the environmental flow or otherwise ecological flow is the highest value among the following (a) 30% of mean inflow of June, July and August, (b) 50% of the mean inflow of September and (c) 30 l/s. The values of (a) and (b) result from the available hydrological data.

After the streamflow ends up at the intake, it is diverted to a settling basin, and further on through an open channel to a forebay tank and then, through a penstock, is lead to the turbine unit. The nominal power capacity of the plant depends on the topography and the hydrological regime of the selected area. The topography affects the capacity of the plant since it determines the elevation difference between the water intake and the power station, as well as the layout of the transfer system (affecting the hydraulic losses). On the other hand, the hydrological regime defines the range of the possible discharge values which can be exploited. In order to easily quantify the latter, the formulation of the flow duration curve (in a daily basis) is pivotal, since it reveals the percentage of time during which supply exceeds a specific value in an average year. Depending on the given profile of the flow duration curve, the operation design point is selected, accompanied by a percentage of exceeding time. Regarding run-of-river SHPPs, it is generally acceptable to select a discharge value with an exceedance percentage ranging from 20% to 50% of the time. The selected design point of the turbine unit, along with the available elevation can lead to the selection of the type and size of turbine, by referring to the relevant graphs [37].

Moreover, the type of turbine determines the limits under which the unit will operate. The operation range of the turbine system is defined by two values, i.e., the minimum, q_{min}, and maximum, q_{max}, of discharge. In the case of inflows that do not fall within these limits, the system cannot produce additional power. In other words, as marked in Fig. 1, two areas of inflow remain unexploited. One, when the streamflow q_t is lower than the lower limit of operation, q_{min}, (pink area) and as a result that amount goes unexploited, since the turbine stays inactive, and, another when the inflows q_t are greater than the upper limit of operation, q_{max}, (yellow area) and the surplus flow, $q_t - q_{max}$, remains unused, since the turbine has reached its maximum level of operation. In both cases the turbine system is unable to produce power, due to various physical, mechanical and operational restrictions of the mechanical equipment. These areas of unexploited water in Fig. 1, most likely consist a significant part of the cumulative discharge which could pass through the unit, and is therefore necessary that a solution be found towards utilizing them. The above operation, as described in [15] is summarized by calculating the total discharge passing through the turbine or turbines $q_{turb,t}$ and the overflow (not passing through the turbine) $q_{spill,t}$ at time t respectively:

$$q_{turb,t} = \begin{cases} q_{max}, & if\ q_{max} < q_t \\ q_t, & if\ q_{min} \leq q_t \leq q_{max} \\ 0, & if\ q_t < q_{min} \end{cases} \tag{1}$$

$$q_{spill,t} = \begin{cases} q_t - q_{max} & if\ q_{max} < q_t \\ 0, & if\ q_{min} \leq q_t \leq q_{max} \\ q_t, & if\ q_t < q_{min} \end{cases} \tag{2}$$

The produced power from the SHPP is derived from (3):

$$P = \eta_T \cdot \gamma \cdot q_{turb} \cdot H_{net} \tag{3}$$

where, η_T is the total efficiency of the SHPP, γ the specific weight of water equal to 9.81 kN/m^3, q_{turb} the total discharge passing through the turbine or turbines, and H_{net} the elevation difference between the upstream water level and the tailrace outlet, minus the hydraulic losses across the conveyance system.

The total efficiency of the plant, η_T, results as the product of the turbine, generator and transformer efficiencies, as shown in (4):

$$\eta_T = \eta_{TUR} \cdot \eta_{GR} \cdot \eta_{TR} \tag{4}$$

where, η_{TUR} is the efficiency of the turbine unit, η_{GR} the efficiency of the generator unit, and η_{TR} the efficiency of the transformer unit.

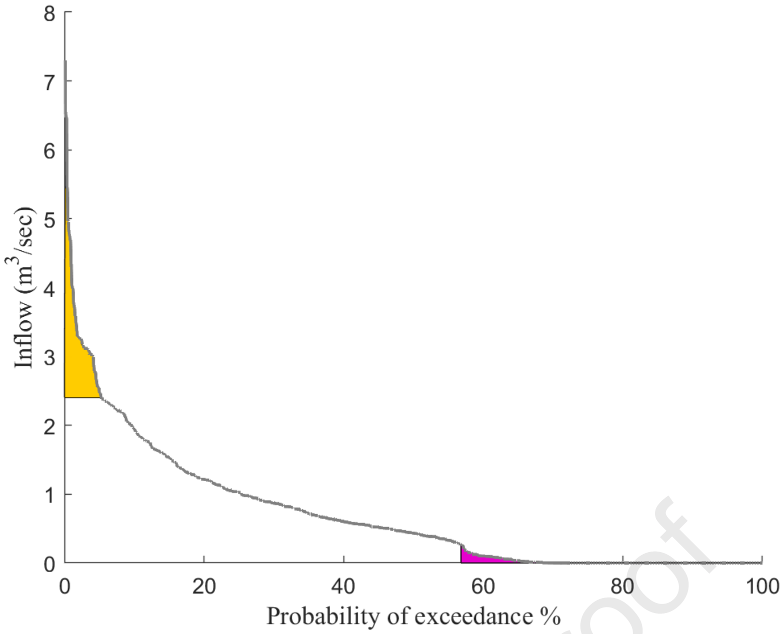


Fig. 1. Flow duration curve and volumes of unexploited areas due to lack of storage in SHPPs

2.2. Augmented operation of an SHPP due to storage

While searching to improve the performance of SHPPs and thus achieving additional energy production, it is investigated how the unit will operate in combination with a storage tank, regulated under an optimal operation rule. The developed optimization method sets as key design parameter the size of the tank, which is determined through the cost of the tank and the profit that can be obtained through the optimal exploitation of the available inflows.

Primarily, it is essential to determine the time limitations, around which the suggested methodology will be developed, followed by the formulation of the algorithm that will define the operation of the SHPP. Given these limitations, and in order to formulate the mathematical background of the problem, two boundary conditions are taken into consideration, $t_{min,oper}$ and t_{min,no_oper}. These represent the operational time frames within which the turbine is bound to operate to ensure proper performance of the electromechanical equipment, and are defined as follows:

i. The minimum operating time $t_{min,oper}$, by which it is ensured that the number of restarts does not exceed the manufacturer's guidelines and that once it is operating, it should continue for a time minimum, for technical reasons, e.g. axis lubrication etc. According to common experience this should be no less than 25 minutes.

ii. The minimum time of no operation t_{min,no_oper}, by which it is ensured that the number of restarts does not exceed manufacturer's guidelines, and that the generator is protected from overheating etc. According to common experience this should be no less than 5 minutes.

Taking into account these conditions, the main boundary condition upon which the algorithm is formulated, results from eqs. (5) and (6). Δt represents the selected time step used to discretize (process) the flow data, which also determines the step of calculations in the algorithmic process. The following express the relation between the time step Δt and the two boundary conditions of operation $t_{min,oper}$ and t_{min,no_oper}:

$$\Delta t \geq t_{min,oper} + t_{min,no\_oper} \tag{5}$$

where, Δt is typically set equal to 1 hour.

$$t_{min,oper} \leq \Delta t_{turb,operation} \text{ and } \Delta t - \Delta t_{turb,operation} > t_{min,no\_oper} \tag{6}$$

where $\Delta t_{turb,operation}$ is the time period during which the turbine produces energy in the case of interrupted operation within Δt.

2.3. Proposed operation rule of SHPP with storage

Taking into consideration the above rationale, the novel operation rule of the SHPP with storage is divided in two main cases, case (I) where $q_t \geq q_{min}$ and case (II) where $q_t < q_{min}$. Both are explained below:

- *Case (I): Inflow conditions (regime)* $q_t \geq q_{min}$: Under this flow regime, the turbine unit operates regardless of the contribution of the storage tank. As a result, it exploits the incoming flows which belong between the operation range of the turbine unit. In particular, two possible scenarios can be observed:
  a. $q_t \leq q_{max}$, in which the amount of inflow that is led directly to the turbine equals to q_t, thus do not leaving water excess to be stored:

$$V_{q,t} = V_{q,t-1} \tag{7}$$

  or to be spilled:

$$spill_t = 0 \tag{8}$$

  where $V_{q,t}$ is the volume of the storage tank at time t, $spill_t$ the spilled volume as excess at time t.
  b. $q_t > q_{max}$, in which the amount of inflow that is led directly to the turbine equals q_{max}, and the surplus (q_t-q_{max}) is stored in the tank. In case of meeting the maximum capacity of the tank $V_{tank,max}$, the surplus in volume is considered as spilled volume. These are described in the following:

$$V_{q,t} = min\{V_{q,t-1} + (q_t - q_{max}) \cdot \Delta t, V_{tank,max}\} \tag{9}$$

$$spill_t = (q_t - q_{max}) \cdot \Delta t - \left(V_{q,t} - V_{q,t-1}\right) \geq 0 \tag{10}$$

  This flow regime occurs sporadically resulting to high values of q_t especially during flood events. Under these conditions, in order to protect the unit and its equipment from damage, shut down is mandatory. It becomes clear that periods of extreme inflows are periods of no revenue for the SHPP. This is addressed through the addition of a storage tank, which will store as much water as possible for future use.
- *Case (II): Inflow conditions (regime)* $q_t < q_{min}$: During low flow periods, when the inflow q_t sets below the lower limit of turbine operation q_{min}, it is selected, if possible, to store the inflow in the tank, calculating the potential storage volume (without having maximum volume restrictions, as it can be utilized during this period) $proxV_{q,t}$, at time point t, equal to:

$$proxV_{q,t} = V_{q,t-1} + q_t \cdot \Delta t \tag{11}$$

  If the storage tank is not available, these amounts of water will go unexploited.
  Aiming that the operating point of the SHPP will be equal to the design point, it is first examined whether the condition of the potential storage volume $proxV_{q,t}$, at time period t, can ensure that the discharge passing through turbine q_t is equal to the design supply q_{des}. It is then examined if the period of operation Δt_{opt} satisfies (5) and (6), calculated as follows:

$$\Delta t_{opt} = proxV_{q,t}/q_{des} \tag{12}$$

  As a result, three possible scenarios arise:
  a. If $\Delta t_{opt} \geq t_{min,oper}$ and Δt-$\Delta t_{opt} \geq t_{min,no\_oper}$, the turbine operates under its design discharge q_{des} for the time period Δt_{opt}:

$$q_{turb,t} = q_{des} \tag{13}$$

  while the volumes of the storage tank $V_{q,t}$ and of spillage $spill_t$ are given by (14) and (15), respectively.

$$V_{q,t} = min\{proxV_{q,t} - q_{des} \cdot \Delta t_{opt}, V_{tank,max}\} \Rightarrow V_{q,t} = 0 \tag{14}$$

$$spill_t = \left(q_t \cdot \Delta t - q_{des} \cdot \Delta t_{opt}\right) - \left(V_{q,t} - V_{q,t-1}\right) \geq 0 \Rightarrow spill_t = 0 \tag{15}$$

  On condition that the maximum capacity of the tank $V_{tank,max}$ is greater than the necessary volume of water that must be supplied, during the operating phase, that is:

$$V_{tank,max} \geq (q_{des} - q_t) \cdot \Delta t_{opt} \tag{16}$$

  b. If $\Delta t_{opt} < t_{min,oper}$, the turbine cannot operate under its design discharge q_{des}. In this case the discharge q_t passing through the turbine cannot be equal to the design supply q_{des}, as it is mandatory that the time condition $t_{min,oper}$ is satisfied. Thus, the potential discharge that the turbine may exploit $q_{turb,p,t}$ is given by:

$$q_{turb,p,t} = proxV_{q,t}/t_{min,oper} \tag{17}$$

  However, the turbine must comply with the operating restrictions, so in this case the lower limit that was initially activated is checked again, i.e. the turbine operates with discharge flow q_{turb} for the time period $t_{min,oper}$:

$$q_{turb,t} = \begin{cases} q_{turb,p,t}, & if\ q_{turb,p,t} \geq q_{min} \\ 0, & if\ q_{turb,p,t} < q_{min} \end{cases} \quad (18)$$

While for the rest time interval Δt- $t_{min,oper}$ is zero.

The volumes of the storage tank $V_{q,t}$ and of spillage $spill_t$ derive from piecewise functions, given by (19) and (20), respectively.

$$V_{q,t} = \begin{cases} min\{proxV_{q,t} - q_{turb,t} \cdot t_{min,oper} = 0, V_{tank,max}\} = 0, & if\ q_{turb,p,t} \geq q_{min} \\ min\{proxV_{q,t}, V_{tank,max}\}, & if\ q_{turb,p,t} < q_{min} \end{cases} \quad (19)$$

$$spill_t = \begin{cases} 0, & if\ q_{turb,p,t} \geq q_{min} \\ q_t \cdot \Delta t - (V_{q,t} - V_{q,t-1}) \geq 0, & if\ q_{turb,p,t} < q_{min} \end{cases} \quad (20)$$

On condition that the maximum capacity of the tank $V_{tank,max}$ is greater than the necessary volume of water that must be supplied, during the operating phase, that is

$$V_{tank,max} \geq (q_{turb,t} - q_t) \cdot t_{min,oper} \quad (21)$$

c. If Δt-Δt_{opt}< t_{min,no_oper}, the turbine is regulated to operate for a smaller period of time and a discharge higher than its design discharge q_{des}, in order to comply with the time condition boundary, so the period of operation will be equal to Δt-t_{min,no_oper}. Thus, the potential discharge that the turbine may exploit $q_{turb,p,t}$ is given by:

$$q_{turb,p,t} = proxV_{q,t} / (\Delta t - t_{min,no\_oper}) \quad (22)$$

However, the turbine must comply with the operating restrictions, so in this case the upper limit that may be activated, due to the brief operating time of the turbine, is checked, i.e. the turbine operates with discharge flow q_{turb} for the time period (Δt-t_{min,no_oper}):

$$q_{turb,t} = \begin{cases} q_{max}, & if\ q_{turb,p,t} \geq q_{max} \\ q_{turb,p,t}, & if\ q_{turb,p,t} < q_{max} \end{cases} \quad (23)$$

While for the rest time interval t_{min,no_oper} is zero.

The volumes of the storage tank $V_{q,t}$ and of spillage $spill_t$ are given by (24) and (25), respectively.

$$V_{q,t} = min\{proxV_{q,t} - q_{turb,t} \cdot (\Delta t - t_{min,no\_oper}), V_{tank,max}\} \quad (24)$$

$$spill_t = \left(q_t \cdot \Delta t - q_{turb,t} \cdot (\Delta t - t_{min,no\_oper})\right) - (V_{q,t} - V_{q,t-1}) \geq 0 \quad (25)$$

On condition that the maximum capacity of the tank $V_{tank,max}$ is greater than the necessary volume of water that must be supplied, during the operating phase, that is

$$V_{tank,max} \geq (q_{turb,t} - q_t) \cdot (\Delta t - t_{min,no\_oper}) \quad (26)$$

To understand the above line of reasoning, let's consider a small hydroelectric power unit, with a single turbine, that operates between a minimum flow rate q_{min}=1.00 m^3/s and a maximum flow rate q_{max}=2.40 m^3/s, with design supply q_{des}=2.00 m^3/s, minimum operating time $t_{min,oper}$ =25 min, minimum time of no operation t_{min,no_oper}=10 min, with a maximum active tank volume $V_{tank,max}$=2,000 m^3, initial available active volume $V_{q,t-1}$=100 m^3, while the time step Δt is 1 h. Depending on the available streamflow q_t, the following indicative examples arise:

- If the streamflow q_t is equal to 1.80 m^3/s, i.e. between q_{min} and q_{max}, then according to case I(a) all the streamflow q_t is channeled through the turbine, the stored volume of the reservoir does not change, according to eq. (7), and there is no overflow according to eq. (8). This continues up until the streamflow q_t changes.
- If the streamflow q_t is equal to 2.70 m^3/s, i.e. greater than q_{max}, then according to case I(b) the turbine receives the maximum flow q_{max}, while the remaining flow rate q_t-q_{max} =0.30 m^3/s is initially channeled into the tank until it is filled. Specifically, for the first time step Δt 0.30 m^3/s·3600 s=1,080 m^3 are available, so the stored volume of the tank $V_{q,t}$ changes, according to eq. (9), to 1,180 m^3 (which is less than 2,000 m^3) and there is no overflow according to eq. (10). During the second time step Δt, 1,080 m^3 are again available, but now the initial stored volume from the previous time point $V_{q,t-1}$ is 1,180 m^3, hence the stored volume of the tank $V_{q,t}$ changes, according to eq. (9), to 2,000 m^3 (as 1,080+1,180=2,260 m^3 would be available, but the maximum active volume is 2,000 m^3). Therefore, 260m^3 overflow, as calculated from eq. (10). The turbine continues to operate at maximum flow rate q_{max}. During the third time step Δt, 1,080 m^3 are again available, though now the initial stored volume from the previous time point $V_{q,t-1}$ is 2,000 m^3, so the stored volume of the tank $V_{q,t}$

remains equal to 2,000m^3, according to eq. (9), since 1,080+2,000=3,080 m^3 would be available, when the maximum active volume is 2,000 m^3. So, 1,080 m^3 overflow, as calculated from eq. (10). The turbine continues to operate at maximum flow q_{max}. This continues up until the streamflow q_t changes.

- If the streamflow q_t is equal to 0.90 m^3/s, i.e. less than q_{min}, then the potential storage volume $proxV_{q,t}$ is calculated to be 100+0.90m^3/s·3,600s= 3,340 m^3, according to eq. (11), and the period of operation Δt_{opt}, under the design supply q_{des}, is equal to 3,340 m^3/2.00 m^3/s= 1,670s, by eq. (12). The turbine can operate under the design supply q_{des} for a longer time than the minimum operating time, as Δt_{opt}=1,670 s> $t_{min,oper}$ =1,500 s, while it interrupts its operation per time step Δt for a time longer than the minimum time of no operation, since Δt-Δt_{opt}=3,600-1,670=1,930 s> t_{min,no_oper} = 600 s. Hence, this falls under II(a), where initially the tank stores water for Δt-Δt_{opt}=1,930 s, reaching a total volume equal to 100+0.90m^3/s·1,930 s= 1,837 m^3, which is less than the maximum active volume $V_{tank,max}$=2,000 m^3 according to eq.(16). Then the stored water is delivered to the turbine for a period of time Δt_{opt}=1,670s. The turbine operates under the design supply q_{des}=2.00 m^3/s, where the streamflow q_t provides 0.90 m^3/s and the remaining supply is provided by the tank. At the end of time step Δt=1h, the stored volume of the tank $V_{q,t}$ changes, according to eq. (14), to 0 m^3 and there is no overflow, by eq. (15).
- If the streamflow q_t is equal to 0.20 m^3/s, i.e. less than q_{min}, then the potential storage volume $proxV_{q,t}$ is calculated to be 100+0.20m^3/s·3,600 s= 820m^3, according to eq. (11), and the period of operation Δt_{opt}, under the design supply q_{des} is equal to 820 m^3/2.00 m^3/s= 410s, according to eq. (12). The turbine cannot operate under the design supply q_{des}, for a time equal to the minimum operating time, as Δt_{opt}=420 s< $t_{min,oper}$ =1,500 s. So this falls under II(b), where the potential discharge, that the turbine may exploit $q_{turb,p,t}$, is calculated as equal to 820 m^3/ 1,500s =0.5467 m^3/s , which is less than the minimum operating flow q_{min}=1.00 m^3/s, so the turbine does not operate, i.e. $q_{turb,t}$=0, as per eq. (18). Therefore, during this time step water is stored in a tank $V_{q,t}$ reaching a volume $proxV_{q,t}$ of 820 m^3, which is less than the maximum active volume, $V_{tank,max}$=2,000 m^3, according to eq. (19). Also, there is no overflow, according to eq. (20). In the next time step, again with the same streamflow q_t, the potential storage volume $proxV_{q,t}$ is calculated to be 820+0.20 m^3/s·3,600 s= 1,540 m^3, by eq. (11), and the period of operation Δt_{opt}, under the design supply q_{des}, is equal to 1,540 m^3/2.00 m^3/s= 770s, according to eq. (12). The turbine cannot operate under the design supply q_{des} for a time equal to the minimum operating time, since Δt_{opt}=770 s< $t_{min,oper}$ =1,500 s. Therefore, this falls under II(b), where the potential discharge $q_{turb,p,t}$ is calculated to be 1,540m^3 / 1,500s =1.02667m^3/s, which is greater than the minimum operating flow q_{min}=1.00 m^3/s, thus the turbine operates with $q_{turb,t}$=1.02667 m^3/s as per eq. (18). Initially, the tank stores water for Δt-$t_{min,oper}$ =3,600-1,500=2,100 s, reaching a total volume equal to 820+0.20 m^3/s·2,100s= 1,240 m^3, which is less than the maximum active volume $V_{tank,max}$=2,000 m^3 according to eq. (21). Then the stored water is delivered to the turbine, for a period of time $t_{min,oper}$=1,500 s. The turbine operates with $q_{turb,t}$=1.02667 m^3/s, where the streamflow q_t provides 0.20 m^3/s and the remaining flow is from the storage tank. At the end of the time step Δt=1h, the stored volume in the tank $V_{q,t}$, changes according to eq. (19) to 0 m^3 and there is no overflow, as per eq. (20).

To activate II(c), a different case of tank is required, regarding the aforementioned turbine. Let us consider now that the tank has a maximum active volume $V_{tank,max}$=6,000 m^3 and with an initial available active volume $V_{q,t-1}$=3,000 m^3. If the streamflow q_t is equal to 0.90 m^3/s , i.e. less than q_{min}, then the potential storage volume $proxV_{q,t}$ is calculated equal to 3,000+0.90 m^3/s·3,600 s= 6,240m^3, according to eq. (11), and the period of operation Δt_{opt}, under the design supply q_{des}, equal to 6,240m^3/2.00 m^3/s= 3,120s, according to eq. (12). The turbine can operate under the design supply q_{des} longer than the minimum operating time, as Δt_{opt}=3,120 s> $t_{min,oper}$ =1,500 s, while it cannot interrupt its operation per time step Δt, for time greater than the minimum time of no operation, as Δt-Δt_{opt}=3,600-3,120=480 s< t_{min,no_oper} = 600 s. So this falls under II(c), where the potential discharge that the turbine may exploit $q_{turb,p,t}$ is calculated to be equal to 6,240m^3 / (3,600-600) s =2.08 m^3/s according to eq. (22) (which is less than the maximum operating flow q_{max}=2.40 m^3/s), so the turbine operates with $q_{turb,t}$=2.08 m^3/s, according to eq. (23). That is, initially the tank stores water for t_{min,no_oper} = 600 s, reaching a total volume equal to 3,000+0.90 m^3/s·600 s= 3,540 m^3, which is smaller than the maximum active volume $V_{tank,max}$=6,000 m^3, by eq. (26). Then the stored water is delivered to the turbine for a time period Δt-t_{min,no_oper} = 3,000 s. The turbine operates with $q_{turb,t}$=2.08 m^3/s, where the streamflow q_t provides 0.90 m^3/s and the remaining flow is provided by the tank. At the end of the time step Δt=1h, the stored volume of the tank $V_{q,t}$ changes, according to eq. (24), to 0 m^3 and there is no overflow, as per eq. (25).

3. Cost Analysis of SHPP with Storage Tanks

In order to ensure financial viability, the technical and economic characteristics of the infrastructure and their mathematical expression should be determined. In the following sections, the parameters for the applied techno-economic assessment are presented.

3.1. Technical parameters of tanks

The parameters to be considered during cost estimate, in this case, are the features of the storage tank, such as the material of construction, the quality of the material (mechanical strength), the geometric characteristics (volume, height, bottom area and shape formation), possible reinforcement (steel bars) as well as additional layers of material for strength and stability.

The material of the tank can vary from reinforced concrete to metal or plastic. Each case has different advantages and disadvantages, depending on usage and treatment. In Table 1 some of the main differences for the mentioned material types of storage tanks, are cited. The weather conditions, the nature of the stored material (water) as well as the isolated location of run-of-river SHPPs lead to the selection of the most suitable material for the storage tank. Concrete tanks are considered the most appropriate choice, since they perform better, in terms of durability, maintenance, capacity, resistance to weather conditions and endurance through time are considered as the most appropriate choice.

Table 1: Main differences between reinforced concrete, metal and plastic storage tanks

Aspect	*Concrete tanks*	*Metal tanks*	*Plastic tanks*
Durability	Long-lasting, resistant to corrosion	Durable but prone to rust if untreated	Less durable, UV-sensitive over time
Cost	High initial cost	Moderate cost	Generally low cost
Maintenance	Low maintenance, but repairs are costly	Requires coating for corrosion resistance	Minimal maintenance
Installation	Complex, requires specialized labor	Moderate complexity, requires specialized study and labor for big volumes	Easy to install
Capacity	Suitable for large-scale storage	Wide range of sizes available	Ideal for small to medium storage
Weight	Very heavy	Heavy but lighter than concrete	Lightweight, easy to transport
Resistance to Weather	Excellent heat and fire resistance	Good but varies by coating	Can degrade under extreme UV or heat
Environmental Impact	High due to cement production	Moderate, recyclable	Lower, but not easily recyclable
Typical Life-Cycle (Years)	40–60+	20–40	10–25
Factors Affecting Life-Cycle	Proper design, quality of concrete, exposure to chemicals, and maintenance	Type of metal (e.g., stainless steel vs. galvanized), corrosion protection, coatings	UV exposure, type of plastic (e.g., HDPE), exposure to chemicals, temperature extremes

A typical suitable quality of concrete for a storage tank is C25/30. Moreover, the reinforcement of the tank with steel bars follows the analogy of 100 kg steel per m^3. Regarding its geometric features, it is reasonable to conceive a square base, where the only dimensions that need to be determined are those of height and side of base. These dimensions of the storage tank are related to its maximum volume $V_{tank,max,k}$, where the total capacity of storage $V_{tank,max}$ is equal to:

$$V_{tank,max} = \sum_{k=1}^{n} V_{tank,max,k} = \sum_{k=1}^{n} A_k \cdot H_{tank,k} \tag{27}$$

where, n is the total number of similar tanks, in case of a group (n=1 when only one tank is needed), A_k the area of k-th tank and $H_{tank,k}$ the height of k-th tank.

The selected maximum capacity of the tank arises from the percentage c_{tank} (%) of the average daily volume of the river $V_{daily,average}$ according to:

$$c_{tank}(\%) = 100\% \cdot V_{tank,max}/V_{daily,average} \tag{28}$$

It is noted that the average daily volume of the river $V_{daily,average}$ emerges from the available historic data of inflows. Depending on the selected tank capacity, the alternative of a group of tanks may be opted for, instead of an unreasonably big one, in accordance with eq. (27). In that case, the number of tanks will result from the selected height, bottom area and desired storage capacity. The height should take values within a reasonable range, for purposes of accessibility, maintenance and construction.

In the instance of concrete tank, it is also important to consider the addition of a blanketing layer of Crushed Quarry Material (CQM), as well as the appliance of an unreinforced concrete (C12/15) layer. The CQM layer can be easily compacted, providing thus a stable base that evenly distributes the load of the structure. The above contributes to the minimization of the differential settlement (load distribution) and ensures that the structure remains level. On the other hand, the unreinforced concrete layer offers a smooth, protective flat surface over which the tank can be laid with precision.

3.2. Total investment cost of concrete tanks

The Total Investment Cost (*TInvC*) of each concrete task must be calculated, so as to examine the financial viability of the investment. This is achieved by taking into consideration the respective costs of concrete C_A, unreinforced concrete layer C_B, blanketing layer C_C, reinforcement steel C_D, as well as the percentage surcharge coefficients due to contractor's expenses and benefits p_c, unforeseen construction work p_u, taxes p_{VAT}:

$$TInvC = (C_A + C_B + C_C + C_D) \cdot (1 + p_c) \cdot (1 + p_u) \cdot (1 + p_{VAT}) \tag{29}$$

3.3. Economic criteria

The goal of this study is to estimate the storage capacity which provides the maximum energy production and profit at the lowest possible cost, thus increasing the operator's total profit. In order to evaluate different possible scenarios of storage, three Key Performance Indicators (KPIs) are used:

- Net Present Value (NPV), which is calculated by:

$$NPV = -TInvC + \sum_{t'=0}^{n_T} {NC_{t'}}\Big/{(1+i)^{t'}} \tag{30}$$

where, t' is the time period, n_T the economic lifespan, i the discount rate, $NC_{t'}$ the net cashflow at period t'.

- Internal Rate of Return (IRR), which is the discount rate that makes the NPV equal to zero:

$$0 = -TInvC + \sum_{t'=0}^{n_T} {NC_{t'}}\Big/{(1+IRR)^{t'}} \tag{31}$$

- Benefit- Cost ratio (B/C), which is calculated by:

$$B/C = \sum_{t'=0}^{n_T} {B_{t'}}\Big/{(1+i)^{t'}} \Bigg/ \sum_{t'=0}^{n_T} {C_{t'}}\Big/{(1+i)^{t'}} \tag{32}$$

where, $B_{t'}$ is the benefit (cash inflows) at period t', $C_{t'}$ the cost (cash outflows) at period t'.

It is noted that net income results from the product of the electricity sold, E, at selling price c_{kWh}, reduced by a percentage due to taxes and other proportional expenses p_o, as well as from any annual fixed expenses C_{anc}:

$$NC_{t'} = E_{t'} \cdot c_{kWh,t'} \cdot (1 - p_o) - C_{anc,t'} \tag{33}$$

Accordingly, the income and expenses for (32) are formed.

Eqs. (29) to (32) are applied for different storage capacities to support the evaluation of each case's profitability.

3.4. Sensitivity analysis

The economic return of the proposed SHPP will be determined by establishing a relationship between the electricity prices and the resulting revenue. To assess how strongly the price at the electricity market impacts on the model's income, a sensitivity analysis needs to be applied for different energy market prices, investment costs, discount rates and economic lifespans. The comparison of the KPIs for different cases will express the sensitivity of the investment to ups and downs in the trading market.

4. Case Study

4.1. Study area

The selected SHPP of the present case study is a typical run-of river plant, located at Argyri (see Fig. 2) on Platanias River, tributary of the Achelous, in Thessaly. Its augmented operation with storage is examined by running simulations of eleven different design scenarios. Main goal of the study is to detect the most cost-optimal capacity for the storage tank. In each simulation, the *proposed operation rule of SHPP with storage* is applied to calculate the additional energy production which can be achieved. Specifically, the algorithm is built emphasizing on the inflows, which are left unutilized under the current operating scheme of the SHPP. To represent more accurately the performance of the plant, the rule of operation considers the minimum operating times and non-operation times of the electromechanical equipment. The two time parameters are considered to be of great significance, during the development of the algorithm.

Fig. 2. Layout of existing SHPP, at the Argyri area, of river Platanias, Greece.

4.2. Hydrological characteristics

Before proceeding to the analysis of the 11 tested scenarios, it is fundamental to specify the hydrological and technical characteristics of this case study. The daily inflow data refer to a five-year period, from 2017 to 2021 (see Fig. 3). In this analysis, an hourly step is considered, regarding the simulation of inflows arriving at the intake. This fine temporal discretization is essential for the efficient running of the algorithm, since the regulation of the storage tank is chosen to be in a daily basis. In order to extract the hourly inflows from the given daily values, it is assumed that the inflows follow a linear pattern.

The approximate hourly inflows are used as input data to the developed operation rule of the SHPP with storage. The regulation is applied for eleven scenarios, in terms of tank capacity. For each scenario, the benefits in energy production due to storage are examined. Main purpose of the tank is to ensure the most efficient management of the incoming flows, meaning the reduction of the volume of water that goes unexploited, having taken into account the environmental flow requirements. As already mentioned, the quantities which are left unused are those below of q_{min} and over q_{max}. The first ($q_t<q_{min}$) occurs more frequently since the second ($q_t>q_{max}$) occurs during extreme weather conditions, causing floods.

First of all, the environmental flow to be released downstream of the intake is examined. After applying the Greek legislation methodology, the environmental flow results as equal to 50% of the mean discharge of September. The latter is equal to 0.149 m^3/s, considering the daily inflows of the given period (2017-2021). The accumulated streamflow is diverted from the intake to a forebay tank, through an open channel, and later, through a penstock, is lead to the powerhouse.

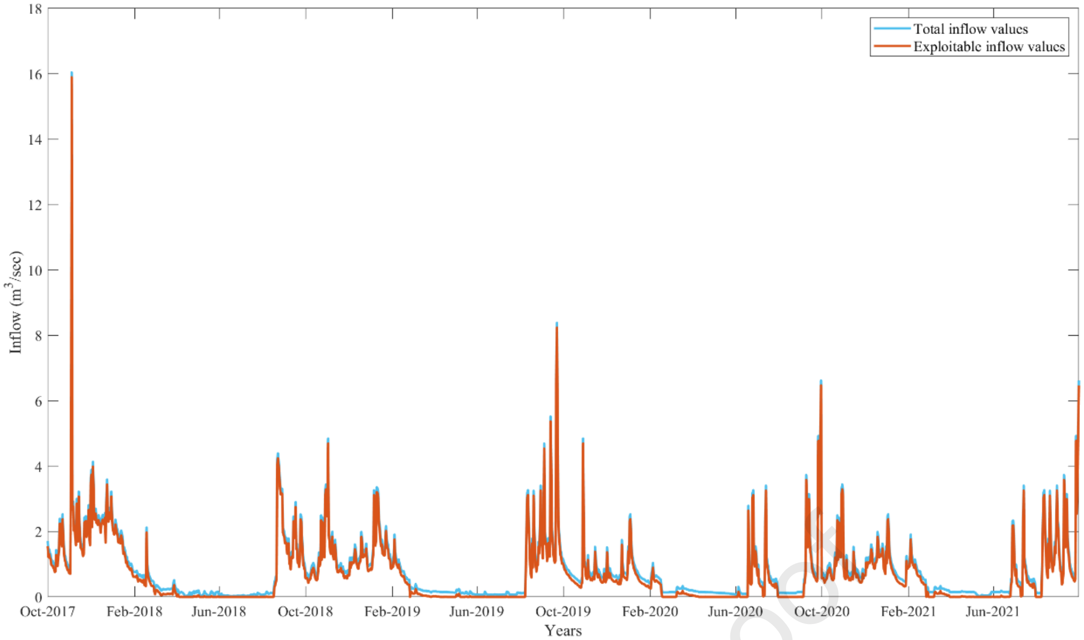


Fig. 3. Daily inflows at Argyri area of Platania river from 2017 to 2021.

4.3. Technical characteristics for electromechanical equipment

The run-of river SHPP is equipped with a 6-nozzle Pelton turbine of 6.904 MW nominal capacity. The elevation difference between the water intake and the power station, known as gross head H_{gross}, is 310 m, while the net head H_{net}, i.e. after subtracting hydraulic losses, is estimated at 300 m and is considered constant. The operation range of the turbine is defined by the minimum q_{min} and maximum discharge q_{max}. The inflow values which do not fall within these limits cannot offer additional energy production. In the examined case the Pelton turbine has as the lower limit of operation the value of q_{min}=0.27 m^3/s and as for upper limit the value of q_{max}=2.40 m^3/s. The design discharge of the turbine, meaning the value under which the efficiency becomes maximum, is equal to q_{des}=1.50 m^3/s. Additionally, the SHPP includes a synchronous generator with nominal apparent power equal to 7,893 kVA, nominal active power of 6,709 kW, frequency of 50 Hz, and inductive power factor of 0.85.

The total efficiency of the plant is derived from the product of the individual efficiencies of the turbine, generator and transformer. In particular, the turbine efficiency depends significantly on the water supply and the elevation difference, while the generator and transformer efficiencies can be considered relatively stable (especially their product, when the technical minimum of the water supply does not take small values) according to [38]. In the present case, the efficiency of the generator was obtained as the weighted mean value with respect to the generator loading percentage, considering the values provided by the manufacturer, considering power factor cosφ=0.85 (Table 2, third column), thus resulting equal to 0.9618. The transformer efficiency was also considered constant and equal to 0.99. Certain characteristic values of the turbine efficiency and the system total efficiency are provided in Table 3. Through the utilization of the calculated values of Table 3, an analytical relationship of the total efficiency η_T, of the power generation unit is obtained, based on the least squares method (see also Fig. 4).

$$\eta_T = -0.0053 \cdot q_t^2 + 0.0159 \cdot q_t + 0.8581 \tag{29}$$

Table 2: Synchronous generator's efficiency for different percentages of apparent power output, for two power factors

Percentage of nominal apparent power	Efficiency of generator	
	Power factor $\cos\varphi$=1	Power factor $\cos\varphi$=0.85 (inductive)
100%	97.80%	97.30%
75%	97.50%	97.10%
50%	96.70%	96.40%
25%	94.10%	93.90%

Table 3: Pelton turbine's efficiency for various values of discharge and SHPP's total efficiency for inductive power factor equal to 0.85

Discharge (m^3/sec)	Turbine efficiency	Total efficiency
2.40	0.906	0.866
1.80	0.910	0.870
1.20	0.910	0.870
0.60	0.906	0.866

4.4. Technical characteristics of concrete tank

If the total volume capacity $V_{tank,max}$ is given, the geometrical properties of the proposed installation are suggested, which means the number of the reinforced concrete (C25/30) tanks and their dimensions (height and base area). For a typical tank the base is a square of 20 x 20 m^2. The thickness of the walls and bottom in all cases is assumed to be the same and equal to 0.50 m and 0.60 m, respectively. The proposed height of each tank H_{tank} (m) is selected to vary between the values of 1.0 and 4.5 m, for purposes of accessibility, maintenance and construction ease. The number of tanks results from the selected height of tanks and the desired total capacity of storage. The reinforcement for each tank follows the rule of 100 kg steel bars per m^3. Finally, for each tank the technical works, along with their equivalent costs, the application of blanketing layer of Crushed Quarry Material (CQM) with a thickness of 0.5 m, below storage installation, as well as the addition of an unreinforced concrete (C12/15) layer, of 0.15 m thickness, are considered.

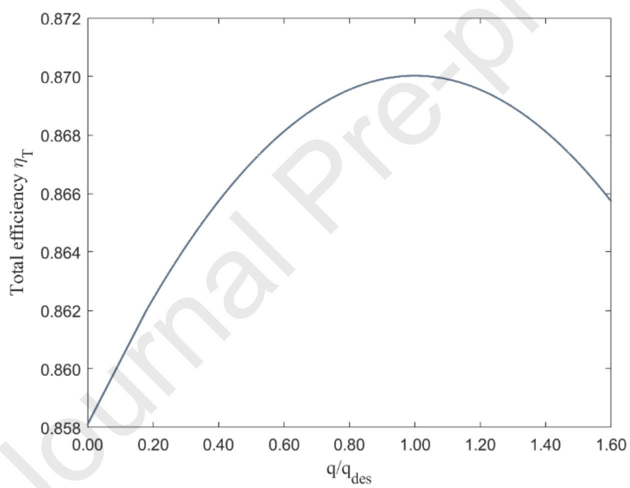


Fig. 4. Approximated total efficiency curve with respect to q/q_{des} ratio

4.5. Economic parameters

The costs related to the concrete tanks are analyzed below, at July 2023 prices. Specifically, the cost of concrete C25/30 is equal to 95.5 €/m^3, of the unreinforced concrete C12/15 layer is equal to 79.5 €/m^3, of the blanketing layer of CQM is equal to 14.85 €/m^3, of the reinforcement steel is equal to 0.94 €/kg, which multiplied by the respective quantities, render the C_A, C_B, C_C, C_D costs, respectively. The percentage surcharges due to contractor's expenses and benefits p_c, due to unforeseen works p_u, due to taxes p_{VAT} are 18%, 9% and 24% respectively.

Additionally, in an effort to examine the sensitivity of the power plant's operation in relation to the cost of electricity, two cases are examined, by setting c_{kWh} = 0.114 €/kWh in the first case (I), and by assigning a 20% higher price in the second case (II). The reduction percentage due to taxes and other proportional expenses p_o is 15%. This means that the net cost of selling energy is 0.097 €/kWh in case (I) and 0.116 €/kWh in case (II). The electricity price was chosen to be studied from the perspective of sensitivity analysis, since it is considered to be one of the parameters that mostly affect the SHPP's feasibility [39]. Moreover, the annual fixed costs C_{anc} for possible works of maintenance and/or additional technical visits due to the existence of the tanks are €2,400.

4.6. Storage scenarios for evaluating the performance of the SHPP

Next step is the simulation of eleven scenarios of different storage capacity $V_{tank,max}$ through the proposed regulation scheme. The different volumes of each scenario are expressed as a percentage c_{tank} (%) of the average daily volume passing through the intake of the SHHP.

Firstly, seven main combinations of storage capacity are examined, as presented in Table 4. The percentages of the average daily volumes c_{tank} (%), which are proposed, vary from 2.5 to 50.0%. The operation rule is simulated through the above seven scenarios, as has been already indicated. By calculating the surplus in energy production and evaluating the *NPV*, *IRR* and *B/C* values of each scenario (using (25) to (27)), the optimal region of storage capacity is determined.

Table 4: Geometrical parameters for the seven investigated scenarios

No. Scenario	c_{tank} (%)	$V_{tank,max}$ (m^3)	Number of tanks	H_{tank} (m)
Sc_1	2.5	1,542	1	4.0
Sc_2	5.0	3,084	2	4.0
Sc_3	10.0	6,169	4	4.0
Sc_4	15.0	9,253	6	4.0
Sc_5	20.0	12,337	7	4.5
Sc_6	25.0	15,422	9	4.5
Sc_7	50.0	30,844	18	4.5

This results in more scenarios being selected to be examined around the area of optimal tank design. The calculations show that the above area is located between scenarios 1 and 2 (c_{tank} =2.5 to 5.0%). Therefore, four more scenarios are generated, as shown in Table 5 along with their characteristics, and the simulation procedure is executed once again. The geometrical and structural characteristics of the additional four scenarios follow the same principles, as presented above for the seven scenarios.

Table 5: Additional scenarios of storage capacity, located in the optimal area of design

No. Scenario	c_{tank} (%)	$V_{tank,max}$ (m^3)	Number of tanks	H_{tank} (m)
Sc_A	0.5	308	1	1.0
Sc_B	1.0	617	1	2.0
Sc_C	1.5	925	1	3.0
Sc_D	3.0	1,851	2	2.5

5. Results & Discussion

5.1. Assessment of the operation rule

To highlight the benefits of the proposed methodology, it is necessary to examine the extent to which the exploitable discharge is increased, with the addition of storage.

To this end, Fig. 5, represents the results of the operation rule simulation, in the Sc_D scenario. The Sc_D scenario is chosen as an average option among the examined scenarios, regarding its performance. Through the selected simulation, the operation of the turbine along with the storage tank are tested, according to the above presented methodology (paragraph 2.3). By using as reference, a characteristic spring day (31 May 2018), the additional volume that can be exploited due to storage addition is evaluated. The flow regime during this season is considered to show a more varying profile, since snow has already begun to melt away as runoff, thus leaving for the following months low streamflow accompanied by sporadic flood events. As indicated by Table 4, when the available volume, stored in the tank through previous steps, is sufficient enough to set the turbine on, the corresponding discharge is released to the turbines and additional energy is produced. The time constraints of minimum operation $t_{min,oper}$ and no operation t_{min,no_oper} duration, of 25 min and 5 min, respectively, define when the turbine will be able to exploit the available stored volume. Through the presented event analysis, it becomes obvious how the storage system can enhance energy production, by benefiting from the gathered volume of water, through successive periods.

It is of note the fact that the integration of a storage system to an existing RES can expand its energy supply capacity, always respecting the downstream environmental requirements at the riverine and riparian area. Furthermore, a tank as storage system, instead of battery, allows for the utilization of flows, otherwise unexploited, during maintenance or of low water supply that could not activate the turbine. In fact, the latter is only feasible through water storage. However, flood flows cannot be utilized, to avoid the entrance of large amounts of sediments.

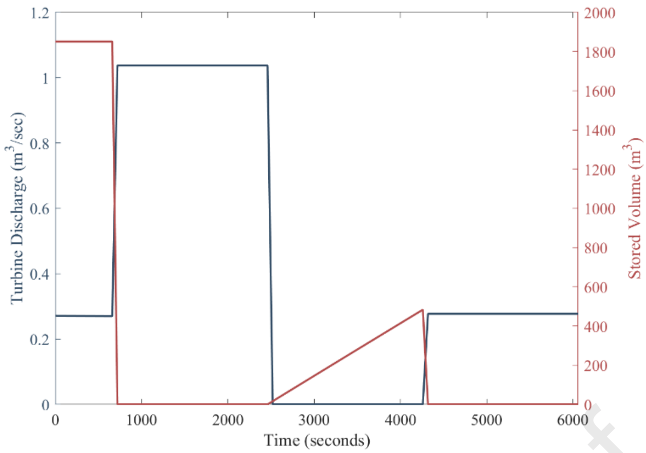


Fig. 5. Results of turbine's simulated operation, in terms of exploited discharge, on 31th of May 2018 for scenario Sc_D

5.2. Techno-economic assessment

The most profitable scenario among the examined cases is determined after considering for each one, the following values:

a. the benefit due to additional energy production (surplus)
b. the Total Investment Cost (*TInvC*), including the VAT,
c. the Net Present Value (*NPV*)
d. the Internal Rate of Return (*IRR*) and
e. the Benefit-Cost ratio (*B/C*).

The implementation of the presented operation rule for the performance of an SHPP combined with a storage tank, leads to the augmented energy production, as shown below in Table 6. As is expected, the scenarios with the largest storage capacity promise higher surplus of production. However, it is essential to highlight that a larger storage system is not necessarily the optimal solution, since an increase in capacity leads to higher capital cost. The latter is defined after considering approximately values for the unit costs regarding the works for the storage installation.

After considering the geometrical features for the eleven proposed schemes, the quantities of the required structural materials are shown in Table 7. At the same time, the total investment cost *TInvC* is calculated, taking into account the costs per quantity unit and the surcharge coefficients of par. 4.5, through (24), for each scenario. For each of the eleven examined scenarios a techno-economic analysis is conducted. When applying the analysis, the economic lifespan is assumed to be 20 years (n_T=20). Also, by assuming that the construction time of the storage system is negligible within the year, the economic simulation begins to run from the first year. In the calculations the discount rate *i* is assumed at 6% and aims to define the present value of a monetary amount which is planned to be spent or received in the future. In Table 8 the economic benefit due to additional annual energy production and the KPIs (Net Present Value, Internal Rate of Return and Benefit- Cost ratio) for both cases, (I) and (II), are presented. By utilizing the results in Table 8, it results that, in both cases (I) and (II), the optimal scenario is Sc_B, for which the tank structural features, energy and economic data are listed as follows:

- one tank of 2 m height;
- storage capacity of 617 m^3, which corresponds to 1% of the mean daily streamflow;
- surplus in annual energy production 523,452 kWh;
- economic benefit due to surplus, € 50,775 (case I) and € 60,930 (case II);
- NPV € 436,493 (case I) and € 552,969 (case II);
- IRR 40.83% (case I) and 49.43% (case II);
- B/C ratio 3.99 (case I) and 4.79 (case II).

Table 6: Results of energy production for the 11 scenarios in both current and examined operation, and the surplus due to storage installation

No. Scenario	Current energy production (kWh)	Energy production with storage system (kWh)	Surplus of energy production (kWh)
Sc_A	14,391,746	14,843,244	451,498
Sc_B	14,391,746	14,915,198	523,452
Sc_C	14,391,746	14,915,974	524,228
Sc_1	14,391,746	14,917,524	525,778
Sc_D	14,391,746	14,918,017	526,271
Sc_2	14,391,746	14,918,017	526,271
Sc_3	14,391,746	14,921,918	530,172
Sc_4	14,391,746	14,926,460	534,714
Sc_5	14,391,746	14,930,218	538,472
Sc_6	14,391,746	14,934,996	543,250
Sc_7	14,391,746	14,955,342	563,596

Table 7: Structural features and total costs of the storage installation for the 11 scenarios

No. Scenario	Concrete volume of tank or tanks (m^3)	Unreinforced concrete volume (m^3)	CQM volume (m^3)	Steel bars (kg)	Total investment cost *TInvC* (€)
Sc_A	305.6	66.2	220.5	30,560.0	105,972
Sc_B	346.6	66.2	220.5	34,660.0	118,363
Sc_C	387.6	66.2	220.5	38,760.0	130,755
Sc_1	428.6	66.2	220.5	42,860.0	143,146
Sc_D	734.2	132.3	441.0	73,420.0	249,118
Sc_2	857.2	132.3	441.0	85,720.0	286,292
Sc_3	1,714.4	264.6	882.0	171,440	572,584
Sc_4	2,571.6	396.9	1,323.0	257,160	858,876
Sc_5	3,143.7	463.1	1,543.5	314,370	1,045,393
Sc_6	4,041.9	595.4	1,984.5	404,190	1,344,076
Sc_7	8,083.8	1,190.7	3,969.0	808,380	2,688,152

Table 8: Economic benefit of each scenario and KPIs for the sensitivity analysis cases (I) and (II)

	Case (I): $c_{kWh\ (I)}$=0.114 €/kWh, p_o=15% → net cost of electricity 0.097 €/kWh				Case (II): $c_{kWh\ (II)}$=1.20·$c_{kWh\ (I)}$, p_o=15% → net cost of electricity 0.116 €/kWh			
No. Scenario	Benefit due to surplus (€)	NPV (€)	IRR (%)	B/C (-)	Benefit due to surplus (€)	NPV (€)	IRR (%)	B/C (-)
Sc_A	43,795	368,830	39.01%	3.76	52,554	469,295	47.31%	4.52
Sc_B	50,775	436,493	40.83%	3.99	60,930	552,969	49.43%	4.79
Sc_C	50,850	424,964	36.99%	3.68	61,020	541,614	44.80%	4.42
Sc_1	51,000	414,298	33.85%	3.43	61,201	531,292	41.03%	4.11
Sc_D	51,048	308,874	18.92%	2.12	61,258	425,978	23.27%	2.54
Sc_2	51,048	271,700	16.14%	1.87	61,258	388,803	20.02%	2.24
Sc_3	51,427	-10,252	5.78%	0.98	61,712	107,720	8.23%	1.18
Sc_4	51,867	-291,491	1.39%	0.67	62,241	-172,508	3.39%	0.81
Sc_5	52,232	-473,826	-0.5%	0.56	62,678	-354,007	1.40%	0.67
Sc_6	52,695	-767,194	-2.6%	0.44	63,234	-646,312	-0.93%	0.53
Sc_7	54,669	-2,088,633	-7.7%	0.23	65,603	-1,963,224	-6.31%	0.28

In Fig. 6, 7 and 8 the three KPIs are presented in a graphical form, for the eleven examined scenarios, by considering both of the sensitivity analysis cases (I) and (II).

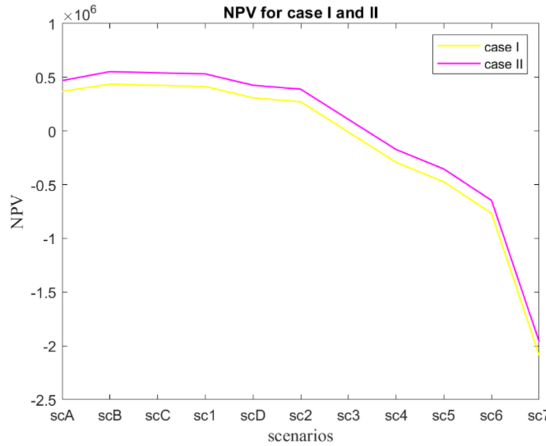


Fig. 6. Net Present Value for the eleven examined scenarios, for two cases of energy cost (I: net cost of electricity 0.097 €/kWh, II: net cost of electricity 0.116 €/kWh).

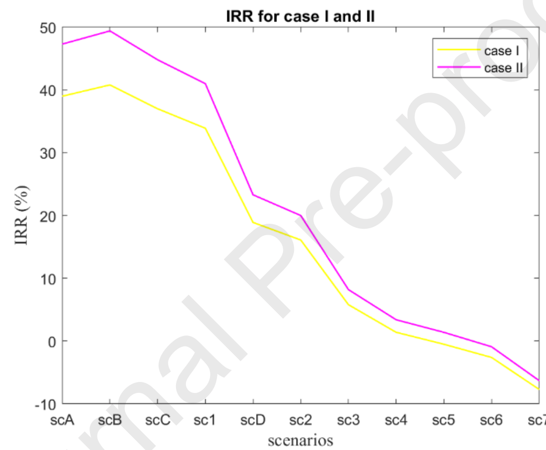


Fig. 7. Internal Rate of Return for the eleven examined scenarios, for two cases of energy cost (I: net cost of electricity 0.097 €/kWh, II: net cost of electricity 0.116 €/kWh).

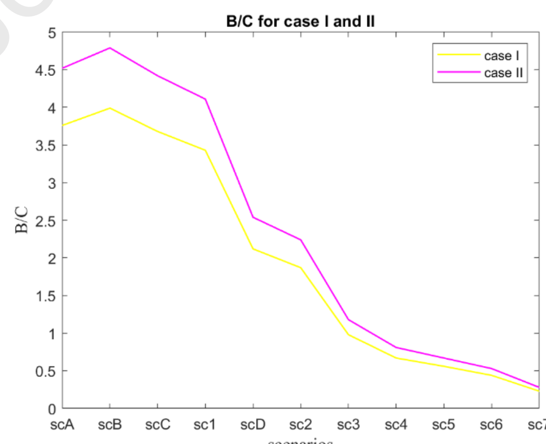


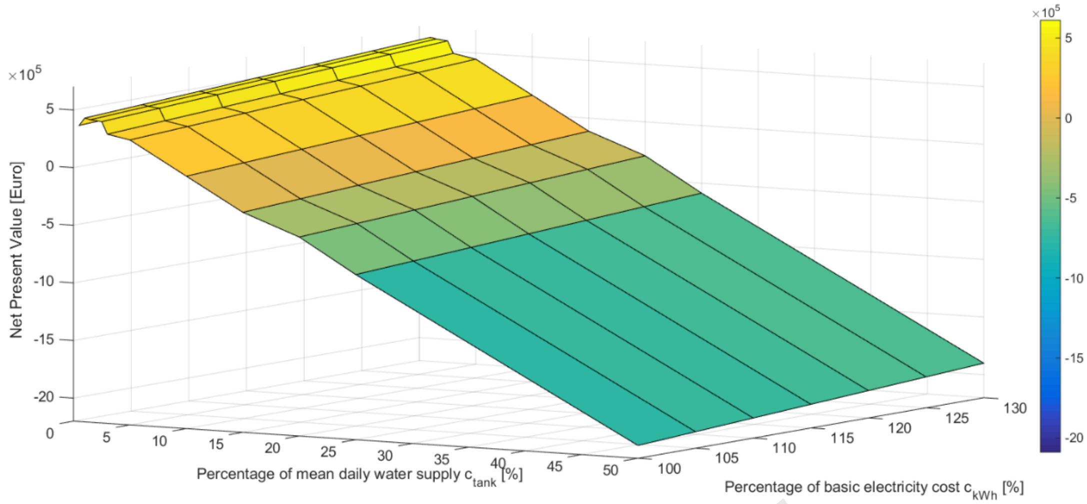
Fig. 8. Benefit to Cost ratio for the eleven examined scenarios, for two cases of energy cost (I: net cost of electricity 0.097 €/kWh, II: net cost of electricity 0.116 €/kWh).

As can be observed from these figures, the area of sustainable investments falls in case (I) between scenarios Sc_A to Sc_2 and in case (II), between scenarios Sc_A to Sc_3, which corresponds to tanks of a 5% and 10% of the mean daily water supply, respectively. Thus, it is concluded that a rise in the selling price of electricity of case II, leads to an additional scenario being financially viable (*NPV*>0, *IRR*>6%, *B/C*>1). Last but not least, from the results of the sensitivity analysis, it is found that by setting a higher price by 20%, it is possible to gain a surplus of annual profit equal to 10,155 €, regarding the optimal scenario.

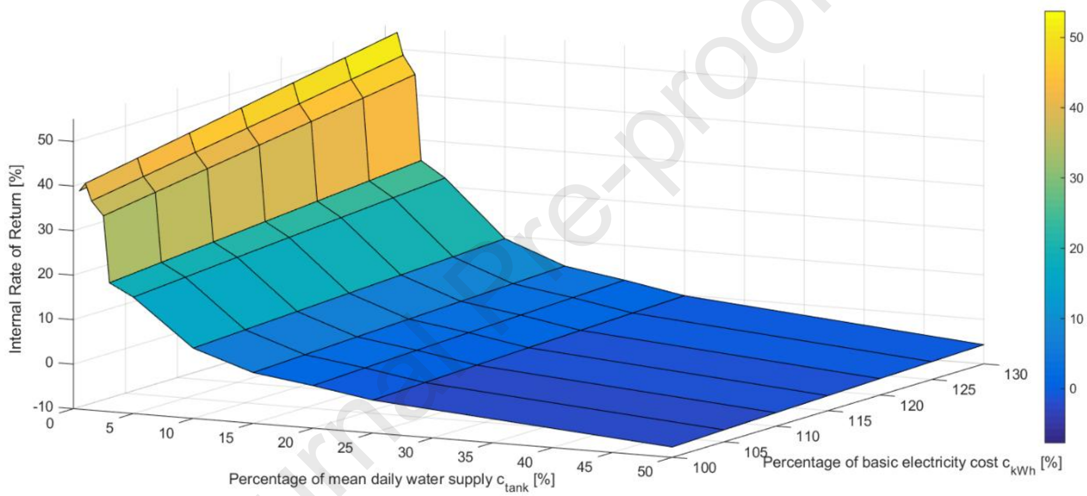
5.3. Sensitivity analysis

Next, a sensitivity analysis is conducted, to examine the financial sustainability of the investment. Specifically, the following are carried out:

- The cost of electricity c_{kWh} varies, from the base value up to +30%, with a step of 5%. The corresponding results improve the area of sustainable investments, as from the acceptable scenarios Sc_A to Sc_2 there is a transition to the scenarios Sc_A to Sc_3 (i.e. a tank volume corresponding to 10% of the mean daily water supply) with an increase in the cost of electricity of only 5%. However, in all cases the best results are observed for the scenario Sc_B, which corresponds to tank of a 1% of the mean daily water supply, as can also be seen in the graphs in Fig. 9 of Net Present Value, Internal Rate of Return and Benefit to Cost ratio in correlation with the cost of electricity c_{kWh} and tank volume, as a percentage of the mean daily water supply.
- The Total Investment Cost *TInvC*, varies from the base value up to +30% with a step of 5%. The corresponding results, with the increase in the Total Investment Cost, present more unfavourable scenarios, as expected, with no change, however, in the optimal scenario (which is still Sc_B), while the area of sustainable investments shows no substantial changes. This is confirmed by the graphs in Fig. 10 of the Net Present Value, Internal Rate of Return and Benefit to Cost ratio Benefit- Cost ratio in correlation with Total Investment Cost *TInvC* and tank volume, as a percentage of the mean daily water supply.
- The discount rate i varies from 2% to 12%, with a step of 1%, having 6% as base value. With the increase in the discount rate, more unfavourable results arise, as expected, with no change in the optimal scenario (which is still Sc_B), while the area of sustainable investments does not present substantial changes. On the contrary, for a discount rate of 5% and below, the area of sustainable investments improves, as from the acceptable scenarios Sc_A to Sc_2 there is a transition to the scenarios Sc_A to Sc_3 (i.e. as a tank volume corresponding to 10% of the mean daily water supply). The above is seen in the graphs of Fig. 11 of the Net Present Value and Benefit to Cost ratio, in correlation with discount rate i and tank volume as a percentage of the mean daily water supply.
- The economic lifespan n_T varies from 6 to 30 years, in 2-year steps, with a base value of 20 years. With the increase in the economic lifespan, better results are obtained, as expected, with no change in the optimal scenario (which is still Sc_B). The area of financially sustainable investments presents minor changes, because for an economic lifespan of 22 years and above, the respective area expands, since from the acceptable scenarios ScA to Sc2 there is a transition to scenarios ScA to Sc3 (i.e. to a tank volume of 10% of the mean daily water supply, instead of 5%). Correspondingly, from 6 years and below, the results deteriorate significantly, as the area of sustainable investments is limited, where from the acceptable scenarios Sc_A to Sc_2 there is a transition to the scenarios Sc_A to Sc_1 (i.e. as a tank volume corresponding to 2.5% of the mean daily water supply). This is seen in the graphs of Fig. 12 of Net Present Value, Internal Rate of Return and Benefit to Cost ratio in correlation with economic lifespan n_T and tank volume as a percentage of the mean daily water supply. It is worth mentioning that the Internal Rate of Return stabilizes for small investment costs, that is, for tanks with small percentages of the mean daily water supply (up to 5%), at the respective value that they have for an economic lifespan equal to 20 years.



(a)



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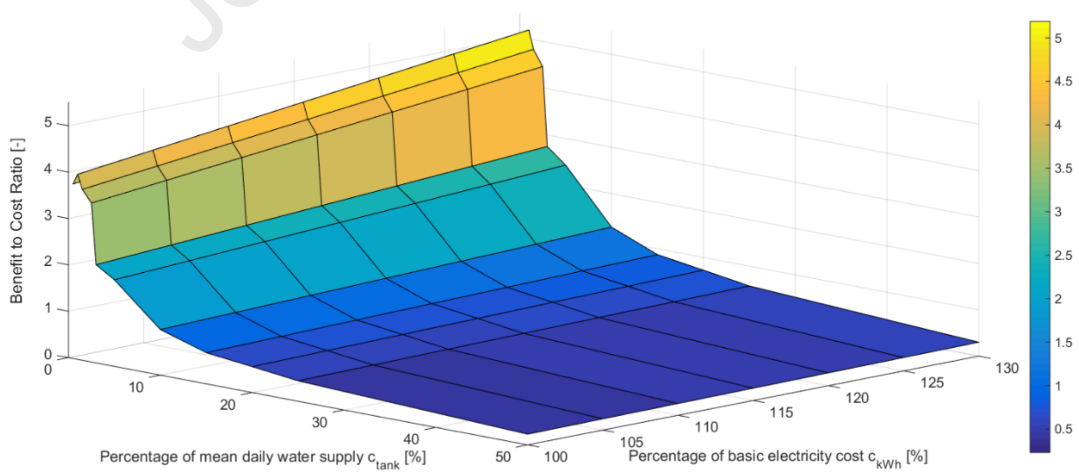
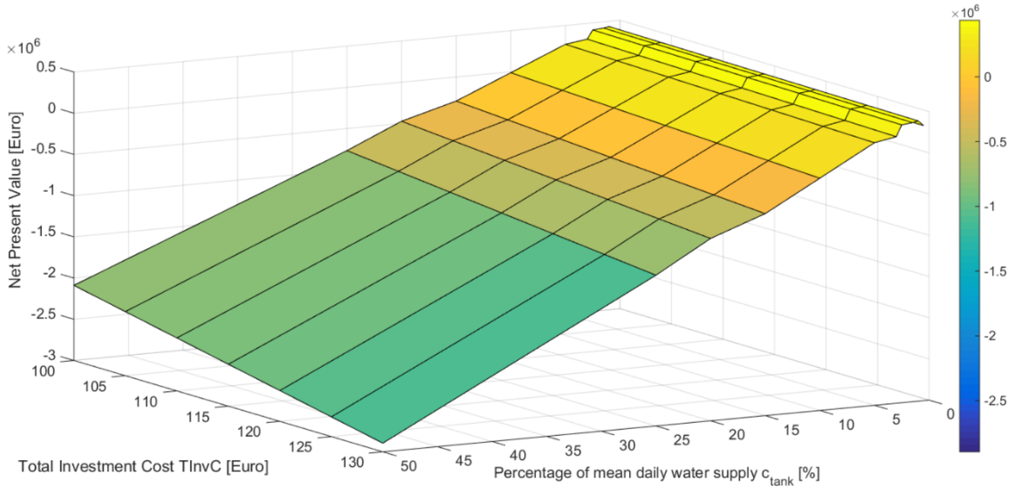
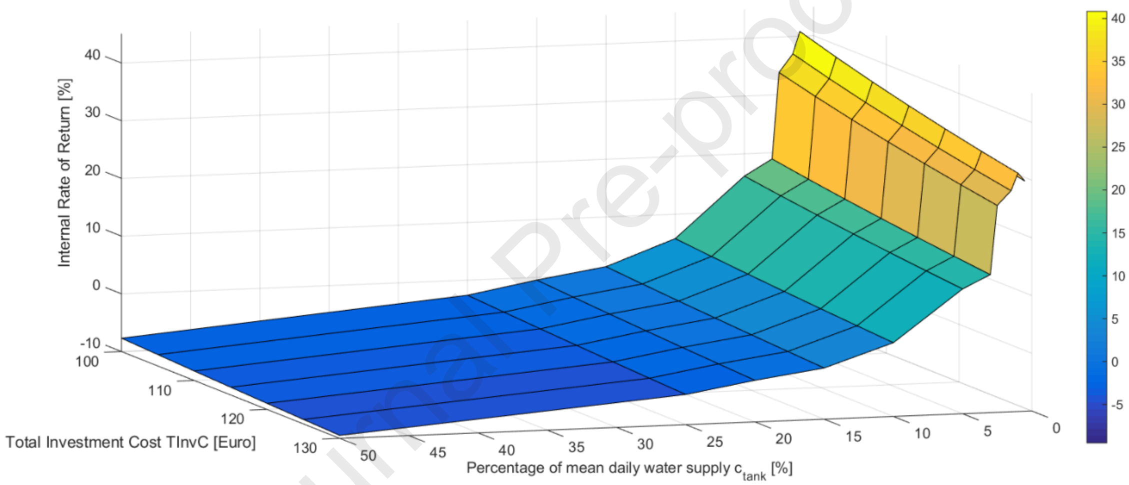


(c)

Fig. 9. (a) Net Present Value, (b) Internal Rate of Return, (c) Benefit to Cost ratio for the eleven examined scenarios of tanks with different percentage of mean daily water supply, for different electricity net cost (100% to 130% of base value).



(a)



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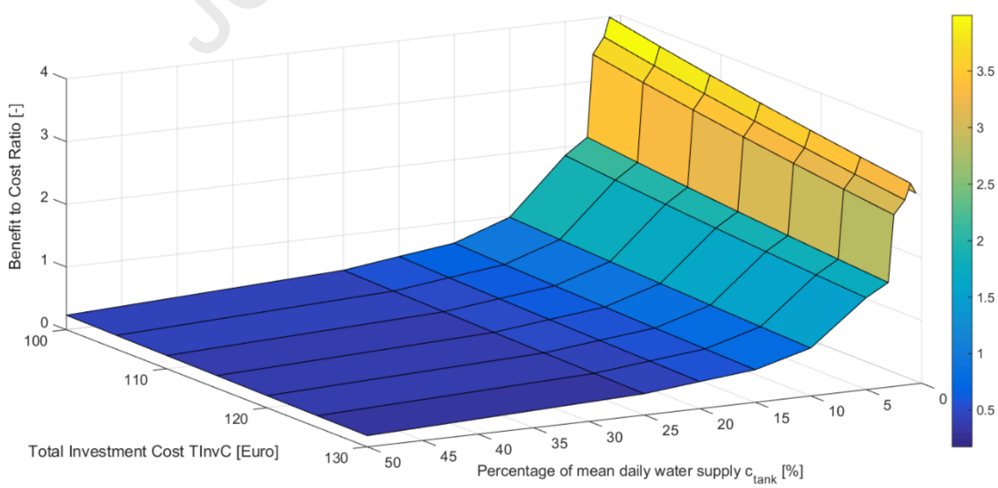
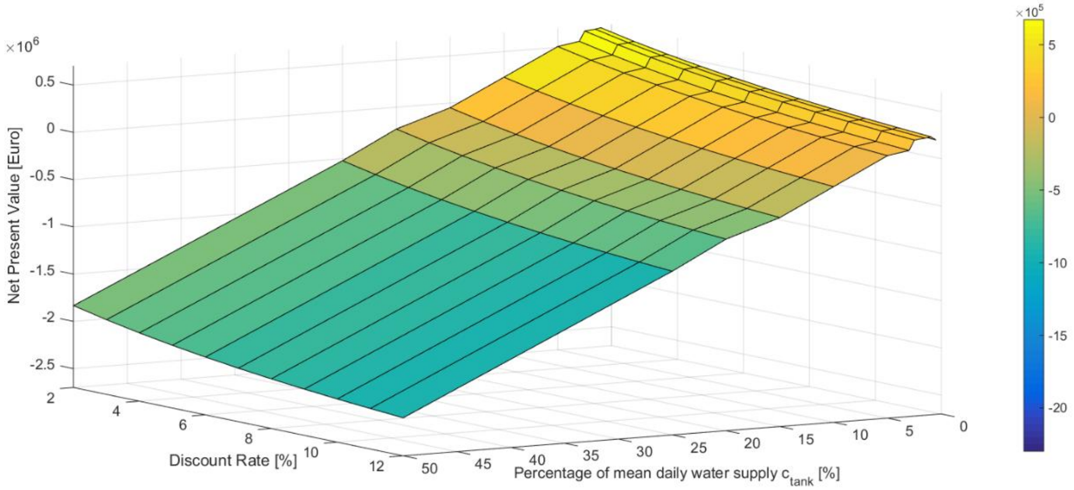
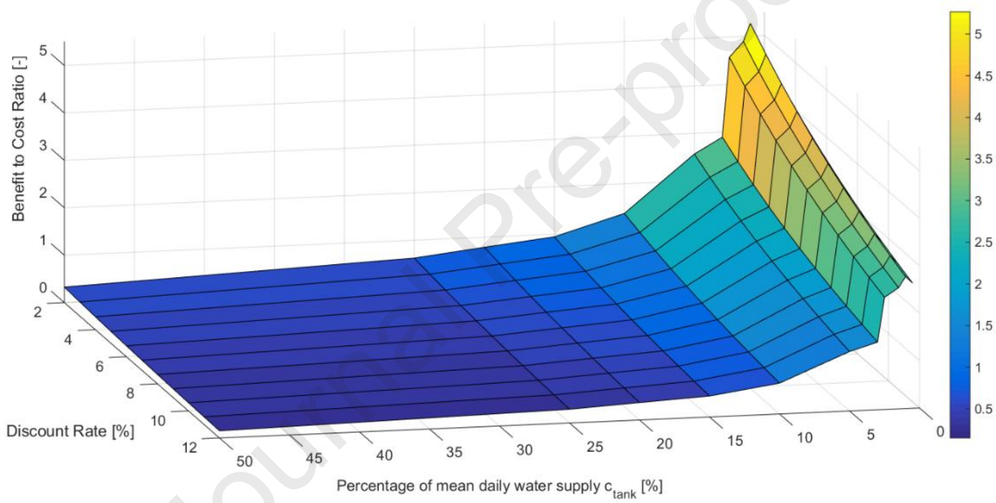


(c)

Fig. 10. (a) Net Present Value, (b) Internal Rate of Return, (c) Benefit to Cost ratio for the eleven examined scenarios of tanks with different percentage of mean daily water supply, for different Total Investment cost (100% to 130% of base value).



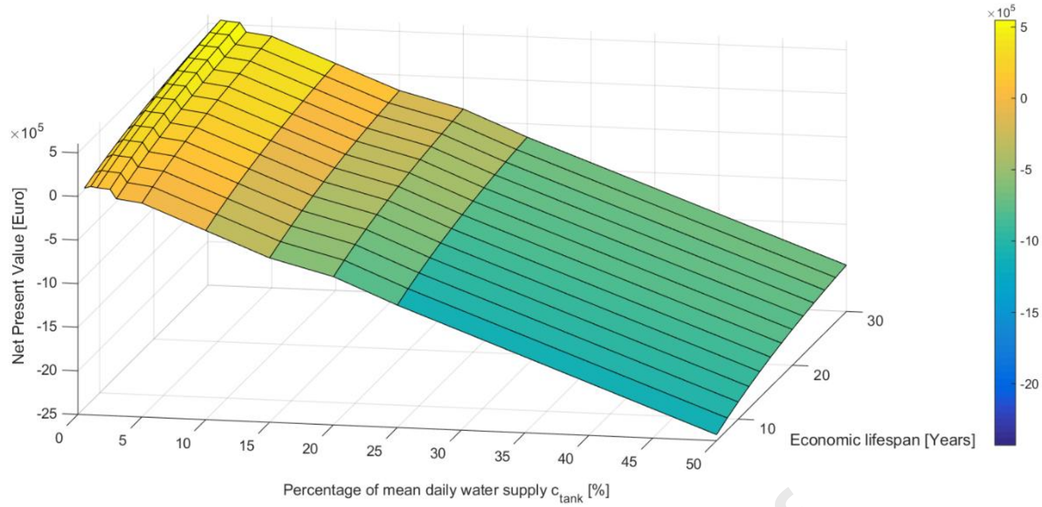
(a)



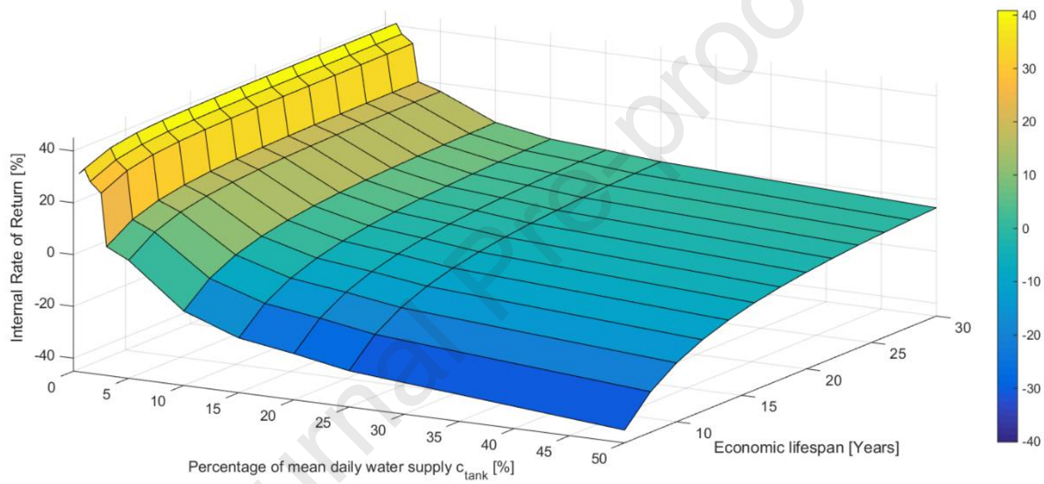
(b)

Fig. 11. (a) Net Present Value, (b) Benefit to Cost ratio for the eleven examined scenarios of tanks with different percentages of mean daily water supply, for different discount rates (2% to 12%).

It is, therefore, ascertained that the best results are achieved for the Sc_B scenario, which corresponds to a tank of a 1% of the mean daily water supply, despite the variations in the above four parameters, demonstrating the economic viability and stability of the proposed solution. This is also confirmed through the combined display of the Net Present Value, Internal Rate of Return and Benefit to Cost ratio as a correlation of the cost of electricity c_{kWh} and Total Investment Cost *TInvC* in Fig. 13, which is characterized by an improvement in the economic indicators as the cost of electricity c_{kWh} increases and the Total Investment Cost *TInvC* decreases. The cost of electricity c_{kWh} is a more critical parameter, since its changes cause greater changes in the economic indicators than the total investment cost. Through the combined display of the Net Present Value and Benefit to Cost ratio (in correlation with the economic lifespan and the discount rate) in Fig. 14, an improvement in the economic indicators is observed, as the economic lifespan increases and the discount rate decreases. In fact, the changes become very pronounced for small discount rate values and great economic lifespan values.



(a)



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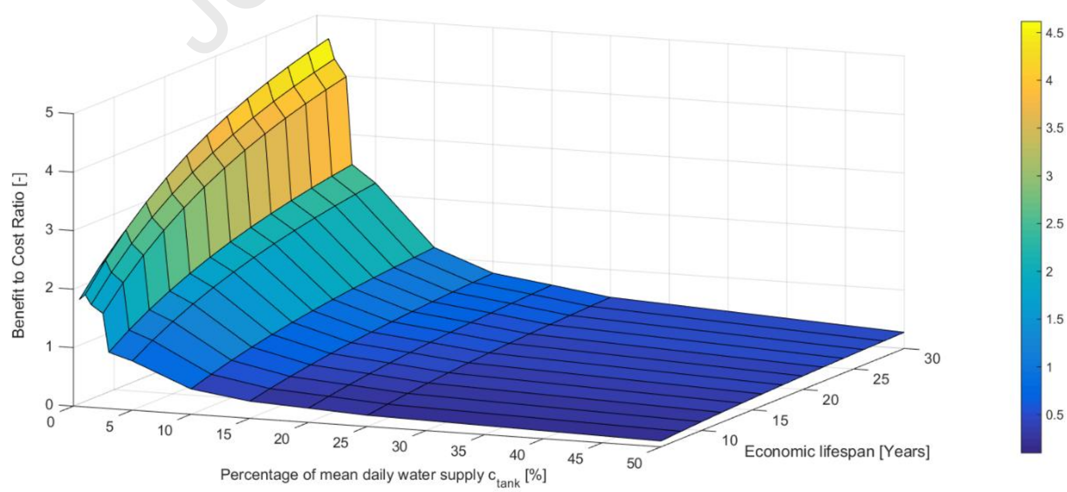
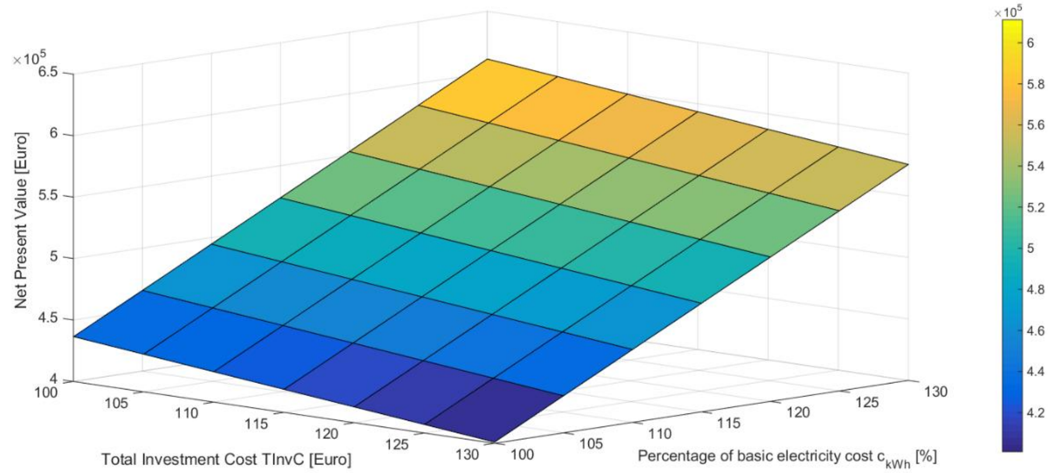
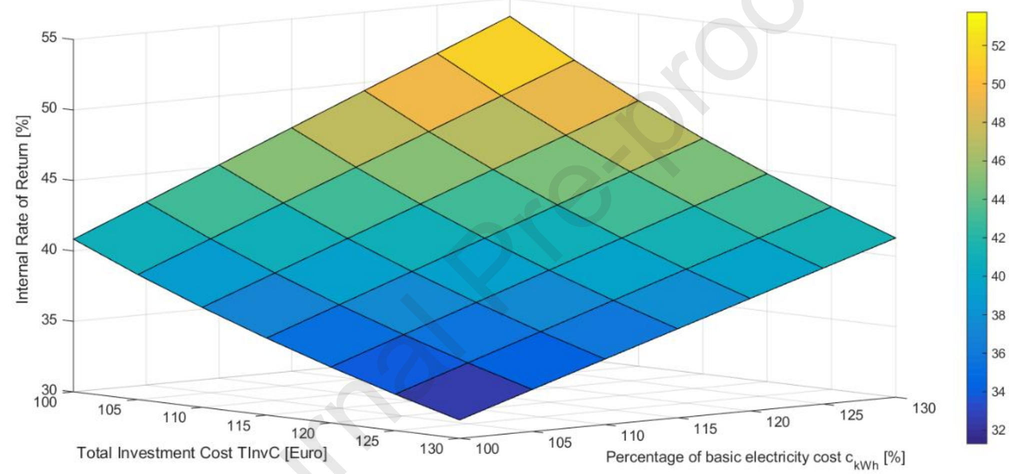


(c)

Fig. 12. (a) Net Present Value, (b) Internal Rate of Return, (c) Benefit to Cost ratio for the eleven examined scenarios of tanks with different percentages of mean daily water supply, for different economic lifespans (6 to 30 years).



(a)



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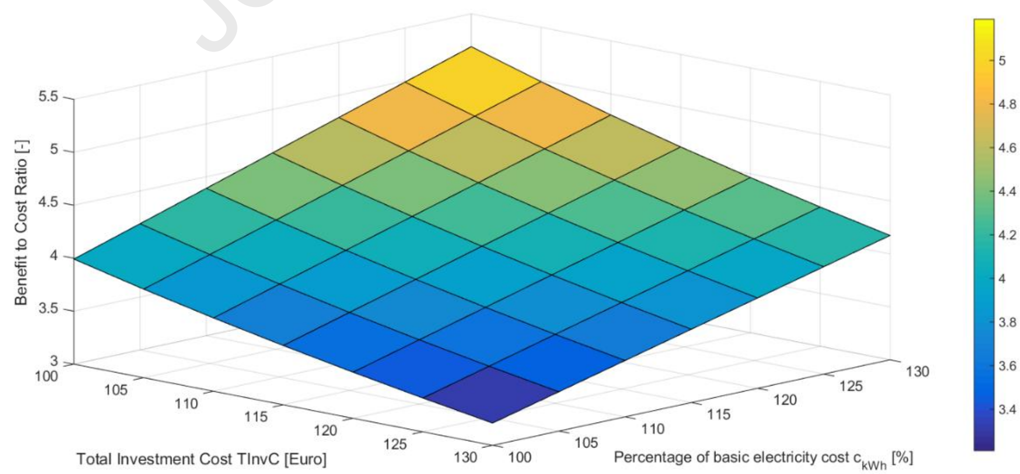
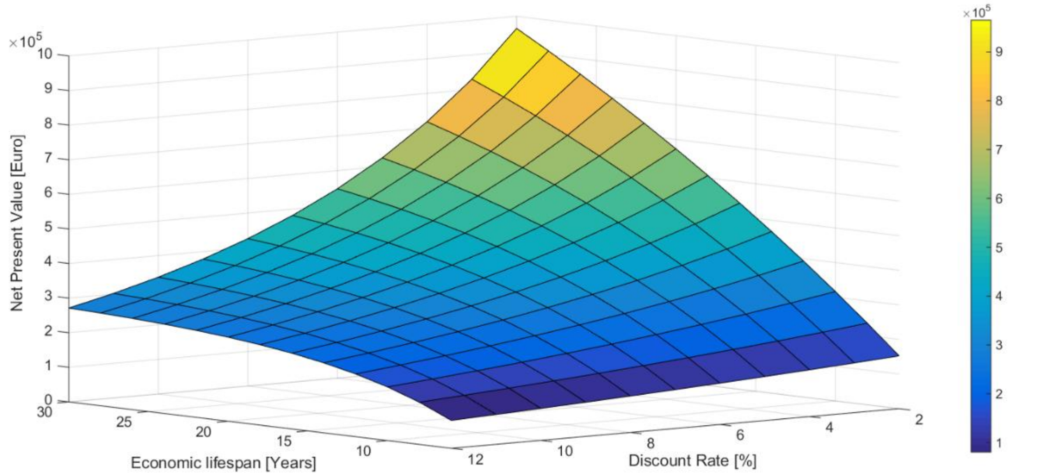


(c)

Fig. 13. (a) Net Present Value, (b) Internal Rate of Return, (c) Benefit to Cost ratio for the scenario Sc_B (tank of a 1% of the mean daily water supply) for different electricity net cost (100% to 130% of base value) and different total investment cost (100% to 130% of base value).



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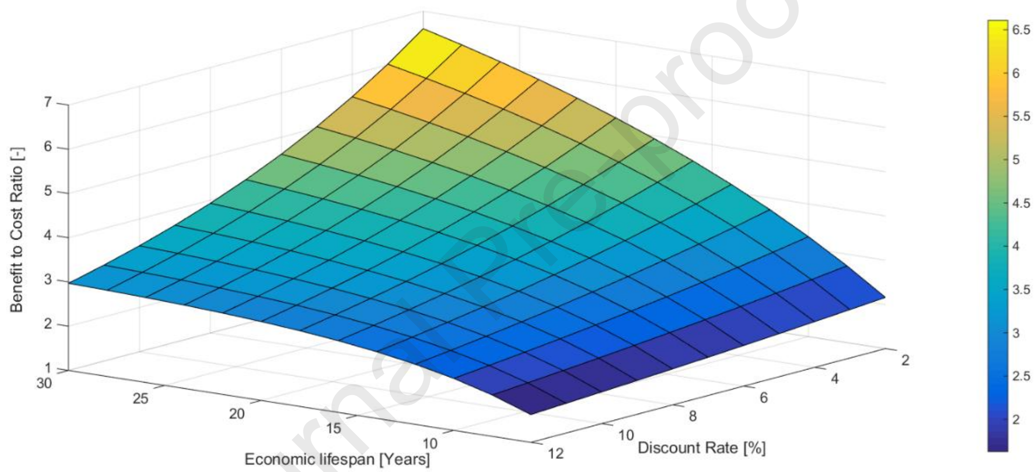

(b)

Fig. 14. (a) Net Present Value, (b) Benefit to Cost ratio for the scenario Sc_B (tank of a 1% of the mean daily water supply) for different economic lifespan (6 to 30 years) and different discount rate (2% to 12%).

6. Conclusions

Hydropower has been one of the most dominant and reliable forms of renewable sources, at the universal scale. Its two main advantages are its flexibility and its immediate response to fluctuations in energy demand. However, the above can be achieved only when a reservoir accompanies the hydropower plant, which is generally not the case for run-of river plants. The present paper examines how to improve the efficiency of this type of power plants, by equipping them with daily-regulated storage facilities.

In this context, an augmented regulation is proposed, regarding the operation of an existing run-of river Small Hydropower Plant (SHPP) of nominal power 6.9 MW, net head 300 m, maximum inflow 2.40 m^3/s at the Argyri area of river Platanias, Greece. Main interest of the study is to evaluate if by implementing a relatively small-scale and thus low-cost storage facility to the plant's equipment, a better control of production in terms of efficiency and revenues can be gained. In this study, an original rule of operation was suggested. This rule takes into account the additional regulative conditions, with which the SHPP with storage must comply.

The results of energy production from the new SHPP's regulation are then examined and compared to the previous ones, where no additional storage was considered. In total, eleven different storage scenarios are tested to select the optimal storage capacity, with rated size based on the flow regime of the studied area.

Three Key Point Indicators (KPIs), *NPV*, *B/C*, *IRR*, are considered as the main indices for selecting the most suitable size for the storage facility. The different costs deriving from the construction of the storage facility, its accompanied works as well as its future maintenance routine along with the gained revenues, are the values which help the authors to quantify the KPIs and eventually to come to a conclusion. Apart from the question of the techno-economic evaluation, a sensitivity analysis is also conducted, for different energy market prices (from 100% to 130% of base value, with a 5% step), total investment costs (from 100% to 130% of base value, with a 5% step), discount rates (from 2% to 12% with an 1% step, and 6% base value) and economic lifespans (from 6 to 30 years, with 2-year steps and 20 years base value). The results of each case are then compared, and the sensitivity (of the volume size of the selected tank) is evaluated, with respect to the four aforementioned parameters. KPIs improve as the cost of electricity and economic lifespan increase, and as the total investment cost and discount rate decrease. Larger changes present for cost of electricity and for the combination of small discount rate values and large economic lifespan values. Financially viable solutions arise when the volume is equal to 5% of the mean daily water supply, for the base values of the aforementioned parameters, while for more suitable combinations the area of sustainable investments extends to tank volumes corresponding to 10% of the mean daily water supply. In case of very small economic lifespan (i.e. 6 years and below) the area of sustainable investments decreases to tank volumes that correspond to 2.5% of the mean daily water supply. Summing up, through the present study, it results that the optimal tank volume is that of 1% of the mean daily water supply with an active volume of 620m^3, a basic cost of 120k€ with a Net Present Value equal to 436 k€, an Internal Rate of Return equal to 40.83% and a Benefit-Cost ratio equal to 3.99, for an economic lifespan of 20 years and a discount rate of 6%. This tank is the optimal choice and economically viable for all cases of changes in the four aforementioned parameters examined in the sensitivity analysis, for all KPIs, with Net Present Value ranging from 80 k€ to 965 k€, Internal Rate of Return from 31.3% to 53.7%, and Benefit-Cost ratio from 1.6 to 6.6, with the higher values being more common.

Future research may focus on further improvements of the proposed configuration, by applying a mixing of turbines with different characteristics, and providing a generic methodology for the simultaneous optimization of power and storage capacities, along with the underlying operational rules. Nevertheless, the overall idea of enhancing the role of small hydropower plants, towards making them more flexible, more reliable and eventually more attractive from the investment's viewpoint, will allow to facilitate their penetration into the energy mix. This shift will also make them more effective compared to other intermittent sources (such as wind and solar), as the quality of the produced energy will maintain a level of reliability similar to the one of conventional sources.

Nomenclature

Abbreviation

B/C	Benefit – Cost ratio
CQM	Crushed Quarry Material
ESS	Energy Storage System
EU	European Union
GHG	GreenHouse Gas
IoT	Internet of Things
IRR	Internal Rate of Return
KPI	Key Performance Indicator
NPV	Net Present Value
PSHP	Pumped Storage Hydropower Plant
RES	Renewable Energy Sources
SHPP	Small HydroPower Plant

Parameters

A_k	Area of *k*-th tank (m^2)
B/C	Benefit - cost ratio (-)
$B_{t'}$	Cash inflows (benefit) at time period t' (€)
C_A	Cost of concrete for walls, roof, floor of tank (€)
C_B	Cost of concrete for unreinforced concrete layer of tank (€)
C_C	Cost of concrete for blanketing layer of tank (€)
C_D	Cost of concrete for reinforcement steel of tank (€)
$C_{anc,t'}$	Annual constant outflows because of storage existence at time period t' (€)
$C_{t'}$	Cash outflows (cost) at time period t' (€)

$E_t^{/}$	Annual energy production by SHPP because of storage (€)
H_{gross}	Gross head - elevation difference between forabay tank and turbine runner outlet (m)
H_{net}	Elevation difference minus hydraulic losses (m)
$H_{tank,k}$	Height of *k*-th tank (m)
IRR	Internal rate of return (%)
$NC_t^{/}$	Net cashflow at time period $t^{/}$ (€)
NPV	Net present value (€)
P	Produced power from SHPP (W)
$TInvC$	Total investment cost (€)
$V_{daily,average}$	Average daily water volume of the river (m^3)
$V_{q,t}$	Volume of the storage tank at time t (m^3)
$V_{tank,max}$	Maximum capacity of the storage tank(s) (m^3)
$V_{tank,max,k}$	Maximum capacity of *k*-th tank (m^3)
$c_{kWh,t^{/}}$	Sell energy cost at time period $t^{/}$ (€/kWh)
c_{tank}	Percentage ratio of maximum capacity of the storage tank(s) to the average daily water volume of the river (%)
$cos\varphi$	Power factor (-)
i	Discount rate (%)
n_T	Economic lifespan (year)
$proxV_{q,t}$	Potential storage volume at time t (m^3)
p_{VAT}	Percentage increase coefficient because of value added tax (%)
p_c	Percentage increase coefficient because of contractor's expenses and benefits (%)
p_o	Percentage decrease coefficient because of value added tax and of proportional costs in relation to the energy produced (%)
p_u	Percentage increase coefficient because of unexpected works (%)
q_{des}	Design flow rate of the turbine unit (m^3/s)
q_{max}	Upper limit of inflows through the turbine unit (m^3/s)
q_{min}	Lower limit of inflows through the turbine unit (m^3/s)
$q_{spill,t}$	Overflow (not passing through the turbine) at time t (m^3/s)
q_t	Inflow at time t (m^3/s)
q_{turb}	Inflow through the turbine unit (m^3/s)
$q_{turb,t}$	Inflow through the turbine unit at time t (m^3/s)
$q_{turb,p,t}$	Potential inflow through the turbine unit at time t (m^3/s)
$spill_t$	Spilled volume as excess at time t (m^3)
t	Time (s, hr)
$t^{/}$	Time period for financial criterions (year)
t_{min,no_oper}	Minimum no operation time of the turbine (s, hr)
$t_{min,oper}$	Minimum operation time of the turbine (s, hr)
Δt	Chosen time step for discretizing the flow data (s, hr)
Δt_{opt}	Time period of optimum operation (s, hr)
$\Delta t_{turb,operation}$	Time period in which turbine produces energy during Δt (s, hr)
γ	Specific weight of water (N/m^3)
η_{GR}	Efficiency of generator (-)
η_T	Total efficiency of SHPP (-)
η_{TR}	Efficiency of transformer (-)
η_{TUR}	Efficiency of turbine (-)

Acknowledgement:

The authors are grateful to Spyridon Gialampidis for his work on the original and revised text versions.

Author contributions:

Korina-Konstantina Drakaki carried out the conceptualization, the data curation, the formal analysis, the investigation, the methodology, the resources, the software, the validation, the visualization, the writing-original draft, the writing – review and editing.
George J. Tsekouras carried out the conceptualization, the formal analysis, the investigation, the methodology, the project administration, the resources, the supervision, the validation, the visualization, the writing-original draft, the writing – review and editing.
George S. Mitsis carried out the formal analysis, the methodology, the writing – review and editing.
Andreas Efstradiadis carried out the data curation, the validation, the visualization, the writing-original draft.
Dimitrios E. Papantonis carried out the conceptualization, the investigation, the methodology, the resources.
Vasilis Riziotis carried out the formal analysis, the methodology, the supervision.

Funding source:

This research was not funded.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: